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The effects of planting stock size and weeding on survival and growth of small-leaved lime under drought-heat stress in the Czech Republic

Effekt von Pflanzmaterialgröße und Unkrautbekämpfung auf Überleben und Wachstum der Winterlinde unter Dürre und Hitzestress in der Tschechischen Republik

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Keywords: *Tilia cordata, afforestation, abandoned agriculture, climate, drought, chlorophyll, Sapling, mortality*

Schlüsselbegriffe: *Tilia cordata, Aufforstung, Wiederbewaldung, Klima, Dürre, Chlorophyll, Heister, Mortalität*

Abstract

A plantation of small-leaved lime (*Tilia cordata* Mill.) containing two types of planting stock – large-sized transplants (LST) and standard-sized transplants (SST) – was planted on a site with strong weed competition. The aim was to compare the growth, survival and health of those types of planting stock under a weeded and non-weeded regime in a dry and warm climate. Recorded variables were: overall mortality, stem height, root-collar diameter and chlorophyll content. Increments in height and root collar diameter were calculated. Precipitation, soil and air temperatures were continuously monitored by an automatic climate station. Soil analysis revealed equal conditions for the treatments. Simple analysis of costs was calculated.

The results showed that LST exhibited greater height increment than SST in the first 5

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years after afforestation under strong weed competition. Non-weeded (under the regime of no weeding) SST also showed increased mortality. Weeding regime positively influenced the height increment of SST but did not influence the height increment of LST. Chlorophyll content was significantly higher in the leaves of LST than in SST in the first growing period. Economic analysis showed that the number of trees was the most important variable, while weeding was less important. LST can be recommended for reforestation of weed-infested sites, even if they have relatively low annual precipitation.

Zusammenfassung

Eine Aufforstung mit Winterlinde (*Tilia cordata* Mill.) und zwei Sorten Pflanzmaterial – Heistern (LST) und Standardpflanzenmaterial (SST) – wurde an einem Standort mit hoher Konkurrenz durch Bodenvegetation bewertet. Ziel war es, die Wachstumsdynamik und Leistung von Bäumen mit und ohne Unkrautbekämpfung zu vergleichen und Unterschiede bei trockenem und warmem Klima zu untersuchen. Die bewerteten Parameter waren: Gesamtmortalität, Gesamthöhe, Wurzelhalsdurchmesser, Höhen- und Wurzelhalsdurchmesserwachstum sowie der Chlorophyllgehalt. Niederschlag sowie Luft- und Bodentemperatur wurden kontinuierlich von einer automatischen Klimastation aufgezeichnet. Eine Bodenanalyse bestätigte vergleichbare Bedingungen der zwei Varianten. Wir berechneten eine einfache Kostenanalyse der untersuchten Varianten.

An dem stark verunkrautetem Standort in der Anfangsphase waren LST in der Dynamik des Höhenwachstums dem SST überlegen. SST ohne Unkrautbekämpfung zeigte eine erhöhte Mortalität. Unkrautbekämpfung beeinflusste das Höhenwachstum von SST positiv, das Höhenwachstum von LST blieb jedoch unverändert. Der Chlorophyllgehalt war in den Blättern LST in der ersten Vegetationsperiode signifikant höher. Die ökonomische Analyse zeigte, dass die Pflanzkosten mehr Einfluss auf die Gesamtkosten der Aufforstung hatten als die Unkrautbekämpfung. Für die Wiederaufforstung von verunkrauteten Standorten kann man daher LST empfehlen, auch bei geringen Niederschlagsmengen.

Introduction

Small-leaved lime (*Tilia cordata* Mill.; lime for further reference) is a typical tree species with a scattered occurrence in temperate woodlands and distributed all over the Western, Central, and Eastern Europe (Jaworski et al., 2005; EUFORGEN, 2009; Aas, 2016). Lime prefers fresh, nutrient-rich forest sites and shaded ravines or north-oriented slopes, and tolerates short-term flooding, therefore its typical natural site is the understory of riparian forests, together with hornbeam (*Carpinus betulus* L.) (Machar, 2008; Král et al., 2014). Lime exhibits a wide ecological tolerance and solitary trees high longevity; the life span can reach up to 1000 years (De Jaegere et al., 2016). The wood is traditionally used for woodcarving, for which it is particularly well suited

(Sayers, 1978; Musil and Möllerová, 2005). The lime blossoms are commonly used in traditional medicine as herbal tea against cough and tiredness (Pieroni et al., 2015) and they are very attractive to bees, effective pollinators (e.g. Pawlikowski, 2010; Hausmann et al., 2016). The species can be found commonly in alleys along roadsides and in urban areas as street and park trees (Moser et al., 2015; Sæbø et al., 2003; Sjöman et al., 2012). In addition to air pollution, lime is a relatively resistant tree species, adaptable to ongoing climate change (warming, more frequent droughts, climatic extremes etc.) (Vacek et al., 2019a).

The common silviculture of lime is mostly limited to its use as secondary species in the understory of commercially more important species, such as oaks (*Quercus* spp.) (Slávik and Khun, 2014; Vacek et al., 2018a), where it benefits from its shade-tolerant character (Faltl et al., 2016). Reforestation with lime is not very common, however, it has been successfully used in unfavourable conditions, e.g. at restorations of surface mine areas and sandpits (Katzur and Haubold-Rosar, 1996; Vacek et al., 2018b), and for the transformation of Norway spruce (*Picea abies* [L.] Karst.) monocultures (Jakobsen and Emborg, 2000). Lime litterfall has a favourable chemical composition, and the tree is considered an ameliorative species, which improves the soil properties (increasing base-nutrients content, preventing soil acidification) (Augusto et al., 2002; Hagen-Thorn et al., 2004; Kacálek et al., 2013; Schmidt et al., 2015).

Thus, using lime in Czech forestry is mainly for soil-improving and stand enriching purposes (Faltl et al., 2016; MZe, 2017a) in mixed stands, especially in forests of lower and middle altitudes (Podrázský and Remeš, 2005; Vacek et al., 2019b). Its share in forest cover is relatively low and the recent national inventory does not even recognize the species individually, as it is incorporated within the group of soft-wood broadleaves, which occupies approximately 4.6 % of the forest area (FMI, 2014). Another source, Ministry of Agriculture, reported that the percentage of *Tilia* was 1.1 % of total forest cover without distinguishing between *Tilia* species (MZe, 2017b).

Even though lime is widespread in Europe, there are very few investigations in the literature providing quantitative results on its planting, growth, yield and management (De Jaegere et al., 2016). Because lime grows in a very wide range of site conditions and has a high tolerance to unfavourable conditions, it is predestined to be used for specific purposes, for example for the diversification of monoculture forest stands, enrichment of tree species composition and afforestation of abandoned agricultural land or restoration (Katzur and Haubold-Rosar, 1996; Daugaviete et al., 2015).

Afforestation of marginal and former agricultural lands can bring benefits for the site and its surroundings; besides wood production (Podrázský et al., 2009; Vacek et al., 2018c; Cukor et al., 2019), it increases carbon sequestration (Laganiere et al., 2010; Cukor et al., 2017a), reduces warming (Peng et al., 2014; Syktus and McAlpine, 2016), prevents wind erosion (Vacek et al., 2018d), reduces noise and dust along urban areas (Xu et al., 2014), and supports biodiversity (Vacek et al., 2017) and water retention

(Kahle et al., 2005).

This study tests the growth, health status and survival rate of large sized and standard sized planting stock (for example Kuneš et al., 2014; Baláš et al., 2016 or Gallo et al., 2018). The initial size of plants can influence prosperity of a plantation in the long term, because the initially smaller and slow-growing plants may have the traits of long-lived trees (Jurásek et al., 2009). The establishment of plantations with LST is most often associated with the use of single-operator earth augers (Baláš et al., 2016), because the technological progress of portable augers in recent years has been particularly obvious and therefore this technology is becoming applicable in forestry practice (STIHL, 2006).

Besides measuring total height and root collar diameter, we assessed the tree vitality by measuring the chlorophyll content. The absorption of solar radiation by chlorophyll is the first stage in the photosynthetic pathway. Thus, the leaf chlorophyll content is one of the most significant variables related to the physiological status of plants (Silla et al., 2010). We used a non-invasive optical method using the Opti-Sciences CCM-300 chlorophyll fluorometer (OPTI-SCIENCES, 2011).

The advantages and disadvantages of large-sized planting stock were assessed in mountain conditions – better resistance to late frost events of LST thanks to the elevated position of the terminal bud, which is out of the zone of most severe near-ground frost (Kuneš et al., 2014). However, different factors, such as limited precipitation and strong weed competition (Bílek et al., 2014; Vacek et al., 2017), may influence the plantations in middle-elevated sites. The applicability of bare-rooted LST in comparison with SST on such sites has not been investigated in sufficient detail yet. Our main hypothesis was that LST would maintain the initial superior height and diameter compared to SST under the conditions of strong weed competition even on drought-prone sites at mid elevation. The second hypothesis was that weeding in these conditions was crucial for growth and survival of SST but not for LST. To test these hypotheses, we evaluated the performance of the two different sizes of planting stock of lime and assessed the influence of weeding on growth and survival on a drought-prone, sunlit former agricultural site with a strong weed competition at mid-elevation sites.

Material and Methods

Site characteristics

The experimental plot was situated in the Truba Research Station close to Kostelec nad Černými lesy, the Czech Republic (GPS: N50°0.35', E 14°50.20', altitude 365 m a.s.l.). The bedrock was sandstone, the terrain was flat, the soil texture was sandy-loam, and the area was exposed to direct sunlight. The plantation was established on abandoned agricultural land formerly cultivated for a long time and then used as a forest nursery. The area was stock fenced (protection from deer, hares and rabbits).

Climate

Climatic characteristics were measured by an LEC 3010 datalogger (produced by Libor Daneš Co., Czech Republic). Monitored variables included hourly temperatures at three heights above ground, soil temperature (10 cm below ground) and precipitation. Averages and totals were calculated (Table 1a). Average temperatures were calculated (according to standards) as weighted arithmetic mean from daily values (at 7, 14, and 2 × 21h). Temperatures near the ground were, on average, lower than those recorded at a higher level above the ground. During heat wave events, typical in Central Bohemian low and mid-elevation sites, temperatures near the ground (at 30 cm) were more extreme in comparison to temperatures at 200 cm and 100 cm above the ground (Figure 1). This is important for understanding the conditions under which terminal buds of different planting stock sizes exist. Cumulative precipitation was in accordance with the climatic and elevation zone, i.e. mid-elevation site in warm region (MT9) according to climatic regions by Quitt (1971). Long term climatic data (1941–2018) from nearest meteorological station in Ondřejov operated by the Czech Hydrometeorological Institute - ČHMI (GPS: N 49°54.63333', E 14°47.01667' altitude 528 m a.s.l.) suggest that the average temperature was rising (Table 1b). Between 1941 – 1950 the mean of average annual temperature was 7.3 °C and it reached 8.9 °C between 2011 – 2018. Since 2011 the average annual temperature has not decreased below 9.0 °C. Only in 1994 (9.0 °C) and in 2007 (9.4 °C) the value also reached this threshold during the whole monitoring. Sum of precipitation in the long-term was balanced, however, the changes in the intensity and extremes cannot be determined from the summarized data.

Table 1a: Climatic data on the experimental plot.

Tabelle 1a: Klimadaten aus der Versuchsfläche.

	Mean annual temperature measured at different levels above ground [°C]			Mean temperature of soil [°C]	Sum of annual precipitation [mm]
year	200 cm	100 cm	30 cm	-10 cm	
2013	8.8	8.9	8.4	10.6	747
2014	10.4	10.6	10.0	11.6	563
2015	10.6	10.7	10.2	11.5	451
2016	9.3	9.5	-*	10.7	455
2017	9.6	9.7	9.6	11.4	533

*Data missing – technical problems

Table 1b: Long term climatic data from meteorological station Ondřejov.

Tabelle 1b: Langzeit-Klimadaten von der Klimastation Ondřejov.

Period	Temperature [C°]	Precipitation [mm]	Year	Temperature [C°]	Precipitation [mm]
1941-1950	7.3	632.4	2011	7.8	618.4
1951-1960	7.3	619.4	2012	7.4	690.4
1961-1970	7.2	682.8	2013	7.7	825.6
1971-1980	7.4	679.7	2014	9.8	700.0
1981-1990	7.6	662.7	2015	9.8	557.7
1991-2000	8.1	637.0	2016	9.1	664.5
2001-2010	8.3	696.0	2017	9.9	557.7
2011-2018	8.9	659.8	2018	9.5	664.1

Source: ČHMI

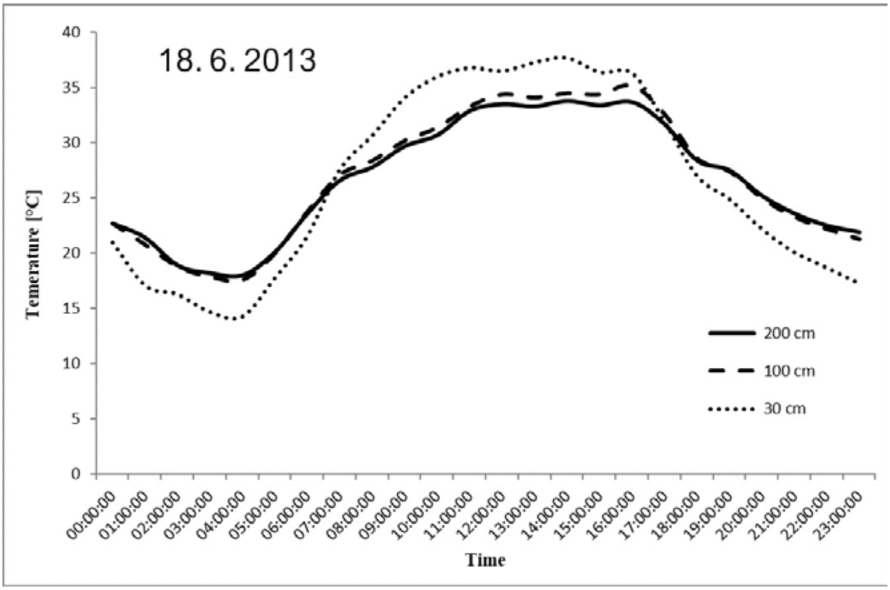


Figure 1: Dynamics of a typical heat wave event on 18 June 2013. Higher amplitude of temperature at the lowest level above the ground (30 cm) was clearly observed.

Abbildung 1: Dynamik eines typischen Hitzewellenereignisses vom 18. Juni 2013. Eine höhere Temperaturamplitude auf der niedrigsten Ebene über dem Boden (30 cm) wurde deutlich beobachtet.

Soil analysis

To determine principal soil characteristics, we collected 18 soil samples. We collected only a mixed sample of horizon 0–20 cm as no detailed horizons were distinguished in the formerly agriculturally cultivated soil. Variables measured were as follows: pH (H_2O), pH (KCl), soil N (Kjeldahl), soil organic carbon (Springer-Klee), Ca, Mg, K and P (Mehlich III), soil bases content, cation exchange capacity and base saturation.

Soil physical and chemical characteristics are shown in Table 2. Soil reaction was medium acidic. The soil organic matter (Hox = 1.8) was low, which, on sandy textures, relates to is a very low value of cation exchange capacity (below 8 meq/100 g). The soil can be characterized as slightly saturated with bases showing the base saturation values of 62 %. The soil nitrogen content (Kjeldahl) was low. The concentration of (Mehlich III) extractable soil P was moderate, the concentrations of extractable soil K and Mg were normal to optimal (Nárovcová et al., 2016).

Table 2: Soil characteristics on investigated experimental plot. SBs – sum of soil bases, CEC – cation exchange capacity, BS – base saturation, sd – standard deviation.

Tabelle 2: Informationen zu Bodeneigenschaften auf der untersuchten Versuchsfläche. SBs - Summe der Bodenbasen, CEC – Kationenaustauschkapazität, BS – Basensättigung, sd ist die Standardabweichung.

Soil characteristic	unit	mean value	*sd*
pH/H_2O	-	5.5	0.43
pH/KCl	-	4.7	0.55
SBs	*meg/100g*	4.6	2.53
CEC	*meg/100g*	6.8	2.07
BS	*%*	61.9	18.79
Humus (Springel-Klee)	*%*	1.8	0.45
Oxidizable Carbon	*%*	1.0	0.26
Nitrogen (Kjeldahl)	*%*	0.1	0.01
P	*mg/kg*	55.0	5.97
K	*mg/kg*	120.4	43.31
Ca	*mg/kg*	991.7	354.20
Mg	*mg/kg*	99.4	14.73

Planting & planting stock

The plantation was established at the end of November 2012. The soil was mechanically prepared with the soil cutter before tree planting to homogenize the soil conditions across the plot. We compared two types of bare-rooted planting stock sizes, large-sized transplants (LST) and common- (or standard-) sized transplants (SST), subjected to two types of weeding regimes: non-weeding (control) and weeding that was applied once a year in the midsummer period. Thus, the experiment consisted of four combinations (treatments) of the planting stock size and weeding regime. In total, 799 SST and 704 LST were planted. The plantation was established in alternating blocks of rows of LST and SST (3 rows of LST, followed by 3 rows of SST etc.). The spacing of the experimental plantation was 1 × 1.5 m (density of 6,667 trees/ha), regardless of planting stock type or weeding regime. The distance of trees in a row was 1 m, the distance between the rows 1.5 m (spacing). Planting holes were drilled by earth auger STIHL BT 121 (with 12, resp. 20 cm diameter of auger bits for SST and LST, respectively). One half of the plantation was weeded by brush cutter (the weeding regime, i.e. cutting the weed once a year in midsummer), the rest of the plantation was not weed-controlled (non-weeding regime).

The planting stock of SST and LST was bare-rooted, originated in the eastern part of the Czech Republic (Region: Českomoravské mezihoří, Předhoří Hrubého Jeseníku). LST were characterized by a height class of 80–120 cm, root collar diameter of 11 mm, while it was 36–50 cm and 8 mm respectively in the case of SST. Both types of planting stock were three years old, root-pruned and transplanted (1–1+1) during nursery production.

Measurements

The heights and root collar diameters were measured for the first time in early spring 2013 (prior to growing period), when the initial values of height and root collar diameter were registered. Periodic measurements of the height and root collar diameter as well as records of mortality rates were taken annually in autumn 2013–2017 (after the growing season). Mortality rates were calculated as the percentage of dead trees related to the initial numbers of plants. The height was measured with an accuracy of 1 cm, and the root collar diameter was measured to the nearest 1 mm.

Chlorophyll content

The chlorophyll foliage content (concentration in mg/m² of the leaf sample area) was measured by a CCM300 chlorophyll content meter (OPTI-SCIENCES, 2011) in 2013 and 2014 on composite samples consisting of 50 and 30 leaves per each planting stock size, respectively. Only healthy and non-damaged leaves were randomly taken from the sun-exposed parts of the crowns. Measurements were taken on 4 Aug 2013 and 3 June 2014 in the evening to reduce the influence of the sun (see Demarez, 1999; Dawson et al., 2003; Van Wittenberghe et al., 2012).

Data evaluation & statistical analyses

Statistical tests were performed in R environment (R Core Team, 2018). A Chi-square test of dependence in a pivot table was used to evaluate the mortality rate (Agresti et al., 2008). Mortality was low and therefore the analysis had limited relevance. Height increment (2013–2017) and diameter increment (2013–2017) were analysed with a Kruskal-Wallis test with subsequent multiple comparisons (Siegel and Castellan, 1988) as the assumption of normality for ANOVA was not met in all cases. Normality of the data was tested by a Shapiro-Wilk test. The differences in the chlorophyll content were statistically evaluated by a Student's *t*-test for each year of the study separately as the assumptions of normality and equal variances were met in both cases.

Economic analysis

A simple comparison of costs was undertaken on the economic effectiveness of the two different reforestation approaches: planting using LST or SST. The costs related to the purchase of planting stock, planting labour, transport, weeding and protection were compared. Two concepts were considered for the analysis. The first concept is to plant a fixed number of transplants per ha – 4,000 of SST vs. 4,000 of LST at a fenced forest site. The second concept is to plant the trees as admixture to an existing forest and protect them individually. In this case, the number of LST can be reduced according to legislation, in contrast to SST. This concept may be relevant under specific conditions: for example, if a forest practitioner needs to introduce the required broadleaved (soil improving and stand stabilizing) admixture to an existing coniferous plantation or young natural coniferous stands. Transport to the planting location was considered to be equal for both types of planting stock, as LST is intended especially for small-scale use to complement existing plantations, for underplanting and interplanting. Therefore, a pick-up with trailer is sufficient. The transport costs are, of course, strongly dependent on the distance. The price of planting stock was derived from the current prices in Czech Republic (Burda, 2019), the exchange rate between EUR and CZK was 1:26. For the purposes of the analysis, we considered the labour costs to plant one LST and SST to be EUR 0.45 and EUR 0.3 respectively. The fencing costs were estimated to be EUR 4,000, corresponding to approx. CZK 100,000 per km, based on our previous experience. In this case, 500 m to fence 1 ha (400 m of a perfect square plus extra 100 m for irregularities in the real shape) was considered. The price of plastic shelter for individual tree protection is approximately 2 Euro. For weeding, the costs were derived from a typical price in the region (ca CZK 10,000 per ha), although it may vary considerably and is dependent on supplier-customer contracts.

Economic differences between LST and SST include, among others, the issue of weeding: SST must be weeded twice a year in the first two years and once in the third year (until the trees reach the LST initial height), while LST require no weeding. The weeding needs vary in practice considerably, depending on climate and specific site characteristics.

Results

Mortality rate

The relative mortality rate (in %) was the highest in the non-weeded SST followed by the weeded SST in the first half of the monitored period. In 2016–2017, the initial mortality in the non-weeded LST occurred after a drought period during the summer of 2015. The statistical analysis showed significant, but merely indicative results, because the number of dead individuals was very low in proportion to live individuals (Table 3). The non-weeded SST showed worse performance than the other variants in 2015–2017.

Table 3: Mortality of small-leaved lime (Tilia cordata Mill.) (%) on the investigated experimental plot. Different planting stocks are in columns, values in different years in rows. LST – large-sized transplants, SST – standard-sized transplants, non-weeding – no weed control regime, weeding – weed control regime. Within each year, different letters indicate significant differences between treatments.

Tabelle 3: Mortalität von Linde (Tilia cordata Mill.) (%) auf der Versuchsfläche. Verschiedene Pflanzenmateriale, d.h. SST und LST, sind in Spalten angegeben, Werte in verschiedenen Jahren sind in Zeilen angegeben. Verschiedene Buchstabenindizes zeigen statistische Signifikanz.

Planting stock and weeding regime	*Year*			
	2014	**2015**	**2016**	**2017**
SST non-weeding	2^a	5^a	6^a	7^a
SST weeding	1^a	1^b	1^b	1^b
LST non-weeding	0^a	1^b	2^b	2^b
LST weeding	0^a	0^b	0^b	0^b

Growth characteristics

Regardless of the weeding regime, the median of initial height of the trees was 38 cm for SST vs. 98 cm for LST. In the final year, the median height reached 171 cm in SST and 234 cm in LST.

The median of initial root collar diameter was 1.0 cm in SST and 1.8 cm in LST. In the final year, the median of root collar diameter in SST and LST reached 3.2 cm and 4.2 cm, respectively. Thus, it is apparent that the LST keep advance over SST in height as well as in root collar diameter, which is described in more detail in the analysis of increments later in the text. Figure 2 shows the comparison of (a) heights and (b) root collars between SST and LST in the weeding and non-weeding regime over the period (2012–2017). In Figure 2, a successively increasing effect of weeding on height and root collar-diameter of both sizes of planting stock is apparent, although the statistics classed only the SST as significant (2017).

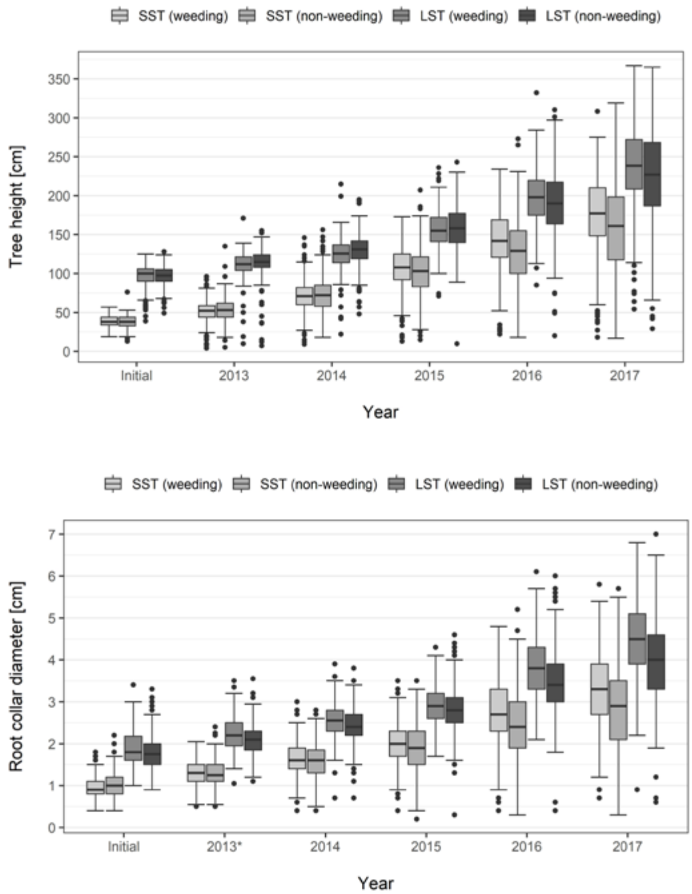
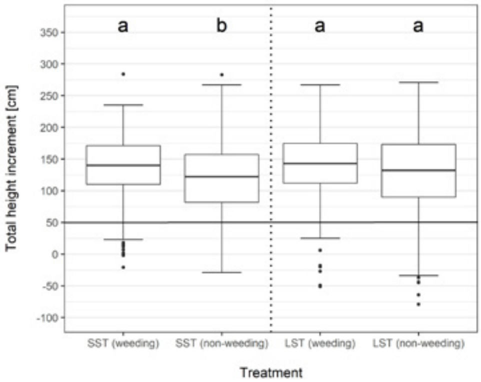


*Figure 2: Dynamics in development of total height (a) and root collar diameter (b) of large-sized transplants (LST) and small-sized transplants (SST) of lime (Tilia cordata Mill.) in 2012–2017. Non-weeding – no weed control regime, weeding – weed control regime. Root collar diameter in 2013 was interpolated from 2012 and 2014 data. The upper whisker stands for the largest value lesser than UQ + 1.5 * IQR (where UQ is upper quartile value and IQR is the inter-quartile range) and vice versa for lower quartile. Data outside of whiskers range were identified as outlier values and are plotted separately. Different indexes above boxes depict significant differences between respective variants at significance level alpha=0.05.*

Abbildung 2: Dynamik in der Entwicklung der Gesamthöhe (a) und des Wurzelhalsdurchmessers (b) von Winterlinde (Tilia cordata Mill.) Heißtern (LST) und Standardtransplantaten (SST) in den Jahren 2012–2017. Der Wurzelhalsdurchmessers wurde 2013 aus den Daten für 2012 und 2014 interpoliert. Der obere Whisker steht für den größten Wert kleiner als UQ + 1,5 * IQR (wobei UQ der obere Quartilwert und IQR der Interquartilbereich ist) und umgekehrt für das untere Quartil. Daten außerhalb des Whisker-Bereichs wurden als Ausreißerwerte identifiziert und separat dargestellt. Unterschiedliche Indizes über den Feldern zeigen signifikante Unterschiede zwischen den jeweiligen Varianten bei einem Signifikanzniveau von Alpha = 0,05.

The non-weeded SST showed significantly lower total height increment than its weed-controlled SST counterpart (119.7 cm vs. 136.7 cm) over the monitored period 2013–2017 (Fig. 3a). At the same time, there was no significant difference in height increment between weed-controlled and non-weeded LST, although in absolute numbers the weed-controlled LST showed a higher value of height increment over the whole monitored period (140.1 cm vs 129.9 cm).

Non-weeding treatments showed significantly lower root collar diameter increment when compared to the weeding treatment of the same planting stock size (Fig. 3b). The weed-controlled LST showed the best results. The non-weeded LST showed identical results as weed-controlled SST. The lowest root collar diameter increment was determined in the non-weeded SST.



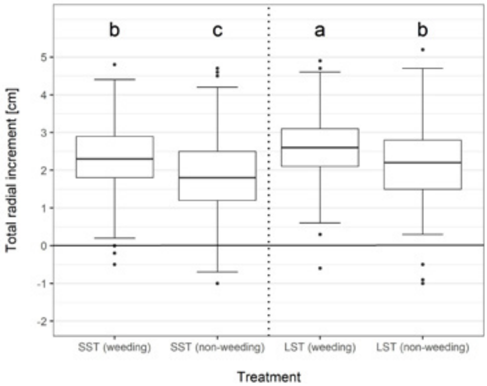


*Figure 3: Total increments in height (a) and root collar diameter (b) in 2013–2017 comparing LST and SST under weeding and non-weeding regime. SST – standard-sized transplants, LST – large-sized transplants. Total height increment was analysed with Kruskal-Wallis test, Chi-Square value 31.755; degrees of freedom = 3, p < 0.001. Total diameter increment was assessed by Kruskal-Wallis test, Chi-Square value 97.332; degrees of freedom = 3, p < 0.001. The upper whisker stands for the largest value lesser than UQ + 1.5 * IQR (where UQ is upper quartile value and IQR is the inter-quartile range) and vice versa for lower quartile. Data outside of whiskers range were identified as outlier values and are plotted separately. Different indexes above boxes depict significant differences between respective variants at significance level alpha=0.05.*

Abbildung 3: Gesamtinkremente in Höhe (a) und Wurzelhalsdurchmesser (b) in den Jahren 2013–2017 im Vergleich von LST und SST unter Unkrautkontrol- und Nicht-Unkrautkontrol-Regime. SST - Transplantationen in Standardgröße, LST - Heißtern. Das Gesamthöheninkrement wurde mit dem Kruskal-Wallis-Test, Chi-Quadrat-Wert 31,755, analysiert. Grad der Freiheit = 3, p < 0,001. Das Gesamtdurchmesserinkrement wurde durch den Kruskal-Wallis-Test bewertet. Chi-Quadrat-Wert 97,332; Freiheitsgrade = 3, p < 0,001. Der obere Whisker steht für den größten Wert kleiner als UQ + 1,5 * IQR (wobei UQ der obere Quartilwert und IQR der Interquartilbereich ist) und umgekehrt für das untere Quartil. Daten außerhalb des Whisker-Bereichs wurden als Ausreißerwerte identifiziert und separat aufgezeichnet. Unterschiedliche Indizes über den Feldern zeigen signifikante Unterschiede zwischen den jeweiligen Varianten bei Signifikanz Level Alpha = 0,05.

Chlorophyll content

The LST showed a significantly higher content of chlorophyll than the SST in 2013 (t-test, t = –3.23, df = 98, p-value = 0.002). It reached 446 mg/m² in the LST and 378 mg/m² in the SST. However, almost no difference in chlorophyll concentration between the SST and LST was observed in 2014 (t-test, t = –0.06, df = 58, p-value = 0.95), see Figure 4. The mean values were 403 mg/m² in SST and 404 mg/m² in LST.

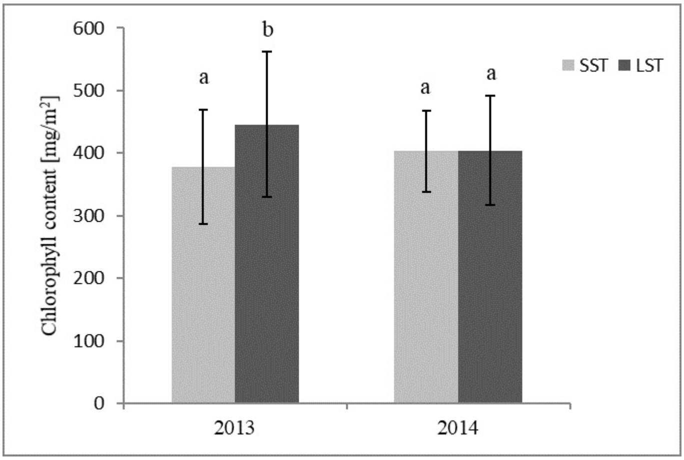


Figure 4: Mean chlorophyll content in leaves of large-sized transplants (LST) and standard-sized transplants (SST) in 2013 and 2014. Error bars depict standard deviations. Indexes above bars depict statistically significant difference between treatments.

Abbildung 4: Mittlerer Chlorophyllgehalt in Blättern von Heißtern (LST) und von Standardtransplantaten (SST) in den Jahren 2013 und 2014. Fehlerbalken zeigen Standardabweichungen. Indizes oberhalb der Balken zeigen einen statistisch signifikanten Unterschied zwischen den Behandlungen.

Economic analysis of planting

Concept 1 of an economic analysis (Table 4a) showed that when the same number of SST and LST per areal unit is used, the LST is costlier due to higher costs of LST plants and planting labour, even though less post-planting care is needed.

Table 4a: Economic analysis – Concept 1: 4,000 SST (standard-sized transplants) and 4,000 LST (large-sized transplants) planted in a fenced area. Weeding was considered necessary only in the case of SST.

Tabelle 4a: Ökonomische Analyse - Szenario 1: 4000 SST (Transplantate in Standardgröße) und 4000 LST (Heißtern), die in einem umzäunten Gebiet ausgepflanzt wurden. Unkraut wurde nur für SST als erforderlich angesehen.

	SST			*LST*		
Items	Unit cost €	Number of units	Total cost €	Unit cost €	Number of units	Total cost €
1 plant	0.4	4,000	1,600	1.1	4,000	4,400
Transport	150	1	150	150	1	150
Labour	0.3	4,000	1,200	0.45	4,000	1,800
Weeding per ha	384	5	1,920			
Fence	4,000	0.5	2,000	4,000	0.5	2,000
Total Cost:			**6,870**			**8,350**

Table 4b: Economic analysis – Concept 2: individually protected trees planted as an admixture, comparing SST (standard-sized transplants) vs. LST (large-sized transplants).

Tabelle 4b: Ökonomische Analyse – Szenario 2: einzeln geschützte Bäume, die als Beimischung gepflanzt wurden, wobei SST (Transplantate in Standardgröße) mit LST (Heißtern) verglichen wurden.

	SST			*LST*		
Items	Unit cost €	Number of units	Total cost €	Unit cost €	Number of units	Total cost €
1 plant	0.4	2,000	800	1.1	500	550
Transport	150	150	1	150	1	150
Labour	0.3	2,000	600	0.45	500	225
Plastic shelters	2	2,000	4,000	2	500	1,000
Total Cost:			**5,401**			**1,925**

In the second concept – when introducing a broadleaved admixture to existing coniferous stands – the LST showed lower costs due a reduced number of planted trees and therefore a lower number of protective plastic shelters and lower labour costs (Table 4b).

Discussion

When afforesting or regenerating a site with specific to harsh environmental conditions or introducing a tree species admixture there, various factors need to be considered (Duesberg et al., 2014). Beside the choice of tree species (Tužinský et al., 2015; Cukor et al., 2017b), spacing and mechanization (Savill et al., 1997), it is also the planting stock selection that needs to be considered (Kuneš et al., 2011). In our study, we compared SST with LST of lime to verify biologic and economic advantages of the use of broadleaved plants with larger initial dimensions in middle elevations of Bohemia, i.e. in an area where existing coniferous spruce and pine forests are endangered by the progressing climate change (Kolář et al., 2017; Vacek et al., 2017) and bark beetle calamity (Šafařík et al., 2019; Dobor et al., 2020).

Lime, as a broadleaved tree species, is available in a variety of sizes (standard size: ≤50 cm, semi-sapling: 51–120 cm, and sapling: 121–180 cm). The production of large-sized planting stock (81–180 cm) is costlier (in comparison to standard-sized plants), nevertheless, it might have its uses in reforestation or afforestation in many cases (Burda and Nárovcová, 2015). For example, saplings of rowan (*Sorbus aucuparia* L.) outperformed the standard-sized plants in a mountain frost hollow, due to the terminal bud being placed above the zone of most severe near-ground frost (Kuneš et al., 2014). Analogous principles should be verified on nutrient-rich sites with vigorous weed growth, which threaten the survival of standard-sized plants, when not regularly removed. Elsewhere, saplings and semi-saplings may suitably diversify spruce monocultures (Neruda, 2000).

In our study, we monitored afforestation of former agricultural land. We tested two different sizes of planting stock under two different weeding regimes. Weeding is a common, but costly practice in Central European forestry (McCarthy et al., 2011). Small transplants are weeded to be protected from heavy weed growth competition (typically genera *Calamagrostis* and *Rubus*). This operation is demanding on the workforce and dangerous for the target trees themselves (accidental cutting, trampling and the like). Nowadays, we face a serious issue of the lack of local and qualified workforce (Erber, 2018; Toth et al., 2019). To reduce the need for workforce, we might opt for the LST (reduced weed control, fewer trees planted).

The position of the terminal bud above the ground is known to affect growth and survival (Geiger, 1950; Gallo et al., 2014). Mean annual temperatures near the ground were in our research lower compared to those in at a higher level above the ground (Table 1), but with heat extremes in growing period (Fig. 1), which suggests different site conditions for LST and SST as their most important part, the terminal bud, was at a different level above the ground. The terminal bud of larger tree is located above the negative influence of early summer weed competition and can thrive. That was, at least, our assumption, confirmed during the monitoring.

Under the conditions of generally low mortality of the planted trees, the non-weeded LST showed similar mortality as the weeded SST. Weeding had no significant impact on mortality of the LST, but the non-weeded SST showed increased mortality. The overall differences were not high, the same pattern was registered in height increment of the trees. The LST were not affected by weed, whereas the SST responded positively to weeding. The non-weeded SST also showed the lowest increment of root collar diameter.

As large-sized plants are often susceptible to a more intensive transplant shock than the common-sized plants (Watson, 2005; Struve, 2009), even a comparable growth pace can be considered a success, because the large-sized plants keep their advance in size. LST can save extra post-planting costs for the care and weed control. On acidic sites, the positive effect of reduction in competition might be lower due to less competition by weeds. Therefore, as on specific mountain sites, also at mid-altitudes, LST should be used in specific cases and as a complement to SST. Other negative factors – such as deer browsing, gnawing and fraying – cannot be easily controlled, although the LST can more efficiently utilize the lifespan of selected deer protection measures such as fencing and individual shelters (Kuneš et al., 2011).

The light sandy-loam soil with a tendency to drying out meant that both SST and LST were negatively affected by the repeated drought events during the summer, especially by the extraordinary intense drought event in the summer of 2015 (Dong et al., 2016; Orth et al., 2016). Although lime is considered to be tolerant of high temperatures, it needs sufficient water supply in the soil (De Jaegere et al., 2016). The decrease in the water content in the soil profile exceeding the lime tolerance caused partial senescence of leaves during the drought event resulting in decreased increment and even an increased mortality rate. Preliminary results from other sites and species showed similar dynamics: *Quercus robur* on sandy soil on a site reclaimed after sand mining, as well as *Fagus sylvatica* (Gallo et al., 2018) and *Prunus avium* on a forest clear-cut (nutrient-rich) site (Gallo et al. 2019). The LST are generally more susceptible to water stress than the SST in the initial years after planting (Watson 1985). However, in all mentioned cases, LST maintained the initial height advance and lower mortality. This could allow foresters to establish a stable and structured stand sooner and more effectively.

The chlorophyll content was significantly higher in the LST in 2013, but equal to the values of the following year. This possibly could be ascribed to a larger amount of nutrients still incorporated stored in the tissue of LST from a nursery. A reduced chlorophyll content could also point to increased stress of plants (Van Den Berg and Perkins, 2004). Determining an ideal or universal value is problematic, though. The variability within one tree individual and throughout vegetation period is also generally high (Demarez, 1999). Based on this knowledge, determination of vitality differences between the SST and LST could not be based on the chlorophyll content.

Regarding the costs of the planting, the most important variable was the number of trees, followed by the planting stock type. Weeding requirements and other post-planting care come secondary. Therefore, if we can reduce the number of individuals by using LST, the costs of establishing a plantation can be significantly reduced.

Conclusion

We compared the survival and growth performance of LST and SST of small-leaved lime (*Tilia cordata*) on a dry, sun-exposed site of a former agricultural land with strong weed competition. The highest mortality was registered in the SST under the non-weeding regime. Other variants showed very low mortality, the LST under the weed control regime showed zero mortality. The LST showed slightly better dynamics of height and diameter increments than the SST over the monitored period, i.e. in the initial stage of reforestation. Weeding positively influenced the height increment of the SST but did not influence the height increment of the LST. The LST maintained the initial height difference and can therefore shorten the time during which the protection against game and weed is needed. The LST are, however, more costly and more laborious for planting. Therefore, we can recommend LST for sites, where reducing the planting density (numbers of trees per area) is not a problem, and where weed control is restricted or cost-intensive.

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