Cent. Eur. For. J. 66 (2020) 131–140 sciendo DOI: 10.2478/forj-2020-0010

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Tree height and species composition of young forest stands fifteen years after the large-scale wind disturbance in Tatra National Park

Vladimír Šebeň[1]*, Bohdan Konôpka[1, 2]

[1] *National Forest Centre - Forest Research Institute Zvolen, T. G. Masaryka 2175/22, SK – 960 01 Zvolen, Slovak Republic*
[2] *Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, CZ – 165 00 Praha 6 – Suchdol, Czech Republic*

Abstract

In November 2004, the windstorm Alžbeta damaged over 12 thousand ha of forests in the High Tatra Mts. It was the largest wind disaster in the modern forestry history of Slovakia. The process of forest regeneration at the post-disturbance area has to be monitored together with the effectiveness of implemented forestry measures. Therefore, we focused on tree measurements at 90 monitoring plots (MP) in 1 × 1 km net placed in the post-disturbance area in the Tatra National Park. We recorded tree species, number of trees (density) and tree heights. Besides that, stem diameters of trees with breast height diameter over 7 cm were measured. The field work was performed in the growing season of 2019, i.e. about 15 years after the wind disturbance. In total, 20 tree species, 15 broadleaves and 5 coniferous ones, were recorded at MP. The most frequent (28.9% of all trees) species was Norway spruce followed by silver birch (18.6%), rowan (16.9%) and goat willow (15.2%). Four species, i.e. European larch, wild cherry, grey alder and common alder contributed to the total number of trees between 1.8 and 4.8% each. Share of all other species together was about 5%. Tree height frequency was left-sided for the whole sampling set (all species together), as well as for individual species. Most of young trees were less than 1m high, but some of them exceeded 10 m. Further, tree density of over 100 individuals per are (100 m^2) was found at 1/3 of all MPs. As many as 25% of MPs were characterized with tree densities between 61 and 90 individuals. At 23% of MPs, the number of trees was up to 30 individuals per are, and 20% of MPs had between 31 and 60 small trees per are. The results suggested that the post-disturbance forest stands in the High Tatras would be more resistant to wind storms and very probably also to bark beetles after reaching maturity than those, which were destructed and declined at the beginning of 21st century.

Key words: post-disturbance area; forest regeneration; young forest stands; tree density; tree species

Editor: Jaroslav Holuša

1. Introduction

Both historically and recently, wind storms have become the most serious destructive factor in the prevailing part of boreal and temperate forests in Europe (Seidl et al. 2014). Risk of wind disturbance in forests is increasing not only with the rising severity of the harmful agent (due to inherent phenomena of climate change) but also with the status of forest stands, specifically their stability. i.e. resistance to destruction. The risk of disturbance increases with the increase of tree aboveground biomass stock, at the same time, more wood volume per hectare can be damaged during a single episode (Mitchel 2013). It is generally known that standing stocks of forests have been substantially increasing especially in the regions of Western, Central and Northern Europe for the last five decades (Gregow et al. 2017). For instance, standing stock of Slovak forests almost doubled between the years 1980 and 2018 (Ministry of Agriculture and Rural Development of the Slovak Republic 2019).

As for the conditions of Slovakia, two extremely large windstorm disturbances happened in the 21st century – the first one on November 14th, 2004 (Alžbeta) and the second one on May 14th and 15th, 2014 (Žofia). Both windstorms destroyed prevailingly spruce-dominated mature stands with the epicentre in the Tatra National Park (TANAP). The windstorm Alžbeta uprooted or broke trees in the TANAP on the area of over 12 thousand ha (Koreň 2005). In fact, it was the largest wind disaster in the modern forestry history, specifically regarding forestry evidence available since 1960 (Konôpka et al. 2016). In the TANAP, the windstorm damaged mostly stands aged between 61 – 120 years, which practically dominated among local forests. These forest stands were

**Corresponding author. Vladimír Šebeň, e-mail: seben@nlcsk.org*

rather unstable since they were composed mostly by Norway spruce, which represented about 80% of the standing stock at the end of the last century (Vološčuk et al. 1994). The windstorm Alžbeta had huge negative consequences on fulfilling a variety of ecosystem services in forests including carbon storage (Fleischer et al. 2017). Besides ecosystems services, biodiversity of plants and animals are the most valuable properties of forests and contributes to quality of life for human beings (Diaz et al. 2018). Biodiversity of forests is much influenced by disturbances whether immediately or in short time periods after destructive episodes. However, while consequences of natural disturbances to carbon balance in forests are evidently negative ones (e.g. Seidl et al. 2014), their influence on biodiversity is less known and need to be studied further in future.

Restoration of broad range of ecosystem services in forests of the TANAP depends on continuous and undisturbed processes of forest regeneration. Although, most destroyed sites were expected to be regenerated by natural processes, especially zones with higher degree of nature conservation, some places had to be promoted by foresters in the form of artificial or combined (combination of natural and man-made) reforestation (Šebeň et al. 2010a,b). At the same time, the process of forest regeneration had to be monitored to evaluate the success of forest regeneration and also the effectiveness of forestry measures, which were implemented in the area. This kind of monitoring must cover not only quantitative characteristics such as number of trees per hectare and their size, but also qualitative features especially tree species composition (Šebeň & Konôpka 2019). In fact, only a few works focused on development of young forests following wind or other kinds of natural disturbances (e.g. Homolová et al. 2015; Szmyt & Dobrowolska 2016; Diaci et al. 2017; Fidej et al. 2018; Orman et al. 2018). Very probably, a generalization of findings on post-disturbance forest development would require a huge bulk of results that consider a variety of factors, including a type (e.g. wind, bark beetles, fire) and a size (large-scale, small-scale, scattered etc.) of disturbances.

The goal of the paper was to analyse current tree density, species composition and tree height structure in young forest stands of the TANAP, which were established after the windstorm in November 2014.

2. Material and methods

2.1. Study area

Field survey was carried out in the TANAP (represented by the High Tatra Mts. and a part of Tatra Foothill) region. The substantial portion of the forests (cca 13 thousand ha) in this area was destroyed by a devastating windstorm called "Alžbeta" in November 2004. Main parts of damaged forests were located between 700 and 1,200 m a.s.l, while trees were more often uprooted than broken. Undamaged trees or stands remained within the area only sporadically. The Revitalization Project (Jankovič et al. 2007) was elaborated to ensure forest regeneration of disturbed area. The technical proposal of natural and artificial regeneration of the project included a recommendation to implement monitoring of revitalization process.

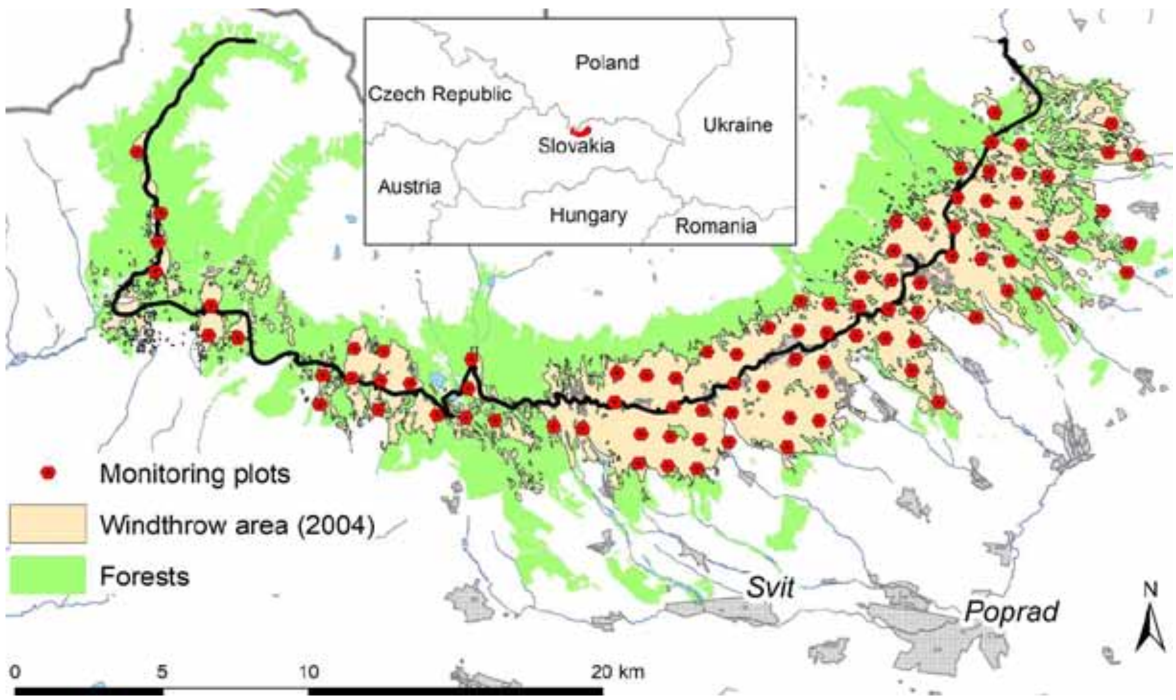

Fig. 1. Wind-damaged forests (episode in November 2004), undamaged forests and monitoring plots in the TANAP.

Therefore, between years 2007 – 2008 specialists of the National Forest Centre (NLC) established a financially exigent and a time-consuming network of monitoring plots (MP) in a regular grid of 0.5 × 0.5 km. The MPs were located not only in the wind calamity area, but also in the neighboring, i.e. undamaged forest stands. In total, 924 MPs were established. The area was about ten thousand hectares. This bases have been used later also for the selection of our monitoring works.

For repetitive measurements in the year 2019 we selected only the plots in spacing 1 × 1 km from the basic grid of MPs. Hence, a number of our MPs was 90 (Fig. 1).

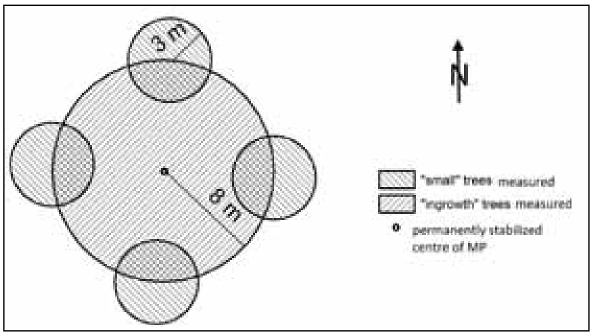

Fig. 2. Each monitoring plot (MP) was composed of central circular plot and four circular satellites, i.e. sub-plots (SP).

2.2. Field measurements

Field survey was conducted in spring and summer of 2019. We followed initial field survey methods and monitoring guidelines (see also Kulla et al. 2007). Our attention was focused on regeneration, i.e. young trees growing after the disturbance in 2004.

The basic sampling unit of the monitoring system is a circular MP with a constant area of 200 m^2. The centre of the MP was permanently stabilized with an iron tube. The first step was to identify the MP centres in the field based on their coordinates using a GPS device with an accuracy of 3 – 5 meters. The second step was to find the stabilization iron tube using a metal detector.

We distinguished two categories of young trees growing after the disturbance: so called "small trees" with a diameter at breast height (DBH) up to 7 cm, and thicker trees named "ingrowth trees" with DBH ≥ 7 cm. For each tree we recorded: tree species, height (with an accuracy of 0.1 m), and for ingrowth trees also DBH. Ingrowth trees were recorded at a whole MP with a radius of 8 m. Small trees were measured and recorded at sub-plots (four satellites at each MP). The reason for this design was to obtain a better estimation of variability in tree number, sizes and species at micro-sites. Thus, four circular sub-plots (SP), each with a radius of 3 m, were placed around the centre of MPs in the azimuths to the north (0°), east (90°), south (180°) and west (270°). Horizontal distance of each sub-plot from the MP centre was 8 m (Fig. 2). At each SP, all trees with a height of over 0.1 m were considered.

2.3. Data processing and statistical calculations

The data from the field survey were checked with regard to the completeness and accuracy as well as the logical context. The design of four subplots was dedicated to small trees (each subplot with an area of 28.27 m^2) and a total area of MP (cca 200 m^2) was utilized for ingrowth trees measurements and subsequent calculations. The data from both survey designs were converted to the same area unit (are or hectare) and subsequently further calculation was made for all trees together. Next to evaluation direct measured parameters, as tree number or tree heights, we calculated derived basal area (BA) from measured diameter of breast height (DBH), but only for ingrowth trees.

The results of the survey were expressed as average values for sampling units (i.e. MP or SP). Variability was described using standard deviation (SD). Another result is share of selected trees or MP, calculated as contribution of selected category to total amount (%). Results were expressed for trees species from tree numbers, basal area and high categories.

3. Results

Analyses of the data showed that MPs were established at altitudes from 697 to 1,388 m a.s.l. Most of the plots (27.8%) were located in the altitudinal range between 801 and 900 m a.s.l. (Table 1). The most frequent (30.0%) aspect was south-east. There were nearly no MPs with a northern aspect and very few MPs were oriented to north-west and west. The MPs were most common (18.9%) on slopes between 8% and 9%. Slopes of over 10% were recorded only at 1/5 of all MPs.

Table 1. Basic terrain characteristics for the monitoring plots (MP).

Altitude [m a. s. l.]	Share of MPs [%]	Aspect [°]	Share	Slope [%]	Share
below 700	1.1	N (338–22°)	0	0–1	8.9
701–800	16.7	NE (23–67°)	8.9	2–3	26.7
801–900	27.8	E (68–112°)	23.3	4–5	17.8
901–1,000	17.8	SE (113–157°)	30.0	6–7	10.0
1,001–1,100	16.7	S (158–202°)	22.2	8–9	18.9
1,101–1,200	8.9	SW (203–247°)	11.1	10–11	7.8
1,201–1,300	7.8	W (248–292°)	3.3	12–13	6.7
over 1,300	3.3	NW (292–337°)	1.1	>14	3.3

Considering all MPs together (each with an area of 200 m^2), mean height of small trees was 2.05 m, mean number of small trees was 87 individuals and mean number of species was about five (Table 2) at a plot. As for the SP (an area of about 28.7 m^2), mean height of small trees was 2.02 m, mean number of small trees was 22, and number of species was about three. A different situation was found for ingrowth trees, which were measured and also expressed exclusively on the whole area of MP. Specifically, mean height of ingrowth trees was 6.6 m, mean number of ingrowth trees about 11 and mean number of species per MP was slightly over two.

Table 2. Basic tree characteristics for the monitoring plots (MP; area of about 200 m^2) and subplots (SP; area 28.27 m^2).

Tree category	Tree characteristics	Mean ±SD	Min.	Max.
Small trees*	Mean tree height [m] at SP	2.02 ±0.90	0.28	5.30
	Mean tree height [m] at MP	2.05 ±0.65	0.66	3.65
	Number of trees at SP	22.2 ±19.5	0	97
	Number of trees at MP	87.3 ±58.7	3	291
	Number of tree species at SP	3.1 ±1.4	1	7
	Number of tree species at MP	5.3 ±1.7	2	9
Ingrowth trees**	Mean tree height [m] at MP	6.6 ±2.1	0	12.5
	Number of trees at MP	10.7 ±9.1	0	42
	Number of tree species at MP	2.2 ±1.1	0	5

*Small trees – all individuals with DBH < 7 cm

**Ingrowth trees – all individuals with DBH ≥ 7 cm.

In total, we recorded 20 tree species, 15 broadleaved and 5 coniferous ones at MPs (Table 3). The most frequent (28.9% of all small trees) species was Norway spruce followed by silver birch (18.6%), rowan (16.9%) and goat willow (15.2%). Four species, i.e. European larch, wild cherry, grey alder and common alder, contributed to total number of trees with a share between 1.8 and 4.8% each. Share of all other species together was about 5%. In the case of ingrowth trees, Norway spruce contributed with 44.7% and silver birch with 21.9%. This means that the two species made up as much as 2/3 of all ingrowth trees. Interesting information was found for rowan and goat willow that had a high share (both together 32.1%) in small trees, but only a small share (6.4%) in ingrowth trees. On the other hand, a reverse situation was recorded for Scots pine with a contribution of only 1.1% to small trees but 10.6% to ingrowth trees.

Further, our results showed that the density of small trees of over 100 individuals per are (100 m^2) was found at 1/3 of all MPs. As many as 25% of MPs were characterized with tree density between 61 and 90 individuals (Fig. 3a). At the same time, 23% of MPs had up to 30 individuals of small trees per are and 20% of MP between 31 and 60 small trees per are. On the other hand, maximum three ingrowth trees per are were recorded at nearly 1/2 of MPs (Fig. 3b). Only 10% of MPs had ten and more ingrowth trees per are.

If we consider small trees (although this situation is more-less the same for all trees together, i.e. small and ingrowth individuals), 5 – 6 tree species occurred at nearly 1/2 of all MPs (Fig. 4). Nine and more tree species were recorded only at 5% of MPs. Ingrowth trees were most frequently represented by 1 – 2 species (58% of MPs) and 3 – 4 species (33% of MPs).

The results showed sharp left-sided distribution of tree heights by species (Fig. 5). Spruce dominated among coniferous in all height classes. Interestingly, number of trees of three broadleaved tree species (birch, rowan and willow) in height classes between 1.1 and 5.0 m was very similar. Comparison of tree height classes by species in ingrowth trees showed that spruce dominated in classes up to 9.0 m and birch in classes of over 9.0 m (Fig. 6).

Further, we expressed percentage contribution of tree species to total number of trees in height classes (Fig. 7a). Clearly, contribution of willow and rowan decreased with an increasing height. The reverse situation was found for birch. Contribution of spruce was evident mainly in height classes between 1.1 and 8.0 m. A decreasing trend with increasing tree height classes was recorded not only for the number of trees (from 3,392 to 63 individuals) but also for the number of species (from 18 to 11 species; Fig. 7b). Although contribution of other broadleaved species increased with tree height classes, a reverse trend was found for the number of species in this group (there were as many as eight broadleaved species in the height class up to 1.0 m, but only three in the height class of over 9 m).

Table 3. Tree species recorded at the monitoring plots (number of individuals per hectare; tree species are in the descending order of the density of small trees).

Species	Latin name	Small trees (i.e. DBH <7 cm)		Ingrowth trees (i.e. DBH ≥7 cm)		All trees together	
		Number n	Share [%]	Number N	Share [%]	Number N	Share [%]
Norway spruce	*Picea abies*	2,364	28.9	203	44.7	2,567	29,7
Silver birch	*Betula pendula*	1,527	18.6	99	21.9	1,626	18.8
Rowan	*Sorbus aucuparia*	1,384	16.9	16	3.5	1,400	16.2
Goat willow	*Salix caprea*	1,243	15.2	13	2.9	1,256	14.5
European larch	*Larix decidua*	391	4.8	28	6.1	418	4.8
Wild cherry	*Padus racemosa*	358	4.4	2	0.4	359	4.2
Grey alder	*Alnus incana*	182	2.2	7	1.5	188	2.2
Common alder	*Alnus glutinosa*	176	2.2	7	1.6	183	2.1
Sycamore	*Acer pseudoplatanus*	145	1.8	6	1.3	152	1.8
Silver fir	*Abies alba*	116	1.4	6	1.2	122	1.4
Aspen	*Populus tremula*	113	1.4	18	4.0	131	1.5
Scots pine	*Pinus sylvestris*	90	1.1	48	10.6	138	1.6
Downy birch	*Betula pubescens*	45	0.6	0	0.0	45	0.5
White willow	*Salix alba*	29	0.3	0	0.0	29	0.3
Common ash	*Fraxinus excelsior*	8	0.1	0	0.0	8	0.1
European beech	*Fagus sylvatica*	7	0.1	1	0.1	7	0.1
Wych elm	*Ulmus glabra*	6	0.1	0	0.0	6	0.1
Small-leaved lime	*Tilia cordata*	2	0.0	0	0.0	2	0
Norway maple	*Acer platanoides*	1	0.0	0	0.0	1	0
Arolla pine	*Pinus cembra*	1	0.0	0	0.0	1	0
All	Total	8,187	94.7	454	5.3	8,641	100.0

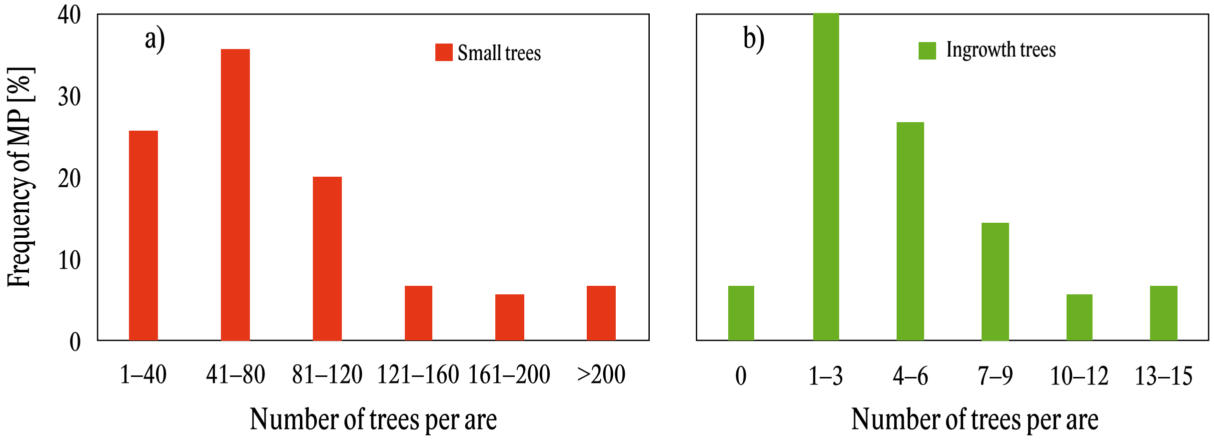

Fig. 3. Frequency of MPs with regard to number of trees per are (100 m^2). Small trees and ingrowth trees are shown in separate graphs.

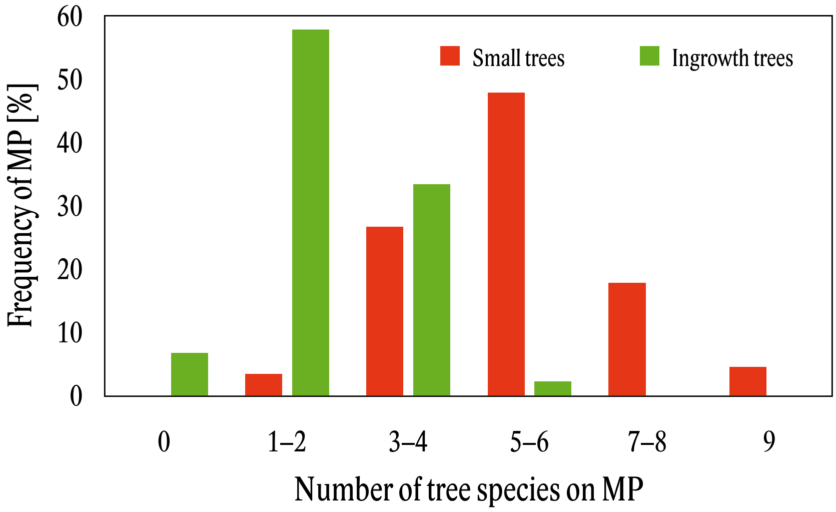

Fig. 4. Frequency of MPs with regard to number of tree species at MP (an area of 200 m^2). Small trees and ingrowth trees are shown by separate bars.

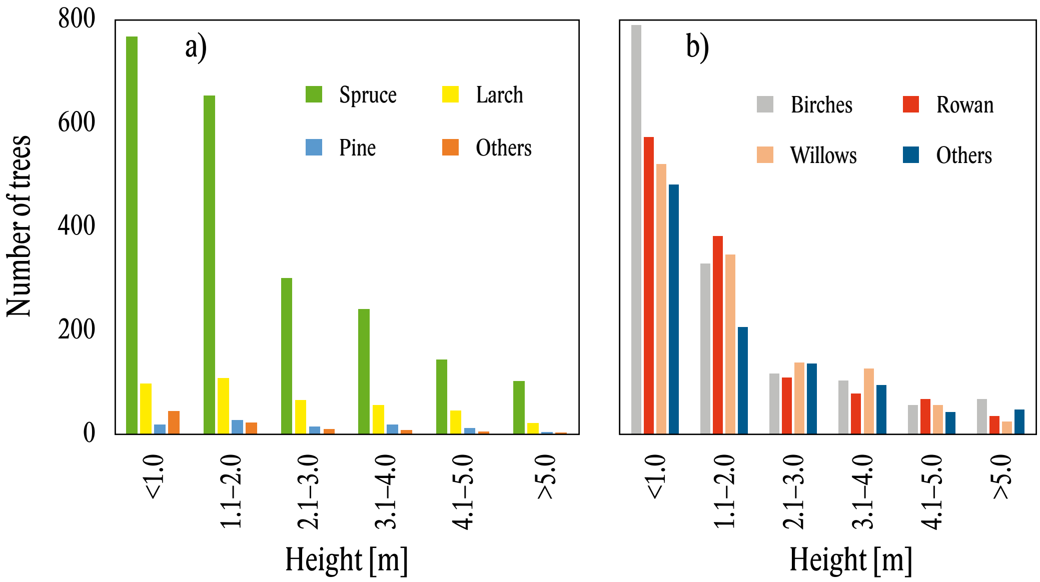

Fig. 5. Height distribution of small trees separately for a) coniferous and b) broadleaved species. Cumulative results for all MPs together.

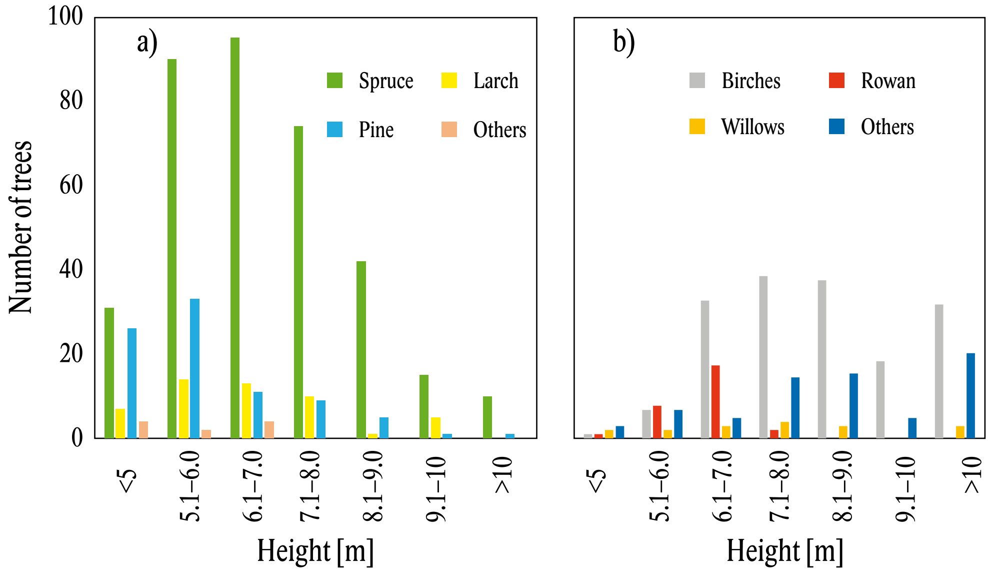

Fig. 6. Height distribution of ingrowth trees separately for (a) coniferous and b) broadleaved species. Cumulative results for all MPs together.

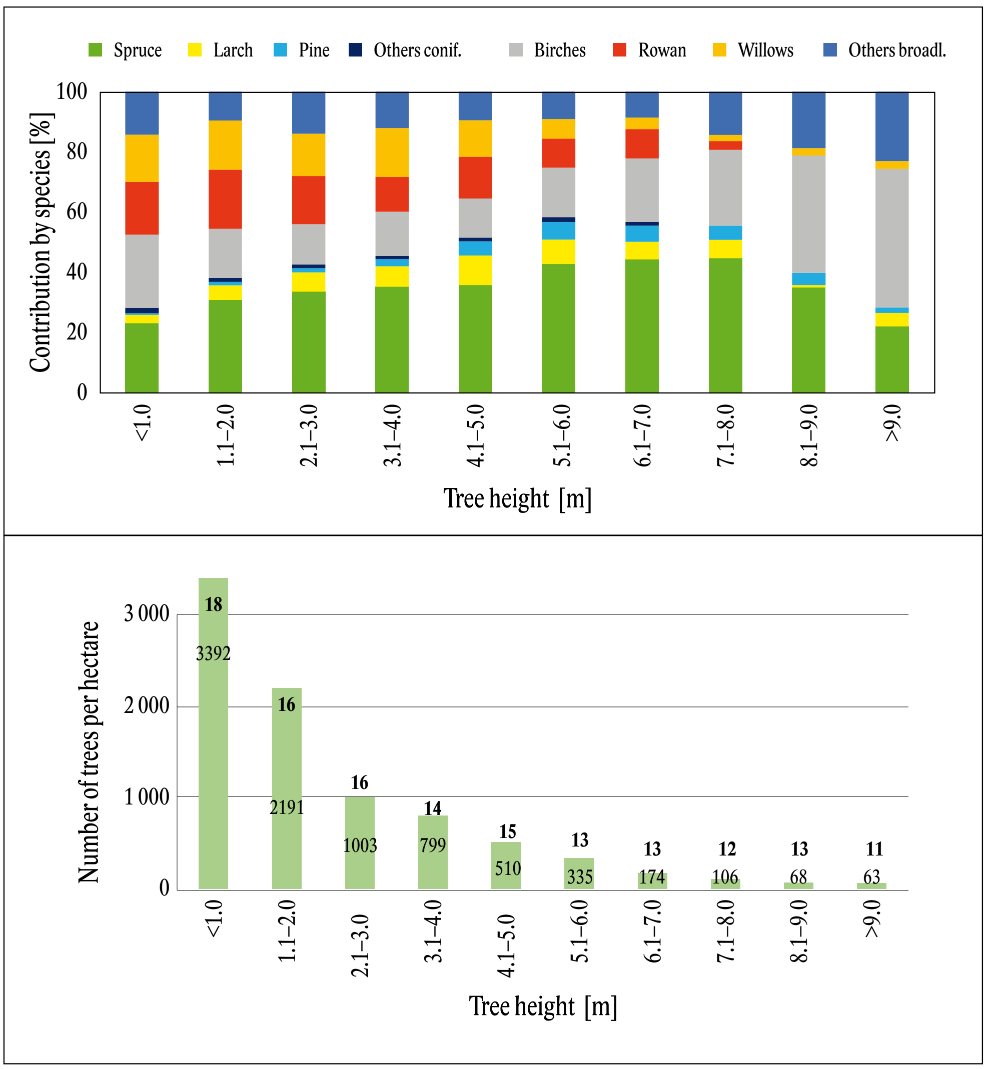

Fig. 7. Tree species composition in height classes considering a) percent contribution of tree species, and b) number of trees (y–axis and lower-placed numbers) together with number of species (higher-placed numbers). Cumulative results for all MPs together.

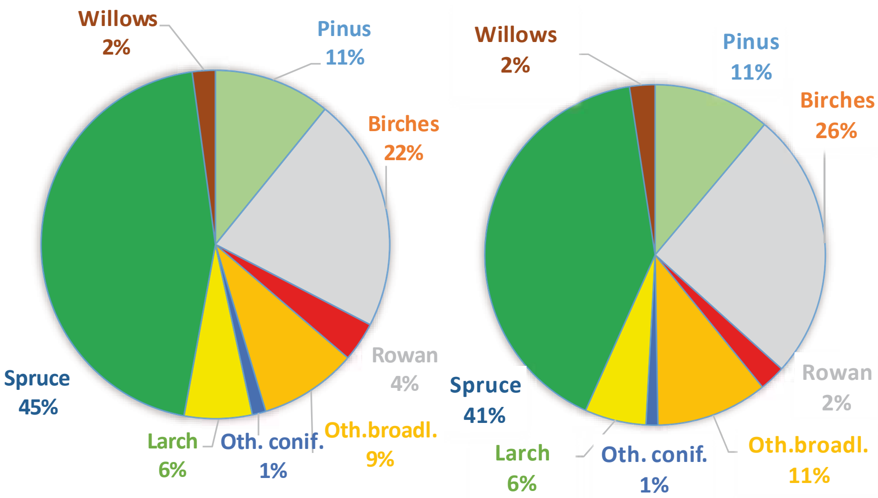

Fig. 8. Tree species composition calculated from a) total number of trees b) total basal area (only data of ingrowth trees were used for the calculation). Cumulative results for all MPs together.

Finally, contribution of tree species (here only ingrowths were included because DBHs of small trees were not measured) to total number of trees (Fig. 8a) and total basal area (Fig. 8b) was analyzed. The highest contribution to either of the two characteristics was found for spruce, followed by birch, pine and larch. While the contribution of some species (pine, larch and willow) was the same from the point of number of trees and basal area, other species (especially spruce, birch and rowan) had a contrasting contribution to number of trees in comparison with their contribution to basal area. Specifically, spruce: 45% versus 41% (number of trees against basal area), birches 22% versus 26% and rowan 4% versus 2%. This points out at evident differences between species in their stem size.

4. Discussion

4.1. Tree height structure

Our results showed that fifteen years after the disturbance episode, young forest stands in the TANAP were still composed by prevailingly small trees with heights up to 1.0 m. This was expected and corresponds with frequently occurred pattern for tree height distribution in young forest stands especially from natural regeneration (e.g. Landsberg & Sands 2011). The statement, that is needless to say, would be related rather to total number of trees than to total tree biomass. Frequency of tree heights was markedly left-sided. Number of dominant and best growing (as for actual height) trees was very low. This pattern was evident not only for all trees regardless of species but also for nearly all tree species recorded at the post-disturbance area. Sharp left-sided distribution of heights is very typical in young growth stages of forests (e.g. Bondarchuk 2015) and a height lag of the major part of trees in comparison to highest individuals might be related to a variety of internal and external factors (see for instance Landsberg & Sands 2011). For instance, Szmyt & Dobrowolska (2015) found lowest values of height variability in severely disturbed forests, while highest variability was in moderately disturbed stands.

Based on knowledge shown in a book of Kacálek et al. (2017), we expected that so called pioneer tree species (especially aspen, birch, rowan and willow) would overgrow coniferous ones (Norway spruce, European larch and Scots pine). However, this phenomenon was not clear due to a number of reasons. Potential differences in actual tree heights or tree heights frequencies between “fast-growing” and “slow-growing” tree species can be diminished by timing of seed germination, competition by weed, browsing by deer or micro-site variability in soil moisture and fertility (possibly also altitudinal gradient). Therefore, we can not make any exact statement as for inter-specific difference in height frequency in our post-disturbance forest stands. On the other hand, we can make a conclusion for stem volume or quantity of aboveground biomass. Our results based on trees with DBH exceeding 7 cm showed that the birch trees contributed to number of trees by 22%. At the same time, their share to basal area was as much as 26%. This difference between contribution to total number of trees and to basal area indicates that birch trees had thickest stems, and possibly also the largest aboveground biomass of all tree species.

4.2. Tree species composition

Our results showed rich tree species composition in young forest stands at the studied mountain sites. Specifically, as many as twenty species, fifteen broadleaves and five coniferous, were recorded at the monitoring plots. Six tree species occurred at more than 50% of monitoring plots and eleven species at more than 10% plots. Unfortunately, we have no exact scientific data on tree species composition in the TANAP forests before the wind disturbance to perform inter-temporal comparisons. Existing forest management plans show only main tree species, those with low contribution to standing stock are usually omitted. However, according to the estimates of Vološčuk et al. (1994), as much as 80% of standing stock in Tatra forests was made up by Norway spruce at the end of the 20th century. The rest (nearly 20%) was represented prevailingly by European larch and Scots pine. Similarly, our previous analyses (Konôpka et al. 2019) based on forest management plans from 1996 showed that Norway spruce contributed to standing stock by about 75%, while Scots pine and European larch made over 20% of standing stock, and the contribution of other tree species was under 5%. These values suggest that other, especially broadleaved species, had a very small contribution to standing stock. They were just sparsely scattered in forest stands and mostly grew suppressed under the main canopy. Therefore, we can state that the current post-disturbance tree species composition is evidently richer than the one existing before the wind disturbance. Michalová et al. (2017) presented research from the same post-disturbance area in TANAP with regard to tree regeneration. They compared managed and unmanaged sites. Spruce dominated at both site types, and larch and rowan were often admixed, but they found only seven tree species in total. However, their design of measurements did not cover the whole post-disturbance area in the TANAP, but only 100 ha of it. We confirm a dominance of Norway spruce, but we found richer tree species composition with higher proportion of birch and other broadleaves over the whole post-disturbance territory (about 10 thousand ha). Spruce, pine and birch belong to typical pioneer tree species, they often grow on wind post-disturbance areas in Central Europe (e.g. Szmyt & Dobrowolska 2015) However, their occurrence depends also on the structure of remaining (undamaged) parts of forest stands. For instance, removal of canopy by 10 – 30% promotes regeneration of prevailingly shade-tolerant tree species (Diaci et al. 2017).

Our finding that the number of tree species decreased with increasing height classes might be hypothetically explained at least in two ways. First, it can be related to diminishing probability of a variety of tree species to occupy new micro-sites with increasing time period after the disaster. Another possible explanation might be gradual elimination of some tree species, especially light demanding or slow-growing ones, due to inter-specific competition. We suppose that the first mentioned assumption would be more probable under the actual conditions in the High Tatra Mts. because inter-specific tree competition seems to be still rather small (with a few exceptions especially in the case of dense spruce-dominated clusters).

In general, effects of forest disturbances on flora and fauna biodiversity, including tree species diversity is not clear and might be manifested in contrasting ways. Tree species diversity is perhaps related both to the extent of disturbed area (e.g Ilison et al. 2007) and time period after the episode (Allen et al. 2012). The effects of disturbance (certainly not instantaneous but after a couple of years) on biodiversity were often positive (Thom & Seidl 2016). In fact, this phenomenon, often named as “disturbance paradox”, has been mentioned in several works for a variety of ecosystems (e.g. Wilkinson 1999; Thom & Seidl 2016). On the other hand, a meta-analysis revealed frequent conflicting or insignificant consequences (Mackey & Currie 2001). We expect no further increase of tree species diversity in the future, but its gradual decline in TANAP. Most likely, frequency of some trees species, especially aspen, goat willow, and rowan will be reduced by intensive deer browsing (Merganič et al. 2009; Pajtík et al. 2015). In the long run, i.e. in the horizon of 4 – 5 decades, we assume a reduction in the share of short-living trees species, namely birch, rowan, goat willow, and eventually other broadleaved species. On the contrary, long-living species (especially spruce, pine and larch or other deciduous trees) will form a "frame" of old stands in the future.

5. Conclusions

We may conclude that although the current tree species composition in young stands is richer than in the old pre-disturbance stands, future forests in the TANAP might converge to composition of the stand which grew here before November 2004. The reason is that contribution of short-living trees species (e.g. birch, rowan, goat willow, and eventually other broadleaved species) in stand composition will be gradually decreasing. Hypothetically, we might assume that potential improvement of ecological stability and resistance of the forests stands to harmful agents (especially wind and bark beetles) in future might be determined by spatial and height structure of forests rather than by tree species composition. Unfortunately, accurate long-term prediction on development of these forest properties is not possible by using recently available tools (e.g. growth simulators). Hence, our assumption can not be proved by any scientific arguments. On the other hand, continuous long-term monitoring of the stands in the TANAP would through more light in knowing processes of post-disturbance succession of forest ecosystems.

Acknowledgements

The research was supported by the projects APVV-14-0086 and APVV-18-0086 from the Slovak Research and Development Agency, and by grant "EVA4.0", No. CZ.02.1.01/0.0/0.0/16 _019/0000803 financed by OP RDE, as well as by the project

"Research and innovation for supporting competitiveness of the Slovak forestry sector" (SLOV-LES) financed by the Ministry of Land Management and Rural Development of the Slovak Republic. Dr. Katarína Merganičová is acknowledged for valuable comments and also English language revision on the manuscript.

References

Allen, M. S., Thapa, V., Arévalo, J. R., Palmer, M. W., 2012: Windstorm damage and forest recovery: accelerated succession, stand structure, and spatial pattern over 25 years in two Minnesota forests. Plant Ecology, 213:1833–1842.

Bondarchuk, S. N., 2015: Study of the Young Growth of Main Forest-forming Coniferous Species in the Primary Forests of the Sikhote-Alin Nature Reserve. Achievements in the Life Sciences, 9:37–50.

Diaci, J., Rozenbergar, D., Fiedej, G., Nagel, T. M., 2017: Challenges of uneven-aged silviculture in restoration of post-disturbance forests in Central Europe: a synthesis. Forests, 8:378.

Díaz, S., Pascual, U., Stenseke, M., Marín-López, B., Watson, R. T., Molnár, Z. et al., 2018: Assessing nature's contributions to people. Science, 359:270–272.

Fidej, G., Rozman, A., Diaci, J., 2018: Drivers of regeneration dynamics following salvage logging and different silvicultural treatments in windthrow areas in Slovenia. Forest Ecology and Management, 409:378–389.

Fleischer, P., Pichler, V., Fleischer, P., Holko, L., Máliš, F., Gömöryová, E. et al., 2017: Forest ecosystem services affected by natural disturbance, climate and land-use changes in the Tatra Mountains. Climate Research 73:54–71.

Gregow, H., Laaksonen, A., Alper, M. E., 2017: ncreasing large scale windstorm damage in Western, Central and Northern European forests, 1951–2010. Scientific Reports, 7:1–7.

Homolová, Z., Kyselová, Z., Šoltés, R., 2015: Dynamika vegetácie na kalamitných plochách v spoločenstve Lariceto-Piceetum. Štúdie o Tatranskom národnom parku, 44:191–199.

Ilison, T., Köster, K., Vodde , F., Jogiste, K., 2007: Regeneration development 4-5 years after a storm in Norway spruce dominant forests, Estonia. Forest Ecology and Management, 250:17–24.

Jankovič, J. et al., 2007: Projekt revitalizácie lesných ekosystémov na území Vysokých Tatier postihnutom veternou kalamitou dňa 19. 11. 2004. Zvolen, NLC, 75 p.

Kacálek, D., Mauer, O., Podrázský V., Slodičák, M. et al., 2017: Meliorační a zpevňující funkce lesních dřevin. Lesnická práce, 300 p.

Konôpka, B., Zach, P., Kulfan, J., 2016: Wind – an important ecological factor and destructive agent in forests. Lesnícky časopis – Forestry Journal, 62:123–130.

Konôpka, B., Šebeň, V., Pajtík, J., 2019: Species composition and carbon stock of tree cover at a postdisturbance area in Tatra National Park, Western Carpathians. Mountain Research and Development, 39:71–80.

Koreň, M., 2005: Vetrová kalamita 19 novembra 2004: nové pohľady a konsekvencie. Tatry, Special issue, 6–29.

Kulla, L., Šmelko, Š., Šebeň, V., Rizman, I., Jankovič, J., 2007: Monitoring poškodených lesných ekosystémov Vysoké Tatry 2007. Metodika terénneho zberu údajov. Zvolen, NLC, 42 p.

Landsberg, J., Sands, P., 2011: Physiological Ecology of Forest Production. Principles, Processes and Models. Amsterdam, Elsevier, 331 p.

Mackey, R. L., Currie, D. J., 2001: The diversity-disturbance relationship: is it generally strong and peaked? Ecology, 82:3479–3492.

Merganič, J., Russ, R., Beranová, J., Merganičová, K., 2009: Assessment of the impact of deer on the diversity of young trees in forest ecosystems in selected localities of the Czech Republic. Ekológia (Bratislava), 28:424–437.

Michalová, Z., Morrissey, R., Wohlgemuth, T., Bače, R., Fleischer, P., Svoboda, M., 2017: Salvage-logging after windstorm leads to structural and functional homogenization of understory layer and delayed spruce tree recovery in Tatra Mts., Slovakia. Forests, 8:88.

Ministry of Agriculture and Rural Development of the Slovak Republic, 2019: Report on Forestry in the Slovak Republic per year 2019 (Green Report). Bratislava, MARD, 66 p.

Mitchell, S. J., 2013: Wind as a natural disturbance agent in forests: a synthesis. Forestry – an International Journal of Forest Research, 86:147–157.

Orman, O., Dobrowolska, D., Szwagrzyk, J., 2018: Gap regeneration patterns in Carpathian old-growth mixed beech forests – Interactive effects of spruce bark beetle canopy disturbance and deer herbivory. Forest Ecology and Management, 430:451–459.

Pajtík, J., Konôpka, B., Bošeľa, M., Šebeň, V., Kaštier, P., 2015: Modelling forage potential for red deer: A case study in post-disturbance young stands of rowan. Annals of Forest Research, 58:91–107.

Seidl, R., Schelhaas, M. J., Rammer, W., Verkerk, P. J., 2014: Increasing forest disturbances in Europe and their impact on carbon storage. Nature Climate Change, 4:806–810.

Szmyt, J., Dobrowolska, D., 2016: Spatial diversity of forest regeneration after catastrophic wind in northeast Poland. iForest – Biogeosciences and Forestry, 9:414–421.

Šebeň, V., 2007: Praktická realizácia terestrickej monitorovacej siete na sledovanie vývoja poškodených lesných ekosystémov po veternej kalamite. Seminár: Pokalamitný výskum v TANAPe. Tatranská Lomnica, 25.10. 2007.

Šebeň, V., 2010a: Prirodzená obnova po kalamite z novembra 2004 vo Vysokých Tatrách. In: Výskum smrečín destabilizovaných škodlivými činiteľmi. Vedecký recenzovaný zborník. Zvolen, NLC, LVÚ, Zvolen, p. 297–308.

Šebeň, V., 2010b: Podiel a skladba prežívajúcej umelej obnovy na kalamitisku vo Vysokých Tatrách. In: Výskum smrečín destabilizovaných škodlivými činiteľmi. Vedecký recenzovaný zborník. Zvolen, NLC, LVÚ, Zvolen, p. 309–320.

Šebeň, V., Bošeľa, M., Kulla, L., 2011: Terrestrial network for monitoring of revitalisation processes of the windfall and its surrounding in the High Tatra. Studies on Tatra National Park, 10:13–24.

Šebeň, V., Konôpka, B., 2019: Vývoj kalamitiska vo Vysokých Tatrách do roku 2019 podľa terestrického monitoringu. Štúdie Tatranského národného parku, 13:9–25.

Thom, D., Seidl, R., 2016: Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. Biological Reviews, 91:760–781.

Vološčuk, I. et al., 1994: Tatranský národný park. Martin, Gradus, 558 p.

Wilkinson, D. M., 1999. The disturbing history of intermediate disturbance. Oikos, 84:145–147.

Cent. Eur. For. J. 66 (2020) 141–150 sciendo DOI: 10.2478/forj-2020-0002

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Combined fertilizers versus dolomitic limestone: A comparative study from a forest habitat with Norway spruce

Aleš Kučera[1]*, Jana Rosíková[1], Jan Pecháček[3], Peter Dundek[1], Dušan Vavříček[2]

[1] *Mendel University in Brno, Department of Geology and Pedology, Zemědělská 3, CZ – 613 00 Brno, Czech Republic*
[2] *Mendel University in Brno, Department of Forest Botany, Dendrology and Geobiocenology, Zemědělská 3, CZ – 613 00 Brno, Czech Republic*
[3] *Forest Management Institute, Brandýs nad Labem, Vrázova 1, CZ – 616 00 Brno - Žabovřesky, Czech Republic*

Abstract

The research paper with character of case study deals with the influence of amelioration on soil as well as the Norway spruce nutrition and growth, with the focus on dolomitic limestone and combined fertilizer applications. The study was performed in the 7-year-old forest stand (Nízký Jeseník Mountains, Czech Republic, 100% Norway spruce, podzol, mor humus form, slightly undulated slope, 770 m a.s.l.). The soil properties (soil reaction, nutrient status, C/N ratio and cation exchange capacity), the plant nutrition, the plant biomass production and the health status were measured. Neither the expected significant increase in pH due to liming in the root zone nor the increase in calcium and magnesium in the soil was confirmed. In the dolomitic limestone treatment, the highest hydrolytic acidity reaching 260 $mmol_+/kg$, the worst development of assimilatory organs, the growth and health status of individuals were ascertained one year after the usage. The application of combined fertilizers resulted in the highest response in the needle biomass production (0.35 g/100 needles compared to less than 0.30 g/100 needles in the dolomitic limestone treatment), in the potassium and phosphorus nutrition status (suboptimal 4–4.5% of potassium in dolomitic limestone and the control treatment compared to optimal 5.5–7.5% in the combined fertilizers treatments) and simultaneously to the optimization of the health status. Specifically, in forest stands, the effect of dolomitic limestone is rather overestimated and furthermore, chemical amelioration requires the detailed knowledge of the forest site.

Key words: forest soil; acidification; reclamation practice; plant nutrition; nutrient antagonism

Editor: Erika Gömöryová

1. Introduction

Soil acidification, defined as the decrease in the neutralization capacity (Merry 2009), is the process by which the base cation content is reduced and the acidic cation content is increased (Singh & Agrawal 2008). The alteration in soil chemistry originates from the contradictory effect of acidifying or alkalizing factors and the soil buffering capacity (Huang et al. 2014). In humid climate, in particular, soil acidification occurs through various natural mechanisms (Hruška & Ciencala 2005; Merry 2009). Numerous authors have attached minimal importance to natural acidification mechanisms in comparison with anthropogenic acidification (Ingerslev 1999; Ingerslev & Hallbäcken 1999), associated with the forest dieback linked to the acid deposition of atmospheric pollutants (Bäck et al. 1995) and inappropriate woody species compositions (Augusto et al. 2002).

Over the past several decades, the elimination of anthropogenic acidification in the Czech Republic has been predominantly based on aerial liming of forest stands (Klimo and Vavříček 1991; Kuneš 2003; Vavříček et al. 2005; Novotný et al. 2008; Kulhavý et al. 2009; Baláš et al. 2010; Šrámek et al. 2012).

However, the outcomes of the liming measures have frequently been inconsistent due to the specificities of forest habitats and forest soils in general (Kreutzer 1995; reviewed for Central-European conditions by Hruška & Ciencala 2005) and many authors have been concerned with the use of combined fertilizers rather than large-scale aerial liming (Lomský et al. 2006; Vacek et al. 2006) for the soil environment and mainly forest stand health and nutrition status improvement. Some of the studies mention a risk joined with forest soil amelioration and only short-term effectiveness in regards to forest production and health status, especially in large scale area applications.

*Corresponding author. Aleš Kučera, e-mail: ala.coutchera@gmail.com, phone: +420 545 13 4521

The application of combined slow-release mineral fertilizers on an individual basis to each transplant has been implemented by several authors (Kuneš et al. 2013; Pecháček et al. 2017). These fertilizers have demonstrated the impact on the optimization of the nutrient and health status of plants and the soil environment. The effect of fertilizers can be accentuated by using growth regulators (Simpson 1986; Seaby & Selby 1990), such as NAA Na^+, SNP Na^+ and IBA K^+.

The scientific treatise reflects on the effect of forest soil amelioration on the soil and the forest stands at the juvenile stage of planted Norway spruce (*Picea abies* [L.] H. Karst), focusing on a comparison of different ameliorative materials including combined fertilizers and dolomitic limestone. The hypothesis was based on the mentioned presumptions that dolomitic limestone is the less effective ameliorative material for soil amelioration, the plant growth as well as the health and nutrition status optimization compared to combined fertilizers. We presumed weak amelioration effect of the dolomitic limestone in contrast to combined fertilizers in the Norway spruce conditions with regards to pH and base saturation improvement nor nutrient status optimization.

2. Materials and methods

The case study study was performed in the 7-year-old forest stand (100% Norway spruce; Nízký Jeseník Mountains, Solná hora Mountain, Czech Republic; GPS coordinates 50.2095833N, 17.4506389E). The effects were tested for the presence of compound fertilizers with a specific composition of macronutrients (Table 1) and growth regulators and dolomitic limestone, compared to the control treatment.

Site Description (Table 2): The soil was covered by 100% with dominance of *Calamagrostis epigejos* (80%), *Avenella flexuosa* (30%), *Senecio Fuchsii* (10%) and bryophytes. The soil taxonomical unit was Entic Skeletic Podzols (Loamic) (IUSS Working Group WRB 2014) with the mor humus form of 6–8 cm thickness; 770 m a.s.l.; slightly undulated slope; N–W exposition (azimuth 285°); slope inclination 21%; annual mean precipitation 800 mm; mean air temperature 6.8 °C; annual mean soil moisture at 8 and 20 cm depth 27.8 % vol. and 27.4% vol., respectively; annual mean soil temperature at 8 and 20 cm depth 6.7 °C and 6.8 °C, respectively.

The soil is characteristic of the dominant podzolization soil-forming process on the shallow soil forming substrate of carboniferous graywacke mixed with clay shale partially metamorphosed to argillaceous schist inclined in angle of 60–75° to the soil surface with stoniness of 80–90% in the soil forming substrate, 50–70% in subsoil and 30–50% near the soil surface, which is very substantial for water regime and water drainage of the habitat in relation to water, as well as nutrient availability.

The rectangular research plot (120 × 150 m) was parcelled out to obtain six identical zones with the dimensions of 20 × 150 m containing 180 to 200 regularly distributed individuals per treatment. The treatment distribution on the plot was performed randomly. 160 g of the ameliorative material was applied individually to the soil surface within the crown projection on the individual basis (cca 80–120 cm in diameter which is cca 0.50 – 1.13 m^2 which would correspond to doses of 1.4–3.2 t of the ameliorant per ha) of each treated spruce in April 2014 and 2015.

The data collection was conducted in October 2015 via (1) mixed soil samples: 5 replicates per treatment (from the root zone under organic horizons; sampling

Table 1. Overview of the treatments and the composition of the tested ameliorative materials.

Treatment symbol	Trade mark / form[1]	Nutrient concentration [%]						Plant growth regulators[3]
		N	P	K	Mg	Ca	S	[%]
C	(Control)	—	—	—	—	—	—	—
SR50_s2	Silvamix®R50+s2	14.5 [1]	3.08	14.94	3.0	—	1.3	0.17
SR_s	Silvamix®R30+s	10.0 [2]	3.08	14.94	4.5	—	4.3	0.35
SR	Silvamix®R30	10.0 [2]	3.08	14.94	4.5	—	4.3	—
SA_s2	AGLUFORM®90+s2	19.0 [2]	3.08	9.13	2.88	—	4.0	0.17
DolLim	Dolomitic limestone	—	—	—	11.22	22.9	—	—

[1] 55% of N as urea-formaldehyde;
[2] 34% of N as urea-formaldehyde;
[3] when 0.17%: NAA Na+ 0.025%; DA-6 0.07%; SNP Na+ 0.05%; IBA K+ 0.025%;
when 0.35%: NAA Na+ 0.15%; DA-6 0.10%; SNP Na+ 0.075%; IBA K+ 0.025%.

Table 2. Properties of the soil profile in FS Solná hora Mountain within the different soil layers.

Soil layer characteristics	Sampling depth [cm]	Nutrient Content pH		Corg	Nt	C/N	P	Mg	Ca	K	CEC [mmol$_+$/kg]	BS
		H_2O	KCl	[%]			[mg/kg]					[%]
Organomineral	12–17	3.93	2.94	8.17	0.40	20	29	306	864	31	379.3	18.2
Eluvial	19–25	4.01	3.21	5.41	0.28	19	30	162	384	25	312.9	10.6
Spodic	34–44	4.21	3.72	5.16	0.27	19	73	75	216	20	271.5	6.4
Soil forming substrate	60–80	4.37	4.10	2.35	0.14	17	71	41	182	9	154.3	8.2
							2390*	21819*	46862*	19540*		

Corg – organic carbon; Nt – total nitrogen; CEC – cation exchange capacity; BS – base saturation; *total element content in substrate horizon using hydrofluoric acid.

depth 8–12 cm; below the crown projection); each replicate was composed of 3 individual samples; (2) mixed samples of needles: 3 replicates per treatment (from the upper third of the crown; from last two shoot year-classes separately as one-year-old and two-year-old needles); each sample was comprised of needles from 10 to 15 individuals; and (3) biometric data: 50 individuals per treatment.

The soil was analysed to assess the soil reaction (pH/H_2O and pH/KCl) in the soil: the eluent ratio of 1:2.5 (w:v); H^+ concentration [$mmol_+$/kg] using dual pH measurement (Adams & Evans 1990); available mineral nutrients (Ca, Mg, K) [mg/kg] from Mehlich II leachate (Mehlich 1978); P content [mg/kg] using spectrophotometry in a solution of ascorbic acid, H_2SO_4 and Sb^{3+}; organic carbon (C_{org}) [%] content spectrophotometrically in a chromosulphuric acid; total nitrogen (N_t) [%] content using the Kjeldahl method in % (Kirk et al. 1950); sulphur content [g/kg] using Regulation (EC) 2003/2003; mobile Al^{3+} content [$mmol_+$/kg] (Sokolov 1939); cation exchange capacity (CEC) [$mmol_+$/kg] using a summation method; base saturation (BS) [%] using the equation BS = (Ca^{2+} + Mg^{2+} + K^+) / CEC; the particular cation content using the equation Cmmol = Cmg / (M/Oxn), where Cmmol is the nutrient concentration in $mmol_+$/kg; Cmg is the nutrient concentration in mg/kg; M is the element molar mass, and Oxn is the nutrient oxidation number; the total element content in the soil substrate using mineralization in hydrofluoric acid. The total nutrient amount in the soil sample was reduced when C_{org} content exceeded 7.25% (12.5% of humus) using the equation $Sn = S_{N\text{-}anal} / \{1/[(100–H_{ox})/H_{ox}]·7\}$, where $S_{N\text{-}anal}$ is the nutrient content in mg/kg; H_{ox} is the humus content (C_{org} · 1.724) and 7 is the empirical value (Vavříček & Kučera 2017). The cation ratio in molar mass was used to obtain the Ca/Al and Bc/Al ratios where the Bc is the sum of base cations.

Biomass was analysed to assess the contents of macrobioelements [N in %; P, K, Ca, Mg, S in g/kg] (Strížová 2014). The nutrient ratio was used in one-year-old and two-year-old needles separately to obtain the Ca/Mg, K/Mg, Ca/N and Mg/N ratios. Biometry was assessed for annual height increment [cm], weight of 100 needles dried at 105 °C [g] and health status (1 – the best to 5 – the worst).

Data processing was performed with R software, version 3.6.2 (2019-12-12) and RStudio, version 1.2.5033. As graphical tools, we used the boxplot graphs (the boxes show medians and quantiles 0.25 and 0.75) and plotting with 95% confidence intervals in case of parametric multiple comparison, using ´plotmeans´ function from package ´gplots´ version 3.0.1.2. We applied the parametric and nonparametric analyses of variance (ANOVA, Kruskal-Wallis test, respectively), the parametric and nonparametric post-hoc analyses (Tukey HSD and nonparametric multiple comparison – nonparametric relative contrast effect with "Tukey" type of contrast, respectively). The normality was tested using Shapiro-Wilk test with $\alpha = 0.05$. The Principal component analysis (PCA) was performed with the ´vegan´ package version 2.4-3 after data standardization.

The abbreviations used in the graphical figures are as follows: Soil_C_N – C/N ratio; Soil_pH_H_2O and Soil_pH_KCl – active and exchangeable soil reaction, respectively; Soil_Ca, Mg, K, P, S, Nt, H – element content in soil; Soil_BS – base saturation; Soil_CEC – cation exchange capacity; Nutr_P, Mg, Ca, K, N, S, CaMg, KMg – nutrient content in needles and the nutrient ratio; HundrNeedl – weight of 100 needles; GrowAnn – annual height increment; Health – health status. The individual treatment variants in the experiment are labelled according to Table 1.

3. Results

The high variability of the soil properties resulted in the use of the nonparametric tests, which revealed the differences among all the parameters.

The soil reaction was strongly acidic for all the treatments, with the lowest acidity observed in C (Fig. 1; see also Table 3). The soil exchangeable reaction was the lowest for the DolLim, which also had the most variable values.

Based on Table 3, merely the control treatment (C) was typical of the statistically different (higher) values of

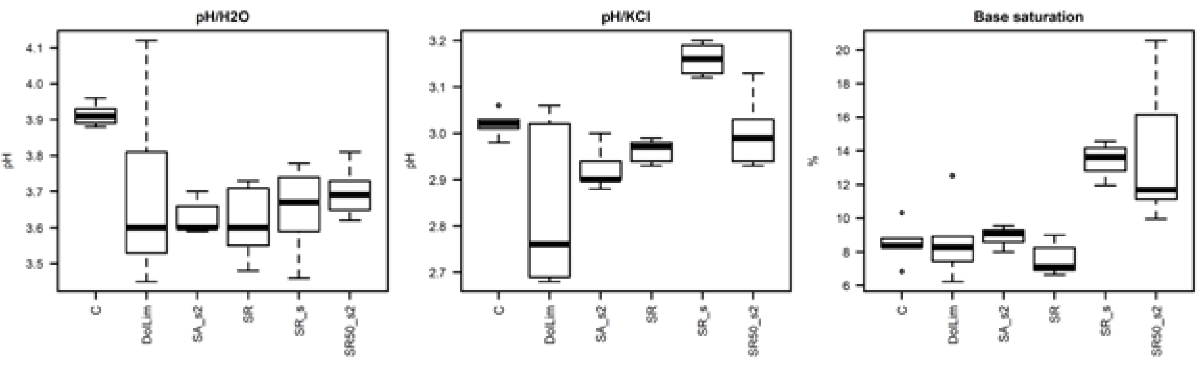

Fig. 1. Physical-chemical soil parameters in the individual treatments in the organo-mineral soil horizon (for the abbreviations, explanations see Materials and Methods Section and Table 1).

the active soil reaction while the exchangeable reaction was more diverse (the lowest in DolLim and the highest in SR_s). However, the values of pH/H_2O in the control treatment correspond with the natural situation in the soil (cf. with Table 2) while in other treatments the soil reaction was lower and close to the natural situation in the treatments SA_s2 and SR in case of pH/KCl.

Base saturation was the lowest in SR but statistically equal with C, DolLim and SA_s2 while the BS of the treatments SR_s and SR50_s2 was even above 10%. In all the treatments the BS was markedly lower than in the natural soil.

Using fertilizers, the nutrient content in the soil (Fig. 2, Table 4) was optimized or even supraoptimized in case of K and partially also for P while the Mg and Ca contents were suboptimal neither in the natural soil, typical of medium or high values nor in mineral (eluvial) horizon. The nitrogen content was the highest in DolLim (not significantly) and the lowest in SR – in all the treatments in high levels, which can be related to the elevated organic carbon content in the whole soil profile (Table 2), bonding nitrogen, as well as other nutrients via cation exchange. The C/N ratio was in the optimal values which could even seem to be untypical of the forest soil with Norway spruce. ANOVA revealed significantly higher C/N ratio in the treatments with DolLim and SR50_s2 which are still in the optimal values. Such high nitrogen content is probably due to high stoniness and organic matter infiltration to the depth, being characteristic of leptic soils. Acid cations, both H^+ as well as Al^{3+}, are highly concentrated with the significant differences in all the treatments with the highest values surprisingly in Dol-

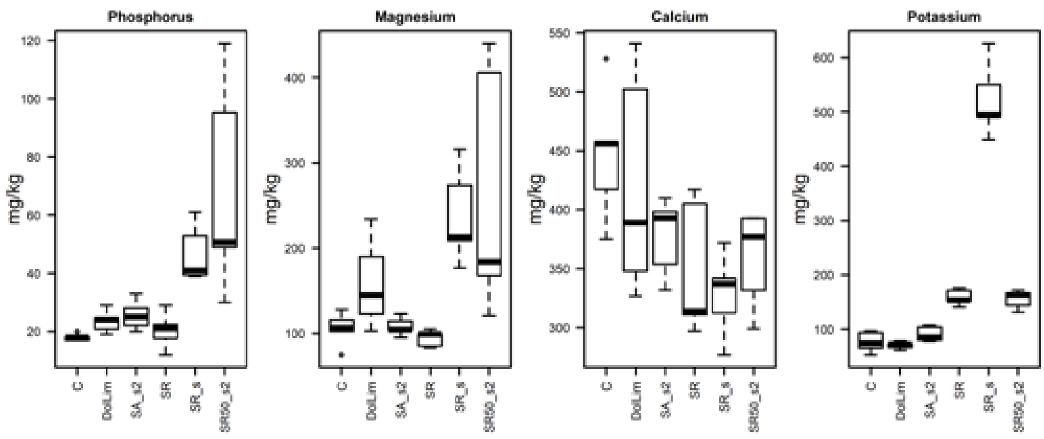

Fig. 2. Exchangeable nutrients content (Mehlich II) in the soil in the individual treatments in the organo-mineral soil horizon (for the abbreviations, explanations see Materials and Methods Section and Table 1).

Table 3. Mean values and results of statistical testing of the physical-chemical soil parameters in the individual treatments in the organo-mineral soil horizon.

Parameter	Units	C	DolLim	SA_s2	SR	SR_s	SR50_s2	Test Type	p–value
		mean							
pH/H_2O	—	3.91^{a}	3.70^{b}	3.63^{b}	3.61^{b}	3.65^{b}	3.70^{b}	aov	*
pH/KCl	—	3.02^{ab}	2.84^{b}	2.92^{ab}	2.96^{ab}	3.16^{a}	3.00^{ab}	aov	***
CEC	$mmol_+$/kg	387.2^{a}	417.1^{a}	337.9^{b}	386.2^{a}	366.8^{b}	314.7^{b}	aov	***
Bc	$mmol_+$/kg	33.0^{b}	36.0^{b}	30.0^{b}	29.4^{b}	49.4^{a}	43.4^{b}	K-W	*
BS	%	8.5^{b}	8.7^{b}	8.9^{b}	7.6^{b}	13.4^{a}	13.9^{a}	K-W	**

Superscripts following the mean values denote mutual statistical differences at α=0.05 on the basis of the post-hoc multiple comparison (test type: "aov" – parametrical ANOVA; "K–W" – Kruskal-Wallis test; p–values: " *** " < 0.001; " ** " 0.001–0.01; " * " 0.01–0.05; " . " 0.05–0.1). For the abbreviations, explanations see Materials and Methods Section and Table 1.

Table 4. Mean values and results of statistical testing of the nutrient content, the C/N ratio, the acid cations content and the Ca/Al and Bc/Al ratios in the individual treatments in the organo-mineral soil horizon.

Parameter	Units	C	DolLim	SA_s2	SR	SR_s	SR50_s2	Test Type	p–value
		mean							
P	mg/kg	18.0^{b}	23.5^{b}	25.6^{b}	20.4^{b}	46.7^{a}	68.8^{a}	K–W	***
Mg		105.5^{b}	158.9^{a}	108.2^{b}	94.3^{b}	237.7^{a}	263.7^{a}	K–W	**
Ca		446.7^{a}	421.4^{b}	377.4^{b}	348.8^{b}	328.1^{b}	358.7^{b}	aov	*
K		76.6^{b}	70.0^{b}	90.8^{b}	158.8^{ab}	522.2^{a}	155.5^{ab}	K–W	***
N	%	0.34^{a}	0.41^{a}	0.31^{a}	0.27^{b}	0.34^{a}	0.32^{a}	K–W	.
C/N	—	18.7^{b}	23.1^{a}	20.3^{b}	20.2^{b}	15.3^{b}	23.3^{a}	aov	***
H^+	$mmol_+$/kg	199.0^{ab}	226.9^{a}	206.8^{a}	187.5^{b}	189.2^{b}	184.5^{b}	K–W	*
Al^{3+}		155.2^{a}	154.4^{a}	101.0^{b}	169.5^{a}	128.2^{ab}	86.6^{b}	K–W	***
Ca/Al	—	0.14^{b}	0.14^{b}	0.19^{a}	0.10^{b}	0.13^{b}	0.21^{a}	aov	***
Bc/Al	—	0.21^{b}	0.23^{b}	0.30^{a}	0.17^{b}	0.39^{a}	0.52^{a}	K–W	***

Superscripts following mean values denote mutual statistical differences at α=0.05 on the basis of post-hoc multiple comparison (test type: "aov" – parametrical ANOVA; "K–W" – Kruskal-Wallis test; p–values: " *** " < 0.001; " ** " 0.001–0.01; " * " 0.01–0.05; " . " 0.05–0.1). For the abbreviations, explanations see Materials and Methods Section and Table 1.

Lim, and rather equal in all the variants with the lowest in SR50_s2, respectively.

The response of the trees within the treatments was marked more in the plant nutrition than in biometrics. The annual growth was evaluated as almost being equal (Table 5), nevertheless, the highest in SR_s and SR50_s2 treatments and the lowest in DolLim followed by the control. Needle biomass was diversified in one-year-old needles with the most massive biomass in SR_s and the least massive in DolLim. The DolLim treatment was also distinctive to the worst health status (decolouration, multicoloured needles, etc.).

Compared to the soil nutrient content, the plant nutrition was specific for rather normal data distribution (Table 6) and the significant differences among the treatments. In two-year-old needles the lowest and the highest content of P was in DolLim and SR50_s2, respectively.

Among the macrobioelements which were mostly contained in the optimal concentrations (mainly Mg, Ca), S and K occurred in the low limit values. The sulphur content was markedly lower (on the lower optimum limit) in one-year-old needles in C and DolLim treatments while potassium was deeply below the optimal values in both needle years in the treatments. The nitrogen content was the lowest in C and DolLim in both years of needles – in two-year-needles even below the optimum limit in DolLim. The nutrient ratio is rather in the optimal values except for DolLim in Ca/Mg due to the extremely low Ca content and except for C and DolLim in K/Mg due to the extremely low K content. The proportions of Ca/N and Mg/N were found as optimal, however significantly differentiated according to the treatment.

4. Discussion

Chemical amelioration, namely liming, substantially affects organic horizons especially on humus-rich sites (Nilsson et al. 2001; Hruška & Ciencala 2005). The alterations are performed mainly in soil organic layers in the sense of intensive mineralization and related biological/biochemical processes. In our study, we reached the lower pH values in all the treatments compared to the control one. The phenomenon of the distinct soil chemistry is not necessarily grounded in the treatments. However, we applied either alkaline or physiologically acidic ameliorative materials which can lead to the decrease of pH below surface organic layers for different reasons (Huettl & Zoettl 1993). As we sampled the soil in the rooting zone typical of the wide range of natural reasons for soil acidification, such as root exudates and nutrient uptake or also stimulation of plant metabolism using phytostimulants, which lead to lower pH/H_2O values.

The mean values of the soil exchange reaction properties showed the least favourable state in the DolLim, even with the respect to base saturation which was the highest in SR_s and SR50_s2 treatments. The nutrient contents in the soil (Fig. 2 and Table 4), as well as in needles (Fig. 3) indicated the antagonism of bivalent cations with potassium, which was significantly suppressed. Despite the assumptions stated in the literature (Formánek & Vránová 2003), the concentration of acidic protons and, notably, aluminium (Al^{3+}) was not reduced; this finding was accompanied by very strong hydrolytic acidity.

Our results demonstrated that there was an increased concentration of protons bound to the soil sorption complex (see also Fig. 1 and Table 4), which occupied over 90% CEC. After displacement from the soil sorption complex, these protons moved downwards into the root zone of the soil profile, increasing the risk of elevated aluminium mobility (see also Matzner 1992).

With regard to excessive soil chemistry alterations caused by chemical amelioration, the issues related to potassium are fundamental, yet little is known about them (Sardans & Peñuelas 2015). The presence of potassium in the soil can particularly be ensured by a targeted supply of fertilizers (cf. Fig. 2), and, in contrast, a high susceptibility to leaching by antagonistic bases can cause an imbalance in the soil trophic state in the root zone. This finding was also confirmed in the DolLim treatment, which had a significant excess of Ca^{2+} and Mg^{2+} and in SA_s2 due to the excessive dosage of a monova-

Table 5. Mean values and results of statistical testing of shoot biomass and the health status of the individuals in the individual treatments.

Parameter	Units	C	DolLim	SA_s2	SR	SR_s	SR50_s2	Test Type	p-value
		mean							
Annual growth	cm	54.3	48.0	57.9	55.9	62.2	62.1	K–W	.
Health	—	2.0[a]	2.7[b]	1.9[a]	1.6[a]	1.8[a]	1.7[a]	K–W	***
100 needles (1st yr)	g	0.30[b]	0.28[b]	0.32[b]	0.31[b]	0.36[a]	0.31[b]	aov	**
100 needles (2nd yr)	g	0.39	0.41	0.38	0.38	0.42	0.37	aov	>0.1

Superscripts following the mean values denote mutual statistical differences at α=0.05 on the basis of the post-hoc multiple comparison (test type: "aov" – parametrical ANOVA; "K–W" – Kruskal-Wallis test; p–values: " *** " < 0.001; " ** " 0.001–0.01; " * " 0.01–0.05; " . " 0.05–0.1). For the abbreviations, explanations see Materials and Methods Section and Table 1.

Table 6. Results of the variance analysis of the nutrient content and the ratio in assimilatory organs separately for one-year-old and two-year-old needles of the individuals in the individual treatments at α = 0.05.

Needle Age	Parameter	P	Mg	Ca	K	N	S	Ca/Mg	K/Mg	Ca/N	Mg/N
1st yr	Test Type	aov	aov	aov	K–W	aov	aov	aov	K–W	aov	aov
	p–value	***	***	***	***	***	***	***	***	***	***
2nd yr	Test Type	aov	aov	aov	aov	aov	aov	aov	K–W	aov	aov
	p–value	***	***	*	***	**	*	***	***	**	***

(test type: "aov" – parametrical ANOVA; "K–W" – Kruskal-Wallis test; p–values: " *** " < 0.001; " ** " 0.001–0.01; " * " 0.01–0.05; " . " 0.05–0.1). For the abbreviations, explanations see Materials and Methods Section and Table 1.

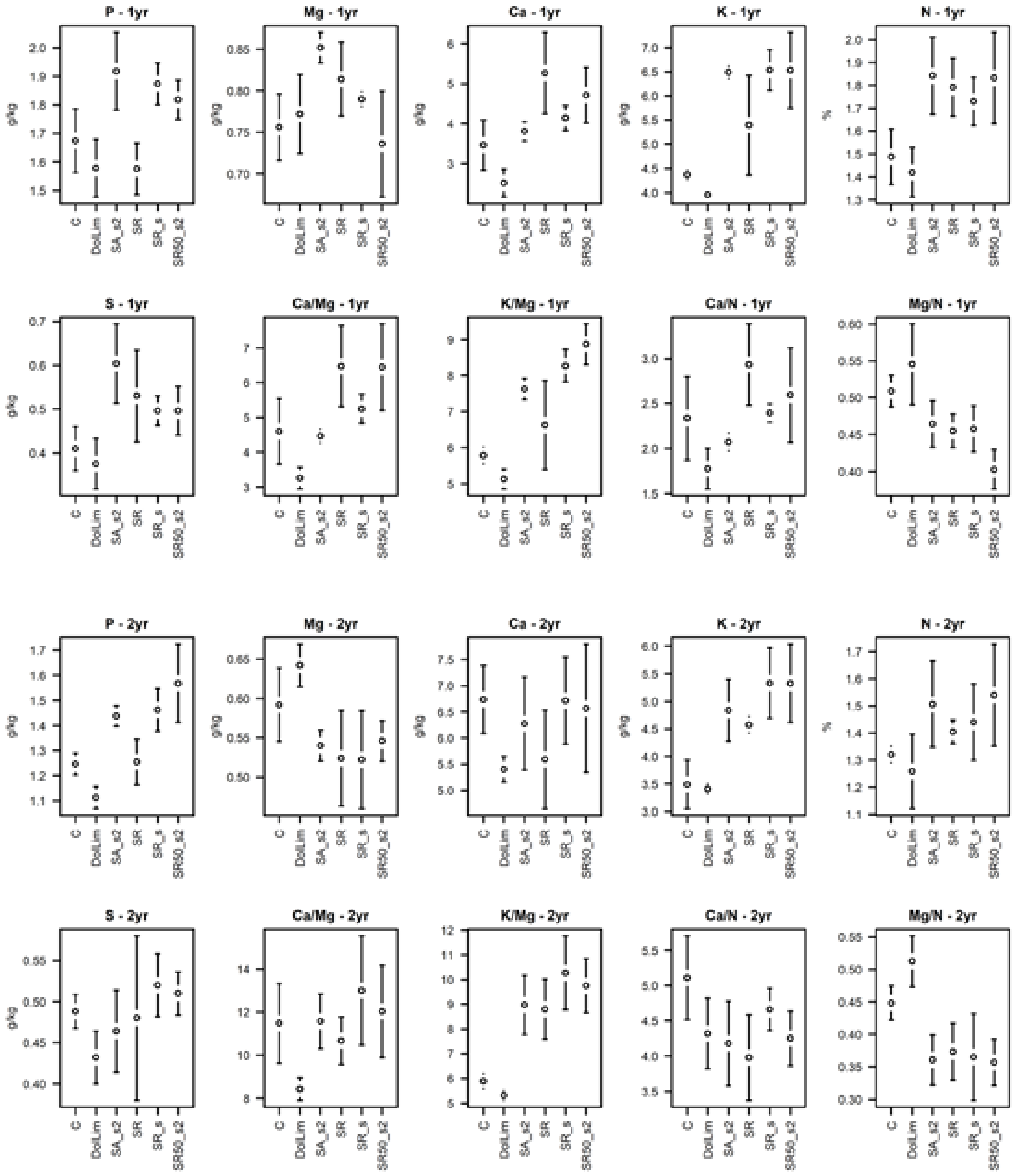

Fig. 3. Content of the nutrients in one-year-old needles (a) and two-year-old needles (b) in the individual treatments, expressed as the post-hoc multiple comparisons with the mean values and 95% confidence intervals. (for the abbreviations, explanations see Materials and Methods Section and Table 1).

lent ammonium ion (NH_4^+) with comparable lyotropic properties.

The Ca/Al and Bc/Al ratios contribute to the optimum level of soil chemistry in addition to absolute concentrations. These ones are at very low levels (far below 1, even below 0.2) in most cases, which has already been considered a significant environmental risk (Cronan & Grigal 1995; Vanguelova et al. 2007).

Nevertheless, the growth and nutritional responses of the stand are differentiated, although this ratio had not been significantly differentiated by any measure. On the contrary, the biomass production and the health status are the most favourable at treatments with combined fertilizers supplemented with the growth regulators. However, it should be noted that a considerable number of the literature (including that one listed here) operates with the Ca/Al and Bc/Al ratios in the soil solution, not the soil sorption complex. Nonetheless, according to the ratio law (Schofield 1947 in White 2006), it is also possible to take this ratio into account as a guideline for the assessment of soil chemistry.

The higher nitrogen content in values up to the supraoptimal concentration (Table 4) for DolLim can result in its accelerated mineralization and loss from the root zone not only of nitrogen, but also to equivalent loss of Mg, Ca and K (Huettl & Zoettl 1993). In soil chemistry with the C/N ratio lower than 30 and ammonia nitrogen form dominance, mineralization and nitrification lead to the increase in H^+ concentration and acidification of lower soil parts and heavy metals mobilization. Hence the amelioration on one side can be interlinked to the risk of nitrogen leaching (Huettl & Zoettl 1993; Vesterdal & Raulund-Rasmussen 2002), on the other side, it can precede nitrogen immobilization via biological fixation when the C/N ratio higher than cca 30–35 (Kai et al. 1969; White 2006).

The growth responses were not significantly different in the annual growth (Table 5) but showed the lowest effect in the DolLim treatment, which corresponded with the lowest vitality. The lowest biomass production in one-year-old needles was in DolLim treatment and the highest in SR_s treatment; in two-year-old needles the needles biomass production was not under the direct influence of the treatments as the needles developed before the experiment commencement.

The effect of treatments on the assimilation organ development was documented in the factorial plane (Fig. 4); in one-year-old needles, the vector of the HundNeedl categorical variable evinced a slight negative relation in DolLim, while in two-year-old needles, the same vector manifested no relation with the treatment.

The element content in biomass and nutritional balance were highlighted in Table 6 and Fig. 3, with a detailed representation of the graphical display of the PCA (Fig. 4). The cumulative proportion of explained variability with the first two principal components was 53.02% and 53.76% for dataset with one-year-old and two-year-old needles, respectively. In one-year-old assimilation organs (Fig. 4a), the Mg nutrient concentration was relatively unresponsive to Ca, and its intake was bound to the Silvamix compound fertilizers. In the C and DolLim treatments, potassium was at the lower optimum limit, especially in the two-year-old needles. In the two-year-old needles (Fig. 4b), the K/Mg nutrient ratio was completely antagonistic; Mg was forwarded at the expense of K, and Mg was distributed to a younger needle year-class (da Silva et al. 2011) while presenting a deficiency due to a suboptimal intake during the dry period throughout the vegetation. In connection with the initial natural (soil) conditions, the question is the legitimacy of forest ecosystem subsidy with magnesium, which was in the optimum values in the soil within the particular area and yet did not enter into nutrition due to the limited income in relation to its hydration requirements (Gransee & Führs 2013) that manifest during the short-term drought in the growing season. Thus, Mg is still within the optimum range in one-year needles while it is below the limit of deficiency in two-year needles. Furthermore, when using combined fertilizers, the K/Mg ratio was more optimized than C and DolLim.

Based on herein results and other works, fertilization and amelioration of forest ecosystems still seem to be questionable measures and many research studies provide contradictory interpretations, depending on forest management, as well (Podrázský 1994; Nilsson et al. 2001; Sjöberg et al. 2004; Remeš et al. 2005; Vacek et al. 2006; Vavříček et al. 2010; Šrámek et al. 2012). Compared to agrosystems, where liming is an essential part of the soil environment care (Goulding 2016), the overhead humus forms that are typical of forest soils (Klinka et al. 1990) represent a significant buffering factor (James & Riha 1986), as well as an important nutrient reservoir. From this perspective, it seems to be auspicious to repeat the investigation in the longer time horizon.

Soil buffering is a significant factor affecting the liming efficiency, especially treatments targeting elevated

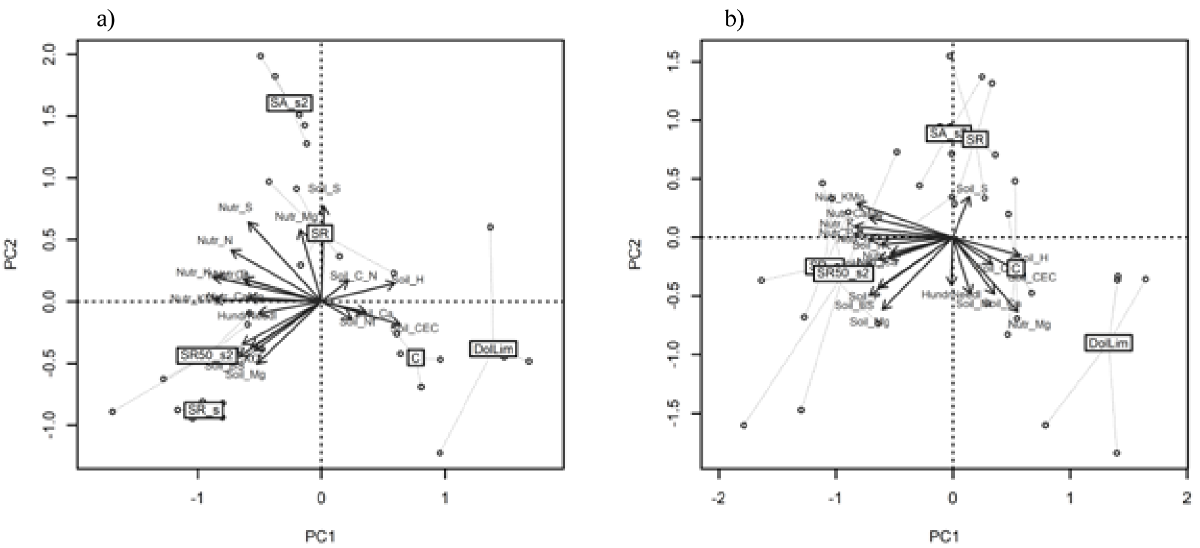

Fig. 4. PCA ordination graph illustrating the relation between categorical variables and the individual treatments (a): concerning the nutritional status of one-year-old needles; (b) concerning the nutritional status of two-year-old needles (for the abbreviations, explanations see Materials and Methods Section and Table 1).

mountainous locations with a naturally acidic soil reaction (pH/KCl even < 3.0) in the podzol soil zone. In organo-mineral and mineral horizons, the buffering capacity extends to the exchange zone and even down to the aluminium zone (Matzner 1992). Liming of these habitats results in conflicts related to the paradoxical application of the carbonate buffering zone in the naturally occurring buffer zone of iron and aluminium. Based on the frequently contradictory standpoints, the positive effect of liming (especially the air largescale) is not unquestionable. Hence, beside the routine soil parameters (pH, exchangeable nutrient content, base saturation), the nutritional status of the stand, the forest floor vegetation and site conditions should be individually examined.

5. Conclusion

The combined fertilizers use in the forest ecosystems was more effective for soil chemistry, the plant growth, as well as the nutrition status compared to the dolomitic limestone. Liming negatively affected the nutrient status of the soil and plants in comparison with the effects of compound fertilizers and caused disproportionate nutrient levels on soil colloids and nutritional imbalances.

Liming can significantly impact ion exchange processes in the soil sorption complex, the soil chemical status and, consequently, biological activities, mineralization processes, humus conditions, the plant nutrition and health statuses.

Soil chemistry, nutrition status and biometrical parameters of the Norway spruce individuals were positively affected using combined fertilizers. In addition to liming, there are alternative amelioration methods, e.g. the application of compound fertilizers containing a wide range of macrobioelements using nanotechnologies, such as growth regulators, for improving tree vitality, metabolism, nutrient uptake and root system development.

Individual application of ameliorative materials is optimal method for stands with juvenile development stage.

Acknowledgement

The study was funded by the project QJ1320040 (Ministry of Agriculture, Czech Republic). It was also supported by the projects QK1920328 (Ministry of Agriculture, Czech Republic) and IGA_PSV_2017008 (Mendel University in Brno, Faculty of Forestry and Wood Technology).

References

Adams, F., Evans, C. E., 1990: A rapid method for measuring lime requirement of yellow podzolic soils. Soil Science Society of America Journal, 26:355–357.

Augusto, L., Ranger, J., Binkley, D., Rothe, A., 2002: Impact of several common tree species of European temperate forests on soil fertility. Annals of Forest Science, 59:233–253.

Bäck, J., Huttunen, S., Turunen, M., Lamppu, J., 1995: Effects of acid rain on growth and nutrient concentrations in Scots pine and Norway spruce seedlings grown in a nutrient-rich soil. Environmental Pollution, 89:177–87.

Baláš, M., Kuneš, I., Zahradník, D., 2010: Reaction of Carpathian birch on liming and nitrogen fertilization. Zprávy lesnického výzkumu, 55:106–115.

Cronan, C. S., Grigal, D. F., 1995: Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. Journal of Environmental Quality, 24:209–226.

da Silva, E. C., Nogueira, R. J. M. C., da Silva, M. A., de Albuquerque, M. B., 2011: Drought stress and plant nutrition. Plant Stress 5 (Special Issue 1):32–41.

Formánek, P., Vránová, V., 2003: A contribution to the effect of liming on forest soils: review of literature. Journal of Forest Science, 492:182–190.

Goulding, K. W. T., 2016: Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Soil Use and Management, 32:390–399.

Gransee A., Führs, H., 2013: Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. Plant Soil, 368:5–21.

Hruška, J., Ciencala, E. (eds.), 2005: Dlouhodobá acidifikace a nutriční degradace půd – limitující faktor současného lesnictví (in Czech). Praha, Česká geologická služba, 153 p.

Huang, J., Jiangming, M., Zhang, W., Xiankai, L., 2014: Research on acidification in forest soil driven by atmospheric nitrogen deposition. Acta Ecologica Sinica, 34:302–310.

Huettl, R. F., Zoettl, H. W., 1993: Liming As a Mitigation Tool in Germany Declining Forests – Reviewing Results From Former and Recent Trials. Forest Ecology and Management, 61:325–338.

Ingerslev, M., 1999: Above ground biomass and nutrient distribution in a limed and fertilized Norway spruce (*Picea abies*) plantation. Part I. Nutrient concentrations. Forest Ecology and Management, 119:13–20.

Ingerslev, M., Hallbäcken, L., 1999: Above ground biomass and nutrient distribution in a limed and fertilized Norway spruce (*Picea abies*) plantation. Part II. Accumulation of biomass and nutrients. Forest Ecology and Management, 119:21–38.

James, B. R., Riha, S. J., 1986: pH Buffering in Forest Soil Organic Horizons: Relevance to Acid Precipitation. Journal of Environmental Quality, 15:229–234.

Kai, H., Ahmad, Z., Harada, T., 1969: Factors affecting immobilization and release of nitrogen in soil and chemical characteristics of the nitrogen newly immobilized: I. Effect of Temperature on Immobilization and Release of Nitrogen in Soil. Soil Science and Plant Nutrition, 15:207–213.

Kirk, P. L., 1950: Kjeldahl Method for Total Nitrogen. Analytical Chemistry, 22:354–358.

Klimo, E., Vavříček, D., 1991: Acidifikace a vápnění lesních půd v Beskydech. Lesnictví – Forestry, 37: 61–72.

Klinka, K., Wang, Q., Carter, R. E., 1990: Relationships Among Humus Forms, Forest Floor Nutrient Properties, and Understory Vegetation. Forest Science, 36:564–581.

Kreutzer, K., 1995: Effects of forest soil liming on soil processes. Plant and Soil, 168:447–470

Kulhavý, J., Marková, I., Drápelová, I., Truparová, S., 2009: The effect of liming on the mineral nutrition of the mountain Norway spruce (*Picea abies* L.) forest. Journal of Forest Science, 55:1–8.

Kuneš, I., 2003: Prosperity of spruce plantation after application of dolomitic limestone powder. Journal of Forest Science, 49:220–228.

Kuneš, I., Baláš, M., Balcar, V. et al., 2013: Effects of fertilisation on growth and nutrition of Norway spruce on a harsh mountain site. Journal of Forest Science, 59:306–318.

Lomský, B., Šrámek, V., Maxa, M., 2006: Fertilizing measures to decrease Norway spruce yellowing. Journal of Forest Science, 52:65–72.

Matzner, E., 1992: Acidification of forests and forest soils: Current status. Studies in Environmental Science, 50:77–86.

Mehlich, A., 1978: New extractant for soil test evaluation of phosphorus, potassium, magnesium, calcium, sodium, manganese and zinc 1. Communication in Soil Science and Plant Analysis, 9:477–492.

Merry, R. H., 2009: Acidity and alkalinity of soils. In: Sabljic, A. (ed): Environmental and Ecological Chemistry. Eolss Publishers Co. Ltd. Oxford, UK, p. 115–131.

Nilsson, I. S., Andersson, S., Valeur, I. et al., 2001: Influence of dolomite lime on leaching and storage of C, N and S in a spodosol under Norway spruce (*Picea abies* [L.] Karst.). Forest Ecology and Management, 146:55–73.

Novotný, R., Lachmanová, Z., Šrámek, V., Vortelová, L., 2008: Air pollution load and stand nutrition in the Forest District Jablunkov, part Nýdek. Journal of Forest Science, 54:49–54.

Pecháček, J., Vavříček, D., Kučera, A., Dundek, P., 2017: The effect of slow-release fertilizers on the soil environment of spread windrows in the Krušné Hory Mts. Journal of Forest Science, 63:331–338.

Podrázský, V., 1994: Provozní vápnění v Krkonoších. Opera Corcon, 31:59–70.

Remeš, J., Podrázský, V., Ulbrichová, I., Meduna, V. 2005: Fertilization of Norway spruce plantations on the bulldozer-spread windrows in the Ore Mts . Journal of Forest Science, 51:49–53.

Sardans, J., Peñuelas, J., 2015: Potassium: A neglected nutrient in global change. Global Ecology and Biogeography, 24:261–275.

Seaby, D. A., Selby, C., 1990: Enhanced Seedling Root Development in 8 Conifer Species Induced By Naphthalene Acetic-Acid. Forestry, 63:197–207.

Simpson, D. A., 1986: Auxin stimulates lateral root formation in container grown interior Douglas-fir seedlings. Canadian Journal of Forest Research, 16:1135–1139.

Singh, A., Agrawal, M., 2008: Acid rain and its ecological consequences. Journal of Environmental Biology, 29:15–24.

Sjöberg, G., Knicker, H., Nilsson, S. I., Berggren, D., 2004: Impact of long-term N fertilization on the structural composition of spruce litter and mor humus. Soil Biology and Biochemistry, 36:609–618.

Sokolov, A. V., 1939: Determination of exchangeable Al in soil. Chemizacija socialističeskogo zemledelija, 7:30 – 35.

Šrámek, V., Fadrhonsová, V., Vortelová, L., Lomský, B. 2012: Development of chemical soil properties in the western Ore Mts. (Czech Republic) 10 years after liming. Journal of Forest Science, 58:57–66.

Strížová, I., 2014: Jednotné pracovní postupy, Analýza rostlinného materiálu. ÚKZÚZ (Central Institute for Supervising and Testing in Agriculture), Brno.

Vacek, S., Podrázský, V., Hejcman, M., Remeš, J., 2006: Effect of Mg fertilization on yellowing disease of Norway spruce at higher elevations of the Šumava Mts., Czech Republic. Journal of Forest Science, 52:474–481.

Vanguelova, E.I., Hirano, Y., Eldhuset, T.D., et al. 2007: Tree fine root Ca/Al molar ratio - Indicator of Al and acidity stress. Plant Biosyst 141:460–480.

Vavříček, D., Pecháček, J., Jonák, P., Samec, P. 2010: The effect of point application of fertilizers on the soil environment of spread line windrows in the Krušné hory Mts. Journal of Forest Science, 56:195–208.

Vavříček, D., Samec, P., Šimková, P., 2005: Soil properties as a component of predisposition factors of Norway spruce forest decline in the Hanušovická highland mountain zone. Journal of Forest Science, 51:527–538.

Vavříček, D., Kučera, A., 2017: Základy lesnického půdoznalství a výživy lesních dřevin. Lesnická práce, Kostelec nad Černými lesy, 364 p.

Vesterdal, L., Raulund-Rasmussen, K., 2002: Availability of nitrogen and phosphorus in Norway spruce forest floors fertilized with nitrogen and other essential nutrients. Soil Biolchemistry, 34:1243–1251.

White, R. E., 2006: Principles and Practice of Soil Science: the Soil as a Natural Resource, fourth. Blackwell, Oxford.

Other sources:

IUSS Working Group WRB, 2014: World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Regulation (EC) 2003/2003 (2003) Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers.

List of Abbreviations

aov	– ANOVA
Bc	– base cations
C	– control
CEC	– cation exchange capacity
DolLim	– dolomitic limestone
GrowAnn	– annual height increment
Health	– health status
HundrNeedl	– weight of 100 needles
K–W	– Kruskal-Wallis test
Nutr_P, Mg, Ca, K, N, S, CaMg, KMg	– nutrient content in needles and the nutrient ratio
SA_s2	– AGLUFORM®90+s2
Soil_BS	– base saturation
Soil_C_N	– C/N ratio
Soil_Ca, Mg, K, P, S, Nt, H	– element content in soil
Soil_CEC	– cation exchange capacity
Soil_pH_H_2O and Soil_pH_KCl	– active and exchangeable soil reaction, respectively
SR	– Silvamix®R30
SR_s	– Silvamix®R30+s
SR50_s2	– Silvamix®R50+s2

Cent. Eur. For. J. 66 (2020) 151–158 sciendo DOI: 10.2478/forj-2020-0005

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Cutting practices in mature stands of *Tilia cordata* Mill.

Rida Sultanova*, Maria Martynova, Svetlana Konashova, Elvira Khanova, Vasilina Yanbaeva

Federal State Budgetary Educational Institution of Higher Education "Bashkir State Agrarian University", 50-letiya Octyabrya St., 34, Ufa, 450001, Russia

Abstract

The right timing for replacing mature and over-mature forest stands with a young generation of trees is evident as it ensures continuity in forest management. The study aimed to assess the efficiency of cutting practices in mature stands of *Tilia cordata* Mill. Mono-dominant and poly-dominant, even- and different-aged linden tree forests in the southern Urals were studied. The study found that in the first years following the small scale forest cutting practices (the Murakhtanov method), retention trees of *Tilia cordata* Mill. showed longer crowns (by 0.3 ± 0.01 m) and higher crown diameter indices (by 0.11 ± 0.04 m). A single selection showed that nectar secretion potential was 2.1 ± 0.06 mg/flower in the first assessment year, the index was 1.8 ± 0.03 mg/flower in the control forest area where no trees were cut. In the third assessment year, nectar secretion potential rose to 4.1 ± 0.04 mg/flower, while the index fell to 2.0 ± 0.01 mg/flower in the control forest area. The comparative analysis of the shoot growth capacity in stools of different diameters showed that shoots regrew from 82% of stumps. Shoots did not regrow from stumps affected by rot, those ones destroyed in the cutting process, and also from stumps of 59 – 62 cm in diameter.

Key words: coppice shoots; nectar-producing tree; regeneration; small-forest cutting; *Tilia cordata* Mill.

Editor: Jiří Novák

1. Introduction

Forest stands of *Tilia cordata* Mill. (henceforth referred to as TC) make up the bulk of the primary deciduous forests (Bauhus et al. 2010). In temperate forests, TC is the most widespread (Bauhus et al. 2010; Samsonova 2012; Kulakov 2013) among the four species of the *Tilia* genus growing naturally in Europe. Growing in less than 5% of forests (Forest Peoples Program 2017), the species population varies significantly across Europe (Bauhus et al. 2010; Harmon et al. 2013). TC grows in a wide range of environments. In Northern Europe, the species grows as far as Central Sweden and southern Norway (Svejgaard 2003; Pigott 2012). In the south, the species prevails in forest stands as far as Northern Greece and the Northern Iberian Peninsula. TC stands extend from Northern Ireland to the TransUrals (Gellini&Grossoni 1998; Pigott 2012).

Compared to other deciduous woody plants, TC is less sensitive to temperatures and soil fertility (Konashova et al. 2018; Sultanova et al. 2019). Broad adaptability of the species is recognised by most researchers (Hölscher et al. 2005; Bréda & Badeau 2008; Popescu et al. 2014; Gilman et al. 2016; De Jaegere et al. 2016; Lundmark et al. 2017). Due to its high shade tolerance when young and thanks to its advantageous vegetative reproduction, TC can be considered a competitive species. The shade tolerance varies from moderate (Popescu et al. 2014) to high (Pigott 2012) in the species. This feature mainly depends on the growth stage, climatic aspects, and geographical location (Diekmann 1996). A relatively high occurrence of the linden tree may be accounted for by its vegetative origin as the species grows through coppice shoots and root suckers. TC produces more coppice shoots than oaks and hornbeams. Also, the linden coppice shoots have higher length and diameter growth indices (Pigott 2012; Sultanova et al. 2019). Due to the aspects mentioned earlier, the linden tree is widely used in protection forests, urban greening practices, and for commercial wood and nectar-related purposes.

Among all *Tilia* species, TC is of the highest value due to its full ecological range and numerous silvicultural advantages, when growing in mixed forest stands in particular (Pigott 2012). TC can prevail in the canopy formation, often mixed with genera such as *Quercus*, *Acer*, *Betula* (Tóth et al. 2012; Beaune et al. 2013). The TC shows good growth indices when mixed with *Carpinus betulus* L., *Picea abies* (L.) Karst, *Abies alba* Mill. and *Pinus sylvestris* L. (Jaworski et al. 2005). In the southern Urals, the TC stands build a complex dynamic system

*Corresponding author. Rida Sultanova, e-mail: sultanovarida@rambler.ru

characterized by population-related, environmental, geographical, and biocenotic features. TC grows in the area of 1148.4 thousand hectares on the territory of the Republic of Bashkortostan (henceforth referred to as RB), occupying 22% of the forest-covered lands with a total reserve of 209.3 thousand m^3.

The area of 157.7 thousand hectares is devoted to the 'nectareous linden' working circle in RB. The efficient application of TC for honey-related purposes can be reached through forming a composite, uneven-aged forest stand with two and more layers. Uneven-aged forest stands ensure continuous production for commercial wood and nectar-related purposes and increase the nectar secretion period in the trees.

The principal objective of successful forest management is to enhance productivity, improve the age and quality structure in TC stands, appropriately use wood resources as well as ensure regeneration of linden trees. There are many forest management practices aimed at obtaining efficient and continuously productive TC stands. Priority is placed on various cutting practices as they have a long term effect (Ministry of Natural Resources and Ecology of the Russian Federation 2016, 2017; Sultanova et al. 2019). Cutting practices ensure the rapid growth of stool coppice shoots. The coppice method is a crucial factor in the successful regeneration of deciduous forests (Popescu et al. 2014; Sultanova et al. 2019). The selection of trees for cutting is based on several factors, such as economic, qualitative, and bio-ecological characteristics of wood species. The key point in determining the cutting practice parameters is the selection of trees for cutting, taking into account their environmental biological and qualitative characteristics (Crecente-Campo et al. 2009; Ministry of Natural Resources and Ecology of the Russian Federation 2016, 2017). The following criteria are employed by some researchers to assess the efficiency of cutting practices: the forest standing volume, growth, stand density, and tree growing area (Gellini & Grossoni 1998; Crecente-Campo et al. 2009; Li et al. 2017).

Although TC is widely distributed in Europe, few studies described its growth and productivity. The studies focused on growth aspects in various environments. For example, Böckmann (1990) presented growth stage tables reflecting changes in the forest stand volume to the growing area and geographical location in Germany. Many data are available on linden tree regeneration based on various cutting methods. However, most of the studies considered the self-reproduction of linden tree forest stands without regard to the parent canopy structure. The issue of forest productivity with the prevailing TC has not been adequately addressed. With that in mind, it is crucial to determine optimal parameters and cutting methods ensuring productive linden tree forest stands for commercial wood and nectar-related purposes.

The study aims to assess the efficiency of cutting practices in mature TC stands. The practices ensure the growth of continuously productive linden tree forest stands and improve their production indices.

Long-term comprehensive studies on the efficiency of cutting practices in mature TC stands were conducted. There are three hypotheses put forward in the study. In essence, the age of the mother stand and the cutting area determine the efficiency of the small-scale cutting in the nectar-producing part of the forest stand (1); the season of the narrow-strip clear-cutting in linden forests (summer, winter) determines the composition of the next regeneration (2). The third hypothesis (3) of the variability in TC nectar productivity was particularly crucial for the study.

2. Materials and methods

2.1. Research design

Experiments were conducted in the PTA of the Nurly forest district to evaluate vegetative regeneration potential in linden trees. The forest stands affected by winter and summer cutting operations in 1993 were studied. The full forest quality assessment was conducted to evaluate the regeneration processes. Based on the study measurements, forest indices of the linden tree were analysed, natural regeneration processes were assessed, and statistical indices of the tree stands were calculated.

2.2. Study sites

Mono-dominant and poly-dominant, even- and different-aged linden tree forests of the southern Urals were studied. An experimental study was conducted in 1986-2018. The study encompassed forest assessment, nectar production, regeneration indices based on the cutting practices, timber production aspects in mature and over-mature TC stands. The experiment used seventeen permanent trial areas (PTA). The trial plot areas ranged from 0.5 to 2.7 ha.

Trial area establishment was performed based on the regulatory requirements under the Russian industry standard 56 – 60 – 83 'Trial areas for forest management. The establishment method included the optical measurement in determining bio-morphological indices (for instance, trunk diameter, trunk height, crown width and length). The natural regeneration on summer and winter clear-cuts was analysed to specify the number of shoots in the coppice, their height, and the diameter at the root collar. The visual assessment of the trees used indicators of the crown length including flowers and the number of generative organs in the crown layers. The Abney level was used to measure the crown height and length. The quantitative study of flowering was conducted on the type trees (done in the North-South and West-East directions), the crown of the type trees was divided into two-meter segments along the length. Blotting up with filter paper, or washing and rinsing procedures were used to extract the nectar from the linden flowers.

The trial was performed in goutweed type forests of Gafuri and Ufa districts of RB, Russia.

Natural regeneration establishment was analysed on the sites where winter and summer clear-cut operations were performed within the goutweed linden tree stand aged 70 years of the Nurly forest district. Long-term experiments were performed in the Krasnoyarsk and Tabyn forest districts to assess the efficiency of small scale forest cutting (the Murakhtanov method). Small-scale forest cutting is performed under the following technical parameters: the length of the cutting strips does not exceed 1,000 m, the width is 50 – 100 – 150 m, and the number of the retained nectar-producing linden trees is 50 – 75 – 100 per 1 ha (Murakhtanov 1972).

2.3. Equipment used

Textolite calipers, Suunto optical height meter, Bitterlich angle gauge, and a tape measure were used in the measurement operations.

2.4. Statistical analysis

Methods of variational statistics, the correlation, and regression analysis, as well as Microsoft Excel and Statistica 6.0 application packages, were employed to process experimental data. The Student's t-test was used to compare the same-named properties. The coefficient of variation (V, %) was calculated to assess the variation of properties.

2.5. Limitations of the study

Currently, there is insufficient objective evidence for providing a rationale for forest cutting practices and operations used in linden tree forest management for particular purposes.

3. Results

Small scale forest cutting practices aim to preserve nectar-producing potential of linden tree forest stands and prevent the death of trees. The study performed in the Krasnoyarsk forest district established the efficiency of the small-scale forest cutting practice (the Murakhtanov method). The cut areas were located close to an apiary farm. The cutting area varied from 0.5 to 3 hectares. While harvested, 100 TC trees with the best growth and flowering indices were retained as nectar-producing trees on each site.

Experimental site inventories conducted in the first decade after felling revealed that the retained TC trees produced 1.4 times more flowers in the good blooming years than in the stand unfelled (Table 1).

However, 20 years after cutting, the nectar trees stopped producing, and the study areas were overgrown with the hazel (Fig. 1).

The first decade showed dieback of 8 – 22% retained nectariferous trees; in the second decade a 52 – 69% rate with the crown broken in 26% of the trees were reported. Currently, 8 – 20 dying trees with regular breaks have remained out of 100 seed trees on the study forest sites. A more significant number of seed trees have remained on the sites with an area of up 2 ha.

Similar experiments were conducted in the Tabynsky forest district of Gafuri forest area. The small-scale forest cutting was performed in the forest stand made up of 6L – 2B1Ewe – 1As (see Table 1 for explanation) (aged 75 years old) with growth class 3, 0.6 forest stand density in 1.2 ha area. Sixty flowering linden trees were retained after cutting.

Over the three years after the small-scale cutting, all of the retention trees demonstrated longer and wider crowns (by 0.3 ± 0.01 m in length and by 0.11 ± 0.04 m in diameter). A single selection showed higher nectar secretion potential accounting for 2.1 ± 0.06 mg/flower in the first assessment year, compared to the 1.8 ± 0.03 mg/flower in the control forest area where no trees were cut. In the third assessment year, nectar secretion

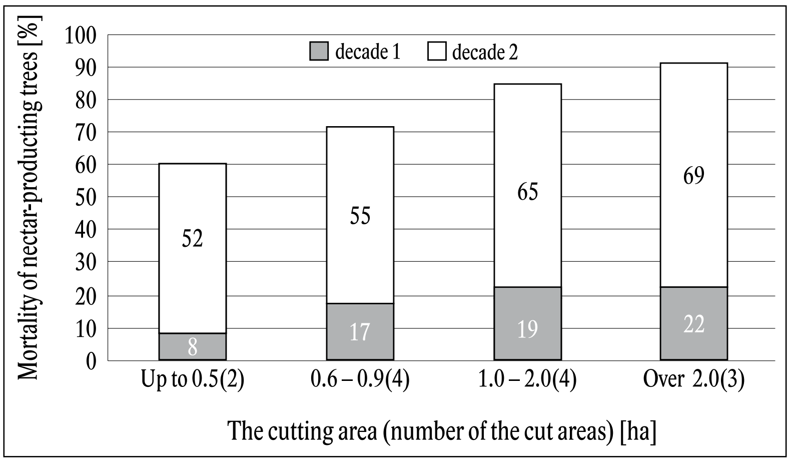

Fig. 1. The mortality rate in nectar-producing linden related to the cutting area.

Table 1. Forest stand characteristics in the cut areas after small-scale felling.

Planning quarter / stratum no.	Area [ha]	Decade 1		Decade 2		Decade 3							
							the second growth						
		number of nectar-producing trees	undergrowth species composition(quantity of linden trees) [thousand trees/ha]	number of nectar-producing trees	undergrowth species composition (quantity of linden trees) [thousand trees/ha]	number of nectar-producing trees	composition	age [years]	height [m]	type	stand density	forest understorey
25/13	2.5	100	7Ewe – 3L (8.3)	82	7Ewe – 3L (2.7)	9	7Ewe – 3L	25	8.0	nm	0.6	hzl, bird cherry; thick
14	2.7	100	6L3 – Ewe – 1M (15)	73	5L – 4Ewe – 1M (3.3)	11	4L – 4Ewe – 2M	24	10	gw	0.5	hzl; thick
15	2.5	100	5L – 3Ewe – 2M (17)	79	4L – 4Ewe – 2M (3)	8	5Ewe – 3L – 2M	24	9.0	gw	0.5	hzl, willow; thick
17	1.0	75	5L – 3Ewe – 2M (18)	61	4L – 4Ewe – 2M (3)	11	5Ewe – 3L – 2M	24	9.0	gw	0.6	hzlraspb, bird cherry
18	2.0	100	5L – 3Ewe – 2M (18.5)	84	4L – 4Ewe – 2M (2.9)	19	5Ewe – 3L – 2M	23	8.0	gw	0.7	hzl, raspb; thick
24	1.9	100	6L – 2Ewe – 2W (17)	81	6L – 2Ewe – 2W (5.2)	15	6L – 2Ewe – 2W	21	8.0	gw	0.5	hzl, raspb, bird cherry
25	2.0	100	5Ewe – 3M – 2L (14)	77	5Ewe – 3M – 2L (1.1)	13	5Ewe – 3M – 2L	21	6.7	nm	0.6	hzl, goat willow, raspb
26/18	0.5	50	7L – 2M – 1Ewe (18.5)	46	4L – 3We – 2M – 1Ewe (2)	20	4L – 3We – 2M – 1W	22	6.5	gw	0.6	hzl, raspberry; mid–lev
19	0.8	50	5L – 2M – 2We – 1Ewe	41	4L – 3M – 2We – 1Ewe (2)	17	4L – 3M – 2We – 1Ewe	22	6.0	gw	0.6	hzl, bird cherry; mid–lev
20	0.9	75	5L – 3M – 2Ewe (12.7)	60	4L – 3M – 2Ewe – 1We(2)	21	4L – 3M – 2Ewe – 1We	22	5.0	gw	0.6	hzl; thick
21	0.6	50	6L – 2Ewe – 2M (15.1)	41	4L – 2Ewe – 1We – 3M (2)	14	4L – 2Ewe – 1We – 3M	22	6.0	gw	0.6	hzl, bird cherry; mid–lev
25	0.7	50	7L – 2M – 1Ewe (16.2)	44	5L – 2M – 2We – 1Ewe (3)	12	4L – 3M – 2We – 1Ewe	25	10	gw	0.6	hzl, bird cherry; mid–lev
Control forest site 25/8	15	10L + Ewe, Age = 85 years H = 19 m, D = 30 cm SD = 0.6, Vol = 210 m³/ha Undergrowth 5M – 3Ewe – 2L, aged ten years old 4.0 m, 2 thousand trees/ha Understorey hazel, bird cherry; thick		10L + Ewe, Age = 100 years H = 22 m, D = 32 cm SD = 0.6, Vol = 260 m³/ha Undergrowth 5M – 3Ewe – 2L, aged 15 years old 4.0 m, 4 thousand trees/ha Understorey hazel, bird cherry; thick		9L – 1Ewe, Age = 109 years, H = 21 m, D = 32 cm, SD = 0.5, Vol = 210 m³/ha Undergrowth 4M – 4Ewe – 1L – 1We, aged 20 years old, 3.0 m, 2 thousand trees/ha Understorey Hazel, bird cherry, raspberry; thick						

The following abbreviations are used in the table:
L – Linden, M – Maple, Ewe – European white elm, W – willow, We – Wych elm; nm – nettle and meadowsweet, gw – goutweed; hzl – hazel, raspb – raspberry, mid-lev – mid-level;
H – height, D – diameter, SD – stand density, Vol – forest volume.

potential rose to 4.1 ± 0.04 mg/flower, while the index fell to 2.0 ± 0.01 mg/flower in the control forest area. The Student's t-test was used to assess the difference in nectar production potential between the seed trees of the control forest site and the cut area. The first year demonstrated a statistically insignificant difference. The third assessment year showed significant variations in the nectar amount secreted by tree flowers in the cut areas and the control site. $t_{fact} = 2.36 \geq_{theor} = 2.04$ ($P = 5\%$, $n_1 + n_2 = 37$). At the end of the tenth period, the retention trees started dying.

Forest cutting practicon, particularly on the coppice type cutting performed in linden forests. The findings are confirmed by robust vegetative regeneration of linden trees resulted from rapid coppice shoot growth (Matula et al. 2012; Sultanova et al. 2019).

Repeated forest inventory of linden tree regeneration in the study areas showed that distribution in natural diameter class varied significantly (Fig. 2): A multimodal curve with a left side asymmetry ($Ka = 0.15$) reflected the summer cut area. The winter cut area was represented by a similar multimodal curve that had a distinct asymmetry ($Ka = -3.88$).

The analysis of the linden coppice shoots distribution resulted in the following findings. In essence, TC stands mixed greatly with *Acer platanoides* and *Ulmus glabra* were represented by multimodal curves with an asymmetry reflecting smaller diameters due to the species competition. Statistical data of linden tree assessment are presented in Table 4.

Table 2. Biometric indices of TC coppice shoots

Stump diameter [cm]	The number of shoots [pcs.]	Root collar diameter [cm]			Shoot height [m]		
		average	minimum	maximum	average	minimum	maximum
Summer cutting							
32	3±1.4	2.73±2.00	1.2	5	1.83±1.44	1	3.5
35	9±1.1	2.33±0.94	1	3.5	1.72±0.23	1.5	1.8
40	7±1.8	2.67±0.25	1	4.2	1.99±0.51	0.4	2.8
42	3±2.0	2.53±0.83	1.6	3.2	1.97±0.15	1.8	2.1
46	4±1.1	2.68±0.36	2.4	3.2	2.00±0.08	1.9	2.1
Winter cutting							
16	5	4.70±0.51	2	6	3.58±0.30	2.2	4.1
18	3	4.67±0.21	4.5	5	3.27±0.15	3	3.7
20	5.4±1.5	3.40±1.16	1.1	7	3.12±0.52	1.7	5.1
22	4±1.1	2.38±0.63	1.5	5.1	2.57±0.11	1.5	3.6
26	7±3.1	3.93±0.58	1.5	5.9	3.13±0.42	1.7	5.2
28	11	3.27±0.69	1.5	6	2.91±0.57	2	4.5
30	8.5±3.1	3.23±0.77	1.3	6	3.10±0.40	1.5	5.6
36	9.4±3.8	3.34±0.78	1.5	7	2.99±0.53	1	4.6
40	9.5±3.1	3.17±0.67	1.1	6.8	3.31±0.29	1	4.7
42	6.5±4.9	3.69±1.12	2	6.5	3.83±0.67	3.2	5.1
46	10±3.3	3.19±0.56	1	5.5	3.31±0.29	1.7	5
50	9±2.9	2.67±0.53	1	5.2	2.97±0.41	1.5	4.5
56	12	4.46±1.60	2.5	6.1	3.36±0.44	2	4.6
60	12.6±5.7	3.31±0.59	1	8	3.09±0.29	1.5	5.2

Regeneration processes were analysed to show that forest cutting practices significantly encouraged vegetative regeneration of the TCs. A year later, coppice shoots density was considerably higher on the winter clearings compared to the regeneration indices of the summer-cleared glades. The comparative analysis of the shoot growth capacity in stools of different diameters showed that shoots regrew from 82% of stumps. Shoots did not regrow from stumps affected by rot, those ones destroyed in the cutting process, and from stumps of 59 – 62 cm in diameter. The most significant number of shoots was observed on stumps of 30 – 42 cm in diameter (Table 2).

The study found that the cut areas mainly featured coppice shoot regrowth for 25 years. *Ulmus laevis* and *Acer* trees prevailed in the summer cut areas. TC and *Ulmus laevis* trees prevailed in the winter cut areas (Table 3).

Table 3. Regeneration indices in the cut areas to the cutting season (1995 and 2018 inventory years.

Cutting season	Wood species	Height [m]		Number	
		average	maximum	thousand trees/ha	%
1995 inventory					
Winter 1993	L	1.20	2.30	36.6	87.3
	M	0.35	0.50	5.1	12.2
	Ewe	1.20	1.75	0.2	0.5
Total				41.9	100
Summer 1993	M	0.40	0.50	5.8	71.6
	L	1.00	2.00	2.3	28.4
Total				8.1	100
2018 repeated inventory					
Winter	L	3.31	6.70	1.100	47.8
	Ewe	2.75	4.90	1.100	47.8
	M	2.43	4.69	0.100	4.4
Total				2.300	100
Summer	L	2.41	5.30	0.300	8.1
	Ewe	2.98	3.42	3.200	86.5
	M	2.63	4.70	0.200	5.4
Total				3.700	100

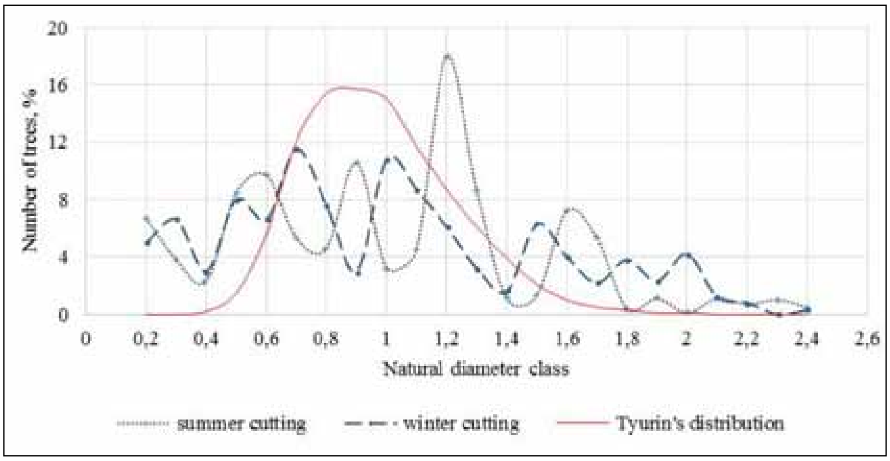

Fig. 2. Linden coppice shoots distribution in diameter classes (2018 inventory).

Table 4. Statistical indices of linden tree regeneration.

Statistical indices	Cutting season	
	summer	winter
Diameter [cm]		
Mean diameter [cm]	7.1	7.9
Standard error [cm]	0.3	0.2
Coefficient of variation [%]	28.7	18.4
Asymmetry	0.15	-3.88
Minimum [cm]	0.5	0.5
Maximum [cm]	11.1	12.9
Selection volume	75	229
Reliability level	1.24	0.77
Height [m]		
Mean diameter [cm]	2.41	3.31
Standard error [cm]	0.07	0.07
Coefficient of variation [%]	0.2	0.1
Minimum [m]	0.5	0.5
Maximum [m]	5.3	6.7
Reliability level	0.03	0.01

The statistical analysis showed that the calculated coefficient of variation indicated a significant deviation from the mean values for the summer cut area (V = 28.7%), and a moderate deviation for the winter cut area (V = 18.4%).

4. Discussion

To choose the practice and procedure of cutting for higher productivity indices is crucial to deciduous forests in European countries (Bürgi 1999; Pukkala et al. 2014; Jacobsen et al. 2018). Many forest researchers point out the need to adjust forest harvesting operations based on the forest site specifications and biological features of the species harvested. So cutting operations should be more adapted to specific conditions (Matula et al. 2012; Konashova et al. 2018; Sultanova et al. 2019). Our study showed that experimental small-scale forest cutting practices in linden tree forest stands did not ensure the nectar-producing continuity. The failure to ensure the continuity is due to the death of the seed trees (nectar-producing trees) and the lack of the linden tree undergrowth. Low economic outcomes after ten years resulted from some aspects related both to the cutting technology and cutting procedures. The selection of trees for cutting is based on the economic, qualitative, and biological and ecological characteristics of the wood species (Li et al. 2017).

The study revealed that TC regenerates rapidly through coppice shoots. The number of shoots decreases with time due to competition and external factors. Similar findings have been obtained when characterizing the little leaf linden tree in a changing climate (De Jaegere et al. 2016). The study demonstrates that TC has an increased potential for vegetative reproduction. Therefore, the species can outnumber other tree species. About 90 % of mature and over-mature linden tree forest stands in the Bialowieza National Park have a coppice shoot origin (De Jaegere et al. 2016).

As expected, we have found that the stump diameter has a significant effect on the shoot growth and its characteristics. Similar studies were conducted in Central Europe (Matula et al. 2012). The studies found that the stump diameter had a diverse effect on the initial shoot growth in different tree species. The number of shoots grown from the stump increased significantly with the stump diameter in oak trees. The stump diameter in the linden tree caused changes in the number of shoots, shoot height, and diameter.

Cutting practices have a considerable effect on the stand structure, but changes in the horizontal distribution are quite slow. More notable changes might be found in the vertical structure with the intensive natural regeneration (Vacek et al. 2018).

Several studies on the natural forest regeneration deal with the vegetative structure and specific composition, and some are concerned with environmental factors (Fayolle et al. 2105; Gilman et al. 2016; Poorter et al. 2016). We have studied the natural regeneration as related to the season when the cutting practice is performed. The experimental study has established that cutting operations in TC forest stands should be regulated by the seasons, taking into account the higher efficiency of winter cuttings for regeneration processes. Our findings demonstrate that there is rapid height growth observed in linden trees during the first years after cutting. For instance, two years after cutting, the linden tree reached 2.3 m in height in the winter cut areas. The findings obtained in Lower Saxony show that the height and volume growth rate in linden trees after winter cutting is higher than in other commercial trees (Bréda & Badeau 2008).

5. Conclusions

In terms of multifunctional forest use, TC is the most promising tree species. It serves not only as a source of wood (the share of the commercial linden tree in RB is about 67% of the total area linden tree stands) but also as the most productive basis for beekeeping (the area of the nectar-producing linden tree stands is about 33%). Also, TC stands are of significant environmental and social importance; the share of linden tree forest stands in various protection forests is 243.5 thousand hectares or 21.9%.

The study assessed the efficiency of cutting practices in mature TC stands. The practices ensure the growth of continuous productive linden tree forest stands and improve their production indices.

The study confirmed the need to perform small-scale cutting operations in nectar-producing linden tree forest stands bearing in mind the age limit and decay potential in linden trees. However, it is essential to ensure pre-generation undergrowth and subsequent linden coppice shoot regeneration in the cut areas to provide continuous growth of the nectar-producing trees. It is essential to prevent the parent forest stand aged 85-88 years old from over-maturing. The cutting area should not exceed 2 hectares.

No seed trees of the undergrowth were observed in the linden tree forest stands. Support for natural regeneration included cutting down the forest understorey and undergrowth of *Ulmus laevis*, *Ulmus glabra*, soil mineralization, retention of seed trees. However, the measures failed to ensure linden tree seed regeneration in all of the cut areas. Compared to other tree species, the linden trees possess an excellent potential for coppice shoot regeneration. So the linden tree are capable of growing in forests disturbed by various cutting practices.

Summer cuttings did not show any regeneration efficiency unless reliable pre-generated undergrowth was obtained. In terms of forest management, winter cuttings of linden trees (36.6 thousand trees/ha) had the best regeneration effect showing good biometric and quantitative indices. The season for the strip cutting (summer, winter) in linden tree forest stands affects the composition of the subsequent regeneration. In essence, summer cutting produces mainly regeneration of secondary tree species such as *Ulmus laevis* and *Ulmus glabra*. The process indicates the replacement of the main tree species. As a result, winter cutting practices produce regenerated linden trees of the coppice shoot origin, preserving the parent species in the forest stand.

Acknowledgments

The study was conducted with the financial support of the government of the Republic of Bashkortostan as part of the research project "Optimizing the intended forest use in the beekeeping industry," Decree of the Head of the Republic of Bashkortostan dated February 7, 2020, no. UG-43.

References

Bauhus, J., van der Meer, P., Kanninen, M., 2010: Ecosystem goods and services from plantation forests. London, Routledge, 240 p.

Beaune, D., Fruth, B., Bollache, L., Hohmann, G., Bretagnolle, F., 2013: Doom of the elephant-dependent trees in a Congo tropical forest. Forest Ecology and Management, 295:109–117.

Böckmann, T., 1990: Wachstum und Ertrag der Winterlinde (*Tilia cordata* Mill.) in Niedersachsen und Nordhessen. Ph.D. Thesis. Göttingen, Universität Göttingen, 143 p.

Bréda, N., Badeau, V., 2008: Forest tree responses to extreme drought and some biotic events: Towards a selection according to hazard tolerance? Comptes-Rendus Geoscience, 340:651–662.

Bürgi, M., 1999: A case study of forest change in the Swiss lowlands. Landscape Ecology, 14:567–576.

Crecente-Campo, F., Pommerening, A., Rodríguez-Soalleiro, R., 2009: Impacts of thinning on structure, growth, and risk of crown fire in a *Pinus sylvestris* L. plantation in northern Spain. Forest Ecology and Management, 257:1945–1954.

De Jaegere, T., Hein, S., Claessens, H., 2016: A review of the characteristics of small-leaved lime (*Tilia cordata* Mill.) and their implications for silviculture in a changing climate. Forests, 7:56.

Diekmann, M., 1996: Ecological behavior of deciduous hardwood trees in boreo-nemoral Sweden with light and soil conditions. Forest Ecology and Management, 86:1–14.

Fayolle, A., Ouédraogo, D.Y., Ligot, G., Daïnou, K., Bourland, N., Tekam, P. et al., 2015: Differential performance between two timber species in forest logging gaps and plantations in central Africa. Forests, 6:380–394.

Gellini, R., Grossoni, P., 1998: BotanicaForestale-II: Angiosperme. Padova, CEDAM, 210 p.

Gilman, A. C., Letcher, S. G., Fincher, R. M., Perez, A. I., Madell, T. W., Finkelstein, A. L. et al., 2016: Recovery of floristic diversity and basal area in natural and planted forest regeneration plots in a Costa Rican wet forest. Biotropica, 48:798–808.

Harmon, M. E., Fasth, B., Woodall, C.W., Sexton, J., 2013: Carbon concentration of standing and downed woody detritus: effects of tree taxa, decay class, position, and tissue type. Forest Ecology and Management, 291:259–267.

Hölscher, D., Koch, O., Korn, S., Leuschner, Ch., 2005: Sap flux of five co-occurring tree species in a temperate broad-leaved forest during seasonal soil drought. Trees, 19:628–637.

Jacobsen, J. B., Jensen, F., Thorsen, B. J., 2018: Forest value and optimal rotations in continuous cover forestry. Environmental and Resource Economics, 69:713–732.

Jaworski, A., Kołodziej, Z., Bartkowicz, L., 2005: Structure and dynamics of stands of primeval character composed of the little-leaf linden (*Tilia cordata* Mill.) in the "Las lipowy Obrożyska" reserve (southern Poland). Journal of Forest Science, 51:283–304.

Konashova, S. I., Sultanova, R. R., Khayretdinov, A. F., Gabdrakhimov, K. M., Konovalov, V. F., Rakhmatullin, Z. Z. et al., 2018. Forestry and Ecological Aspects of the Broad-Leaved Forest Formation. Journal of Engineering and Applied Sciences, 13:8789–8795.

Kulakov, V. N. 2013: Honey resources of the subjects of the Russian Federation. Monograph. Moscow, Russian Academy of Agricultural Sciences, 329 p.

Li, Y., Hui, G., Wang, H., Zhang, G., Ye, S., 2017: Selection priority for harvested trees according to stand structural indices. iForest-Biogeosciences and Forestry, 10:561–566.

Lundmark, H., Josefsson, T., Östlund, L., 2017: The introduction of modern forest management and clear-cutting in Sweden: Ridö State Forest 1832–2014. European Journal of Forest Research, 136:269–285.

Matula, R., Svátek, M., Kůrová, J., Úradníček, L., Kadavý, J., Kneif, M., 2012: The sprouting ability of the main tree species in Central European coppices: implications for coppice restoration. European Journal of Forest Research, 131:1501–1511.

Murakhtanov, E. S., 1972: Fundamentals of the complex farm organization for linden tree forest stands of the Middle Volga. Leningrad, LGU Publ., 302 p.

Pigott, D., 2012: Lime-trees and Basswoods: A Biological Monograph of the Genus Tilia. New York, Cambridge University Press, 405 p.

Poorter, L., Bongers, F., Aide, T. M., Zambrano, A. M. A., Balvanera, P., Becknell, J. M. et al., 2016. Biomass resilience of Neotropical secondary forests. Nature, 530:211–214.

Popescu, M. C., Lisa, G., Froidevaux, J., Navi, P., Popescu, C. M., 2014: Evaluation of the thermal stability and set recovery of thermo-hydro-mechanically treated lime (*Tilia cordata*) wood. Wood Science and Technology, 48:85–97.

Pukkala, T., Lähde, E., Laiho, O., 2014: Stand management optimization – the role of simplifications. Forest Ecosystems, 1:1–11.

Samsonova, I. D., 2012: Meteorological studies and nectar secretion. Beekeeping, 8:26–28.

Sultanova, R., Gabitov, I. I., Yanbaev, Y. A., Yumaguzhin, F. G., Martynova, M. V., Chudov, I. V. et al., 2019: Forest melliferous resources as a sustainable development factor of beekeeping. Israel Journal of Ecology and Evolution, 1:1–8.

Svejgaard, J., 2003: EUFORGEN Technical Guidelines for Genetic Conservation and Use for Lime (*Tilia* spp.). Rome, International Plant Genetic Resources Institute, 6 p.

Tóth, E. G., Diószegi, M., Hrotkó, K., 2012: Hungarian and foreign linden varieties' physiological evaluation. Dendrological Days in Mlinany Arboretum SAS, 83 p.

Vacek, Z., Vacek, S., Bílek, L., Král, J., Ulbrichová, I., Simon, J. et. al., 2018: Impact of applied silvicultural systems on spatial pattern of hornbeam-oak forests. Central European Forestry Journal, 64: 3–45.

Other sources:

Forest Peoples Program, 2017: Forest peoples program. Fosseway Business Centre, Moreton-in-Marsh. www.forestpeoples.org (accessed 13 December 2019).

Ministry of Natural Resources and Ecology of the Russian Federation, 2016: Guidelines for harvesting wood. Approved by the decree of the Russian Federation Ministry of Natural Resources of September 13, 2016, no. 474. Available on: https://www.garant.ru/products/ipo/prime/doc/71480564/(accessed 13 December 2019).

Ministry of Natural Resources and Ecology of the Russian Federation, 2017: Guidelines for forest management Approved by the decree of the Russian Federation Ministry of Natural Resources of November 22, 2017, no. 626. Available on: http://docs.cntd.ru/document/542612622 (accessed 13 December 2019).

Cent. Eur. For. J. 66 (2020) 159–169 sciendo DOI: 10.2478/forj-2020-0013

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Silver birch aboveground biomass allocation pattern, stem and foliage traits with regard to intraspecific crown competition

Bohdan Konôpka[1, 2]*, Jozef Pajtík[1], Vladimír Šebeň[1], Katarína Merganičová[2, 3], Peter Surový[2]

[1] *National Forest Centre, Forest Research Institute Zvolen, T. G. Masaryka 2175/22, SK – 960 01 Zvolen, Slovak Republic*
[2] *Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 176, CZ – 165 21 Praha 6 – Suchdol, Czech Republic*
[3] *Technical University in Zvolen, Faculty of Forestry, T. G. Masaryka 24, SK – 960 53 Zvolen, Slovak Republic*

Abstract

In the conditions of Central Europe, silver birch (*Betula pendula* Roth) has so far not been an important species for commercial purposes but might be relevant from ecological point of view. For instance, prompt succession by birch and other pioneer tree species at large-scale post-disturbance areas is necessary to compensate for previous carbon losses by natural disasters. Therefore, our attention was focused on 14-year-old birch trees growing at the wind-thrown area in the High Tatra Mts. (northern Slovakia). We sampled aboveground biomass of 20 silver birch trees representing four classes of crown competition: 0 – competition free crowns, 1 – crowns under mild competition, 2 – crowns under moderate competition, 3 – crowns under severe competition. We studied biomass allocated to stems, branches and foliage, and basic properties of stems and foliage. The crown-competition free birches were nearly 13 m high, and their aboveground tree biomass was 150 kg. The biomass of birches under severe competition was five times lower. Crown competition modified biomass ratios of foliage to branch as well as of branch to stem. Our results showed that birches under severe competition stress invest more in height than in diameter. At the same time, crown competition modified foliage weight and specific leaf area (SLA), which was clear mostly in the upper part of the crowns. However, foliage area was influenced by crown competition only to a negligible extent. Our main finding is that foliage position (upper, middle or lower third of crown) affected foliage properties more than intraspecific crown competition. Finally, we pointed out that silver birch is a rather productive species that is not ecologically demanding. Therefore, it might be a prospective tree species under the ongoing climate change and the present period of intensification in renewable resources utilisation.

Key words: post-disturbance area; Tatra National Park; tree components; crown competition; young stand; specific foliage area

Editor: Miroslav Hájek

1. Introduction

Birches (*Betula* sp.), especially silver birch (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.), are short-lived broadleaved species occurring in most European regions but mainly in Scandinavia and Russia (San-Miguel-Ayanz et al. 2016). In the conditions of Central Europe, either silver birch or downy birch are not important for commercial purposes but are ecologically relevant (Kula 2011). On the other hand, in Scandinavian and Baltic countries birch is an economically relevant species, since its contribution to forest stock is about 16% in Finland and Norway, 11% in Sweden, over 20% in Estonia and Latvia, and 17% in Lithuania (Hynynnen et al. 2010). In the northern countries birch trees represent commercially the most important source of hardwood and an important part of coniferous plantations, especially Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst; see also Kurvits et al. 2020).

Birches have often been studied with regard to soil amelioration via their foliage litter (e.g. Cotrufo et al. 1995; Schua et al. 2015; Kacálek et al. 2017). Since the species are relatively resistant to emissions, they were frequently planted on sites deteriorated by noxious substances, for instance in Czechia (Kula 2011). Moreover, the species often occupy post-disturbance areas and together with other pioneer species, especially common aspen (*Populus tremula* L.), goat willow (*Salix caprea* L.), rowan (*Sorbus aucuparia* L.) create favourable conditions for other climax tree species (Konôpka et al.

Corresponding author. Bohdan Konôpka, e-mail: bohdan.konopka@nlcsk.org

2019). Birch is much less attractive for game as forage than other pioneer species, and thus, it is rarely damaged by browsing (Finďo & Petráš 2007). Therefore, in regions exposed to red deer it has a higher survival rate than other pioneer species. Moreover, on post-disturbance or former agricultural lands birch is usually more productive than most other forest tree species (e.g. Zasada et al. 2014; Konôpka et al. 2019).

Martiník et al. (2018) suggested birch as an alternative trees species in the beech vegetation zone of the north-eastern part of the Czech Republic after spruce decline. Valkonen and Valsta (2001) presented an analysis on the economics of the two-storied birch-spruce mixture in Finland. Their results indicated that in Finnish economic and technical conditions it is profitable to grow a birch over-storey in a spruce plantation up to commercial volume. The main aim of growing downy birch is to produce pulp wood and fuel wood with low costs (Hynynen et al. 2010). Wood of pioneer tree species, including birch, grown on disturbed areas might be a source of wood for renewable energy production (Stark et al. 2013). The size or quality of birch stems is often too poor for veneer and saw logs, especially when growing on infertile or wet sites (Hynynen et al. 2010). Moreover, birch can play an important role in carbon sequestration on sites where other tree species can not grow or develop very slowly.

Most papers on birch biomass come mostly from northern parts of Europe, specifically Finland (Lehtonen et al. 2004; Repola 2008), Sweden (Claesson et al. 2001; Johansson 2007), and Estonia (Uri et al. 2007). Recently, a couple of works focused on birch biomass and wood production in Central Europe (e.g. Bronisz et al., 2016; Jagodzinski et al. 2017; Martiník et al. 2018). Their mutual motive has been great growth potential of birch in terms of biomass production. At the same time, the authors pointed out that intentional or spontaneous replacement of herbaceous vegetation on former agricultural land by forest trees, especially birch, can significantly contribute to carbon fixation and conservation. Prompt reforestation of large-scale post-disturbance areas (by both pioneer and climax tree species) is necessary to compensate previous carbon losses by natural disasters (e.g. Seidl et al. 2014; Konôpka et al. 2019).

While a number of papers focused on birch biomass models or estimates, fewer works studied biomass allocation patterns or components traits in terms of ecological conditions or biological aspects (just partly met in papers Uri et al. 2007; Jagodzinski et al. 2017). Our review of Central European literature focusing on birch indicated neglected interest in this genus. In general, understanding the patterns of biomass partitioning of a variety of species is of high importance in the field of tree physiology and plant ecology, and has also applications for forestry management (Mensah et al. 2016). Considering a variety of tree species, many works studied biomass allocation and foliage traits with regard to competition (e.g. Hommel et al. 2016; Zhou et al. 2018; Yang et al. 2019). Some authors (e.g. Shipley 2006; Milla et al. 2008) used the ratio between foliage and total dry plant biomass (leaf mass ratio) or between foliage area and total plant dry biomass (leaf area ratio) to describe ecological and production interactions.

The Slovak National Inventory data showed that while birch contributed to growing stock in forest lands only by about 1%, much larger contribution (about 6.5%) was estimated for non-forest (prevailingly former agricultural) lands (Šebeň et al. 2017). In Slovakia, the inventory data suggest that birch is more frequent in young stands than in older ones. This is partly caused by large-scale forest calamities that occurred in the last two decades (see for instance Kunca et al. 2019) followed by reforestation with high share of spontaneous natural regeneration of pioneer species. Hence, the contribution of birch to forest standing stock on both forest and former non-forest land might increase in near future due to its biomass accumulation over time and increasing frequency of forest disturbances (Seidl et al. 2014).

Therefore, the main aim of our paper was to quantify the aboveground birch biomass (i.e. dry mass expressed in kg) allocated to individual tree components in a young mixed stand growing at a post-disturbance site 14 years after the wind damage. We hypothesised that crown competition stress influences aboveground biomass allocation patterns as well as stem and foliage traits of birch trees.

2. Material and methods

Our attention was focused on the High Tatra Mts. (the Tatra National Park) situated in northern Slovakia. The bedrock of the region is predominantly formed by sediments of granodiorites. Forest soils are prevailingly lithic leptosols and podzols. The climate is cold (annual mean temperature is nearly 5.0 °C) and moist (annual precipitation total of over 1,000 mm), and snow cover lasts between 110 – 130 days (e.g. Vološčuk et al. 1994). The main part of the territory belongs to the post-disturbance area arisen after the large-scale windstorm on 19^{th} November 2004. The wind destroyed spruce-dominated forests with epicentre at elevations between 700 and 1,400 m a.s.l. The damaged area resembled a continuous belt, which was 3 – 5 km wide and nearly 35 km long (Konôpka et al. 2019). The forest stands inside this belt were nearly completely destroyed (mainly uprooted less stem-broken), except for few forest clusters typical with preponderance of European larch (*Larix decidua* Mill.) and at a few sites also of Scots pine (*Pinus sylvetris* L.). The area of the damaged forests covered almost 10,000 ha. The post-disturbance area was managed in three ways regarding the degree of nature protection: from processing all amount of merchantable wood, through partly-processed calamity wood (30 – 60% of merchantable wood), up to excluding wood processing with exclusive natural succession. The main part of the calamity wood was processed during three years after the disturbance (2005 – 2007). As for forest regeneration, different approaches were implemented with respect to the degree of nature protection. While natural regeneration was preferred, combined natural and artificial reforestation occurred at many sites, and only very few sites were reforested exclusively by planting.

Our field activities were performed during the second half of the growing season in 2018, i.e. 14 years after the wind disturbance. Aboveground biomass sampling and measurements of birch were done around our permanent research transect "Danielov dom" (Konôpka et al. 2017). The sampling site is located about 450 m south from the road No. 537 (well-known as "the Road of Freedom") and 2.0 km southwest from the Tatranská Polianka village. The altitude is between 985 and 990 m a.s.l., southern inclination. The forest stand was composed of silver birch, Norway spruce, European larch, rowan, Scots pine and some other broadleaved species. Number of trees per ha was nearly 9 100 individuals (considering trees with height over 10 cm), mean (Lorey´s) tree height was 4.6 m, mean diameter measured at stem base was 6.7 cm. While European larch was planted at the site, all other tree species originated from natural regeneration. Previous measurements (see Konôpka et al. 2017) showed that the main part of stand biomass was accumulated in silver birch, Norway spruce and European larch. Although Norway spruce had much more individuals per spatial unit than silver birch, main stand canopy was built exclusively by silver birch. In spite of about the same tree age, birches overgrew the other tree species. Thus, inter-tree competition of silver birches in the main canopy was either non-existing (scattered individuals) or only intra-specific (birch clusters).

We selected 20 individuals of silver birch (all were 14-year-old that was proved later on discs at stem bases) equally divided into four different competition classes (i.e. five trees per class), specifically (Fig. 1):

0 – competition free crowns: the upper half of crown without any competition from neighbours,
1 – crowns under mild competition: the upper half of crown influenced by crown neighbours from one side,
2 – crowns under moderate competition: the upper half of crown influenced by crown neighbours from two sides,
3 – crowns under severe competition: the upper half of crown influenced by crown neighbours from at least three sides.

The selected trees were felled with a chain saw at ground surface. For a detailed analysis of foliage, we randomly sampled 5 leaves from the upper, middle and lower third of the crown, totalling 15 leaves from the whole crown (i.e. 300 leaves from all sampled trees). Leaves were packed in labelled (tree code and position in crown) paper envelopes. Afterwards, branches with foliage were cut off from the stems and packed in labelled (tree code) paper bags. The stem length (tree height) as well as stem diameters at breast height, i.e. 130 cm from the ground level (DBH), at 25% and 75% of tree height ($D_{25\%}$ and $D_{75\%}$, respectively) were measured. Stems were cut into 1-m-long sections and packed in marked bags. All tree samples were transported to laboratory.

Bark was manually removed from stems using a knife, and foliage was removed from branches with fingers. Individual tree components, i.e. stem wood, stem bark, branches and foliage, of each tree were packed in paper bags and oven-dried under 95 °C till their weight stabilised (i.e. foliage for circa 24 hours, bark for 48 hours, branches for 72 hours and stems for 96 hours). All components were weighed with a precision of 0.1 g.

Foliage subsamples taken for the detailed analysis were stored in a refrigerator till further processing. Each leaf was scanned and its area was calculated using the Easy Leaf Area software (Easlon & Bloom 2014). The leaves were oven-dried (under 95 °C for 12 hours) and weighed with a precision of 0.001 g.

The following variables were recorded for each tree and used for further calculations: tree height, DBH, $D_{25\%}$ and $D_{75\%}$, area of individual leaves (from three vertical levels of crown) and their dry weight, i.e. leaf biomass, total foliage biomass, branch biomass, stem wood and stem bark biomass.

From these variables we derived biomass models for individual tree components using the following two equations:

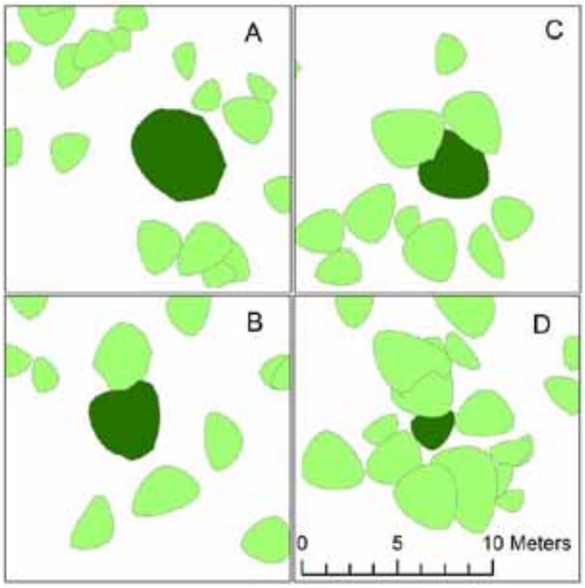

Fig. 1. Examples of the competition classes in sampled silver birches (dark colour indicates a target tree) recorded in the research site, specifically: 0 – competition free crown (scheme A), 1 – crown under mild competition (scheme B), 2 – crown under moderate competition (scheme C) and 3 – crown under severe competition (scheme D). The position of the trees and their crown projection were measured by the Field-Map technology (used exclusively for illustration of four competition classes).

$$B_i = aDBH^b \quad [1]$$

$$B_i = ah^b \quad [2]$$

where:

B_i – the biomass of the i-th component in kg (i is the tree component, i.e. – stem divided into wood and bark, branches, foliage, or above-ground biomass),

DBH – the breast height diameter in cm,

h – the tree height in m, and

a, b – parameters of the equation.

The total leaf area (LA) for each tree was calculated by multiplying the weight of all tree foliage and the average Specific leaf area (SLA; expressed in cm^2 per g):

$$LA = B_{foliage} SLA \quad [3]$$

The average tree-level SLA was determined as an arithmetic mean of 15 leaf samples that were taken from the individual tree.

The two-factor analysis of variance and the Fischer LSD test were used to create homogeneous groups to determine the dependence of leaf weight, leaf area and SLA of individual trees on the position of leaves in the crown (upper, middle and lower crown) and the competition class. Based on this test, homogeneous groups were also formed when testing the dependence of proportions and on the competition class of trees.

All statistical analyses were performed in Statistica 10.0 and R program (R Development Core Team 2012).

3. Results

Heights of silver birch sampled trees varied between 6.3 m and 12.4 m and DBH between 6.4 cm to 23.1 cm (Fig. 2). It means that the variance of DBH was nearly double of that in tree height. Both tree height and DBH varied between the competition classes. Specifically, tree heights in class 0 were from 9.6 to 11.7 m, in class 1 the interval was 9.1 – 12.4 m, in class 2 it was 6.7 – 10.7 m and in class 3 it was 6.3 – 10.3 m. As for DBH, the intervals were as follows: tree category 0 from 18.3 to 23.1 cm, tree category 1 between 13.9 and 22.0 cm, tree category 2 from 10.7 to 14.5 cm and tree category 3 between 6.4 and 10.9 cm (see also Table 1).

Table 1. Mean tree height, diameter DBH, $D_{25\%}$ and $D_{75\%}$ for the sampled silver birches in the separate competition classes (0 – competition free crown, 1 – crown under mild competition, 2 – crown under moderate competition, and 3 – crown under severe competition). Values in brackets are standard deviations. Different index letters within columns indicate significant differences between the competition classes separately for each tree characteristics (LSD test with $\alpha = 0.05$).

Competition class	Tree height [m]	Diameter DBH	Diameter $D_{25\%}$ [cm]	Diameter $D_{75\%}$
0	10.80 (0.80)^{ab}	21.4 (1.9)^{a}	17.2 (1.5)^{a}	4.4 (0.8)^{a}
1	11.08 (1.34)^{a}	11.08 (1.34)^{a}	14.0 (2.5)^{b}	4.2 (0.7)^{a}
2	9.09 (1.62)^{bc}	9.09 (1.62)^{bc}	10.8 (1.5)^{c}	3.6 (1.2)^{a}
3	8.24 (1.47)^{c}	8.24 (1.47)^{c}	7.5 (1.5)^{d}	3.4 (0.8)^{a}

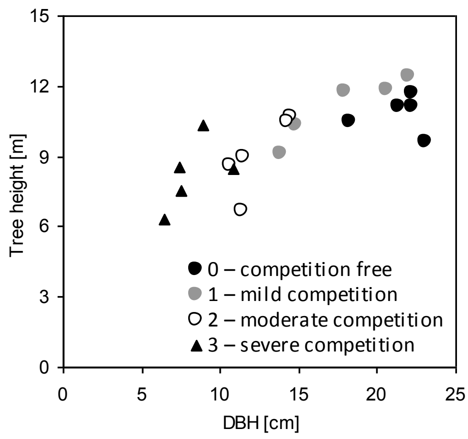

Fig. 2. Tree heights and breast height diameter (DBH) of sampled silver birches with indication of the specific competition classes (0 – competition free crown, 1 – crown under mild competition, 2 – crown under moderate competition, and 3 – crown under severe competition).

Our models (Table 2) expressing biomass of specific tree components, total aboveground biomass and total foliage area showed that DBH was a better explanatory variable than tree height due to a closer relationship with biomass (see values of p, R^2, and mean square error in Table 2). The largest biomass proportion was allocated in stem biomass, followed by branches and foliage (Fig. 3). For instance, while biomass of birches with DBH of 10 cm contained about 12 kg of stem, 4 kg of branches and 1.5 kg of foliage, birches with DBH of 20 cm made up 60 kg of stem, 30 kg of branches and 7.5 kg of foliage. It means that trees with DBH of 20 cm had about three times larger biomass (around 90 kg) than those with DBH of 10 cm (30 kg). As for total foliage area (Fig. 4), birches with DBH of 20 cm had nearly three times higher values (about 115 m^2) than individuals with DBH equal 10 cm (35 m^2).

Further we focused on intra-specific influence on stem shape, specifically slenderness ratio (Fig. 5 top) and taper ratio (Fig. 5 bottom). Both indicators reached the lowest values in trees with no crown competition and the highest values in the case of trees under severe crown competition. This means that trees without crown competition had a more converging stem shape (a cone-like stem) than trees under severe crown competition (with a cylinder-like stem).

Crown competition modified not only stem shape but also allocation of biomass to tree components (Table 3). Specifically, birches with severe crown competition had a higher ratio of foliage biomass to branch biomass (0.344) than competition-free ones (0.179). At the same time, the ratio of branch biomass to stem biomass was higher in crown competition-free birches (0.603) than for the birches under severe crown competition (0.352). Moreover, the comparison of crown competition-free birches to those under severe competition (i.e. tree categories with contrasting statuses) showed very different relative con-

Table 2. Allometric relations for biomass of stem (over or under bark), stem bark, branches, foliage, aboveground parts together and total foliage area in silver birch. Shapes of formulas are $B_i = aDBH^b$ if using breast height diameter (DBH) and $B_i = ah^b$ if using tree height as independent variable. Abbreviations a and b are parameters, S.E. are standard errors, p is p–value, R^2 is coefficient of determination, and MSE is mean square error.

Tree component [unit)]	Independent variable [unit[	a (S.E.) p	b (S.E.) p	R^2	MSE
Stem over bark – biomass [kg]	DBH [cm]	0.186 (0.080) 0.032	1.982 (0.143) <0.001	0.957	44.09
	Tree height [m]	0.00516 (0.010) 0.606	3.907 0.788 <0.001	0.710	296.51
Stem under bark – biomass [kg]	DBH [cm]	0.106 (0.055) 0.071	2.087 (0.173) <0.001	0.946	35.87
	Tree height [m]	0.00203 (0.004) 0.635	4.189 0.856 <0.001	0.707	195.62
Stem bark – biomass [kg]	DBH [cm]	0.118 (0.049) 0.027	1.629 (0.140) <0.001	0.930	2.81
	Tree height [m]	0.00877 (0.014) 0.524	3.063 0.644 <0.001	0.682	12.81
Branches – biomass [kg]	DBH [cm]	0.014 (0.012) 0.237	2.633 (0.269) <0.001	0.931	27.65
	Tree height [m]	0.00305 (0.010) 0.753	3.852 1.297 0.008	0.457	218.78
Foliage - biomass [kg]	DBH [cm]	0.036 (0.018) 0.063	1.792 (0.169) <0.001	0.923	0.87
	Tree height [m]	0.00125 (0.002) 0.613	3.579 0.805 <0.001	0.640	4.11
Aboveground parts together – biomass [kg]	DBH [cm]	0.186 (0.072) 0.018	2.149 (0.127) <0.001	0.972	83.4
	Tree height [m]	0.00921 (0.021) 0.662	3.868 0.931 <0.001	0.627	1109.18
Foliage – total area [m^2]	DBH [cm]	1.470 (0.788) 0.078	1.462 0.181 <0.001	0.864	316.46
	Tree height [m]	0.048 (0.770) 0.540	3.205 (0.666) <0.001	0.667	773.09

Table 3. Ratio between quantities of particular tree component in silver birch with regard to competition class (0 – competition free crown, 1 – crown under mild competition, 2 – crown under moderate competition, and 3 – crown under severe competition). Mean values and standard deviations are shown. Index letters indicate statistical differences between tree competition classes (separately for each row; LSD test with $\alpha = 0.05$).

Relationship between components versus competiton class	Competition class				All trees
	0	1	2	3	
Foliage biomass [kg] / branch biomass [kg]	0.179 (0.037)^{a}	0.264 (0.069)^{ab}	0.287 (0.090)^{b}	0.344 (0.059)^{b}	0.269 (0.064)
Foliage biomass [kg] / stem biomass [kg]	0.105 (0.024)^{a}	0.116 (0.069)^{a}	0.139 (0.022)^{a}	0.126 (0.076)^{a}	0.122 (0.034)
Foliage biomass [kg] / branch + stem biomass [kg]	0.066 (0.015)^{a}	0.080 (0.016)^{a}	0.091(0.022)^{a}	0.089 (0.043)^{a}	0.081 (0.019)
Branch biomass [kg] / stem biomass [kg]	0.603 (0.115)^{a}	0.453 (0.079)^{ab}	0.542 (0.262)^{ab}	0.352 (0.156)^{b}	0.488 (0.153)
Foliage area [m^2] / branch biomass [kg]	2.699 (0.906)^{a}	4.471 (1.298)^{ab}	5.144 (2.092)^{b}	6.252 (1.493)^{b}	4.641 (1.447)
Foliage area [m^2] / stem biomass [kg]	1.559 (0.319)^{a}	1.983 (0.564)^{a}	2.434 (0.378)^{a}	2.244 (1.025)^{a}	2.055 (0.671)
Foligae area [m^2]/ branch + stem biomass [kg]	0.981 (0.243)^{a}	1.366 (0.370)^{a}	1.597 (0.274)^{a}	1.596 (0.807)^{a}	1.385 (0.424)

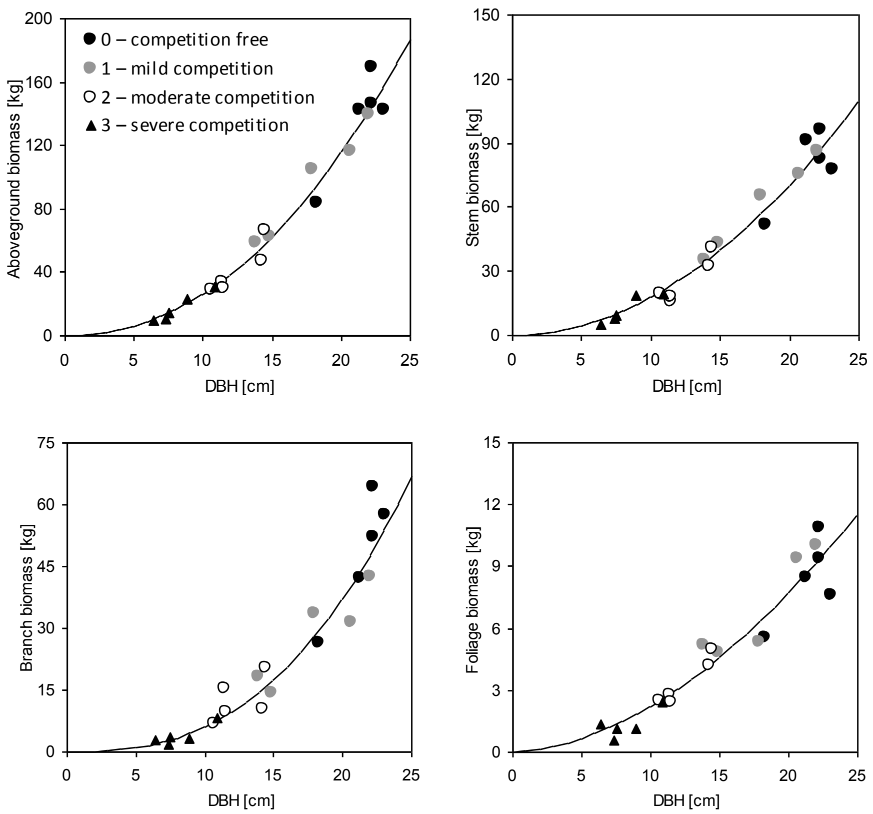

Fig. 3. Relationship between breast height diameter (DBH) and aboveground biomass (top left), stem biomass (top right), branch biomass (bottom left), foliage biomass (bottom right) of silver birch trees with indication of the specific crown competition classes (0 – competition free crown, 1 – crown under mild competition, 2 – crown under moderate competition, and 3 – crown under severe competition). The fitted formula is: $B_i = aDBH^b$, values of parameters are in Table 2.

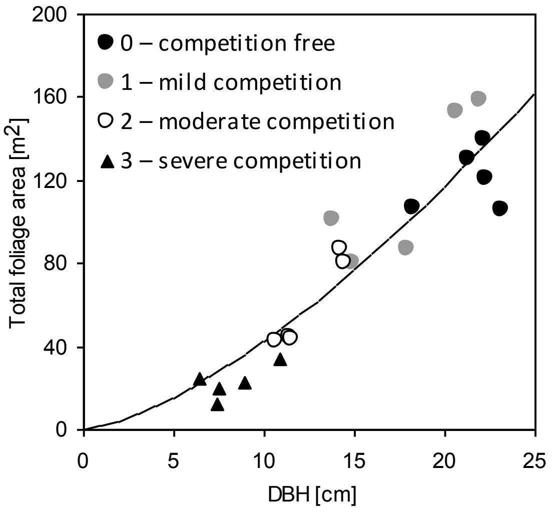

Fig. 4. Relationship between total foliage area and breast height diameter (DBH) of silver birch trees with indication of the specific crown competition classes (0 – competition free crown, 1 – crown under mild competition, 2 – crown under moderate competition, and 3 – crown under severe competition). The fitted formula is: $B_i = aDBH^b$ (values of parameters are in Table 2).

tribution of individual components to total aboveground biomass (Fig. 6). While in competition-free birches the contribution of foliage, branches and stem was 6%, 36%, and 58%, respectively, in the case of birches under severe crown competition 8% of aboveground biomass was in foliage, 22% in branches and 70% in stem. Moreover, the results suggested a higher ratio between foliage area and branch biomass in competition severely stressed birches (6.25 $m^2\ kg^{-1}$) than in crown competition-free trees (2.70 $m^2\ kg^{-1}$, Table 3).

Intensity of crown competition influenced also foliage traits, specifically foliage weight (Fig. 7 – top left) and SLA (Fig. 6 – bottom), but not much foliage area (Fig. 7 – top right; see also Table 4). Both, foliage weight and SLA, of crown competition-free birches differed from those under certain levels of competition stress, mainly from severely stressed trees. The results indicated that foliage traits were more dependent on foliage position along the vertical crown profile than on intra-specific tree competition (Table 4). At the same time, differences in foliage weight between competition classes (i.e. 0 versus 1, 2 and 3) were clear in the upper part of crown, and for SLA in the upper and middle parts of crown. Statistical analyses (ANOVA and LSD test; see Fig. 7 and Table 4) suggested that the influence of individual factors (competition class or foliage position in crown) is stronger than their combined effect (competition class and foliage position in crown together).

4. Discussion

4.1. Aboveground biomass allocation and crown competition

Our stand specific biomass models for silver birch indicated that stem diameter, specifically DBH, is a better explanatory variable (higher values of p, R^2 and MSE) than tree height. This result supports previously published works (e.g. Johansson 1999; Hochbichler et al. 2006; Pajtík et al. 2008; Wang et al. 2011) that proved stem diameter as the most important independent variable for predicting total tree biomass or biomass of individual components. Our paper showed that this principle is valid not only for tree biomass but also for total foliage area.

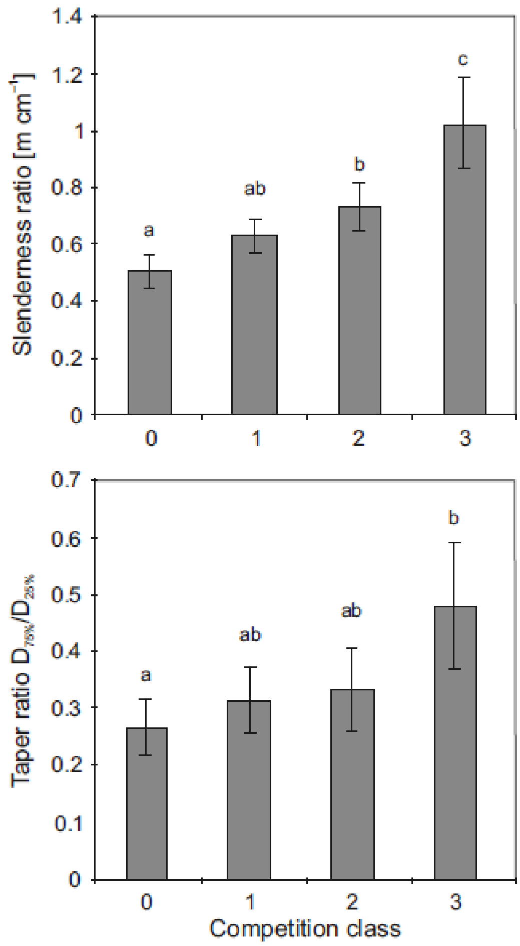

Fig. 5. Slenderness ratio (top) defined as a ratio of tree height to breast height diameter and taper ratio (bottom) calculated from diameters at 25% and 75% tree height in silver birches classified in competition classes (0 – competition free crown, 1 – crown under mild competition, 2 – crown under moderate competition, and 3 – crown under severe competition). Different letters indicate significant differences between competition classes (LSD test with $\alpha = 0.05$). Error bars indicate standard deviations.

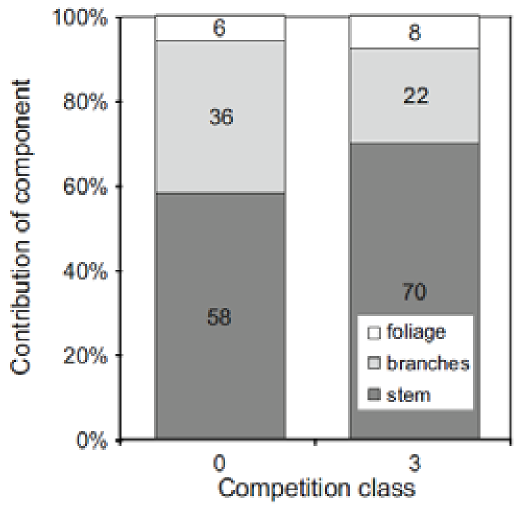

Fig. 6. Comparison on contribution of tree components to aboveground biomass between contrasting tree competition classes, i.e. 0 (competition free crown) versus 3 (crown under severe competition).

The crown-competition free birches reached a height of nearly 13 m, and accumulated as much as 150 kg of aboveground biomass at the age of 14. The average height (± standard deviation) of all sampled trees was 9.80 ± 1.73 m, which coincided with the height of 14-year-old trees according to several birch tables from Northern Europe (Kund et al. 2010). Eriksson et al. (1997) pointed out that birch is typical with rapid early growth, and at best sites it can reach a height of up to 24 – 25 m within 30 years. Similarly, Uri et al. (2007) stressed its fast growth and great production potential. However, birches maintain their vitality and vigorous growth only when growing as dominant trees in a stand with a relatively wide spacing and low degree of within-stand competition (Hynynen et al. 2010). Our measurements showed that crown competition-free silver birches made up approximately five times more aboveground biomass than those under severe crown competition. Generally, since "European" birch species are considered as shade intolerant, lack of light can robustly retard their growth (San-Miguel-Ayanz et al. 2016). Field experiment conducted in Sweden

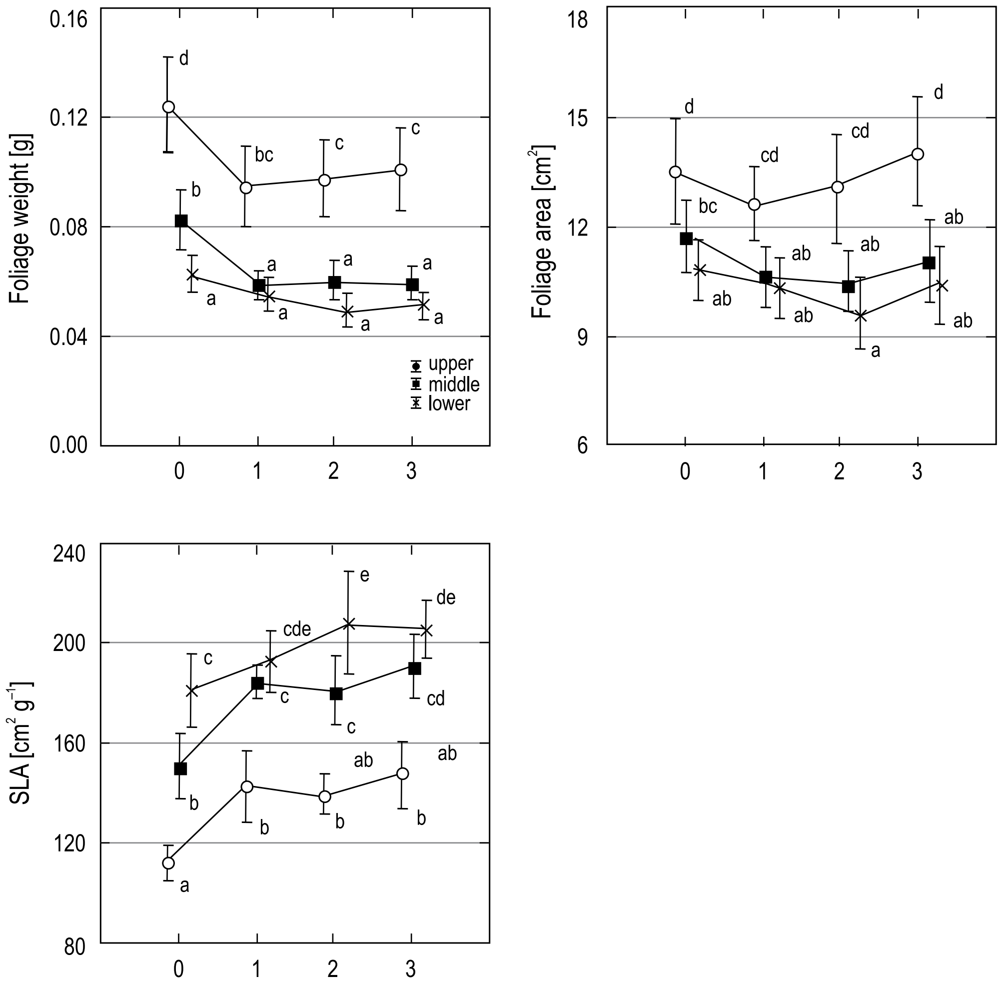

Fig. 7. Individual dry foliage weight (top left), foliage area (top right) and specific leaf area (SLA; bottom) with regard to competition classes (0 – competition free crown, 1 – crown under mild competition, 2 – crown under moderate competition, and 3 – crown under severe competition) and position in the crown of silver birches. Different letters indicate significant differences between tree competition classes (LSD test with $\alpha = 0.05$).

Table 4. Statistical characteristics related to tree competition classes (0 – competition free crown, 1 – crown under mild competition, 2 – crown under moderate competition, and 3 – crown under severe competition) and position in crown to foliage traits in silver birch (LSD test).

Factor versus foliage trait	Foliage weight [g]	Foliage area [cm²]	Specific leaf area [cm² g⁻¹]
		df (F–value) p–value	
Competition class	3.276 (11.551) <0.001	3.276 (2.322) 0.075	3.276 (16.553) <0.001
Position in crown	2.276 (108.41) <0.001	2.276 (34.614) <0.001	2.276 (102.11) <0.001
Compettion class x position in crown	6.276 (0.948) 0.0461	6.276 (0.439) 0.852	6.276 (0.835) 0.543

(Johansson 2007) showed that in young growth stages silver birch is more productive (total biomass production) than downy birch.

Our results showed that competition intensity in birch crowns modified aboveground biomass allocation pattern. While the proportions of aboveground biomass components in competition-free individuals were 6% (foliage), 36% (branches) and 58% (stem), these proportions in birches under severe competition were: 8% : 22% : 70%. Although proportions between foliage biomass to stem biomass as well as foliage biomass to branch + stem biomass did not significantly differ between tree categories, competition stress increased the ratio of foliage to branch biomass but decreased the branch to stem biomass ratio (Table 3). Changes in biomass partitioning to plant organs is an important mechanism to maintain productivity (Sebastia 2007). Commonly respected the Optimal Partitioning Theory assumes that plants allocate more biomass to organs that have limited access to resources (Bloom et al. 1985). For instance, in nutrient-limited soil conditions, plants decrease biomass allocation to foliage and increase biomass allocation to roots (Poorter et al. 2012; Deng et al. 2006). Similar effect has been observed in the case of reduced water availability (Hommel et al. 2016; Friendligstein et al. 1999). Lack of light due to e.g. severe crown competition causes the opposite, i.e. more biomass is allocated to foliage (Fig. 6; Poorter et al. 2012; Konôpka et al. 2016). At the same time, trees under intensive competition (light insufficiency) attempt to increase allocation to stem to increase their height instead of branches (Fig. 6, Wang et al. 2011). Recently Yang et al. (2019) showed in *Quercus liaotungensis* that competition intensity decreased ratio between branch and stem biomass, but other ratios (foliage to stem and foliage to branch) have not changed significantly.

4.2 Stem traits with regard to crown competition

Our results indicated that birches under severe competition stress attempt to invest more biomass in height increment in relative expression to diameter increment in comparison to competition-free trees. Consequently, more stressed trees have slender and relatively high stems with more conic shapes. On the other hand, competition-free birches have thicker stems and their stem forms are closer to a cylinder-like shape. The shape of a tree stem is important for tree resistance against wind or snow damage (e.g. Konôpka & Konôpka 2003; Bošeľa et al. 2014) and for timber quality (Oker-Blom et al. 1988). Snowdon et al. (1981) explained that the shape of a tree stem (bole) could be characterised by at least two basic features: taper and form. Stem taper has been frequently expressed as a ratio between tree height and stem diameter, usually DBH (i.e. slenderness ratio; e.g. Wang et al. 1998; Opio et al. 2000; Sharma et al. 2016). Stem form was studied rather occasionally, mostly as a ratio between stem diameters measured at two different sections of the bole, mostly at 25% versus 75% of tree height (e.g. Wiklund et al. 1995). The previous papers showed that the stem taper changes not only due to tree competition but is also ruled by soil conditions, i.e. both nutrients and water status (Wiklund et al. 1995), and stand age (Bošeľa et al. 2014).

Experiments focusing on initial tree spacing and/or thinning intensity (tree reduction) in forest stands proved that the values of slenderness ratio always increased with stand density (e.g. Mäkinen et al. 2002; Harrington et al. 2009). At the same time, stand density is closely related to tree competition occurring between neighbouring individuals and involves the competition for light resources as well as for aboveground space in canopy, and/or for soil water and nutrients and for the room in soil between belowground root systems (Song et al. 2012). Nilsson (1993) suggested slenderness ratio as a reasonable indicator of competition intensity. Significant increase of slenderness ratio due to competition stress has been proved also in recent works focusing on *Larix principis-rupprechtii* (Zhou et al. 2018) and *Quercus liaotungensis* (Yang et al. 2019).

4.3 Foliage traits with regard to crown competition

Changes in plant leaf morphology are commonly believed to be dependent on growth conditions (Niinemets et al. 2007). Our results indicated that crown competition partly modified foliage weight and SLA. These changes were clear in the upper part of birch crowns. Foliage area was influenced by crown competition only negligibly (Fig. 7). Our main finding is that foliage position (upper, middle or lower third of crown) affected foliage properties more than crown competition among neighbours. Interactive effects of intra-species crown competition and foliage position on foliage properties were negligible. This can be most probably explained by the strong shading effect in the lower parts of crowns caused by branches and foliage situated in middle and upper portions of tree crowns. This effect might be so intense that the additional influence from crowns of neighbouring birches did not further contribute to the final status of foliage in the lower parts of crowns.

Leaf is the only plant organ with the capacity to capture energy and drive growth. Foliage responds to growth conditions within a stand very sensitively, and has been shown to adapt its morphology accordingly (Bussotti et al. 2000). Greater SLA with increasing shading is likely a plant adaptation to low light conditions that ensures light interception (Niinemets et al. 2001). Considering the effect of shading on SLA, mean SLA of small (overtopped) trees is greater than of dominant trees, but the value approximates to that of spruce and beech larger (dominant) individuals (Konôpka et al. 2016). Higher SLA of shaded foliage in young beech stands was recorded for instance by Closa et al. (2010). Barna (2004) showed lower values of SLA in dominant and co-dominant beech trees than in subdominant individuals.

Our results clearly showed that tree competition influences not only tree size but also biomass allocation, stem shape and foliage properties. Since these kinds of findings were missing for silver birch, the results can throw more light on production, physiology as well as ecology of this tree species. Enhanced knowledge on the drivers of biomass allocation is also helpful for forest growth modelling (Merganičová et al. 2019), since allocation has been considered as one of the main weaknesses of simulation models (Le Roux et al. 2001; Richardson et al. 2015). As silver birch is not an ecologically demanding species, but it is very productive (although rather short-living), it would very probably be a perspective species in the conditions of the ongoing climate change and also in the period of intensified utilisation of renewable resources (especially for energy and pulp). Thus, further studies of this species are still requisite.

Acknowledgements

The research was supported by the projects APVV-18-0086 and APVV-15-0265 from the Slovak Research and Development Agency, and by grant "EVA4.0", No. CZ.02.1.01/0.0/0.0/16_019/0000803 financed by OP RDE, as well as by the project "Research and innovation for supporting competitiveness of the Slovak forestry sector" (SLOV-LES) financed by the Ministry of Land Management and Rural Development of the Slovak Republic.

References

Barna, M., 2004: Adaptation of European beech (*Fagus sylvatica* L.) to different ecological conditions: leaf size variation. Polish Journal of Ecology, 52:35–45.

Bloom, A. J., Chapin, F. S., Mooney, H. A., 1985: Resource limitation in plants – an economic analogy. Annual Review of Ecology and Systematics, 16:363–392.

Bošeľa, M., Konôpka, B., Šebeň, V., Vladovič, J., Tobin, B., 2014: Modelling height to diameter ratio - An opportunity to increase Norway spruce stand stability in the Western Carpathians. Lesnícky časopis – Forestry Journal, 60:71–80.

Bronisz, K., Strub, M., Cieszewski, Ch., Bijak, S., Bronisz, A., Tomusiak, R. et al., 2016: Empirical equations for estimating aboveground biomass of *Betula pendula* growing on former farmland in central Poland. Silva Fennica, 50:1–17.

Bussotti, F., Borghini, F., Celesti, C., Leonzio, C., Bruschi, P., 2000: Leaf morphology and macronutrients in broadleaved trees in central Italy. Trees, 14:361–368.

Cotrufo, M. F., Ineson, P., Roberts, D., 1995: Decomposition of birch leaf litters with varying C-to-N ratios. Soil Biology and Biochemistry, 27:1219–1221.

Claesson, S., Sahlén, K., Lundmark, T., 2001: Functions for biomass estimation of young *Pinus sylvestris, Picea abies* and *Betula* spp. from stands in northern Sweden with high stand densities. Scandinavian Journal of Forest Research, 16:138–146.

Closa, I., Irigoyen, J. J., Goicoechea, N., 2010: Microclimatic conditions determined by stem density influence leaf anatomy and leaf physiology of beech (*Fagus sylvatica* L.) growing within stands that naturally regenerate from clear-cutting. Trees, 24:1029–1043.

Deng, J. M., Wang, G. X., Morris, E. C., Wei, X. P., Li, D. X., Chen, B. M. et al., 2006: Plant mass–density relationship along a moisture gradient in north-west China. Journal of Ecology, 94:953–958.

Easlon, H. M., Bloom, A. J., 2014: Easy Leaf Area: Automated digital image analysis for rapid and accurate measurement of leaf area. Applications in Plant Sciences, 2:1400033.

Eriksson, H., Johansson, U., Kiviste, A., 1997: A site-index model for pure and mixed stands of *Betula pendula* and *Betula pubescens* in Sweden . Scandinavian Journal of Forest Research, 12:149–156.

Finďo, S., Petráš, R., 2007: Ekologické základy ochrany lesa proti poškodeniu zverou. Zvolen, National Forest Centre ,186 p.

Friedlingstein, P., Joel, G., Field, C. B., Fung, I. Y. 1999: Toward an allocation scheme for global terrestrial carbon models. Global Change Biology, 5:755–770.

Harrington, T. B., Harrington, C. A., DeBell, D., 2009: Effects of planting spacing and site quality on 25-year growth and mortality relationships of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*). Forest Ecology and Management, 258:18–25.

Hochbichler, E., Bellos, P., Lick, E., 2006: Biomass functions for estimating needle and branch biomass of spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) and branch biomass of beech (*Fagus sylvatica*) and oak (*Quercus robur* and *petrea*). Austrian Journal of Forest Sciences, 123:35–46.

Hommel, R., Siegwolf, R., Zavadlav, S., Arend, M., Schaub, M., Galiano, L. et al., 2016: Impact of interspecific competition and drought on the allocation of new assimilates in trees. Plant Biology, 18:785–796.

Hynynen, J., Niemistö, P., Viherä-Aarnio, A., Brunner, A., Hein, S., Velling, P., 2010: Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in northern Europe. Forestry, 83:103–119.

Jagodzinski, A. M., Zasada, M., Bronisz, K., Bronisz, A., Bijak, S., 2017: Biomass conversion and expansion factors for a chronosequence of young naturally regenerated silver birch (*Betula pendula* Roth) stands growing on post-agricultural sites. Forest Ecology and Management, 384:208–220.

Johansson, T., 1999: Biomass production of Norway spruce (*Picea abies* [L.] Karst.) growing on abandoned farmland. Silva Fennica, 33:261–280.

Johansson, T., 2007: Biomass production and an allometric above- and below-ground relations for young birch stands planted at four spacings abandoned farmland. Forestry, 80:41–52.

Kacálek, D., Mauer, O., Podrázský, V., Slodičák, M. et al., 2017: Soil improving and stabilizing functions of forest trees. Lesnická práce, 300 p.

Konôpka, B., Konôpka, J., 2003: Static stability of forest stands in the seventh altitudinal vegetation zone in Slovakia. Journal of Forest Science, 49:474–481.

Konôpka, B., Pajtík, J., Marušák, R., Bošeľa, M., Lukac, M., 2016: Specific leaf area and leaf area index in developing stands of *Fagus sylvatica* L. and *Picea abies* Karst. Forest Ecology and Management, 364:52–59.

Konôpka, B., Pajtík, J., Máliš, F., Šebeň, V., Maľová, M., 2017: Carbon stock in aboveground biomass of vegetation at the High Tatra Mts. twelve years after disturbance. Central European Forestry Journal, 63:142–151.

Konôpka, B., Šebeň, V., Pajtík, J., 2019: Species composition and carbon stock of tree cover at a postdisturbance area in Tatra National Park, Western Carpathians. Mountain Research and Development, 39:71–80.

Kula, E., 2011: Bříza a její význam pro trvalý rozvoj lesa v imisných oblastech. Prague, Publishing House for Forestry, 276 p.

Kunca, A., Zúbrik, M., Galko, J., Vakula, J., Leontovyč, R., Konôpka, B. et al., 2019: Salvage felling in the Slovak Republic´s forests during the last twenty years (1998–2017). Central European Forestry Journal, 1:3–11.

Kund, M., Vares, A., Sims, A., Tullus, H., Uri, V., 2010: Early growth and development of silver birch (*Betula pendula* Roth) plantations on abandoned agricultural land. European Journal of Forest Research, 129:679–688.

Kurvits, V., Ots, K., Kangur, A., Korjus, H., Muiste, P., 2020: Assessment of load and quality of logging residues from clear-felling areas in Järveselja: a case study from Southeast Estonia. Central European Forestry Journal, 66:3–11.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, J., Liski, J., 2004: Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. Forest Ecology and Management, 188:211–224.

Le Roux, X., Lacointe, A., Escobar-Gutierrez, A., Le Dizes, S., 2001: Carbon-based models of individual tree growth: A critical appraisal. Annals of Forest Science, 58:469–506.

Martiník, A., Knott, R., Krejza, J., Černý, J., 2018: Biomass production of *Betula pendula* stands regenerated in the region of allochthonous *Pice abies* dieback. Silva Fennica, 52:1–15.

Mäkinen, H., Nöjd, P., Isomäki, A., 2002: Radial, height and volume increment variation in *Picea abies* (L.) Karst. stands with varying thinning intensities. Scandinavian Journal of Forest Research, 2:227–228.

Mensah, S., Kakai, R.G., Seifert, T., 2016: Patterns of biomass allocation between foliage and woody structure: the effects of tree size and specific functional traits. Annals of Forest Research, 59:49–60.

Merganičová, K., Merganič, J., Lehtonen, A., Vacchiano, A., Ostrogović-Sever, M.Z., Augustynczik, A.L.D. et al., 2019: Forest carbon allocation modelling under climate change. Tree Physiology, 39:1937–1960.

Milla, R., Reich, P.B., Niinemets, U., Castro-Diez, P., 2008: Environmental and developmental controls on specific leaf area are little modified by leaf allometry. Functional Ecology, 22:565–576.

Nilsson, U., 1993: Competition in young stands of Norway spruce and Scots pine. Swedish University of Agricultural Sciences, Uppsala, PhD. Thesis, 173 p.

Niinemets, Ü., Ellsworth, D.S., Lukjanova, A., Tobias, M., 2001: Site fertility and the morphological and photosynthetic acclimation of *Pinus sylvestris* needles to light. Tree Physiology, 21:1231–1244.

Niinemets, U., Portsmuth, A., Tobias, M., 2007: Leaf Shape and Venation Pattern Alter the Support Investments within Leaf Lamina in Temperate Species: A Neglected Source of Leaf Physiological Differentiation, Functional Ecology, 21:28–40.

Oker-Blom, P., Kellomäki, S., Valtonen, E., Väisänene, H., 1988: Structural development of *Pinus sylvestris* stands with varying initial density: a simulation model. Scandinavian Journal of Forest Research, 3:185–200.

Opio, C., Jacob, N., Coopersmith, D., 2000: Height to diameter ratio as a competition index for young conifer plantations in northern British Columbia, Canada. Forest Ecology and Management, 137:245–252.

Pajtík, J., Konôpka, B., Lukac, M., 2008: Biomass functions and expansion factors in young Norway spruce (*Picea abies* [L.] Karst) trees. Forest Ecology and Management, 256:1096–1103.

Poorter, H., Niklas, K. J., Reich, P. B., Oleksyn, J., Poot, P., Mommer, L., 2012: Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. New Phytologist, 193:30–50.

R Development Core Team, 2012: R: A Language and Environment for Statistical Computing. Vienna: R foundation for Statistical Computing. Webpage: http://www.R-project.org/

Repola, J., 2008: Biomass equations for birch in Finland. Silva Fennica, 42:605–624.

Richardson, A. D., Carbone, M. S., Huggett, B. A., Furze, M. E., Czimczik, C. I., Walker, J. C. et al., 2015: Distribution and mixing of old and new nonstructural carbon in two temperate trees. New Phytologist, 206:590–597.

San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G., Durrant, T.H. et al., 2016: European Atlas of Forest Tree Species. Luxembourg, Publication Office of European Union, 200 p.

Schua, K., Wende, S., Wagner, S., Feger, K.-H., 2015: Soil chemical and microbial properties in a mixed stand of spruce and birch in the Ore Mountains (Germany) – A case study. Forests, 6:1949–1965.

Sebastia, M.-T., 2007: Plant guilds drive biomass response to global warming and water availability in subalpine grassland. Journal of Applied Ecology, 44:158–167.

Seidl, R., Schelhaas, M.-J., Rammer, W., Verkerk, P.J., 2014: Increasing forest disturbances in Europe and their impact on carbon storage. Nature Climate Change, 4:806–810.

Sharma, R.P., Vacek, Z., Vacek, S., 2016: Modeling individual tree height to diameter ratio for Norway spruce and European beech in Czech Republic. Trees, 30:1969–1982.

Shipley, B., 2006: Net assimilation rate, specific leaf area and leaf mass ratio: which is most closely correlated with relative growth rate? A meta-analysis. Functional Ecology, 20:565–574.

Snowdon, P., Waring, H. D., Woollons, R. C., 1981: Effect of fertilizer and weed control on stem form and average taper in plantation-grown pines. Australian Forestry Journal, 11:209–221.

Song, M., Hu, Q., Tian, Y., Ouyang, H., 2012: Seasonal patterns of root and shoot interactions in an alpine meadow on the Tibetan Plateau. Journal of Plant Ecology 5:182–190.

Stark, H., Nothdurft, A., Bauhus, J., 2013: Allometries for widely spaced *Populus* ssp. and *Betula* ssp. in nurse crop systems. Forests, 4:1003–1031.

Šebeň, V., 2017: Národná inventarizácia a monitoring lesov Slovenskej republiky 2015–2016. Lesnícke štúdie 65, Zvolen, National Forest Centre, 255 p.

Uri, V., Lohmus, K., Ostonen, I., Tullus, H., Lastik, R., Vildo, M., 2007: Biomass production, foliar and root characteristics and nutrient accumulation in young silver birch (*Betula pendula* Roth.) stand growing on abandoned agricultural land. European Journal of Forest Research, 126:495–506.

Valkonen, S., Valsta, L., 2001: Productivity and economics of mixed two-storied spruce and birch stands in Southern Finland simulated with empirical models. Forest Ecology and Management, 140:133–149.

Vološčuk, I. et al., 1994: Tatra National Park. Martin, Slovakia: Gradus, Ltd., 557 p.

Wang, Y., Titus, S. J., LeMay, V. M., 1998: Relationship between tree slenderness coefficient and tree or stand characteristics for major species in boreal mixed wood forests. Canadian Journal of Forest Research, 28:1171–1183.

Wang, J., Zhang, C., Xia, F., Zhao, X., Wu, L., von Gadow, K., 2011: Biomass Structure and Allometry of *Abies nephrolepis* (Maxim) in Northeast China. Silva Fennica, 45:211–226.

Wiklund, K., Konôpka, B., Nilsson, L.-O., 1995: Stem form and growth in *Picea abies* (L.) Karst. In response to water and mineral nutrient availability. Scandinavian Journal of Forest Research, 10:326–332.

Yang, X.-Z., Zhang, W. H., He, Q. Y., 2019: Effects of intraspecific competition on growth, architecture and biomass allocation of *Quercus liaotungensis*. Journal of Plant Interactions, 14:284–294.

Zasada, M., Bijak, S., Bronisz, K., Bronisz, A., Gaweda, T., 2014: Biomass dynamics in young silver birch stands on post-agricultural lands in central Poland. Drewno, 57:29–39.

Zhou, W., Cheng, X., Wu, R., Han, H., Kang, F., Zhu, J. et al., 2018: Effect of intraspecific competition on biomass partitioning of *Larix principis-rupprechtii*. Journal of Plant Interactions, 13:1–8.

Cent. Eur. For. J. 66 (2020) 170–176 sciendo DOI: 10.2478/forj-2020-0004

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

An integrated framework for Web-based visualisation of forest resources estimated from remote sensing data

Róbert Cibula[1], Ivan Sačkov[2]*

[1] *State Geological Institute of Dionýz Štúr, Department of Geological Information Systems, Mlynská Dolina 1, SK – 817 04 Bratislava 11, Slovak Republic*

[2] *National Forest Centre - Forest Research Institute Zvolen, T. G. Masaryka 2175/22, SK – 960 01 Zvolen, Slovak Republic*

Abstract

Advanced remote sensing technologies has recently become an effective tool for monitoring of forest ecosystems. However, there is a growing need for online dissemination of geospatial data from these activities. We developed and assessed a framework which integrates (1) an algorithm for estimation of forest stand variables based on remote sensing data and (2) a web-map application for 2D and 3D visualisation of geospatial data. The performance of proposed framework was assessed in a Forest Management Unit Vígľaš (Slovakia, Central Europe) covering a total area of 12,472 ha. The mean error of remote sensing-based estimations of forest resources reached values of 16.4%, 12.1%, −26.8%, and −35.4% for the mean height, mean diameter, volume per hectare, and trees per hectare, respectively. The web-map application is stable and allows real-time visualization of digital terrain model, aerial imagery, thematic maps used in forestry or geology, and 968,217 single trees at forest management unit level.

Key words: geo-visualization; WebGL; level of details; Forest inventory; airborne LiDAR

Editor: Tomáš Hlásny

1. Introduction

The use of remote sensing (RS) data in forest inventory has increased the efficiency of managing forest resources considerably (Vauhkonen et al. 2014; Ginzler & Waser 2017). In recent years, data from both active and passive sensors have been widely applied for estimations of biophysical variables such as mean height, mean diameter, standing volume, tree species, basal area (Surový & Kuželka 2019).

However, the application of RS data within the managing forest resources is still not utilised to its full potential. The primary reason is that most of potential stakeholders in forestry sector (foresters, forest owners, environmentalist, policy makers, etc.) often lack (1) adequate budget to ensure the specific technical and data infrastructure, (2) know-how and skills to use the specific software and data, and (3) time or motivation to learn how to use new methods and techniques.

A web-based visualization technologies present an opportunity for providing complex geospatial data and findings from RS-based estimations of forest resources in simpler manner. In this case, (1) data, users and applications work interactively in a distributed environment and there is no necessity for installing a specific geospatial software, (2) users can interact with the up-to-date data without relying on the platform, and (3) collaborative data analysis is possible as most of the modern web browsers support the implementation of visualizations without requiring any other software installation (Cibulka 2012; Ma et al. 2019).

The main goal of this study is to present an integrated framework for web-based visualisation of forest resources estimated from RS data in Forest Management Unit Vígľaš (Slovakia, Central Europe) covering a total area of 12,472 ha. The forest stands variables, such as mean height, mean diameter, volume per hectare, and trees per hectare, were estimated through an individual tree detection algorithm implemented in the remote forest land explorer (reFLex) software based on airborne LiDAR data and aerial color-infrared images. This technology concept has previously been verified in different types of central European forests (e.g. Sačkov et al. 2016, 2017a, 2019). The web-map application was developed as a single page application primarily using Arcgis API libraries for Javascript.

*Corresponding author. Ivan Sačkov, e-mail: sackov@nlcsk.org, phone: +421 949 381 250

2. Materials and methods

2.1. Study area, datasets and framework

The study was conducted in the territory of the Forest Management Unit Vígľaš (Fig. 1) located in central Slovakia (approx. 48°32´N, 19°21´E). The total area is 12,472 ha and forests occupy 3,215 ha from this area. The elevation of the study area reaches intervals of 374 – 978 meters above sea level. Dominant species in the area include European beech (*Fagus sylvatica* L.), Sessile oak (*Quercus petraea* Matusch), and European hornbeam (*Carpinus betulus* L.) with 65% coverage. The area of the remaining part is covered by conifers, such as European silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* L.).

with Diameter at Breast Height (DBH) higher than 7 cm were measured for stem position, species, height, diameter, and vitality.

The workflow of integrated framework for RS-based estimation and web-based visualization of forest resources is shown in Fig. 2 and described in detail in following sections.

2.2. Estimation of forest resources

The treetops, tree crowns, and tree heights were detected from airborne LiDAR data using the reFLex algorithm (National Forest Centre, Zvolen, Slovakia). These outputs were subsequently exported to point (tree tops) and

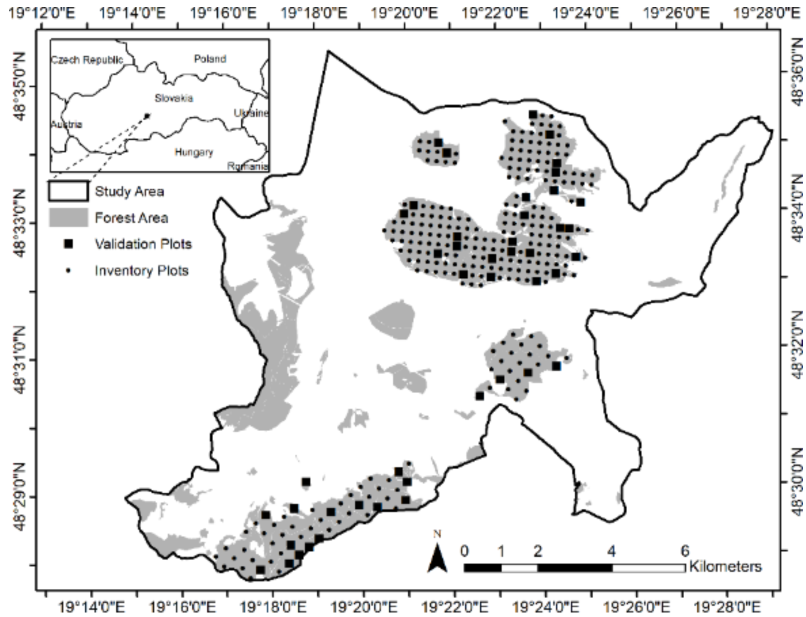

Fig. 1. Location of the study area: Forest Management Unit Vígľaš.

Airborne LiDAR data acquisition was performed in September 2016 using a Leica ALS 70 CM scanner. The study area was scanned from an altitude of 1,290 m with a 43° field of view, and 282 kHz laser pulse repetition rate. The resulting average density of point cloud reached 26 points m^{-2}. The airborne Lidar-derived digital terrain and surface model (DTM and DSM) were interpolated in SCOP++ Software environment (Trimble) and vertical accuracy was expected to be ±0.2 m. A canopy height model (CHM) of 0.5 m resolution was generated as a result of subtraction of the DSM and DTM.

Ground reference data were obtained during the leaf-on season in 2017 within 294 circular plots with radius from 7.5 to 20 m (size of plot was dependent on number of trees). The position of the plot centre was measured using the Global Navigation Satellite System (GNSS) and a positional error from 1.44 m to 6.25 was expected for all plots (Murgaš et al. 2018). A total of 8,846 trees

polygon (tree crowns) vector files in an ESRI shapefile format (Sačkov et al. 2017b).

Tree species of detected trees were determined at the level of identified objects and were classified only into general classes of broadleaved and coniferous trees. For this purpose, an object-oriented classification of RGB and CIR orthophotos with a spatial resolution of 0.25 m was used. This classification was processed with the eCognition Developer 8 software (Trimble GeoSpatial, Munich, Germany).

The DBHs of the detected trees were derived based on nonlinear regression models. The model predictor was tree height for the selected group of tree species (DBH = f(h)). The calibration dataset included 955 broadleaved trees and 747 coniferous trees. The statistical significance of models was assessed using the F-test at a significance level of $\alpha = 0.05$. The average accuracy for these models was 21% at the tree level.

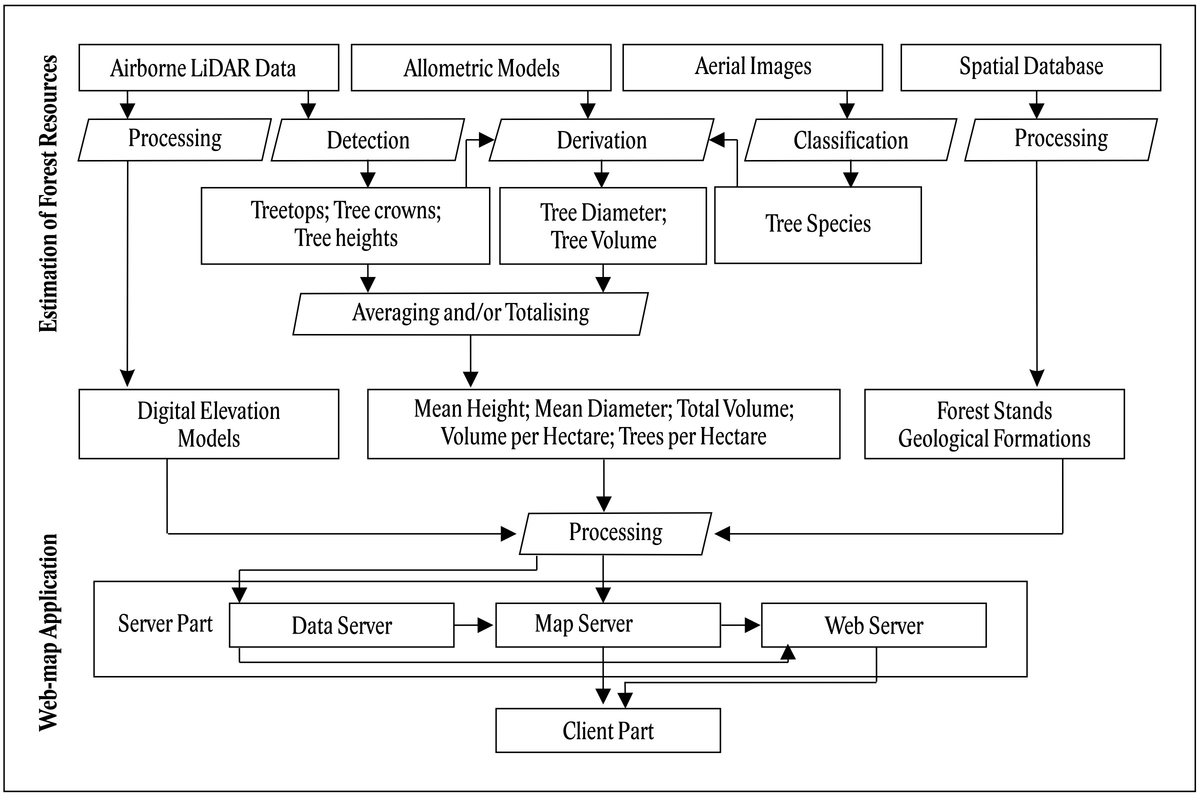

Fig. 2. Integrated framework for remote sensing-based estimation and web-based visualization of forest resources.

The volume for detected trees was derived based on the models introduced by Petráš & Pajtik (1991). For each remotely detected tree, which included the estimated height, assigned attribute of tree species classes, and derived DBH, the volume calculation was applied using the adopted model. As only two classes of tree species were available, the volume functions of the tree species with the highest proportion in the respective growing stock were used as a compromise. For the broadleaved class, the beech function was used. For the coniferous class, the spruce function was used.

Finally, the stand height and stand diameter were calculated as the average of the tree data. The total volume was calculated as a sum of the tree volumes.

2.3. Development of Web-map application

Data formats

The functionality of web-map applications strongly depends on the format of datasets that are displayed to the user via a web browser. The basic requirement is to display the required amount of data in the shortest possible time and in the best possible quality.

In this context, Indexed 3D Scene Layers (i3s) and Limited Error Raster Compression (LERC) data formats were used for the current version of the application. The i3s format was used for streaming large and heterogeneous geospatial datasets with 3D content including discrete 3D objects, large continuous meshes, 3D vector points, and point clouds. The LERC format was used to create a custom tile layer that displays elevation data.

Application

The server part of the application consists of three interconnected servers: (1) *Data server*: we selected PostgreSQL object-relational database management system because this system is freely distributable and, among other benefits, it supports a large part of the SQL standard and extension, including a spatial database extender PostGIS. (2) *Map server*: we selected ArcGIS Enterprise 10.7.1 (ESRI) because this system provides many of the features needed for mapping, data analysis, data visualization, and recent releases include also support for publishing 3D objects. (3) *Web server*: we selected Apache with PHP configuration for hosting an application because this server is freely distributable and providing some built-in resources such as databases, caching tools and other tools for website optimization.

The client part of the application was created as a single page application (SPA) using Arcgis API libraries for Javascript as well as through Query, UnderscoreJS, Backbone, Bootstrap, and jsPanel. SPA interacts with the user by dynamically rewriting the current page rather than loading entire new pages from a server. This approach avoids interruption of the user experience between successive pages. For more realistic 3D visualization of RS-identified trees, we used a model from ESRI 3D Vegetation Library (Peterson 2014). However, only conifer model was adopted for current version of the application. In this context, we used also the concept of "Level Of Detail" (LOD) to increase rendering efficiency by reducing (1) number of objects and (2) complexity of the 3D object, when the scale is changing.

3. Results

3.1. Estimations of forest resources

A total of 968,217 single trees were detected using reFLex algorithm. The RS-based approach evaluated the mean height at 22.3 m by averaging the detected tree heights, the mean diameter at 26.2 cm by averaging the derived tree diameters, the volume at 744,732.6 m^3 by totaling the calculated tree volumes. The differences between ground-measured and RS-estimated forest stands variables reached values of 16.4%, 12.1%, −26.8%, and −35.4% for the mean height, mean diameter, volume per hectare, and trees per hectare, respectively. Additionally, the variability of ground-measured and RS-estimated tree height, tree diameter and tree volume is shown in Fig. 3.

geology (e.g. geological formation). This panel also includes an output from the RS-based estimation of forest resources (e.g. RS-identified trees). The visualization of the RS-identified trees is changing dynamically with respect to the scale. The scales of more than 1 : 20,000 m allows a visualization of trees only as raster object in both 2D and 3D scene (Fig. 5a). The scales from 1 : 20,000 to 1: 1,000 m allows a visualization of tress as vector object (Fig. 5b). The scales less than 1 : 1,000 m also allows a visualization of trees with the unified 3D graphics of conifers and moreover, the size of these 3D objects reflects to the RS-estimated tree height and crown projection (Fig. 5c). The web interface of application also contains a set of geographic tools. In addition to the basic functionality (e.g. zooming, selecting, etc.), the application allows to create cross-sections through layers as well as a measurement of transversal, horizontal and direct distance between individual 3D objects (e.g. tree tops) (Fig. 6).

An initial experiments showed that the web-map application is fully stable and allows real-time visualization of geospatial data. More specifically, the average response time to display page with several hundred trees including 3D graphics of conifers (scale <1 : 1,000) or several hundred thousand trees (scale 1 : 1,000 – 1 : 20,000) was about 5.3 seconds.

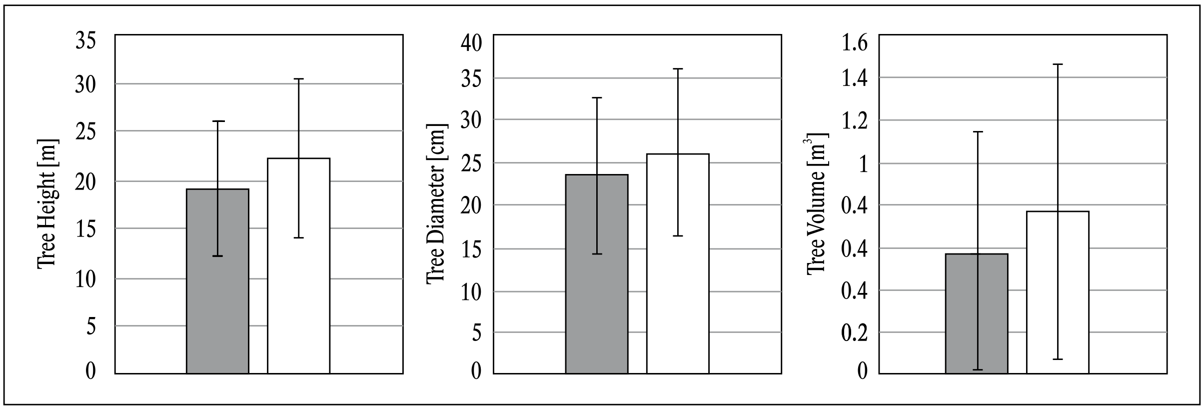

Fig. 3. Ground-measured (grey box) and remote sensing-estimated (white box) forest stand variables including standard deviation (whiskers).

3.2. Visualization of forest resources

The application enables the web-based visualization of geospatial data in 2D and 3D scene including attribute- and location-based querying and 3D data profiling. The availability is provided by map servers of State Geological Institute of Dionýz Štúr and/or National Forest Centre.

The web interface of application consists of two map panels. The first panel contains background layers, such as geographic maps, orthophotos, and digital elevation models (eg. DTM). In the case of 3D visualization, the elevation layer is defined by DTM and all remaining layers are consequently rendered based on this elevation layer (Fig. 4). The second panel contains sublayers, such as thematic maps used in forestry (e.g. forest stand) and

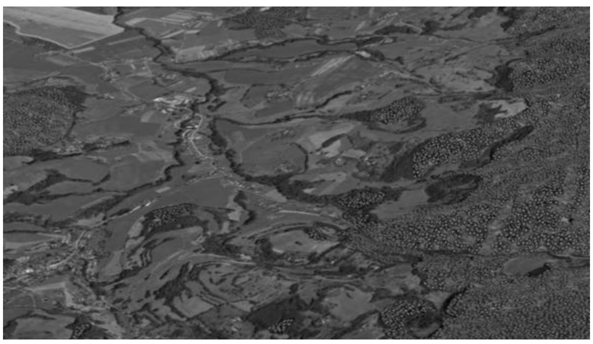

Fig. 4. Visualization of orthophotos (3D background layer) and trees (2D point sublayer). The elevation layer is defined by digital terrain model.

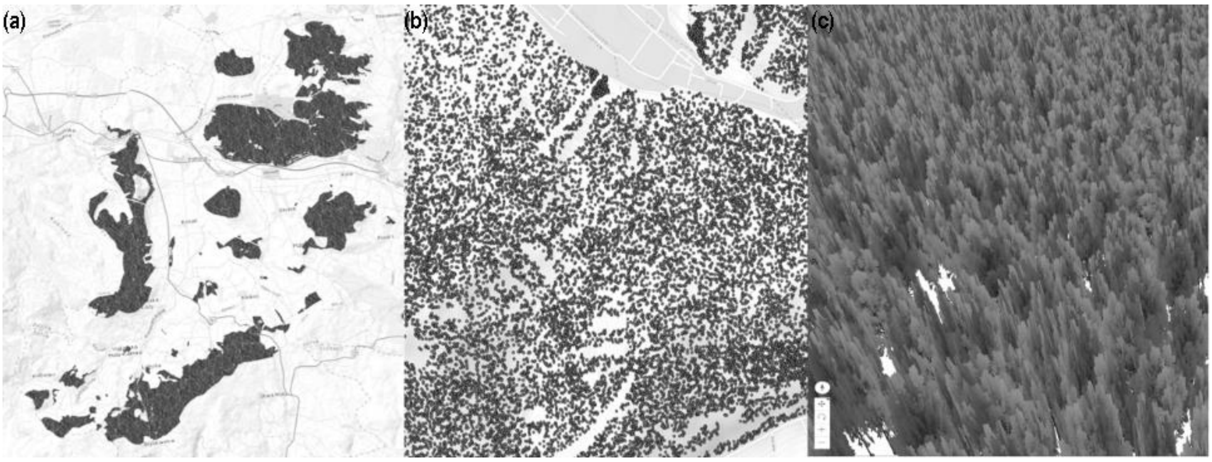

Fig. 5. Visualization of geographic map (background layer) and trees in different scales: (a) Scale >1 : 20,000 displays trees as raster object, (b) Scale 1 : 20,000 – 1 : 1,000 displays trees as vector object, (c) Scale <1 : 1,000 also allows a visualization of trees as 3D object.

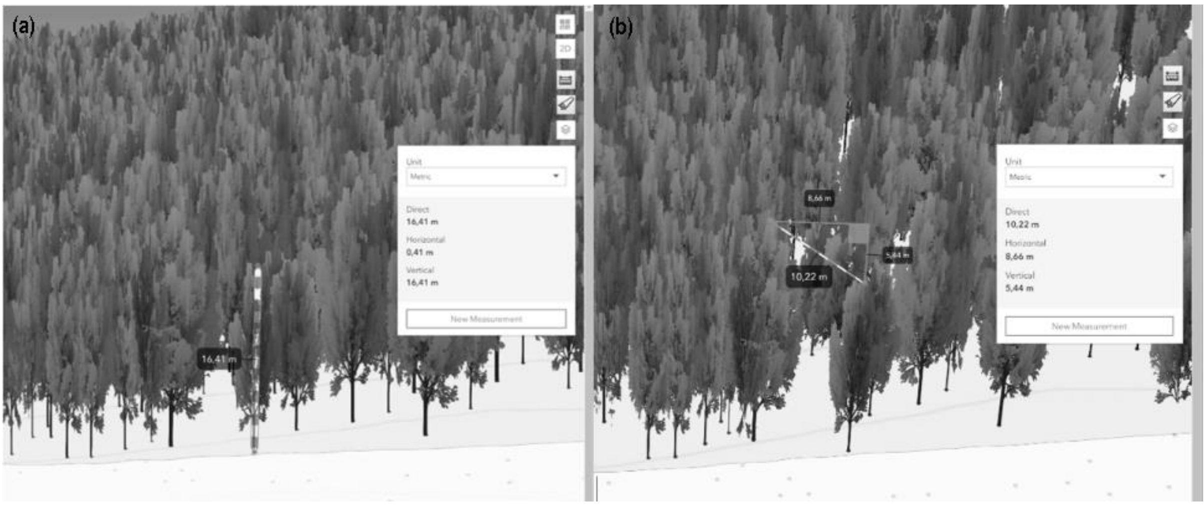

Fig. 6. The application allows to create cross-section through trees and interactive measurement of tree height (a) as well as distance between trees (b).

4. Discussion

A web-based visualization of forest resources estimated from RS data represents an effective technology concept to support precision forestry. Firstly, advanced RS-based techniques allow to estimate forest resources automatically, continuously, with a known accuracy, and at multiscale level. Secondly, web-map applications allow to provide geospatial data to the key stakeholders in forestry sector over mainstream web browsers. We have therefore developed a framework which integrates (1) an algorithm for estimation of forest stand variables based on remote sensing data and (2) a web-map application for 2D and 3D visualisation of geospatial data.

The forest stands variables were estimated through an individual tree detection algorithm implemented in the reFLex software based on combination of airborne LiDAR data and aerial color-infrared images (Sačkov et al. 2017). Although only 64.6% of single trees were identified, the mean error of RS-based estimations did not exceed 16.4% for mean height and 12.1% for mean diameter. On the other hand, the volume was underestimated by 26.8%, probably due to problems in detecting suppressed and understory trees. This problem could be considerably reduced with the area-based algorithm (Kandare et al. 2017). Comparing different approaches, however, our individual tree detection algorithm provided accuracies that were higher or similar to the area-based algorithm. For example, Coomes et al. (2017), Zhang et al. (2017) or Lamb et al. (2018) reported an accuracy of 5 – 11%, 10 – 13%, 12 – 28%, 19 – 30% for estimation of mean height, mean diameter, standing volume, and stem density, respectively.

The developed web-map application displays the geospatial data in a user-friendly manner and it is capable of fast real-time rendering in 2D as well as 3D scene over mainstream web browsers without a plugin. In this context, we confirm its full applicability in design consisting (1) data formats (i3S, LERC), (2) server parts (PostgreSQL data server, ArcGIS Enterprise map server, Apache with PHP configuration web server), and (3) client part (SPA developed by Arcgis API libraries for Javascript). However, there are many other effective frameworks of web-map application that are commonly used for visualization of forest resources. Lim & Honjo (2003) visualized a forest landscape with thousands of trees using Virtual Reality Modeling Language. Singh et al. (2012) developed a web-map application only by open source geospatial systems (e.g. Mapserver, MapScript) and observed that this application also enables user to view, update, customize, retrieve, inquire and analyse data about forest resources. Panizzoni et al. (2015) used GeoBrowser 3D, HTML5, WebGL, CSS 3D and Canvas element for interactive visualization of the forest model. Zápotocký & Koreň (2016) proposed a web-map application for visualization of forestry maps based on Microsoft SQL Server, ArcGIS for Server, and Microsoft Information Server. Wang et al. (2017) used X3DOM and HTML5 and developed a workflow for the construction of WebGL rendering and interactive visualization of forest landscapes from GIS and forest simulation datasets. Stratil & Renner (2019) used a Unity Gaming Technology to visualize spatial data and allowing the forest owners virtually visit their forests. Marano et al. (2019) developed a flexible web-based operational tool to challenge multifunctional and sustainable forestry knowledge for planning and management purposes at the landscape level, with a demonstration of potential deliveries at high spatial detail and for large spatial extent areas.

5. Conclusions

This study demonstrated that our integrated framework is capable of online providing complex geospatial data and findings from RS-based estimations of forest resources at forest management unit level. In this context, we extended the current state of art in the field of utilization of advanced geospatial technology within the forestry sector. Firstly, despite the requirement for large-scale estimation of forest stand variables (12,472 ha), an accuracy of our individual tree detection algorithm was higher or similar to the other studies. Secondly, despite the requirement for online visualization of large amounts of geospatial data (e.g. digital terrain model, aerial imagery, thematic maps used in forestry or geology, and 968,217 single trees), newly developed web-map application showed stability and capability for fast real-time rendering in 2D as well as 3D scene over mainstream web browsers without a plugin.

Future work should include creation of a more detailed visualization of different surfaces (e.g., grassland, forest, open water, building) as well as trees (tree species) and development of various useful geospatial tools (e.g., interactive navigation). Furthermore, there is a potential for expanding this application which will enable the user to download, upload and analyse geospatial data for specific needs.

Acknowledgments

This research was supported by the Ministry of Agriculture and Rural Development of the Slovak Republic in the framework of the project "Research and development to support the competitiveness of Slovak forestry" (SLOV-LES).

References

Cibulka, D., 2012: Uplatnenie webových služieb pri sírístupňovaní a spracovaní geodát. Ph.D. dissertation, Bratislava, Stavebná fakulta, STU v Bratislave.

Coomes, D. A., Dalponte, M., Jucker, J., Asner, G.P., Banin, L. F., Burslem, D. F. R. P.et al., 2017: Area-based vs tree-centric approaches to mapping forest carbon in Southeast Asian forests from airborne laser scanning data. Remote Sensing of Environment, 194:77–88.

Ginzler, Ch., Waser, L. T., 2017: Entwicklungen im Bereich der Fernerkundung für forstliche Anwendungen. Schweizerische Zeitschrift für Forstwesen, 168:118–126.

Kandare, K., Dalponte, M., Ørka, H. O., Frizzera, L., Næsset, E., 2017: Prediction of Species-Specific Volume Using Different Inventory Approaches by Fusing Airborne Laser Scanning and Hyperspectral Data. Remote Sensing, 9:400.

Lamb, S. M., MacLean, D. A., Hennigar, C. R., Pitt, D. G., 2018: Forecasting Forest Inventory Using Imputed Tree Lists for LiDAR Grid Cells and a Tree-List Growth Model. Forests, 9:167.

Lim, E. M., Honjo, T., 2003: Three-dimensional visualization forest of landscapes by VRML. Landscape and Urban Planning, 63:175–186.

Ma, Z., Chen, M., Zhang, B., Wang, M., Shen, C., Yue, S. et al., 2019: A web-based integrated modeling and simulation method for forest growth research. Earth and Space Science, 6:2142–2159.

Marano, G., Langella, G., Basile, A., Cona, F., Michele, C. D., Manna, P. et al., 2019: A Geospatial decision support system tool for supporting integrated forest knowledge at the landscape scale. Forests, 10:690.

Murgaš, V., Sačkov, I., Sedliak, M., Tunák, D., Chudý, F., 2018: Assessing horizontal accuracy of inventory plots in forests with different mix of tree species composition and development stage. Journal of Forest Science, 64:478–485.

Panizzoni, G., Magliocchetti, D., Prandi, F., De Amicis, R., 2015: Interactive virtual planning tools for sustainable forest production in mountain areas. In: Stephanidis, C. (eds.): HCI International 2015 – Posters' Extended Abstracts. Springer International Publishing, Cham, p. 220–225.

Peterson, B., 2014: 3D Vegetation Library Delivers Advanced Models for Urban Design and GIS Professionals. Available at https://www.esri.com/esri-news/releases/14-1qtr/3d-vegetation-library-delivers-advanced-models-urban-design-gis-professionals. (accessed January 30, 2020).

Petráš, R., Pajtík, J., 1991: Sústava česko-slovenských objemových tabuliek drevín. Lesnícky časopis, 37:49–56.

Sačkov, I., Santopuoli, G., Bucha, T., Lasserre, B., Marchetti, M., 2016: Forest Inventory Attribute Prediction Using Lightweight Aerial Scanner Data in a Selected Type of Multilayered Deciduous Forest. Forests, 7:307.

Sačkov, I., Sedliak, M., Kulla, L., Bucha, T., 2017a: Inventory of Close-to-Nature Forests Based on the Combination of Airborne LiDAR Data and Aerial Multispectral Images Using a Single-Tree Approach. Forests, 8:467.

Sačkov, I., Hlásny, T., Bucha, T., Juriš, M., 2017b: Integration of tree allometry rules to treetops detection and tree crowns delineation using airborne lidar data. iForest, 10:459–467.

Sačkov, I., Kulla, L., Bucha, T., 2019: A Comparison of Two Tree Detection Methods for Estimation of Forest Stand and Ecological Variables from Airborne LiDAR Data in Central European Forests. Remote Sensing, 11:1431.

Singh, P. S., Chutia, D., Sudhakar, S., 2017: Development of a web based GIS application for spatial natural resources information system using effective open source software and standards. Journal of Geographic Information System, 4:261–266.

Stratil, M., Renner, O., 2019: Virtual forest. In: Proceedings of GIS Ostrava 2019 – Smart City, Smart Region, Ostrava, p. 1–6.

Surový, P., Kuželka, K., 2019: Acquisition of Forest Attributes for Decision Support at the Forest Enterprise Level Using Remote-Sensing Techniques – A Review. Forests, 10:273.

Vauhkonen, J., Maltamo, M., McRoberts, R.E., Næsset, E., 2014: Introduction to forestry applications of airborne laser scanning. In: Maltamo, M., Næsset, E., Vauhkonen, J. (eds.): Forestry Application of Airborne Laser Scanning: Concept and Case Studies. Springer Netherlands: Dordrecht, The Netherlands, p. 1–16.

Véga, C., Renaud, J., Durrieu, S., Bouvier, M., 2016: On the interest of penetration depth, canopy area and volume metrics to improve Lidar-based models of forest parameters. Remote Sensing of Environment, 175:32–42.

Wang, H., Chen, X., Polys, N., Sforza, P., 2017: A web3D forest geo-visualization and user interface evaluation. In: Proceedings of ACM Web3D 2017 conference, Brisbane, QLD, Australia, p. 1–9.

Zápotocký, M., Koreň, M., 2016: Webová aplikácia pre sprístupnenie digitálnych máp vysokoškolského lesníckeho podniku. Kartografické listy/Cartographic letters, 24:103–111.

Zhang, Z., Cao, L., She, G., 2017: Estimating forest structural parameters using canopy metrics derived from airborne LiDAR data in subtropical forests. Remote Sensing, 9:940.

Cent. Eur. For. J. 66 (2020) 177–187 sciendo DOI: 10.2478/forj-2020-0016

CENTRAL EUROPEAN Forestry Journal

http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Analysis of the time efficiency of skidding technology based on the skidders

Lukáš Orlovský*, Valéria Messingerová, Zuzana Danihelová

Technical Univerzity in Zolen, Faculty of Forestry, T. G. Masaryka 24, SK – 960 01 Zvolen, Slovak Republic

Abstract

The time efficiency and principles of ergonomics related to timber skidding are based on the time consumption per work cycle as well as on the time consumption per individual work operations. Regarding the demands on the environmental requirements and ever increasing cost of work, it is necessary to objectively evaluate the inevitable time consumption required for timber skidding using all technologies. The paper summarised the results of time studies for skidder technologies. The time study compares the time consumption and productivity of cable skidders and cable-grapple skidders, with the main focus on developing time prediction models. The main aim of the study was to objectify the skidder time consumption and establish the impact of production factors on the time consumption of partial work operations of skidders. Within the time study 231 work cycles were measured, and 53 snapshots of work day with using methods continual time study. The overall time consumption of the work cycle and gross production rate of the monitored cable and cable-grapple skidders is affected by the following production factors: the skidding distance, volume of skidded logs and number of skidded logs. The impact of individual production factors on the overall time consumption of the work cycle is different for each group of skidders. Non-operation times of the skidder operators' shifts represent 24.6% with the highest part taken by the technical operation of the work place. The mean gross production rate of the monitored skidders varied from 33.3 to 6.91 $m^3 h^{-1}$.

Key words: time consumption; time study; wheeled skidders; time prediction models; productivity

Editor: Vladimír Šebeň

1. Introduction

Tractor technologies belong to the most often used for timber skidding in the forests of the Slovak Republic. According to the Green Report from 2007, tractor reached 78% (the last official record) of the technologies used, thereof skidders 47.6%. Most of them are cable skidders of the types LKT 81 and LKT 81T. However, other types of skidders, e.g. grapple and clambunk, are used for timber skidding worldwide (Borz et al. 2014a).

Present day performance standards (PS) for skidder technologies published in the proceedings no. 24 of the Ministry of Agriculture and Rural Development of the Slovak Republic are not current and outdated (last issue from 1992). They do not correspond to the current development of forestry equipment and requirements for modern skidders regarding ergonomics and ecology, since various forestry entities (e.g. state enterprise LESY SR) use their own internal performance standards and rules for wages of workers in logging. The time studies into skidders were discussed by many authors in various countries with the aim of determining the impact of various production factors on the productivity and the amount of costs, or with the aim of comparing various skidding methods (winch versus grapple) in various terrain and stand conditions (Proto et al. 2018). Abeli (1996) in his study compared the productivity and costs of three skidders at the Sokoine University. The research results have shown that the differences among skidders were affected significantly by the size and type of the machine, skilfulness of the operators and the stand slope inclination. Kluender et al. (1997) studied the productivity of skidders equipped with cable winch and skidders equipped with hydraulic grapple in the pine forests of the USA. The study came to a conclusion that grapple skidding technology is significantly faster and more productive than skidders with a cable winch. The same results are presented in the study of Mederski et al. (2010) studying the productivity of cable and cable-grapple skidders in the Northern Poland. The results have shown that cable-grapple skidder HSM with hydraulic crane achieved two times higher productivity when compared to the RSG skidder equipped with cable winch. Naghdi et

*Corresponding author. Lukáš Orlovský, e-mail: lukasorlovsky67@gmail.com

al. (2008) compared the skidding productivity of skidders in the conditions of incidental felling and regeneration felling in the company Shafaroud. They found out that the productivity in the case of regeneration felling was higher by 47.7% than in the case of incidental felling. Most of the time studies from abroad were focused only on one type of skidders (Behjou et al. 2008; Zečić et al. 2011; Mousavi 2012a; Mousavi 2012b; Borz et al. 2013; Kulak et al. 2013; Nikooy et al. 2013; Marčeta et al. 2014; Borz et al. 2015; Proto et al. 2018; Kulak et al. 2019), or on several tests carried out using various forestry technologies and equipment (Bavaghar et al. 2010; Spinelli & Magagnotti 2012). Regarding the production factors these studies were focused only on the mean volume of skidded logs ranging from 1.05 to 5.34 m^3 with the mean skidding distance up to 400 m (Sabo & Poršinsky 2005; Behjou 2010; Ghaffarian et al. 2013; Mousavi et al. 2013; Kulak et al. 2017; Proto et al. 2018). In the case of further time studies (Zečíć et al. 2010; Lotfalian et al. 2011; Borz et al. 2013, Borz et al. 2014b; Borz et al. 2015) the skidding distance was more than 800 m.

Evaluating the efficiency in timber logging and timber transportation for various forestry equipment and technology is carried out using the time study (Björheden et al. 1995; Acuma et al. 2012), which is conducted in order to express the consumed time and carried out production related to the relevant impact of factors. From the methodological point of view, there are two types of time studies: correlation studies and comparative studies. Correlation studies are carried out in order to find out the relationship between the work time consumption and factors determining the work, while the aim of comparative studies is to compare the time consumption or productivity of various machines or methods of work used to complete the same task (Mousavi et al. 2013). The results of time studies were mostly used for determining the extent of production and its rationalisation (Björheden 1991; Sarikhani 2001; Nurminen et al. 2006) or for assessing various logging methods in order to find the most economical one. The aim of the present study was to: (i) assess the impact of production factors on the time consumption of individual partial work operations of cable and cable-grapple skidders; (ii) develop models for predicting the time consumption of partial work operation of skidders; (iii) find out and compare the productivity and efficiency of the tested skidders.

2. Material and methods

2.1. Study location

Study of the time consumption was carried out in the University Forestry Enterprise of the Technical University in Zvolen from 23 May to 25 October 2019 in 20 stands mostly beech, beech-fir and beech-oak. During the study 53 snapshots of the work day were taken and 231 work cycles of skidders were measured. Following skidders were observed and tested within the study: cable-grapple skidders (HSM 805HD, LKT 81 ITL (HC) with hydraulic crane, EQUUS 175N) and cable skidders (LKT 81 ITL, LKT 81T). Working groups included from two (LKT 81 ITL, EQUUS 175N) until three members for every skidder. Figure 1 and 2 illustrate the tested cable and cable-grapple skidders. Table 1 presents the characteristics of the production factors of forest stands where the timber skidding was carried out, while Table 2 describes the characteristic parameters of individual monitored skidders analysed within the study.

2.2. Work phase classification

The overall time of the work cycle of skidder operators was divided into following partial work operations:

– Unloaded travel from the forest landing into the stand: the phase begins with the skidder movement from the forest landing towards the stand and finishes when the skidder reaches the cut stems.
– Cable releasing: Initiating the subsequent work operation is preceded by terminating the previous one. The operation begins by releasing the cable from the skidder winch drum and terminates when the choker setter reaches the logs to be skidded.
– Collecting time: the operation begins when the choker setter fastens the logs to the chokers and finishes when he steps back to a safe distance from the log.
– Winching the load from the stand to the skidding line: this phase starts with winching the cable on the


Fig. 1 and 2 on the left EQUUS 175N (cable-grapple skidder) and on the right LKT 81 ITL (cable skidder).

Table 1. Characteristics of production factors of study stands.

Subcompartment	Type of skidder	Skidding distance	Winching distance	Slope inclination	Volume of skidded stems	Mean tree volume
		[m]		[%]	[m³]	
1318	HSM 805HD	424	21.2	30	53.46	2.10
1322	HSM 805HD	87	8.8	35	24.14	1.55
1315	HSM 805HD	1,099	18.0	35	37.04	2.20
1317	HSM 805HD	467	25.3	30	47.64	1.82
1324	HSM 805HD	1,193	37.8	30	33.19	1.66
1338b	HSM 805HD	1,073	11.8	15	31.99	1.23
1291	HSM 805HD	1,356	23.4	60	33.42	0.58
1330	HSM 805HD	1,833	15.5	35	31.51	1.03
1320	HSM 805HD	470	17.4	30	191.16	1.28
1290	HSM 805HD	616	19.4	30	44.08	1.46
721	LKT 81 ITL (HC)	316	21.3	18	40.11	1.82
851c	LKT 81 ITL (HC)	618	18.1	20	39.09	0.43
745	LKT 81 ITL (HC)	526	20.5	35	151.79	2.72
581	LKT 81 ITL (HC)	619	16.1	25	163.23	0.90
1091	LKT 81T	150	6.5	35	19.97	1.48
1093	LKT 81T	300	11.3	35	54.50	1.99
234	LKT 81T	1,059	12.3	40	78.09	1.01
1094a	LKT 81T	178	9.2	35	31.91	1.03
253	LKT 81 ITL	1,112	17.4	40	291.50	1.89
727a	EQUUS 175N	541	18.3	40	359.50	2.00

Table 2. Specifications of the skidders.

Parameter	Type of skidder				
	HSM 805HD	EQUUS 175N	LKT 81 T	LKT 81 ITL (HC)	LKT 81 ITL
Engine power [kW]	129	125	74	85	85
Age of skidder in years	12	1	24	1	3
Number of working day snapshot	15	9	6	16	7
Number of runs	77	34	34	55	31
Composition of the working group	1+2	1+1	1+2	1+2	1+1
Total skidded volume [m³]	527.6	359.5	184.5	394.2	310.1
Number of skidding stems [pcs]	431	199	172	428	185
Equipment of skidder	HC, RC, D	HC, RC, D, C	D	HC, RC, D, C	RC, D

HC – hydraulic crane, RC – radio control, C – clam bunk, D – double drum winch.

skidder winch drum (cable skidders); in the case of chokerless stem skidding the operation begins with the skidder movement towards the skidding line and finishes when the log reaches the skidding line.

– Skidder travel to other logs: this work operation phase was registered with skidders that carried out cable-grapple log skidding. The phase begins by placing the skidded log on the skidding line and continues with the subsequent movement of the tractor to other cut stems. The phase is terminated when the skidder reaches another cut stem.
– Load skidding: the operation starts with skidding the load from the skidding line to the forest landing and finishes when the skidder stops at the forest landing.
– Load unhooking: the operation starts by releasing the cable from the tractor winch drum and finishes by unfastening the load and winding up the cable on the skidder winch drum.
– Handling by the skidder operator: this work operation starts being registered as soon as the skidder operator begins carrying out grading the logs, and it is terminated by cutting all logs into selected assortments.
– Log piling: this work phase begins after finishing the previous phase and terminates after the last log is piled on the assortment piling.

2.3. Data collection

Measuring the time consumption of skidders was carried out using the methods of continual time study, i.e. by connecting the work day snapshot with the fluent chronometry. The work day snapshots were used to record the occurrence of unit, batch and shift times during work shift, e.g. time necessary for preparation and termination of work, biological and recreation break etc. Operative time of the skidder operator and two further categories of time losses, i.e. technical-organisation and personal losses were recorded, as well. All unit, batch and shift times of skidder operators including time losses were recorded throughout the entire shift.

Dividing the times of the skidder operator shift was carried out according to a verified Central European methodology published by the authors (Klouda et al. 1988; Lhotský 2005; Dvořák et al. 2010).

During measuring the time consumption of skidder operator shift, the timekeeper did not interrupt the work process with work orders and recommended technological procedures, which could affect the regular condition of the production process. Nevertheless, the skidder operators were informed that measuring the time consumption of the shift was being carried out. Mostly operators who were expected to follow all work and safety regulations were selected for the study.

The partial phases of work operation of the skidders (collecting time, load skidding etc.) were measured using the fluent chronometry with accuracy to seconds, and subsequently they were transcribed to electronic form for keeping the legibility and transparency.

Besides measuring the time consumption of partial work operations, the study was focused also on factors which affected significantly the time consumption of this technology. Following the results of studies from abroad (Howard 1987; Kluender et al. 1997; Behjou et al. 2008; Borz et al. 2013; Proto et al. 2018), following production factors were selected: the skidding distance, the number of logs in a load, wood species, winching distance, mean tree volume of skidded logs and work cycle load volume.

These factors were measured throughout all skidder work cycles. The skidding distance and winching distance were measured using a digital laser range finder TruPulse 360B or using a GPS receiver. Mean diameter and length of the skidded logs were measured using forestry callipers and tape measure, and subsequently the load volume in individual skidder work cycles was calculated using log volume tables. The number of logs in a load and wood species were recorded visually. Professional digital stopwatch Fastime 26 was used to record the time of partial work operations. Prior to statistical evaluation of measuring the time consumption, the time series was processed and unreliable and erroneous measurements were excluded from the time series. The recorded data were subsequently processed using the methods of generalized linear model (GLM). The statistical analysis was performed in the software STATISTICA 12.0 (StatSoft 2012) and using the programming language R.

3. Results

Table 3 presents the mean time consumption of individual monitored phases of a shift of monitored skidder operators, as well as the mean time of the shift. The data indicate that the operative time is 75.6% on average, and the remaining 24.4% covers non-operation time of the shift (technical service of the workplace, biological and recreational breaks etc.). The highest average percentage of non-operation time was recorded with the technical service of the workplace 8.5%, whereas the lowest average percentage is represented by work orders 1.4%. Technical and organisational time losses caused mainly by skidder operators waiting until the loggers finish their work (delimbing etc.) cover 2.83% of the shift on average. Personal losses represent only 5% of the whole time loses and were caused mainly by personal telephone calls of the skidder operators and talks with other technical staff on extracurricular topics. The average shift length of monitored skidder operators in this study represents 451.2 minutes (7.52 h), being 29 minutes less than the length of a standard shift (8 h). Regarding the average time for biological and recreational breaks during a shift (Table 3), none of the monitored skidder operators met the legally determined length of break for rest and refreshment, which according to § 91 of the Labour Code is at least 30 minutes for work longer than 6 hours.

Table 4 presents the percentage of individual partial operations of cable and cable-grapple skidders. The data show that the highest ratio of the overall work cycle of cable-grapple skidders is represented by log piling with the average of 28%, followed by winching the load (15.3%) and load skidding (13.3%). When analysing the work operations of the operators of cable skidders, 22.5% of the time was taken by two operations – load skidding and handling by the skidder operator, followed by unloaded travel (17%) and load collecting (11.5%). When comparing the percentage of work operations carried out by cable skidder operators (Table 4), it is obvious that the most significant differences were recorded with unhooking the load and log piling, which can be associated with more modern equipment of the LKT 81 ITL skidder compared to LKT 81T and with the skills and experience of the operator. In addition, it can result from significantly different representation of work operations caused by different average skidding distance (Table 5) recorded with these skidders. In the case of cable-grapple skidders, more significant differences in the ratio of handling by the skidder operators of individual skidder types (EQUUS 175N versus HSM 805HD and LKT 81 ITL (HC)) were recorded. The higher percentage of this operation in the case of EQUUS 175N skidder is caused by the division of work within the working group, where a part of the handling process (measuring off) was carried out solely by the skidder operator without the assistance of the logger.

The average time consumption for partial work operations, as well as corresponding average values of production factors of the skidders are illustrated in Table

Table 3. The balance of the average consumption of shift time of skidder operators (Dvořák et al. 2011).

Work shift components	HSM 805 HD	EQUUS 175N	LKT 81T	LKT 81 ITL (HC)	LKT 81 ITL
			[min.]		
Work operation (T_{A1})	338	337	303.5	350	376
Preparation and termination of work (T_{B101})	8	18	18	12	16
Work orders (T_{B102})	4	7	8	7	3.7
Technical service of the workplace (T_{C103})	54	15	78	41	3.2
Technical service of the machine (T_{C104})	13	10	8	7.6	9
Machine defaults repair (T_{C105})	17	25.5	20	1.4	1.7
Biological and recreational breaks (T_2)	20.5	23	7.5	20	7
Technical-organizational losses (T_E)	3	25	8	9	19
Personal losses (T_D)	0.5	0.5	1	1	0.4
Average working time (T)	458	461	452	449	436

Table 4. Time consumption distribution of cable and cable-grapple skidders.

Work phase	Cable-grapple skidder HSM 805 HD	Cable-grapple skidder EQUUS 175N	Cable-grapple skidder LKT 81 ITL (HC)	Cable skidder LKT 81T	Cable skidder LKT 81 ITL
	[%]				
Travel unloaded	13	11	9	16	18
Cable releasing	0	2	1	4	3
Collecting time	10	13	14	10	13
Winching load	16	11	19	7	6
Travel skidder to other logs	5	7	9	1	1
Skidding load	14	15	12	18	27
Unhooking load	6	4	8	8	3
Handling by the skidder operator	3	11	3	23	22
Log piling	33	26	25	13	7

Table 5. Average time consumption of elements work operation of monitored skidders.

Elements of work operation	LKT 81 ITL (HC)	HSM 805 HD	EQUUS 175N	LKT 81T	LKT 81 ITL
	Type of skidder [min.]				
Travel unloaded	6.68	6.99	7.75	8.24	12.90
Cable releasing	0.38	0.09	1.51	1.61	2.13
Collecting time	10.56	5.14	9.04	4.72	8.85
Winching load	13.85	9.04	8.06	3.17	4.14
Travel skidder to other logs	6.52	2.79	4.96	0.25	0.51
Skidding load	9.12	7.55	9.83	9.65	19.78
Unhooking load	6.00	3.17	3.05	3.75	2.32
Handling by the skidder operator	3.41	1.72	8.05	9.25	15.85
Log piling	19.42	18.32	17.66	5.06	5.25
Total cycle time	74.71	54.81	70.16	45.70	69.63
Factors of production					
Number of logs in a load [pcs]	7.98	5.59	6.00	5.06	5.68
Load volume [m^3]	7.95	6.96	11.27	5.43	9.40
Mean tree volume [m^3]	1.41	1.45	1.99	1.38	1.79
Skidding distance [m]	533.68	699.46	530.00	545.85	1,111.51
Winching distance [m]	17.34	17.65	18.56	11.08	15.15

5. The data show that the biggest differences in the time consumption between the cable and cable-grapple skidder operators were recorded in the case of the following operations: releasing the cable into the stand, winching the load, skidder travel to other logs, log piling and handling by the skidder operator. When comparing the average time consumption required for piling the logs, it can be seen that the cable-grapple skidder operators needed 3.5 times more time for this operation than cable skidder operators. This significant difference can be explained by different procedure of carrying out the operation (hydraulic crane versus stacking blade). Differences in time consumption of further two operations, cable releasing and skidder travel to other logs, between the two types of skidders were associated with the working method of the operators of cable skidder (using a cable winch) and cable-grapple skidders (using a hydraulic crane), as well as with applying cable and cable-grapple skidding method. The results of comparing the average time consumption of winching the load of the two types of tractors (Table 5) indicate that cable-grapple skidder operators needed on average 2.8 times more time than the operators of cable skidders. This fact is probably caused by the different method of carrying out the operation (winch versus hydraulic crane), as well as by longer average winching distance by 4.75 m in the case of cable-grapple skidders. The average time consumption of the operation – handling by the skidder operators is by 48% higher in the case of the cable skidders. This difference is caused by the fact that the operators of cable skidders carried out log measuring and log sawing all by themselves, without any assistance of loggers, while in the case of cable-grapple operators, these activities were carried out with the assistance of loggers from the working groups. Regarding the average number of logs in one load, the cable-grapple skidder operators compiled the load from a higher number of logs (6.52 pcs) compared to the operators of cable skidders (5.37 pcs), what eventually affected also the final mean volume of the load. The mean load volume of cable-grapple skidder operators was

Table 6. Mean nett and gross production rate and average driving speeds of skidders.

S	Type of skidder	Skidding distance [m]	Load volume [m^3]	Nett production rate [m^3 h^{-1}]	Normative work performance [m^3 h^{-1}]	Gros production rate [m^3 h^{-1}]	Empty travel speed [km h^{-1}]	Skidding speed [km h^{-1}]
1320	HSM 805HD	470	6.94	7.23	5.16	5.13	3.87	4.51
1318	HSM 805HD	424	8.91	9.04	6.74	6.74	2.73	3.81
1322	HSM 805HD	87	3.02	4.69	3.42	3.33	4.67	5.27
1315	HSM 805HD	1099	7.41	5.97	4.70	4.66	2.54	3.92
1317	HSM 805HD	467	7.94	7.24	6.15	6.15	8.96	8.31
1324	HSM 805HD	1192,5	8.30	8.62	4.29	4.28	7.84	5.62
1338b	HSM 805HD	1073	6.40	6.19	4.16	4.16	8.40	5.87
1291	HSM 805HD	1356	6.68	5.40	4.44	4.41	8.99	5.82
1330	HSM 805HD	1833	7.88	5.04	4.28	4.28	5.65	5.41
1290	HSM 805HD	616	8.63	8.88	7.02	6.91	6.47	4.73
721	LKT 81 ILT (HC)	316	8.01	6.31	4.48	4.21	4.45	3.75
851c	LKT 81 ILT (HC)	618	5.58	4.36	3.64	3.58	4.29	4.29
745	LKT 81 ILT (HC)	526	11.90	5.80	4.84	4.72	3.42	3.36
581	LKT 81 ILT (HC)	619	6.63	4.38	3.60	3.51	6.35	3.43
1091	LKT 81 T	150	3.33	8.53	6.25	5.97	3.26	3.75
1093	LKT 81 T	300	5.45	7.66	4.07	3.91	4.00	4.05
1094a	LKT 81 T	178	6.38	6.22	4.67	4.56	4.35	3.33
234	LKT 81 T	1059	6.01	4.99	3.38	3.38	1.87	2.56
253	LKT 81 ITL	1112	9.40	7.01	6.37	5.97	5.17	3.37
727a	EQUUS 175N	541	10.96	7.58	6.38	5.85	4.19	3.22

S – Subcompartment.

15% higher than the mean volume of the cable skidder operators.

Table 6 presents the mean nett production rate, normative work performance as well as the gross production rate of the skidder operators in individual forest stands. In addition, the table contains also the mean speed of the skidders with and without the load. The mean gross production rate of the monitored skidders varied between 3.33 and 6.91 $m^3 h^{-1}$ depending on the type of the forest stand and the skidding distance. When comparing the differences in the nett production rate and the gross production rate of the skidders (Table 6), it can be concluded that due to affecting the gross production rate by the amount of non-operation shift times, the gross production rate is 24.4% lower than the nett production rate, which covers the skidding efficiency recalculated to the nett time consumption of the skidder operators without the non-operation shift times. Normative work performance of the studied skidders covering the work performance without time losses ranged from 3.42 to 7.02 $m^3 h^{-1}$. When compared to the gross production rate, it represents an increase of 2.83% in work productivity.

The dependence of the gross production rate of the skidders on the skidding distance and the mean load volume is illustrated in Figure 3. The graph shows that the increasing skidding distance and the decreasing load volume causes a decrease in the gross production rate of the skidders.

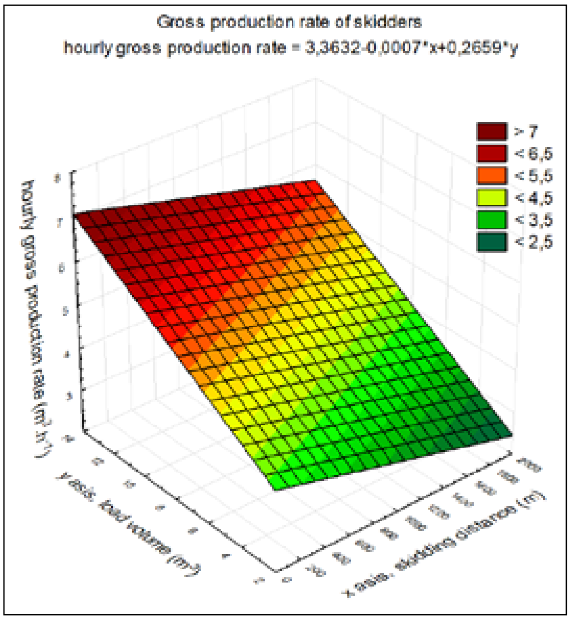

Fig. 3. Three-dimensional graphic illustration of gross production rate in relation to skidding distance and mean load volume.

Tables 7 and 8 illustrate the generalized linear models of time consumption calculated for almost all partial work operations of cable and cable grapple skidders.

After the gradual regression method based on AIC (Akaike Information Criterion) 7 models of partial work operations of cable skidders and 8 models of partial work operations of cable-grapple skidders including a model of overall time of work cycle were created. After comparing the models of time consumption for partial work operations of the two types of skidders (cable versus cable-grapple skidder), it can be concluded that the differences in the number and the type of affecting production factors were discovered in the following operations: load pilling, winching the load, unhooking the load and handling carried out by the skidder operator.

4. Discussion

Due to different conditions in the forest stands and terrain (forest stand composition, operation and terrain conditions) the results of the time study and the models are applicable only in the situations with the same or similar work conditions (Mousavi et al. 2012; Borz et al. 2015).

Non-operation shift times represent on average 24.4% (14 – 33%) of all monitored skidder operators. For illustration and comparison Borz et al. (2015) and Borz et al. (2014a) mention a higher percentage of non-operation times 29.3% and 28%. Sabo & Poršinsky (2005) in their study indicate 32.15% of non-operation time for the cable skidder Timberjack 240C, which can be compared with the percentage of non-operation times of the LKT 81T operator in the present study (33%). The highest amount of non-operation times – 51 and 43% for cable skidders (TAF 690 OP, TAF 657) are mentioned by Borz et al. (2013), whereas the lowest amount of 14% was recorded in the study of Nikooy et al. (2013). This data are in accordance with the amount of non-operation times of the LKT 81 ITL operator monitored in the present study. The amount of non-operation shift times of the skidder operators monitored in this study is affected mostly by the amount of time consumed for the technical operation of the workplace, occurrence of repairs and machinery malfunctions during the sift, as well as by the technical and organisational time losses representing the highest ration of all time losses – 95%. These time losses can be avoided by planning and organising the work better.

The model of the partial work operation – travel from the forest landing into the forest stand of both types of studied skidders depends on the skidding distance (Table 7 and 8). These results are in accordance with other studies (Wang et al. 2004; Nurminen et al. 2006; Mousavi et al. 2012; Mousavi et al. 2013; Marčeta et al. 2014). The operation of cable skidders – releasing the cable is affected only the winching distance, presented also in the following studies (Mousavi 2012a; Mousavi 2012b; Marčeta et al. 2014; Borz et al. 2014a). Generalized linear models for the time consumption of the operation – load winching of the cable skidder revealed that the

Table 7. Generalized linear model of cable skidders.

Elemental of working operation	AIC	Nul dev.	Residual dev.	Coefficient	Estimate	Standard Error	t–value	p–value	
Travel unloaded	296.4	1,593.3	321.8	Intercept	1.831	0.623	2.94	0.005	**
				LKT 81 ITL	−1.793	0.752	−2.39	0.020	*
				xsd	0.012	0.001	13.21	0.000	***
Cable releasing	160.0	76.0	48.3	Intercept	0.300	0.321	0.94	0.353	
				xwd	0.115	0.020	5.67	0.000	***
Collecting time	323.2	1,187.1	485.9	Intercept	−0.268	0.861	−0.31	0.757	
				LKT 81 ITL	3.541	0.707	5.01	0.000	***
				xn	0.986	0.141	6.98	0.000	***
Winching the load	243.4	241.8	177.5	Intercept	0.618	0.738	0.84	0.405	
				xn	0.266	0.095	2.80	0.007	**
				xwd	0.116	0.037	3.12	0.003	**
Skidding load	373.2	4,862.9	1,016.6	Intercept	−5.368	1.870	−2.87	0.006	**
				LKT 81 ITL	−4.449	1.835	−2.43	0.018	*
				xsd	0.017	0.002	10.63	0.000	***
				xvl	1.054	0.295	3.57	0.001	***
Unhooking load	223.5	273.7	104.8	Intercept	0.738	0.399	1.85	0.069	
				LKT 81 ITL	−1.892	0.328	−5.76	0.000	***
				xn	0.595	0.065	9.08	0.000	***
Handling by the skidder operator	377.1	2,234.0	1,398.4	Intercept	1.872	2.011	0.93	0.356	
				xn	0.844	0.265	3.19	0.002	**
				xvl	0.891	0.221	4.02	0.000	***
Total cycle time	457.4	27,559.0	5,882.6	Intercept	0.090	5.179	0.02	0.986	
				xsd	0.026	0.004	5.98	0.000	***
				xwd	0.426	0.249	1.71	0.092	.
				xn	2.868	0.649	4.42	0.000	***
				xvl	2.033	0.686	2.96	0.004	**

(xsd – skidding distance, xwd – winching distance, xvl – volume load, xn – number of logs in a load)
Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

Table 8. Generalized linear model of cable-grapple skidders.

Elemental of working operation	AIC	Nul dev.	Residual dev.	Coefficient	Estimate	Standard Error	t–value	p–value	
Travel unloaded	810.7	2,016.3	1,223.5	Intercept	3.789	0.429	8.84	0.000	***
				HSM	−0.988	0.438	−2.26	0.025	*
				xsd	0.006	0.001	10.28	0.000	***
Collecting time	891.8	4,033.7	2,165.4	Intercept	0.758	1.322	0.57	0.568	
				HSM	−1.779	0.855	−2.08	0.039	*
				LKT 81 ITL	1.679	0.882	1.90	0.059	.
				xn	0.586	0.084	7.10	0.000	***
				xvl	0.419	0.099	4.23	0.000	***
Winching the load	1062.6	8,076.8	5,956.2	Intercept	2.939	1.341	2.19	0.030	*
				LKT 81 ITL	3.546	1.076	3.29	0.001	**
				xn	0.717	0.138	5.21	0.000	***
				xwd	0.102	0.055	1.85	0.066	.
Travel skidder to other logs	727.2	2,461.3	2,065	Intercept	4.048	0.892	4.54	0.000	***
				HSM	−2.065	0.744	−2.78	0.006	**
				xn	0.351	0.100	3.53	0.000	***
Skidding load	802.9	3,346.9	1,153.2	Intercept	2.302	0.685	3.36	0.001	***
				HSM	−2.795	0.456	−6,13	0.000	***
				xsd	0.009	0.001	15.62	0.000	***
				xvl	0.239	0.066	3.64	0.000	***
Unhooking load	709,2	1,204.0	660.8	Intercept	−0,767	0.705	−1,09	0.278	
				HSM	1.053	0.468	2.25	0.026	*
				LKT 81 ITL	3.121	0.482	6.48	0.000	***
				xn	0.265	0.046	5.82	0.000	***
				xvl	0.200	0.053	3.79	0.000	***
Handling by the skidder operator	446.7	1,882.2	1,265.4	Intercept	0.600	1.628	0.37	0.713	
				HSM	−2,064	0.999	−2,07	0.042	*
				xvl	0.738	0.152	4.84	0.000	***
Log piling	1166.1	14,282.0	10,162	Intercept	−1,623	2.725	−0,60	0.552	
				HSM	7.242	1.825	3.97	0.000	***
				LKT 81 ITL	5.789	1.880	3.80	0.002	**
				xn	0.384	0.176	2.18	0.031	*
				xvl	1.510	0.204	7.39	0.000	***
Total cycle time	1408.2	109, 088	43,688	Intercept	4.839	4.141	1.17	0.244	
				LKT 81 ITL	10.799	2.930	3.69	0.000	***
				xsd	0.013	0.004	3.30	0.001	**
				xn	2.793	0.393	7.11	0.000	***
				xvl	3.687	0.381	9.69	0.000	***

(xsd – skidding distance, xwd – winching distance, xvl – volume load, xn – number of logs in a load)
Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

winching distance and the number of logs in the load affected significantly the time consumption of this work operation. Same results were confirmed also in further studies (Mousavi 2012b; Borz et al. 2013). The time consumption of load winching of the cable-grapple skidders is statistically significantly affected only by the number of logs in the load. The time consumption of collecting time in the case of cable-grapple skidders is statistically significantly affected by the volume and number of logs in the load. In the case cable skidder only the dependence on the number of logs was statistically significant, what is in accordance with the study of Mousavi (2012a). Najafi et al. (2007) conducted a time study focused on the skidder HSM-904, which found out that the skidding time depends on the skidding distance and the number of logs in the load. However, Lotfalian et al. (2011) established in their study that the skidding time depends on the skidding distance and the slope inclination. The present study established the skidding distance and load volume to be the statistically significant variables affecting the time consumption of load skidding for both, cable and cable-grapple skidders. These results are in accordance with the results presented in the study by Marčeta et al. (2014). After comparing the models of time consumption of unhooking the load with the two types of studied skidders, the study shows that the number of logs in the load and the load volume are statistically significant factors affecting the time consumption of this operation with the cable-grapple skidders. In the case of cable skidders only the number of logs in the load affects the time consumption of unhooking the load. Nevertheless, the time studies of Mousavi et al. (2013); Proto et al. (2018) did not prove any of the studied independent variables to be statistically relevant in regard to the time consumption of unhooking the load. Wang et al. (2004) found out that the time consumption of unhooking the load depends on the log diameter, mean merchantable height and the number of logs in the load. The overall time of the work cycle of the cable-grapple skidder operators is affected by the following factors: load volume, number of logs in the load and the skidding distance. Similar results were confirmed also in the study of Mousavi et al. (2012). However, different results are presented in the study of Mousavi et al. (2013) confirming the dependence of the overall time consumption of the HSM-904 skidder work cycle only on the number of logs and the load volume. Proto et al. (2018) confirmed the dependence of the overall work cycle time of the cable-grapple skidder John Deere 548H on the skidding distance and the load volume. The overall work cycle time of the studied cable skidders is affected mostly by the skidding distance, number of logs in the load, and the load volume was proven to have the least impact. The same results are presented in the study by Nikooy et al. (2013). However, different findings are presented by Ghaffariyan et al. (2013) indicating the dependence of the overall work cycle time on the skidding distance, winching distance, inclination of the skidding line and the load volume. Behjou et al. (2008) and Behjou (2010) confirmed in their research studies the dependence of the overall work cycle time of skidder Timberjack 450C on the skidding distance, winching distance and interaction between the skidding distance and skidding line inclination. Borz et al. (2013) concluded in their study that the overall work cycle time of the cable skidder (TAF 690 OP, TAF 657) depends on the skidding distance and the winching distance, and in the case of skidder TAF 657 the number of logs was also another statistically significant factor. The partial work operation – log piling performed by the cable-grapple skidder is statistically significantly influenced by the load volume and number of logs in the load. This finding is in accordance with the results presented in the study of Mousavi et al. (2012). In the case of the same operation performed by the cable skidder no dependence on any of the studied factors was confirmed. Regarding the proportion, this work operation represents 10% on average of the shift of the cable skidders. These results can be compared to the results of study by Mousavi et al. (2012). The work operation – handling by the skidder operator is statistically significantly affected by the number of logs in the load and the load volume in the case of cable skidders, whereas in the case of cable-grapple skidders only the load volume was determined as the statistically significant factor.

Some of the conducted time studies revealed that the slope inclination can significantly affect the time consumption of the load winching and the travel from the forest landing into the forest stand. It can also influence the time distribution of partial work operation within a shift (Behjou et al. 2008; Mousavi 2009; Lotfalian et al. 2011; Mousavi 2012a; Magagnotti & Spinelli 2012; Borz et al. 2014b). In the present study the slope inclination was not proven as a statistically significant factor affecting the time consumption of partial work operation – winching the load and travel from the forest landing into the forest stand, although the impact of this factor on the time consumption of the two above mentioned operations cannot be excluded.

In the forest stand conditions of the present study and with the studied skidders the time consumption of the load skidding was higher on average (Table 5) than the time consumption of the travel from the forest landing into the stand. This was reflected in the mean speed of the tractor travel from the forest landing into the stand, which ranged from 3.97 km h^{-1} to 6 km h^{-1}. On the other hand, the mean load skidding speed was lower by 21 % ranging from 3.23 km h^{-1} to 5.56 km h^{-1}. In other studies the recorded mean speed of travel from the forest landing into the forest stand ranged from 4.15 km h^{-1} (Behjou et al. 2008) to 8.58 km h^{-1} (Proto et al. 2018), while the recorded mean skidding speed varied from 1.33 km h^{-1} (Zečić et al. 2005) to 7.31 km h^{-1} (Spineli & Magagnotti 2012). The speed of skidder travel from the forest landing into the stand can be higher or lower than the skidding speed depending on various work conditions. For illustration, the time study of Borz et al (2013) can be mentioned, since this study confirmed a higher mean speed of a loaded skidder than the mean speed of unloaded skidder. Also in the present time study a higher mean speed of a loaded skidder travel was recorded in the subcompartments (1315, 1318, 1320, 1322, 1091 and 1093) than the travel speed of unloaded skidder. This fact is probably associated with the terrain character, soil humidity of the skidding road, as well as with a lower volume of skidded load from the given stands in the case of LKT 81T skidder. The highest mean speed of the skidder travel loaded (5.56 km h^{-1}) and unloaded (6 km h^{-1}) was recorded in the case of HSM 805HD skidder operator. These values are comparable with the results presented in the study by Mousavi et al. (2013), where the mean speed of loaded skidder HSM 904 was 5.17 km h^{-1} and the mean speed of unloaded skidder was 5.96 km h^{-1}. When comparing the mean speed of the travel of the skidder LKT 81 ITL, the results show that both skidders achieve almost the same travel speeds whether loaded or unloaded. The differences do not exceed 0.39 km h^{-1} when unloaded and 0.15 km h^{-1} when loaded, what indicates that the differences in speed are probably caused by the differences in the terrain of skidding road and by accidental circumstances. The lowest mean travel speed of skidder from the forest landing into the forest stand of the studied skidders was recorded in the case of LKT 81T skidder tractor operator (3.97 km h^{-1}). This can be associated with the lowest engine performance (Table 1) when compared with other studied skidders. The lowest mean skidding speed was recorded with the EQUUS 175N skidder operator (3.23 km h^{-1}). This is probably associated with the highest mean load volume 11.27 m^3 (Table 5) from among all the studied skidder operators.

The mean gross production of cable skidders considering the type of the forest stand, mean skidding distance and the type of the skidder, ranged from 3.38 m^3 h^{-1} to 5.97 m^3 h^{-1}, and in the case of cable-grapple skidders a comparable mean gross production ranging from 3.33 m^3 h^{-1} to 6.91 m^3 h^{-1} was recorded. Most of the studies from abroad mention higher gross production of cable-grapple skidders ranging from 6.1 m^3 h^{-1} (Mousavi et al. 2012) to 32.8 m^3 h^{-1} (Zečić et al. 2010). Porter & Strawa (2006) in their study established a mean gross production of the skidder LKT 81T of 7.15 m^3 h^{-1} in an 82-year-old fir stand. By comparison, the present study recorded lower gross production of the skidder LKT 81T of only 5.97 m^3 h^{-1} with the mean skidding distance of 150 m. When compared to the time study by Borz et al. (2013) the gross production of the cable skidders of the TAF type is 3.20 and 3.75 m^3 h^{-1} with the mean skidding distance (980 and 871 m), which is comparable with the production of 3.38 m^3 h^{-1} of the LKT 81T skidder with the comparable skidding distance (1,059 m) presented in this study. The gross production rate of the studied skidders was affected strongly by the ratio of non-operation times within the shift (24.4%) as well as by the mean skidding distance and mean load volume. These results are in accordance with the findings presented in the studies by Fiedler et al. (2008); Lopes et al. (2017), who concluded that the skidding distance and load volume affect the production of skidders to the greatest extent.

5. Conclusion

The submitted paper discussed the time study carried out for cable and cable-grapple skidders employed in the University Forestry Enterprise of the Technical University in Zvolen. One of the tasks of this study was to provide data regarding the work time consumption of the skidder operators and production and efficiency data of individual skidders. The relation between the time consumption of individual partial work operations of cable and cable-grapple skidders and independent variables was generalized in linear models. The generalized linear models indicated that the overall work cycle time of the cable and cable-grapple skidders depends on the skidding distance, load volume and number of logs in the load. The study results revealed noticeable differences in the time consumption and differences in the impact of production factors on individual partial work operation of the two types of skidders. Time losses of the skidder operators represent mean percentage of 2.98% from the overall shift time. This can be decreased by improving the planning and organisation of work. The results of this study can be used to determine the objective costs, work rationalisation, work planning and estimate of the time consumption. In addition, they can be used as background for objective evaluation of wages in the logging operations, since the time consumption analysis has to evaluate objectively the costs for timber skidding using skidder technology in various production and technical conditions while meeting the principles of economic efficiency, work humanisation as well as environmental requirements of forest ecosystems.

References

Abeli, W. S., 1996: Comparing productivity and cost of three sub grading machines. Journal Forest Enginerig, 51:33–39.

Acuma, M., Bigot, M., Guerra, S., Hartsough, B., Kanzian, C., Kärhä, K. et al. 2012: Good practice guidelines for biomass production studies. In: Magagnotti, N., Spinelli, R.: CNR IVALSA, Sesto Fiorentino, 51 p.

Bavaghar, M. P., Sobhani, H., Feghhi, J., Darvishsefat, A. A., Marvi Mohajer, M. R., 2010: Comprehensive productivity models fot tracked and wheeled skidders in the Hyrcanian Forests of Iran. Research Journal of Forestry, 4:65–71.

Behjou, F. K., Majnounian, B., Namiranian, M., Dvořák, J., 2008: Time study and skidding capacity of wheeled skidder Timberjack 450C in Caspian forests. Journal of Forest Science, 54:183–188.

Behjou, F. K., 2010: A techno-economic evaluation of skidding operation by Timberjack 450C and Clark Ranger 666DBS in Caspian forests. Journal of Food, Agriculture and Environmet, 8:1020–1023.

Björheden, R., 1991: Basic time cencepts for international comparisons of time study reports. Journal of Forest Engineering, 2:33–39.

Björheden, R., Apel, K., Shiba, M., Thompson, M., 1995: IUFRO forest work study nomenclature. Swedish Univerzity of Agricultural Science, Department of Operational Efficiency, Grapenberg, 16 p.

Borz, S. A., Dlnulca, F., Birda, M., Ignea, Ch., Clobanu, V.D., Popa, B., 2013: Time consumption and productivity of skidding Silver fir (*Abies alba* Mill.) round wood in reduced accessibility conditions: A case study in windthrow salvage logging from Romanian Carpathians. Annals of Forest Research, 56:363–375.

Borz, S. A., Ignea, G., Popa, B., 2014a: Assessing timber skidding efficiency in a group shelterwood system applied to a fir-beech stand. African Journal of Agricultural Research, 9:160–167.

Borz, S. A., Ignea, G., Popa, B., 2014b: Modeling and comparing timber winching performance in windthrow and uniform selective cuttings for two Romanian skidders. Journal of Forest Research 19:473–482.

Borz, S. A., Ignae, G., Popa, B., Spârchez, G., Iordache, E., 2015: Estimating time consumption and productivity of roundwood skidding in group shelterwood system – a Case study in a broadleaved mixed stand located in reduced accessibility conditions. Croation Journal of Forest Enginering, 36:137–146.

Dvořák, J., Gross, J., Oliva, J., Hošková, P., Malkovský, Z., 2010: Sestavení výkonových norem pro harvestory a vyvážecí traktory podle vykonových třid stroju a výrobních podmínek. Záverečná správa. Praha, ČZU v Praze, 79 p.

Dvořák, J., Bystrický, R., Hošková, P., Hrib, M., Jarkovská, M., Kováč, J. et al., 2011: The use of harvester technology in production forests. Kostelec nad Černými lesy, Lesnícka práce, 156 p.

Fiedler, N. C., Rocha, E. B., Lopes, E. S., 2008: Análise da produtividade de um sistema de colheita de árvores inteiras no norte do Estado de Goiás. Floresta, Curtiba, 38:577–586.

Ghaffariyan, M. R., Naghdi, R., Ghajar, I., Nikooy, M., 2013: Time prediction models and cost evaluation of cut-to-lenght (CTL) harvesting method in a mountainous forest. Small-scale Forest, 12:181–192.

Howard, A.F., 1987: Modeling the cost and profitability of timber harvesting with cable skidders. Northern Journal of Applied Forestry, 4:87–92.

Klouda, M., Syrovátka, K., Bluďovský, Z., 1988: Normování práce v lesním hospodářství. Praha: Ministerstvo lesního a vodniho hospodařstvi a drevospracujúciho prumyslu ČSR, SZN v Praze, 207 p.

Kluender, R., Loretz, D., Mscoy, W., Stokes, B.J., Klepac, J., 1997: Productivity of rubber-tired skidders in southern pine forests. Journal of Forest Products, 47:53–58.

Kulak, D., Stańczykiewicz, A., Szewczyk, G., Kobiałka, P., 2013: Soil disturbances as result of timber skidding in fir-beech mountain stands. Forestry Letters, 105:35–46.

Kulak, D., Stańczykiewicz, A., Szewczyk, G., 2017: Productivity and time consumption of timber extraction with a grapple skidder in selected pine stands. Croatian Journal of Forest Engineering, 38:55–63.

Kulak, D., Stańczykiewicz, A., Szewczyk, G., Wala, Ł., 2019: Wydajność zrywki drewna skiderem na terenach pochyłych. Sylwan, 163:601−609.

Lhotský, O., 2005: Organizace a normování práce v podniku. Praha, ASPI, 100 p.

Lopes, E. S., Oliveira, D., Rodrigues, C. K., Drinko, C. H., 2017: Variables influencing working time and skidder productivity in wood extraction. Nativa: Pesquisas Agrárias e Ambientais, 5:298–302.

Lotfalian, M., Moafi, M., Foumani, B. S., Akbari, R. A., 2011: Time study and skidding capacity of the wheeled skidder Timberjack 450C. Journal of Soil Science and Environmental Management, 2:120–124.

Magagnotti, N., Spinelli, R., 2012: Replacing steel cable with synthetic rope to reduce operator workload during log winching operations. Small-scale Forestry, 11:223–236.

Marčeta, D., Petković, V., Košir, B., 2014: Comparison of Two Skidding Methods in Beech Forests in Mountainous Conditions. Nova mehanizacja šumarstva: Časopis za teoriji i praksu Šumarskoga inženjerstva, 35:51–62.

Mederski, P. S., Bembenek, M., Jörn, E., Dieter, D. F., Karasewski, Z., 2010: The enhancement of skidding produktivity resulting from changes in construction: grapple skidder vs. rope skidder. In: Proceedings of FORMEC 2010, Forest Engineering: Meeting the Needs of the Society and the Environment, Padova, 11.–14. July 2010, Padova, Formec, p. 1–7.

Mousavi, R., 2009: Comparison of productivity, cost and enviromental impacts of two harvesting methods in Northern Iran: short-log vs. long-log [Ph. D. Thesis.] Joensuu, Univerzity of Joensuu, 93 p.

Mousavi, R., 2012a: Time consumption, productivity, and cost analysis of skidding in the Hyrcanian forest in Iran. Journal of Forestry Research, 23:691–697.

Mousavi, R., 2012b: Effect of log length on productivity and cost of Timberjack 450C skidder in the Hyrcanian forest in Iran. Journal of Forest Science, 58:473–482.

Mousavi, R., Nikooy, M., Nezhad, A. E., Ershadfar, M., 2012: Evaluation of full tree skidding by HSM-904 skidder in patch cutting of aspen plantation in Northern Iran. Journal of Forest Science, 58:79–87.

Mousavi, R., Nikooy, M., Naghdi, R., 2013: Comparison of timber using two ground-based skidding systems: grapple skidding vs. cable skidding. International Journal of Forest, Soil and Erosion, 3:79–86.

Naghdi, R., Nikoye Seyahkal, M., Bagheri, I., Javadpour, J., 2008: Comparison of production rate of skidder Timberjack 450C at two planned and unplanned logging condition. Iranian Journal of Forest and Poplar Research, 16:649–659.

Najafi, A., Sobhani, H., Seed, A., Makhdom, M., Marvi Mohajer, M. R., 2007: Time study of skidder HSM 904. Journal Iran. National Research, 60:921–930.

Nikooy, M., Esmailnezhad, A., Naghdi, R., 2013: Productivity and cost analysis of skidding with Timberjack 450C in forest plantations in Shafaround watershed, Iran. Journal of Forest Science, 59:261–266.

Nurminen, T., Korúunen, H., Uusitalo, J., 2006: Time consumption analysis of the mechanized cut-to lenght harvesting system. Silva Fenica, 40:335–363.

Porter, B., Strawa, P., 2006: Analiza pozyskiwania i zrywki drewna w drzewostanach Jodłowych. Sylwan, 1:67–72.

Proto, A. R., Macrí, G., Visser, R., Russo, D., Zimbalatti, G., 2018: Comparison of timber extraction productivity between winch and grapple skidding: A case study in Southern Italian Forests. Forests, 9:1–12.

Sabo, A., Poršinsky, T., 2005: Skidding of fir roundwood by Timberjack 240C from selective forests of Gorski Kotar. Croatian Journal of Forest Engineering, 26:13–27.

Sarikhani, N., 2001: Forest utilization. Tehran Univerzity, Tehran, 728 p.

Spinelli, R., Magagnotti, N., 2012: Wood extraction with farm tractor and sulky: Estimating productivity, cost and energy consumption. Small-scale Forestry, 11:73–85.

Wang, J., Long, C., McNeel, J., Baumgras, J., 2004: Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. Forest Production Journal, 54:45–51.

Zečić, Z., Krpan, A. P. B., Vukušić, S., 2005: Productivity of C Holder 870 F tractor with double drum winch Igland 4002 in thinning beech stands. Croatian Journal of Forest Engineering, 26:49–56.

Zečić, Ž., Vusić, D., Prka, M., Klepac, S., 2010: Utjecaj nagiba traktorskog puta na proizvodnost traktora Timberjack 240C pri privlačenju drvnih sortimenta u preborním šumama. Šumarski list, 134:103–113.

Zečić, Ž., Vusić, D., Nevečerel, H., Mikulin, M., 2011: Utjecaj obujma tovara na proizvodnost traktora Timberjack 240C pri privlačenju debala euroameričke topole u nizinskim šumama. Croatian Journal of Forest Enginnering, 32:357–368.

Zborník výkonových noriem č. 24. Výkonové normy pre sústreďovanie dreva univerzálnymi, pásovými a špeciálnymi lesnými kolesovými traktormi. Bratislava, Ministerstvo lesného a vodného hospodárstva Slovenskej republiky, 1992, 32 p.

Zelená správa 2007. Bratislava, Ministerstvo pôdohospodárstva Slovenskej republiky, 164 p.