Modeling of time consumption for selective and situational precommercial thinning in mountain beech forest stands

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Rationalization and optimization of work is becoming increasingly important in the European forestry sector. In this study a tool for modeling three different precommercial thinning approaches in young beech mountain stands was developed based on several field studies. The simulation examines three primary types of precommercial thinning: selective thinning and two types of situational thinning. We studied the impact of the number of candidates/crop trees and the impact of harvesting intensity on the structure and consumption of productive time. We found that in terms of costs situational precommercial thinning is more rational than selective precommercial thinning, that harvesting intensity has a significant impact on time consumption and that the number of candidates or crop trees has a significant impact on time consumption as well as on the relationships between main and auxiliary productive time. The modeling has shown that situational thinning is an alternative to selective thinning and that, in addition to requiring smaller and more efficient harvesting machines, it offers a cost-effective and ergonomic option (more walking, less chainsaw operation) for the pre-commercial thinning of young forest.

Keywords: Precommercial Thinning, Selective Thinning, Situational Thinning, Modeling, Crop Tree

Introduction

Although the forest industry often focuses on economic results, the market is directly tied to the sustainable long-term management of forest ecosystems (Palosuo et al. 2010). The precommercial thinning of young forest stands is beneficial for the quality of selected trees, species mixture, forest stability and biodiversity (Di Salvatore et al. 2016, Lombardi et al. 2018, Maleki et al. 2020). However, these benefits only become noticeable after a delay (Picchio et al. 2018), and the effects of thinnings are difficult to evaluate directly due

to long production cycles. Thinnings of the earlier developmental stages of the forest play an essential role in the development of mature forest stands (Lombardi et al. 2018). From an economic point of view, however, precommercial thinning today may represent a relatively uncertain investment in the future forest due to the increasing risk of natural disturbances related to climate change (Keenan 2015, Picchio et al. 2020).

In Central Europe (e.g., Switzerland, Slovenia, Italy) selective thinning begins in pole-stage stands and continues to mature stands, when it is replaced by increment or crown thinning (Rozenbergar et al. 2008, Pretzsch 2009). The first entries are in mixed stands of light-demanding species after the thicket phase, which means a relatively large number of candidates (for future crop trees) per unit area (1500-2000 per ha). As a result, many trees favored as candidates in earlier thinnings become competitors or indifferent trees in subsequent thinning interventions, which renders previous interventions somewhat ecologically and economically unjustified (Ammann 2012). Comparative studies of untreated and thinned stands have also shown the negative impact of selective thinning on the course of self-differentiation and collective stand stability of forest stands (Ammann 2013). Due to the frequent interventions throughout the stand as a result of selective thinning, self-differentiation is impeded when compared to less intensive thinning approaches or stands with no intervention (Ammann 2013).

During the last three decades, negative economic results have triggered criticism of selective thinning in young stands due to (i) rising labor costs in relation to the declining market price of timber, (ii) the social and economic situation of forest owners (e.g., employment outside forestry, declining forestry skills), (iii) increased investment risks due to frequent natural disturbances (e.g., concerns about the decline of collective stability) and (iv) difficulty in justifying four to six precommercial tending interventions (Hofer & Altweg 2006, Rozenbergar et al. 2008).

In some respects, the practice of choosing a large number of candidates for selective thinning at younger developmental stages of a forest is seen as controversial. First, in theory the distance between crop trees cannot increase continuously as predicted by selective thinning; rather, it is more likely a multiple of the initial distance. Second, the collective stability of stands is often neglected for the sake of the stability of individual trees. Collective stability is significantly reduced because of the more frequent, all-encompassing and intensive interventions specific to selective thinning in Central Europe (Yücesan et al. 2015).

In the face of difficult environmental and economic conditions, tending models are in need of improvement. They must take into account the economic viability of interventions and the consequences of skipping some interventions for long-term stand development. The overarching goal should be to reduce labor costs and improve revenue for the forest owner without jeopardizing

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the functioning of the forest at the ecosystem level.

In the second half of the last century, situational tending emerged as an alternative model of tending young forest stands in Central Europe (Schütz 1999). It was developed under the influence of rationalization of selective thinning (Ammann 2012) by concentrating from the onset of interventions on a small number of future crop trees which are strictly favored until the regeneration (German "Z-Baum" – Ammann 2005, 2013). Their number depends on the tree species, the thinning method (thinning at half-final or final distance between crop trees – Ammann 2013) and the target diameter of the forest stand (Klädtke & Abetz 2010).

This paper focuses on precommercial situational thinning, which is primarily intended for the tending of monodominant and mixed even-aged stands. These types of managed forest stands are globally dominant and will continue to be important due to the increasing frequency and intensity of natural disturbances.

The fields of traditional and fully mechanized harvesting for commercial thinning appear to be well researched from the standpoint of time studies (Ghaffariyan et al. 2013). On the other hand, precommercial thinning and tending has been somewhat neglected from the standpoint of forestry operation research and productivity, although it accounts for 12-15% of costs within the forest rotation period (Hofer & Altweg 2006). Despite several decades of development and testing of situational precommercial thinning, no detailed studies have been conducted on reducing workload in relation to the smaller number of selected future crop trees; there are only some estimates (Ammann 2012). While some literature already exists pertaining to the use of mechanized harvesting during precommercial thinning (Ligné et al. 2005, Bergström et al. 2007, 2010), there is a lack of knowledge regarding the optimization of motor-manual thinning during precommercial forest operations.

In order to evaluate the differences between situational and selective precommercial thinning, we developed a computer program for thinning simulation based on three previously conducted studies dealing with precommercial thinning of beech stands in Slovenia (Krajčič & Kolar 2000, Orešnik 2009, Arnič et al. 2018). The program is designed to model candidates or future crop tree position networks and remove competitors using three different thinning intensities for selective precommercial thinning and two alternatives of situational precommercial thinning. The research sought to determine: (i) how working time structure and productivity change with the number of selected candidates/future crop trees; (ii) how working time structure and productivity change with increasing thinning intensity; and (iii) differences in the costs of performing different types of precommercial thinning, based on the principle of concentration.

Materials and methods

We developed a program to simulate three different alternatives for the precommercial thinning of young beech stands in mountain forests using MS Visual Basic for Applications (Albright 2001). In the simulation process, we included three different thinning systems: (i) selective precommercial thinning (ST1800), which in this case refers to the precommercial thinning of a stand in the sapling development stage with approximately 1800 selected candidates per ha; (ii) situational thinning at half-final distances (ST400) with approximately 400 selected candidates for crop trees per hectare; (iii) and situational thinning at final distances (ST100) with 100 selected crop trees per ha.

Thinning simulation algorithm

The thinning simulation algorithm is divided into seven procedures: (1) setting the number of simulations; (2) randomly selecting candidate/crop tree positions; (3) determining the processing sequence (walking/processing path); (4) calculating the distance between candidates/crop trees; (5) determining thinning intensity; (6) simulating DBH and productivity; and (7) data management and storage of the individual simulation (Fig. 1).

Number of simulations

At the beginning of the modeling process, the user first sets the number of thinning simulation repetitions. We generated 1000 simulations for each combination of precommercial thinning approach and thinning intensity (Driels & Shin 2004).

Random positioning of selected candidates/crop trees

The virtual plot represents a 1000 m² rectangular forest area with 1056 cells, each with a unique location identification number (ID) starting at 1 in the upper left corner and ending with ID 1056 in the lower right corner (32 columns and 33 rows). The cell ID is intended to identify the positions of the candidate trees within the virtual plot. The program selects a random number between 1 and 1056 when choosing the positions of crop trees based on the minimum distance between neighboring crop trees, which depends on the thinning system (ST1800 - 1; ST400 - 2; ST100 - 5 free cells). The number of crop trees in the virtual plot varies randomly for each simulation and depends on the thinning system (ST1800: between 171 and 189 candidates; ST400: between 36 and 44 crop trees; SR100: between 8 and 12 crop trees).

Determination of processing sequence

The tending operation sequence (virtual worker walking path) between selected crop trees depends on the division of the virtual plot into bands. The bands assist in determining the direction of the harvesting movement during the tending operation. Walking paths are established on the virtual plots systematically in right-to-left or opposite bands, and the band width depends on the thinning system (ST1800: 3 rows; ST400: 7 rows [last 5]; ST100: 11 rows – see Fig. S1 in Supplementary material).

The thinning intervention begins in the upper left corner of the virtual plot in each of the thinning systems and repetitions. The sequence of crop tree processing depends on the direction of virtual worker movement in a band (left or right) and on the column ID of a crop tree (cell location) in the virtual plot. If the direction of processing is to the right (left), the crop trees process in ascending order (descending) according to the column ID. In the case where two cells with crop trees in one band are distributed with the same column, the one whose row label ID is lower takes priority (the upper one).
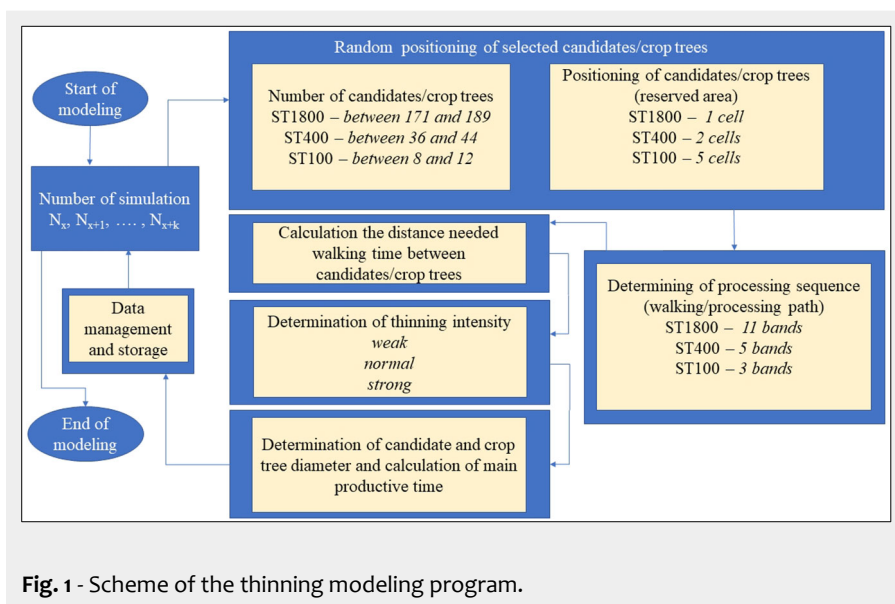

Fig. 1 - Scheme of the thinning modeling program.

Calculation of walking time between candidates/crop trees

The simulation calculates the mutual distances between subsequently processed candidates/crop trees. The calculation of mutual distances (R) simply uses Pythagoras' theorem (eqn. 1), where x represents the absolute distance between columns of neighboring candidate/crop trees in a virtual plot (Id_i and Id_{i+1} – eqn. 2) and y represents the absolute distance between rows of neighboring candidate trees in a virtual plot (Id_z and Id_{z+1}, – eqn. 3).

$$R = \sqrt{x^2 + y^2} \tag{1}$$

$$x = \left| Id_{i+1} - Id_i \right| \tag{2}$$

$$y = \left| Id_{z+1} - Id_z \right| \tag{3}$$

To convert our model distances to actual distances, the simulation program multiplied x by 0.99 (31.62 m in nature/32 columns) and y by 0.96 (31.62 m in nature/33 rows). The walking speed in the virtual plot was taken from previous research conducted in Slovenia (Arnič 2016, Arnič et al. 2018). At an average density of 43,950 trees per ha, with an average DBH of 4.8 cm and terrain slope of 70%, the average walking speed was 5.7 seconds per meter of horizontal distance. To account for the heterogeneity of stand density (43,950 ± 4,000 trees per ha), we calculated the following auxiliary productive time (time spent walking between subsequently selected crop trees – AT). The walking speed (H) for each movement between neighboring candidates or crop trees was randomly determined in the range of 5.7 ± 0.5 seconds per meter and multiplied by the distances between neighboring crop trees (eqn. 4). The variability of the walking speed was assumed based on the heterogeneity of stand density in which the previous study was carried out (Arnič 2016).

$$AT = R \cdot H \tag{4}$$

Determination of thinning intensity

Thinning intensity was determined by the number of competitors per candidate/crop tree. An algorithm for each of the individual candidates or crop trees selects a specific number of competitors from a pre-specified range of possible numbers for each of the three types of thinning intensity. In order to determine the impact of thinning intensity on the performance of tending operations, we ran 1000 thinning simulations and the associated thinning operation for weak (1.5 – competitors per selected crop tree), normal (2) and high thinning intensity (2.5) for each thinning system (Tab. S1 in Supplementary material). The thinning intensities used mimic methods for selection of competitors carried out by the public forestry service in Slovenia. For the first pre-commercial entry, due to the small size of the trees, densities are

used to indicate the thinning intensity and not the basal area of the stand as in the following entries. The development of the model was based on data from studies on the first thinning entries (Arnič 2016).

Determination of candidate and crop tree diameter and calculation of main productive time

The model stand DBH of the candidates and crop trees was generated using data previously collected in Slovenia. The average DBH of candidates was 4.8 cm, the standard deviation was 1.13 cm, the minimum DBH was 3.5 cm and the maximum DBH was 8.1 cm (Arnič 2016).

Due to the lack of competitor DBH data in previous studies, we used the DBH of candidates (x) and its dispersion to derive a productive time equation (Krajčič & Kolar 2000, Orešnik 2009, Arnič 2016). The main productive time (y) was calculated using an exponential equation (Lortz et al. 1997, Behjou et al. 2009 – eqn. 5) and according to the number of competitors assigned to each selected candidate/crop tree within an individual precommercial thinning simulation. The input data of previous studies are also briefly presented in the supplementary material (Tab. S2 in Supplementary material).

$$y = 0.3081 \, e^{0.0719x} \tag{5}$$

Data management and storage of individual simulations

For each thinning simulation, the results were recorded and stored in a database in three levels. At the first level, results were recorded for each selected candidate/crop tree in the individual simulations (ID, diameter, walking distance, number of competitors, main productive time, auxiliary productive time and the walking speed be-

tween the previous and subsequent candidate/crop tree). At the second level, summaries at the simulation level included data on the average diameter, average distance between candidate/crop trees, total number of competitors, total main productive time, auxiliary productive time and average walking speed. The results in the third and final level were summarized in a one-hectare virtual plot.

Information about the simulation model

The thinning simulation model presented in this work is based on time studies and data from the precommercial thinning of a young mountain beech forest with an average terrain slope of between 50-70%, an average tree DBH of 4.8 ± 1.1 cm, a stand density of 43,950 ± 4,000 trees per hectare, limestone bedrock and 100% vegetation coverage (Arnic et al. 2018 – see Tab. S3 in Supplementary material). The simulation model is applicable to all other terrain situations and tree species with previously conducted detailed time studies of thinning to enable the reconstruction of factors needed for the simulation model.

Statistical analysis

Due to a large difference in the number of candidates and also in time consumption among the three tested thinning systems (ST1800, ST400 and ST100 – Tab. 1), we only statistically tested the impact of thinning intensity. Due to the none-normally distributed data, statistical tests were performed using the Kruskal-Wallis test, which is a non-parametric ANOVA test.

The relationship between time consumption (TC) and the number of candidate/crop trees per hectare (NCT) for each category of thinning intensity was a result of the none-normally distributed and heteroscedastic data predicted by a general

Tab. 1 - Labor costs per hectare for the precommercial thinning of a young beech stand using different thinning approaches and different thinning intensities (TI). (ST1800): selective thinning; (ST400); situational thinning at half-final distances; (ST100): situational thinning at final distances. A coefficient of unproductive time for calculating working time and labor cost per working hour data was taken from previous research in Slovenia (Arnič 2016). (*): reduction of cost regarding to selective thinning - Normal TI.

Thinning approach	TI	Productive time (h ha⁻¹)	Working time (h ha⁻¹)	Labor costs (€ ha⁻¹)	Influence of TI (share of normal TI)	Reduction of cost *
ST1800	Weak	27.1 ± 0.9	42.8 ± 1.4	1052 ± 34	80 ± 2	-
	Normal	33.7 ± 1.2	53.3 ± 1.9	1311 ± 47	100	
	High	40.4 ± 1.5	63.9 ± 2.5	1572 ± 60	120 ± 4	
ST400	Weak	7.6 ± 0.5	12.0 ± 0.8	296 ± 19	83 ± 4	73 ± 4 %
	Normal	9.2 ± 0.6	14.5 ± 1.0	356 ± 25	100	
	High	10.7 ± 0.8	16.8 ± 1.2	414± 30	116 ± 7	
ST100	Weak	2.8 ± 0.3	4.5 ± 0.5	110 ± 12	88 ± 6	90 ± 1 %
	Normal	3.2 ± 0.4	5.1 ± 0.6	125 ± 15	100	
	High	3.6 ± 0.5	5.7 ± 0.7	140 ± 18	112 ± 10	
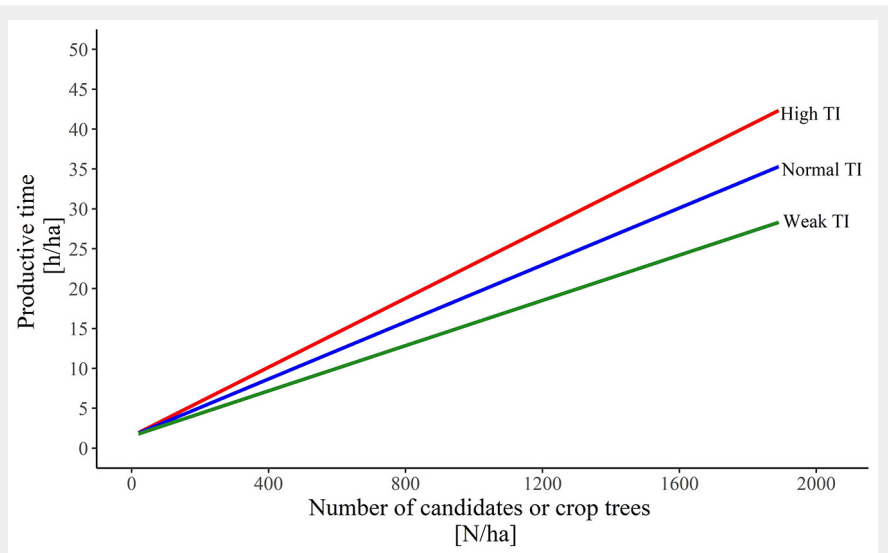
Fig. 2 - Productive time in hours per hectare, depending on the number of candidates/crop trees per hectare with high (red), normal (blue) and weak (green) thinning of a young beech mountain stand.

linear model (eqn. 6):

$$TC = NCT \cdot k + \varepsilon \qquad (6)$$

where k represents the slope and ε is the interception of the general linear model.

Logarithmic regression models were used to predict the relationships between elements of time structure (ETS) and the number of candidate trees per hectare (NCT) for each of the thinning intensities (eqn. 7):

$$ETS = \log(NCT) \cdot k + \varepsilon \qquad (7)$$

where k represents the slope and ε is the interception of of the lin-log model.

Cost analysis

In order to compare thinning systems in terms of costs, productive time was first converted into working time using the coefficient of unproductive time from the national standard times for forest operation. The labor costs (€ 24.6 per working hour) were based on a previous survey in which a cost calculation was done for a chainsaw worker (Arnič 2016).

Results

Productive time

The productive time during precommercial thinning operations in young mountain beech stands increases linearly with the number of candidates/crop trees per ha (Fig. 2). The time consumption was 3.2 h ha⁻¹ for situational precommercial thinning at a normal thinning intensity with final dis-

tances (ST100), 9.2 h ha⁻¹ for situational precommercial thinning with half-final distances (ST400) and 33.7 h ha⁻¹ for selective precommercial thinning (ST1800).

Thinning intensity also has a significant influence on time consumption (Kruskal-Wallis test; ST1800: χ^2 = 26,569, p <0.001; ST400: χ^2 = 2573, p <0.001; ST100: χ^2 = 1920, p <0.001). The average consumption of productive time varied from normal thinning intensity by ± 6.5 h ha⁻¹ for selective precommercial thinning (ST1800) depending on the variation in thinning intensity from weak to strong, by ± 1.5 h ha⁻¹ for situational precommercial thinning at half-final distances (ST400) and by ± 0.4 h ha⁻¹ for situational precommercial thinning at final distances.

Main productive time

Analysis of the relationship between the proportion of main productive time and the number of candidates/crop trees in the precommercial thinning of young beech mountain stands showed that the data are distributed in the form of an increasing logarithmic curve (high thinning intensity: p <0.001, R^2 = 0.936; normal thinning intensity: p <0.001, R^2 = 0.947; weak thinning intensity: p <0.001, R^2 = 0.966 – Fig. 3). In addition to the influence of the number of candidates or crop trees per hectare, a significant effect of thinning intensity was also observed (Kruskal-Wallis test; ST1800: χ^2 = 2968.8, p <0.001; ST400: χ^2 = 2891.6, p <0.001; ST100: χ^2 = 2597.2, p <0.001).

Auxiliary productive time

An analysis of the relationship between the share of auxiliary productive time (movements) within productive time and the number of candidate/crop trees showed that, irrespective of thinning intensity, auxiliary productive time depends on the number of candidates or crop trees. The data are distributed in the form of a descending logarithmic curve (high thinning intensity: p <0.001, R^2 = 0.936; normal thinning intensity: p <0.001, R^2 = 0.947; weak thinning intensity: p <0.001, R^2 = 0.966 – Fig. 4). In addition to the number of candidates or crop trees, thinning intensity is also significantly affected by the auxiliary productive timeshare (Kruskal-Wallis test; ST1800: χ^2 = 2968.8, p <0.001; ST400: χ^2 = 2891.6, p <0.001; ST100: χ^2 = 2597.2, p <0.001).

Cost analysis

Working time consumption was dependent on the precommercial thinning approach and thinning intensity. For selective precommercial thinning, working time varied between 42.8 and 63.9 h ha⁻¹. For situational thinning at half-final distances, time consumption varied between 12 and 16.8 h ha⁻¹, and for situational thinning at final distances, time consumption of varied between 4.5 and 5.7 h ha⁻¹.

The resulting cost of tending young beech stands was between € 1052 and €
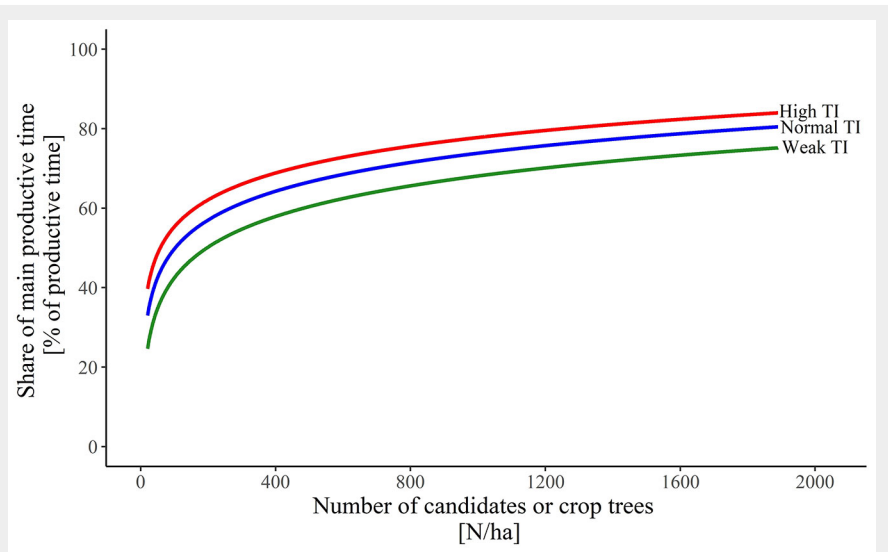
Fig. 3 - Impact of the number of candidates/crop trees on the proportion of main productive time in high (red), normal (blue) and weak (green) thinning intensity of a young beech stand.

1572 for selective thinning, between € 296 and € 411 for situational thinning at half-final distances and between € 110 and € 140 per hectare for situational thinning at final distances. The influence of thinning intensity on labor costs, relative to the deviation from costs at normal thinning strength, decreased between thinning approaches (ST1800: ± 20%; ST400: ± 17%; ST100: ± 12% – Tab. S2 in Supplementary material).

Discussion

The relatively high cost of selective pre-commercial thinning, which is widespread in Southeast and Central Europe has triggered the development of less expensive alternative approaches for precommercial silvicultural operations (Schütz 1999, Klädtke & Abetz 2010, Ammann 2013). Situational precommercial thinning has become a rational alternative to selective precommercial thinning in Switzerland's young forests (Ammann 2005, 2012), and a similar form has also developed in Germany (Rothkegel et al. 2016). The primary reasons for this include the poor economic performance of selective thinning (Schütz 1999), concerns about collective stability (Ammann 2013) and the emergence of even-aged young stands following large-scale disturbances (Ninove et al. 2015). Therefore, when compared to selective thinning, situational thinning maintains collective stand stability through the processes of biological automation and concentration of silvicultural interventions (Ammann 2012, Yücesan et al. 2015).

Due to a lower number of crop trees per hectare, the use of situational thinning leads to more effective rationalization of productive time consumption compared to selective thinning. Situational thinning at half-final distances between crop trees and normal thinning intensity reduced productive time by 67%, and situational precommercial thinning at final distances reduced it by 90%. Stirnweiß (2012) reported an absolute time consumption of between 3-5 hours per hectare, which is similar to the results of our simulation for situational thinning at final distances. Similar time consumption for selective precommercial thinning at half-final distances was also reported in previous field experiments in Slovenia (Arnič et al. 2018).

The structure of simulated productive time significantly differed across the analyzed precommercial thinning approaches with the reduction of candidates/crop trees per hectare. The relationship between main and auxiliary productive time was inverted with a reduced number of candidates/crop trees per hectare. Comparing selective precommercial thinning to situational precommercial thinning at final distances, the share of main productive time decreased from 79% to 49%. Therefore, auxiliary productive time increased between thinning approaches, and in the case of precommercial thinning at final distances and normal intensity, it accounted
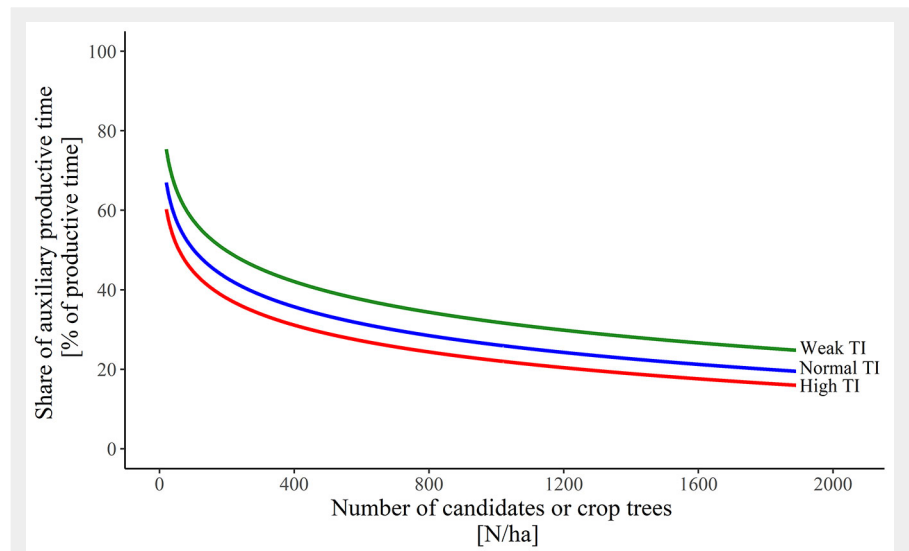
Fig. 4 - Impact of the number of candidates/crop trees on the share of auxiliary productive time in high (red), normal (blue) and weak (green) thinning intensity of a young beech mountain stand.

for 51% of total time. In addition, heart rate readings in the auxiliary productive time compared to main productive time in motor-manual forest work were 10% lower during situational precommercial thinning (Hagen et al. 1993). Therefore, due to the lower time consumption, fuel consumption (Ammann 2012), heart rate and exposure to external factors (*e.g.*, wood dust – Marchi et al. 2017), situational thinning also appears to be ergonomically better than selective precommercial thinning.

Main productive time significantly increased with thinning intensity due to the higher number of felled competitors. Therefore, the greater number of competitors per hectare resulting from high thinning intensity negatively affected the share of auxiliary productive time in the productive time structure. In the case of weak thinning intensity, the relationship was reversed. An increase in thinning intensity from moderate to weak or high resulted in a ± 20% (± 6.1 h ha⁻¹), ± 16% (± 1.5 h ha⁻¹) and ± 12% (± 0.4 h ha⁻¹) change in the share of the productive time consumption for selective thinning, situational thinning at half-final distances and situational thinning at final distances, respectively. Due to the lack of research in the field of thinning intensity in young stands, such findings related to its influence on time consumption are vital for the fields of silviculture, ecology and wood quality. Experience and preliminary research suggest that frequent interventions across the entire stand area with selective thinning decrease collective stand stability, which is problematic in an era of increasing natural disturbance intensity and frequency (Ammann 2013, Saje 2014, Yücesan et al. 2015). Collective stability has a particularly important role in young forest stands where there is a strong relationship between tree diameter and tree height (Ammann 2013). Early onset and high thinning

intensities may also restrict natural self-pruning processes and thus negatively affect future wood quality (Russo et al. 2019). In this respect, situational precommercial thinning based on the principle of concentration is more appropriate for preserving collective stability and positively influences the quality of crop trees (Ammann 2005, 2013).

The simulation of situational precommercial thinning at half-final distances suggested a 73 ± 4% reduction in costs, and at final distances, 90 ± 1% lower costs can be expected when compared to selective thinning (Tab. 1). Similar economic savings of situational thinning have been reported for Switzerland (Ammann 2012) and Germany (Stirnweiß 2012). Situational precommercial thinning was also experimentally used in the thinning of young forests within secondary succession on abandoned agricultural lands where the treatment time consumption was similar to situational thinning at half-final distances in this study. Labor costs of the whole operation in a pole stand were € 336 (Cojzer et al. 2014), which is similar to our results considering lower stand densities on abandoned agricultural lands.

In forest operations the application of situational precommercial thinning is still rare due to its relatively short history and current experimental status. This slow progress may be attributed to: (i) the long-term use of selective thinning which has yielded beneficial results in past economic and climatic conditions; (ii) lack of knowledge on the development and social differentiation of natural stands; (iii) distrust of early final selection of crop trees, which may prevent subsequent corrections; and (iv) a lack of knowledge on the development of crop trees during the process of situational thinning (Stirnweiß 2012). All of these represent important areas for future research

work.

Although the computer simulation showed similar results to those obtained in previous studies on thinning of beech and mixed forests, the results reflect only an approximation of real forest operation work. The most important constructing factors within the simulation model are detailed work time and field studies from which the formulas used for calculating main and auxiliary productive time are constructed. The presented model is transferable to other terrain and species mixtures for which the biggest deficit is the lack of time studies. Therefore, for further validation of the model, it is important to provide additional time studies of thinning forest operations within young forest stands in contrasting situations (*e.g.*, species mixtures, slope conditions, DBH).

Silvicultural treatment of young forests will be an important challenge for the forestry sector in the coming decades. In temperate forests worldwide, the incidence of large-scale natural disturbances such as windthrows and bark beetle outbreaks has significantly increased in the last decades (Seidl et al. 2017). This resulted in large areas covered with young, mostly even-aged forest stands. Interesting new mixtures are emerging, with many options for light-demanding species, many of which are economically interesting. In order to maintain attractive mixtures, the crop tree quality, stand stability and growth potential of these forest areas will need to be properly tended (Maleki et al. 2020). This emphasizes the need for an improved model for the implementation of young forest tending. Mechanized harvest is not feasible in stands following disturbances were intervention is infrequent due to low densities of crop trees. In addition, identification of tree species is required, which can be carried out by a well-trained forest worker. Such operations remain interesting in private forests, where owners carry out logging by themselves.

Looking ahead, it appears that the technological development of pre-commercial thinning will continue to advance. One possibility is the increased use of small harvesting machines (Bergström et al. 2010, Spinelli et al. 2010). However, experience from young successional stands suggests that heavy thinning can trigger a reduction in the collective stability of stands (Cojzer et al. 2014). In addition, mechanized harvesting leads to greater damage to the forest soil and – in the case of inexperienced machine operators – to the remaining stand (Cambi et al. 2015). There are no such problems in the further optimization of moto-manual pre-commercial thinning approaches based on the principle of concertation (such as situational thinning). The third option is based on biological automation, *e.g.*, the preference for small-scale, uneven-aged stands with continuous cover as the primary silvicultural approach (Ammann 2013). Such models, as presented

above, enable the optimization and quick assessment of work costs and investments. Thus, further development with objective field evaluations could increase the importance of computer simulations and support decision-making process in young forest tending (Picchio et al. 2019).

Conclusions

Modelling time consumption for selective and situational precommercial thinning in mountain beech forest stands enables quantitative evaluation of the differences in time consumption (absolute and according to the time element structure) and thus a more accurate prediction of the resources required for alternative silvicultural approaches (material, costs, human work load). Quantifying differences in the resources required enables better planning, implementation and control of silvicultural treatments, which in the same cases is supported by society through fiscal policy measures (subsidies) to ensure sustainable forest management. The main findings are (i) that situational thinning approaches are less time consuming and significantly less expensive than selective thinning, and (ii) due to a larger share of auxiliary productive time (walking operation) and less chain-saw operation, situational thinning approaches also seem to be more ergonomically beneficial for silviculture workers.

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Supplementary Material

Fig. S1 - Example of virtual plot for selective thinning with 11 bands and their marked directions of thinning movements.

Tab. S1 - Differences in thinning intensity.

Tab. S2 - Data from previous studies of pre-commercial thinning in young beech forest stands.

Tab. S3 - Information about simulation model and data from measurement of young beech stand in a previous study.

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