Doctoral thesis

Czech University of Life Sciences

Faculty of Forestry and Wood Sciences

Department of Silviculture

DIVERSIFICATION OF FOREST STANDS AND THE USE OF SAPLINGS AND SEMI-SAPLINGS ON MID-ELEVATION SITES

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Faculty of Forestry and Wood Sciences

Ph.D. THESIS ASSIGNMENT

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Forestry Engineering
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Thesis title

The diversification of forest stands and the use of saplings and semi-saplings on mid-elevation sites

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Objectives of thesis

The objectives of the thesis are as follows:
(1) to analyse and summarize the outcomes of several field experiments focused on testing the large-sized planting stock on mid-elevation sites,
(2) to provide forest owners and managers with a comprehensive supply of afforestation experience with large-sized planting stock on mid-elevation sites,
(3) to embed the results and experience into a set of recommendations and practical proposals for wider use of large-sized planting stock.

Methodology

Broadleaved saplings, semisaplings and common-sized seedlings/transplants were planted within several experiments on selected mid-elevation sites so that their growth performance and overall vitality could be compared.

Prepare a literature review on the topic of the dissertation.

Describe the large-sized planting stock (semisaplings and saplings) analysed in your study in detail.

Define the hypotheses.

Describe the analysed experiments (site characteristics, experimental design etc.).

Process and analyse the data using appropriate methods. Confront the performance of the large sized plants (semisaplings and saplings) with the common-sized stock.

Discuss the results with the available literature sources on the topic.

Derive the conclusions and recommendations for forestry practitioners.

Follow the document submitted at the beginning of your Ph.D. study programme that contains the Material and Methods of your research in more detail.

The proposed extent of the thesis

at least 90 pages

Keywords

reforestation; afforestation; large-sized planting stock; silviculture

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Recommended information sources

BURDA P., NÁROVCOVÁ J., NÁROVEC V., KUNEŠ I., BALÁŠ M., MACHOVIČ I. (2015). Technologie pěstování listnatých poloodrostků a odrostků nové generace v lesních školkách. [Technology of planting of deciduous saplings and semi-saplings a new generation of nurseries] – Certified Methodology – Forest guide 3/2015, Research Institute of Forestry and Wildlife, Strnady, 56 p.

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Chairperson of Departmental Board

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Prohlášení

Prohlašuji, že jsem disertační práci na téma „Diverzifikace lesních porostů a využití poloodrostků a odrostků ve středních polohách [angl. orig.: Diversification of forest stands and the use of saplings and semi-saplings on middle-elevated sites]" vypracoval samostatně s použitím uvedené literatury a na základě konzultací a doporučení školitele. Souhlasím se zveřejněním disertační práce dle zákona č. 111/1998 Sb., o vysokých školách, v platném znění, a to bez ohledu na výsledek obhajoby.

In Prague on the 15th of March 2021

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Author's signature

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Dedication

The research on the basis of which this dissertation was created with material support drawn from a number of grant projects. The following projects contributed the most to the thesis:

GA FLD A_19_24: Testování některých inovativních postupů produkce a výsadby sadebního materiálu pro zalesňování v extrémních podmínkách

GA FLD A_18_18: Obnova a zakládání lesních porostů pomocí vyspělého sadebního materiálu v podmínkách rekultivovaných a bývalých zemědělských půd a zabuřenělých stanovišť

TA04021671: Zakládání a obnova lesa na rekultivovaných a ekologicky specifických lesních stanovištích a využití poloodrostků a odrostků nové generace

Motto

"Make everything as simple as possible, but not simpler"

– Albert Einstein

Diversification of forest stands and the use of saplings and semi-saplings on mid-elevated sites

Abstract

The thesis is aimed at the verification of the use of large-sized planting stock on mid-elevation sites as a contribution to the regeneration and transformation of forest stands to reach the stability and diversity of forests. The goal is primarily to test the suitability of new generation saplings and semi-saplings (NGSS) of deciduous tree species on selected experimental plots for this purpose. The work analyses and summarizes the outcomes of several field experiments focused on testing the large-sized planting stock on mid-elevation sites. Mortality, growth and other characteristics of NGSS on selected research sites were evaluated.

NGSS is characterized by an advanced, rich and compact root system and an improved ratio of aboveground and underground biomass to standard planting material, as well as generally larger dimensions.

The basic hypothesis was that the NGSS show better growth dynamics on (exposed and extreme) habitats. The research was done on the basis of the evaluation of older research experimental plots, but new plots were also established. Additional analyses included the application of brassinosteroids onto advanced planting stock during the post-planting period, analyses of the chlorophyll content of NGSS and standard planting stock, and the determination of aboveground and underground biomass volumes in the tested planting stock types.

New generation saplings and semi-saplings showed generally better increments in both height and root collar diameter as well as improved vitality. This was confirmed on various types of habitats. Therefore, this type of planting stock is recommended for reforestation and afforestation in specific and difficult cases, considering its higher costs.

Basic economic analysis and evaluation of the economic efficiency of using the NGSS system is a part of the work. With different combinations of the number of planted trees and mowing regimes, the economic endurance of the NGSS system can be achieved thanks to the better attractiveness and vitality of the NGSS.

Keywords: large-sized planting stock, broadleaves, reforestation, economics of afforestation, above-ground and below-ground biomass, forest structure

Diverzifikace lesních porostů a využití poloodrostků a odrostků ve středních polohách

Abstrakt

Tato disertační práce je zaměřena na problematiku využití vyspělého sadebního materiálu lesních dřevin ve středních polohách jako doplněním ostatních metod zalesňování, obnovy lesa a přeměny lesních porostů s cílem diverzifikace a stabilizace lesních porostů. Cílem je především otestovat vhodnost poloodrostků a odrostků listnatých dřevin (PONG; angl. NGSS) na vybraných experimentálních plochách založených pro tento účel. Práce analyzuje a shrnuje výsledky několika experimentů zaměřených na testování PONG ve středních polohách. Hodnocena byla mortalita, růst a další charakteristiky PONG.

PONG jsou charakterizovány vyspělým bohatým a kompaktním kořenovým systémem a zlepšeným poměrem nadzemní a podzemní biomasy oproti standardnímu sadebnímu materiálu, jakož zpravidla i celkově většími dimenzemi.

Základní hypotézou bylo, že poloodrostky a odrostky a nové generace by měly vykazovat lepší růstovou dynamiku na specifických (exponovaných a extrémních) stanovištích. Výzkum byl proveden na základě vyhodnocení starších výzkumných výsadbových ploch, ale byly založeny i plochy nové. Dodatečné analýzy zahrnovaly aplikaci brassinosteroidů na vyspělé sazenice během období po výsadbě, analýzy obsahu chlorofylu v PONG a standardních sazenicích a zjišťování objemu nadzemní a podzemní biomasy u testovaných typů sadebního materiálu.

Výsledkem práce je zhodnocení dosavadních zkušeností s použitím PONG. Na všech výzkumných ploch dosahovaly lepších výsledků než standardní sadební materiál z hlediska mortality, přírůstu a celkové vitality. PONG se uplatnily v případě vysýchavých stanovišť (Truba, Vintířov), zamokřených stanovišť (Týniště nad Orlicí – U Glorietu), výsypek (Týniště nad Orlicí – Písník) i dalších.

Součástí práce je základní ekonomická analýza a zhodnocení ekonomické efektivnosti použití systému PONG. Při různých kombinacích počtu vysazených stromů a režimů vyžínání lze díky lepší ujímavosti a vitalitě PONG dosáhnout ekonomické únosnosti systému PONG.

Klíčová slova: vyspělý sadební materiál, listnáče, zalesňování, ekonomika zalesňování, nadzemní a podzemní biomasa, struktura porostů

Contents

1. INTRODUCTION

The thesis presents the topic of large-sized planting stock, namely new generation semi-saplings and saplings (BALÁŠ et al. 2018a; BALÁŠ et al. 2018b) for the purpose of creation, regeneration and diversification of forest at middle-elevated sites. The work builds on previous achievements in this area. The team of authors has already dealt with using semi-saplings and saplings in mountain conditions (BALÁŠ, KUNEŠ 2010; KUNEŠ et al. 2010), where the system of underplantings and inter-planting centres proved to be useful (KUNEŠ et al. 2011b). Publication by BURDA et al. (2015) describes in detail the production of large-sized planting stock. The essential part of its production is the intensive adjustment of root system (WATSON 1985). This planting stock exhibited a much better health and growth than the standard-sized seedlings (KUNEŠ et al. 2014a).

Subsequently, the research plots were extended to the mid-elevation sites. At those plots, various tree sizes and outplanting methods such as planting by earth auger were tested. In mountain conditions, it was found that large-sized planting material facilitates reforestation in conditions of significant frost stress. We encounter this type of stress also at middle elevations, which, however, is not critical to the success of afforestation there. On the contrary, drought-heat stress is strongly manifested in many locations, which can significantly limit the survival of plants, and in theory rather penalizes larger planting material. On the other hand, heavily weeded forest habitats on nutrient-rich substrates are one of the factors that could favour the large-sized planting stock over standard seedlings.

In recent years, a number of problems have occurred in the forestry sector. Extensive Norway spruce (*Picea abies* (L.) Karst.) monoculture management is increasingly proving unsustainable at the lower and middle elevations (FELTON et al. 2016; DUŠEK et al. 2017). In some areas, this most important commercial species is in decline and we can expect a significant decline across the area of the distribution in lower vegetation zones due to bark beetle infestation in recent years (ČERMÁK et al. 2018). Norway spruce is challenged in the phase of so-called thinning by small bark beetles and is under intense pressure from overpopulated red deer, sika deer, roe deer and mouflon (ČERMÁK et al. 2004).

One of the specific problems is also the changing forest ownership – it has been shown in recent years that a series of restituted properties were taken in an unsatisfactory condition. The necessity of reforestation and reconstruction is thereby increased (GALLO et al 2018a).

In the literature review, the importance of forest structure is presented, stability and growth and to present the advancement of knowledge on the use of large-sized planting stock (saplings and semi-saplings) to restore the forest to the structure and species differentiation. Through the evaluation of plantations' prosperity on the existing permanent research plots (PRP), the creation of diversification centres and their assessment will be the subject of further research.

The work extends the research on already established PRP. These areas were reforested with different types of planting stock of suitable tree species for particular habitats. Within the options, large-sized stock was utilized and the possibility of its use as a complementary method to the standard reforestation was verified (BALÁŠ et al. 2011a; BALÁŠ et. 2011b). The new generation saplings and semi-saplings (NGSS) system contains not only the large-sized planting stock but is associated with the use of advanced earth augers (STIHL 2006; BURDA et al. 2015; BALÁŠ et al. 2016; GALLO et al. 2020a), larger planting holes to prevent root deformations, more sophisticated logistics – therefore the whole approach was tested. The possibility of improvement in relation to economic and environmental objectives was assessed.

2. AIMS OF THE STUDY

The objectives of the thesis according to work assignment were the following:

(1) to analyse and summarize the outcomes of several field experiments focused on testing the large-sized planting stock on mid-elevation sites,

(2) to provide forest owners and managers with a comprehensive supply of afforestation experience with large-sized planting stock on mid-elevation sites,

(3) to embed the results and experience into a set of recommendations and practical proposals for wider use of large-sized planting stock.

The aim of the result part is to analyse and summarize the outcomes of several field experiments focused on testing the large-sized planting stock on mid-elevation sites. The basic assumption is that the new generation saplings and semi-saplings show better growth dynamics under the conditions of exposed and extreme habitats. Primarily, mortality and growth characteristics were assessed. Additional analyses on selected sites included assessment of frost damage of trees treated by brassinosteroids, chlorophyll content analysis, and analysis of above-ground and below-ground biomass volume of planting stock.

The basic hypothesis was that advanced planting stock (NGSS) would be more successful in initial stages of growth due to its well-developed root system as well as above-ground part in specific extreme/exposed environmental conditions. The objective of the thesis is to provide comprehensive supply of afforestation, reforestation and diversification experience, for the use of new generation saplings and semi-saplings (NGSS) on selected environmentally specific forest habitats and on lands destined for forest reclamation.

3. LITERATURE REVIEW

3.1. Forest structure, diversification, mixed forests

Most forest stands in European conditions are cultivated and influenced by human activity. The first silvicultural measures were driven by the lack of wood and to secure wood production in the future (MUSTIAN 1978; LAUTENSCHLAGER 2000; SCHMIDT 2012). Subsequently, various silvicultural systems evolved, with differences in inputs, rotation and regeneration periods and following differences in structure and function of forest stands (KENK 1995). The silvicultural systems based on these principles are variable and can be grouped under the common term 'close-to-nature silviculture' (HAVERAAEN 1995). In the past decades, not only wood production, but socio-economic and biodiversity needs have become gained an importance (ŠIŠÁK et al. 2013). Subsequently, the rebuilding of even-aged stands (particularly Norway spruce) to uneven-aged silviculture started to take place as a consequence of close-to-nature silviculture approach (GULDIN 1996; VACEK et al. 2019c). It is a viable model to reach more complex structure not only for Norway spruce, which is mostly problematic in monocultures in the Czech Republic, but also for Scots pine (*Pinus sylvestris* L.) stands (ŠVEC et al. 2015; BÍLEK et al. 2016).

Considering the future of diversified forests, after species and structural changes, some stands could be destined to selection forests. The attention to more ecological forestry in larger scale has been drawn relatively recently (GILLIS 1990; O'HARA 2002). However, the methods have been long known: LIOCOURT (1898) derived the curve of diameter quantity for optimal stocking in selection forest (KERR 2013). The idea of shelterwood system and selection forests was intended almost exclusively for shade-tolerant species, particularly silver fir (*Abies alba* Mill.), partly also for Norway spruce, European beech (*Fagus sylvatica* L.), and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) (SCHÜTZ 1989; KORPEĽ, SANIGA 1993; VACEK et al. 2015) and diverse species mixtures are considered as one of the common features of selection forests (KELTY 2006; SLANAŘ et al. 2017). The balanced and production-convenient structure of selection forest is not determined by natural processes, but it is the result of intentional activity of forest manager (SCHÜTZ 2002).

In addition, large disturbances and decline of Norway spruce have occurred due to air pollution load (KRÁL et al. 2015; KRÁLÍČEK et al. 2017) and ongoing climate change (BADRAGHI et al. 2016; CUKOR et al. 2019a; PUTALOVÁ et al. 2019). Forests have to adapt to a wide range of climatic conditions, and they will have to increase the tolerance to different soil moisture levels and to have a prerequisite for resisting climatic extremes. Therefore, stabilizing parts of forest ecosystem have to be incorporated on both nutrient-poor and rich sites (VACEK et al. 2016a; VACEK et al. 2017).

Up to now, knowledge about diverse stand mixtures show that there is a strong potential of wood production increase (DEL RÍO, STERBA 2009), and potential for establishing more favourable stand structure in comparison with conifer monocultures, with the maintenance of stand stability (PRETZSCH et al. 2013a; SHARMA et al. 2017, 2019). Therefore, artificial regeneration could maintain its importance in the future (GALLO et al. 2018b).

The problems with artificial regeneration are often related to human factor during planting (delayed bud flush, slow growth and high mortality after planting resulting from insufficient morphological and physiological quality of planting stock), as well as to environmental conditions, which in the case of Czech Republic are relatively high temperatures and low precipitation in lowland regions of Central Europe – with a precondition to short-term drought (MARTINCOVÁ 1998) and the combination of drought and fungi disease (NÁROVCOVÁ 2010; NÁROVEC, NÁROVCOVÁ 2012). Similarly, in European forests there are documented changes leading to subsequent dying of light-demanding (and relatively drought-tolerant) pines and oaks (MORÁN-LÓPEZ et al. 2014), probably because of ever dryer and warmer climate in the recent years.

With respect to site conditions, it is stated that on rich sites, diversification can be used for its production advantages, while on poor sites, it should be used as a matter of priority (AMMON 1946). KERN (1966) described that the slenderness coefficient was lower, and the mechanical stability higher in selection forest in comparison to regulated forest. The crucial interval is in DBH dimensions 12–20 cm, i.e. trees of medium layer, where the acceleration of growth is expected. It is the differentiated structure and relations of small groups that creates the conditions of stability. The selection silvicultural system involves the four main intentions: tending, structure formation, regeneration and harvesting (LEIBUNDGUT 1951). The sustainability and continuity of regeneration processes in selection forest was initially considered as matter of course, but in many cases this assumption was not fulfilled (KORPEĽ, SANIGA 1993).

Therefore, it is difficult (in many cases impossible) to apply complete spatial and species diversification at one moment. Partial diversification of even-aged monocultures is necessary (GALLO et al. 2020b).

3.2. Definition of mid-elevation sites

Recently, NGSS were tested in the conditions of mountain forest sites, with good to excellent results (KUNEŠ et al. 2014a). The potential of this system was suggested to be verified also in other important forest sites, namely mid-elevation sites on specific sites exposed to weed competition or ground frost. The term "mid-elevation sites" in this study is derived from the Czech forest classification (VIEWEGH 2003a).

Table 3.2.: Overview of forest vegetation zones in Czech Republic (according to VIEWEGH 2003a (modified); mid-elevation sites are shaded in grey-beige).

Forest vegetation zone		Main tree species	Climatic conditions		
			Precipitation [mm]	**Mean temperature [°C]**	**Vegetation period [days]**
9th	Dwarf pine	*Pinus mugo*	>1500	<2.5	<60
8th	Spruce	*Picea abies*, *Pinus mugo*	1200–1500	2.5–4	60–100
7th	Beech-spruce (predominance of spruce)	*Picea abies*, *Fagus sylvatica*, *Abies alba*	1050–1200	4–4.5	100–115
6th	Spruce-beech (predominance of beech)	*Fagus sylvatica*, *Abies alba*, *Picea abies*	900–1050	4.5–5.5	115–130
5th	Fir-beech	*Fagus sylvatica*, *Abies alba*, *Picea abies*	800–900	5.5–6	130–140
4th	Beech	*Fagus sylvatica*, *Quercus petraea*, *Abies alba*	700–800	6–6.5	140–150
3rd	Oak-beech (predominance of beech)	*Fagus sylvatica*, Quercus petraea, *Q. robur*, *Carpinus betulus*, *Abies alba*, *Pinus sylvestris*	650–700	6.5–7.5	150–160
2nd	Beech-oak (predominance of oak)	*Quercus petraea*, *Fagus sylvatica*, *Carpinus betulus*, *Q. pubescens*, *Q. cerris*	600–650	7.5–8	160–165
1st	Oak	*Quercus petraea*, *Q. cerris*, *Q. pubescens*, *Fraxinus angustifolia*	<600	>8	>165
0th	Scots pine	*Pinus sylvestris*	determined by soils, not climatically		

Note: Main tree species is the typical tree species in terms of management usually occurring on sites of the particular forest vegetation zone.

The overview of forest vegetation zones is presented in Table 3.2. From these zones, 1 and 2 can be described as lowland sites, 7 and 8 as mountain sites. All the zones in between (3–6) are considered as mid-elevation sites for the purposes of this thesis. In the latest version of forest typology, there is also forest vegetation zone (FVS) 10 (Alpine zone) (ÚHUL 2019).

Forest vegetation zones are not directly derived from elevation, but climate and land relief. On the other hand, the classification of forest sites usually corresponds with elevation except for special cases as valleys with frequent occurrence of temperature inversions, extra-zonal or azonal soils.

3.3. Challenges to forest regeneration on mid-elevation sites and potential of large-sized planting stock at its addressing

Most economical and ecologically advantageous would be if the modification of the species composition were due to natural regeneration, i.e. without the substantial planting. Under favourable conditions, the shifting of the species composition can be surprisingly intense only under the influence of natural processes, both in lower and mid-elevations (JELÍNEK, KANTOR 2006) and on mountain habitats (VACEK et al. 2010), or even in the Nordic forests (GÖTMARK et al. 2005). On the other hand, artificial regeneration is considered most reliable and speedy way of forest restoration (REPÁČ et al. 2020).

As result, artificial regeneration is used in specific situations and/or regimes:

1. Under clear-cut silvicultural system
2. If natural regeneration failed
3. To change or shift species composition
4. To change of spatial structure of forest stand
5. For improvement of phenotype quality
6. For fast and intensive regeneration of forest stands

Over 120 million transplants are planted in the Czech Republic every year as a result of clear-cut silvicultural system. That is the most intensive use. Another situation, in which artificial regeneration is useful, is when natural regeneration failed. It is specifically needed for legal purposes, i.e. when the landowner is obliged to reforest and ensure the new generation of forest in a certain period of time.

Therefore, finding the basis for rationalization and innovation in the field of forest regeneration will continue to be one of the key points in the creation of strategic outlooks and forest sector concepts in the near future. For the approximation and analysis of quantitative parameters (outputs) of artificial forest regeneration in the Czech Republic, the available statistical data provided by the Report on the state of forestry of the Czech forest management in 2018 (MZe 2019) can be used. In the last decade, the area of land where the artificial regeneration of forest stands was applied reached around 18 to 22 thousand ha per year, while annual consumption of seedlings reaches the usual amount between 120 and 160 million individuals of planting stock. Specifically, in 2018 the tasks of artificial forest regeneration were carried out on an area of 21,245 ha of land, of which 3,941ha was repeated planting due to previous unsuccessful reforestation. Total planting stock production reached 133 million pcs in 2018 (MZe 2019).

The use of standard planting stock of deciduous trees in harsh conditions is commonly associated with considerable losses in the early years after planting, where mortality may reach tens of percent. BALCAR (1998) reports mortality rate of 45% in a rowan plantation and up to 60% in silver birch plantation in the first three years after planting. On harsh or extreme sites, overcoming the planting shock, when the height increase is totally or almost halted, usually takes several more years (SOUČEK 2004). The terminal bud, therefore, remains for a long time only at a low height above the surface, i.e. in places that are more intensely affected by negative influences compared to the higher layers of air (GALLO et al. 2014). In particular, it is a more pronounced temperature fluctuation (GEIGER 1950; MRÁČEK 1966; SPITTLEHOUSE, STATHERS 1990; LANGVALL, OTTOSSON LÖFVENIUS 2002), weed pressure (PĚNČÍK 1958), and snow damage, and the pressure of herbivorous game. In some specific conditions associated with landscape relief (so-called frost hollows), summer night frosts occur regularly. Securing a planting in unfavourable habitat conditions using a regular size planting material can take a long time, about 10–15 years.

An opportunity, how to overcome the initial unfavourable circumstances for the growth of forest plantings in unfavourable conditions and to shorten the time needed to initial grow, is the utilization of the large-sized planting stock. The main motivation for the use of saplings is that their terminal bud is already at the time of planting high above the surface of the soil, outside the most endangered ground level, where the trees are threatened by frost, weed, and small browsers (KUNEŠ et al. 2014a).

3.4. The utilization of saplings and semi-saplings

Planting stock of deciduous tree species, referred to as new generation saplings and semi-saplings (NGSS), is mainly used to complement existing stands, i.e. to the admixture and underplantings (BALÁŠ et al. 2011a; BALÁŠ et al. 2011; KUNEŠ et al. 2011b). NGSS has always been produced in accordance with valid norms, namely ČSN 48 2115 (ČNI 1998) and its later updates ČSN 48 2115 Z1 (ČNI 2002) and Z2 (ČNI 2010; NÁROVCOVÁ 2019). At present, valid norm is represented by ČSN 48 2115 (ÚNMZ 2012) that came into effect in 2012. Same requirements are present in regulation 29/2004 Coll. and in later adjustments.

There are minor differences in the requirements of the norms regarding the production of standard-sized and large-sized planting stock and they also differ and are specified for different tree species. Bare-rooted semi-sapling was originally defined for most tree species of our interest by tree height 51–120 cm with the condition of undergoing root-pruning, while standard transplant could be up to 70 cm when not root-pruned (ČNI 1998) and saplings (size 121–250 cm), which undergone root-pruning or transplanting during cultivation in the nursery, or a combination of these operations. Generally, NGSS always meet requirements of current valid norms and significantly exceed them.

In the newest norm from 2012 (ÚNMZ 2012) and Regulation 29/2009 Coll., formulars and cultivation formulas were adjusted. Parameters of planting stock (above-ground and below-ground biomass) were not changed in comparison to regulation 29/2004 Coll.

In older literature, the testing and reforestation with the use of large-sized planting stock is described by PEŘINA (1969) in the 1950s. Otherwise, the literature is relatively scarce. Afforestation with advanced seedlings has been presented in the past, for example, by LOKVENC (1978), who recommended the use on heavily weeded sites (experiments in pine woods in the then Eastern Germany), which also evaluates the economic aspect of saplings. It states that not only the price difference of the planting material should be considered, because it is the final effect of afforestation, that is, the cost and the need for human work for the cultivation and the protection of the plantation. It also warns against the risks associated with plant root damage during planting. Similarly, PEŘINA (1969) states the essential advantage of the saplings, which is to reduce later costs of weeding and partly also in protecting against game.

SCHMIDT-VOGT, GRÜTH (1969) pointed out that the size (height) as the only factor for planting stock classification was not correct. As transplants can be artificially boosted by close spacing or fast-growing provenances can be used, the important factors are also root collar diameter, and nowadays (NGSS) also root-to-shoot ratio and physiological stat of the plant.

The use of large-sized planting stock is recommended for afforestation of clear-cut areas (in mountainous areas), because larger plants better resist the pressure of the weed and grow up sooner (KANTOR et al. 1975). Further, for example, ŠINDELÁŘ et al. (2004) pointed to the use of saplings for the replenishment of the already growing advance growths and plantations of other tree species. An experimental transplanting of the beech individuals from the natural regeneration with the sizes corresponding to saplings is described by KANTOR, PEKLO (2001).

MAUER (1998, 1999, and 2008) and NERUDA (1999) have been recently working with saplings too. Saplings are used locally for planting outside the forests, for instance, when planting bio-corridors (JELÍNEK, ÚRADNÍČEK 2010), revitalization of wetlands (DOMOKOŠOVÁ 2006) etc. Besides small operational experiments (VANĚČEK 2001), however, saplings and semi-saplings have not yet been extensively used in forestry practice.

NERUDA, NAVRÁTIL (1998) describe the main potential types of utilization of large-sized plants for:

(1) reforestation of calamity clear-cut areas complicated to reforest in other way,
(2) improving and admixture to especially older already existing forest cultures that contain gaps to fill the stand with plants of similar size,
(3) ensuring the proportion of ameliorative and stabilising tree species within existing forest cultures,
(4) alleys and decorative greenery in landscape.

JOBIDON et al. (2003) described the suitability of large-sized planting stock of black and white spruce (*Picea mariana*, *Picea glauca*) on harsh and weed-infested sites to lower the need for repeated weed control treatments. Larger plants proved to have more ability to compete for light and space. Also, in case of *Picea mariana* planting stock, more intensive site preparation on a heavily weeded site had a positive effect on the initial increment of the plantation, especially for bare-rooted planting stock (THIFFAULT et al. 2012).

Valuable broadleaves like *Juglans regia*, *Sorbus torminalis*, *Acer pseudoplatanus*, *Quercus robur* and others, can be potentially very valuable and therefore can compensate and improve the economic situation of forest enterprises hit by bark-beetle and windstorm calamities (HORÁČEK 2020).

Since 2005, the activities of the research team of the Department of Silviculture of Faculty of Forestry and Wood Sciences CZU in Prague have been developing, in later cooperation with VÚLHM VS Opočno, the process of introducing a deciduous admixture into mountain coniferous forests. A summary of the findings was published by KUNEŠ et al. (2011*a*).

In the most recent period, the activities of this research team moved to forests in lower elevated sites, and the aim is the development and verification of the method of saplings and semi-saplings when introducing an admixture of noble hardwoods into forest stands in an unsatisfactory state at middle elevations.

Modern changes in environmental conditions, including climate change, have a significant impact on forest ecosystems (HLÁSNY et al. 2014). There is a predominant view that the structure of forests in the Czech Republic is not sufficiently adapted to the incoming climate change. Thus, the requirements for structural change of the established forests and the modification of their species composition are in the forefront of interest, in favour of domestic deciduous species of economic, ameliorative and consolidating trees (MAUER 2016; KACÁLEK et al. 2018). It is anchored in legislation by means of regulation 298/2018 Coll.

For the future state of forest ecosystems, the species composition of forest regeneration and its successful growth is of paramount importance. In addition to general soil protection on forest soils and a comprehensive improvement of the landfill function, including direct water retention in forest ecosystems, key preventive and practical remedial measures to mitigate the negative impacts of climate change on forest ecosystems include, in particular, support for appropriate management practices on forest soil, leading to a varied species tree structure and to the varied spatial construction of forest stands (KUNEŠ et al. 2017).

The need to efficiently carry out the required restructuring and forest regeneration (in particular in connection with the introduction of broadleaves into the structure of the forests, as well as the stands based on reclaimed and ecologically specific forest habitats), motivates the search for innovative silvicultural approaches, including the search for documented past forestry experience, which would be appropriate to be followed now in enforcing efforts to transform the species composition of forest stands. However, these earlier experiences must first be critically analysed and then transformed into economic systems (if they prove to be prospective) to meet current needs and the current legislative, technological and economic possibilities of forest management. The topic of bare-rooted semi-saplings and saplings of broadleaves (as well as support for the shape of a low forest and other previously established, proven and now rediscovered cultivation techniques) calls for such an approach (BURDA et al. 2017). It will be drawn mainly from the older forestry literature, which gave positive examples of the afforestation of the large hollows with the large-sized stock in our country (e.g. RŮŽIČKA 1922, 1935, SEKANINA 1922, KASAL 1934, BÁRTA, CHRZ 1956, SKOUPÝ 1967, PEŘINA 1969, LOKVENC 1978).

Due to activities in the recent years, with the joint effort of the research and application sphere, the process of producing saplings and semi-saplings for current forestry practice has been developed in forest nurseries in Nové Město pod Smrkem (Dendria s.r.o.) and in Sepekov (Pavel Burda, Ph.D. – forest nurseries Sepekov). An important innovative element of the proposed technology is that for NGSS of deciduous trees, nursery cultivation has been intentionally directed to ensure that the final crops have a root system that is concentrated in a distance of no more than 10 cm from the stem axis and (depending on species) about 26 to 34 cm in depth. This intention is also adapted to the bare-rooted sapling and semi-sapling cultivation in nursery after transplanting with a one-row transplanter (distance of rows from each other is usually 80 cm, distance of plants in rows about 30 cm) and a whole range of other aspects of the cultivation process in forest nurseries (modification of the root system of plants is achieved exclusively by the combination of root-pruning and follow-up transplanting) (BURDA et al. 2015; BURDA et al. 2017).

To distinguish this innovative technology from the traditional sapling cultivation practices in nurseries (described in detail in e.g. MAUER 2008), therefore, the name "new generation" was inserted into the name of the products. Previously used (introduced) such as KUNEŠ et al. (2011*b*) or NÁROVCOVÁ, NÁROVEC (2013), in the cultivation formula, they are represented: 1–1+1 to 1–1+3. It means they are grown on mineral outdoor seedbeds for two years as standard root pruned seedlings and finalized after transplanting, depending on species, for 1 to 3 years. For limes and cherries, it is mostly one year, for beech two years and for oaks 3 years.

An important fact in the context of proposals for the application of NGSS technology in the forestry practice was the idea that the planting of NGSS will be preferred (on habitats where the soil conditions allow) by digging planting holes by earth auger of the required diameter. It was assumed that the use of spiral drills with a diameter of 20 cm (especially drills further modified by additional triangular prongs reducing the smoothing of the side walls of the holes) would result in a sufficiently sized planting space that would satisfy the requirement that the wall of the drilled well be at least 2 cm from the end of the longest of the lateral root. Czech Technical Standard ČSN 48 2116 Artificial Forest Restoration and Afforestation, published by the Office for Standards, Metrology and Testing (ÚNMZ 2015) in March 2015, and which came into effect on April 1, 2015, included in the conditions for soil preparation by soil drills and planting NGSS with concentrated root system a different requirement: the size of the drilled hole should be at least 10 cm larger than the width (diameter) of the root system of the planted tree so as the process does not cause root system deformation.

A part of the presented thesis is description of the principles and procedures for afforestation of some model types of degraded and reclaimed habitats, with a focus on the use of NGSS. Presented technological process of cultivation and forest planting has been targeted in the past three years (2014–2017) in the framework of the research project entitled "Establishment and Reclamation of Forests on Reclaimed and Ecologically Specific Forest Habitats Using New Generation Saplings and Semi-saplings" (TA04021671) financially supported by the Technological Agency of the Czech Republic (TA CR).

3.5. Characteristics of new generation saplings and semi-saplings used in presented study

Large-sized planting stock is defined as semi-saplings (according to norm ČSN 48 2115 Z2), with a height between 51(71)–120 cm and saplings of 121–250 cm in height, which during the nursery cultivation have usually undergone double transplanting, root cutting or transplanting to containers, or a combination of these operations.

The technological process for production of large-sized bare-rooted planting stock of broad-leaved trees with high-quality root systems, which do not require digging large planting holes at planting on forest sites is in detail is available in the applied methodology by BURDA et al. (2015). The planting stock was labelled as "new generation semi-saplings and saplings" (NGSS). It is based on specific machinery and the aim of reaching more favourable root-to-shoot ratio. As for the planting stock size, the new generation semi-saplings belong to the 81–120 cm height class and the new generation saplings belong to the 121–180 cm height class.

A brief extract from the methodology by BURDA et al. (2015) is as follows:

Required machinery consists of a four-wheel drive tractor with a creeping speed reducer enabling a very slow forward movement with a three-point linkage (BURDA et al. 2015). In terms of soil conditions, sandy-loam soil is the ideal soil texture for the NGSS cultivation in forest nurseries. The minimum depth of plough layer is 50 cm. As for soil chemistry, soil reaction should be 5.5–6 pH (in $CaCl_2$). The cation exchange capacity (Kappen) of plough layer should be at least 15 meq/100 g of soil material (desirable CEC equals 18 meq/100 g or more). The concentration of soil organic matter (Hox) should be at least 5%. Base saturation (BS) of plough layer should range between 75 and 90%. Recommendable concentrations of available nutrients (Mehlich III procedure) in the plough layer are as follows: P > 81 $mg.kg^{-1}$, K > 161 $mg.kg^{-1}$, Mg > 136 $mg.kg^{-1}$, Ca > 1 300 $mg.kg^{-1}$.

The two-year-old, bare-rooted, root-pruned plants (1–1) are used as the initial planting stock entering the further nursery process of NGSS production. The root pruning of 1–1 plants is done in spring of the second growing season. The characteristics of root systems is an important criterion for selection are alongside the above-ground parts.

Root pruning is done manually, and it is a major step in the process of NGSS production. The root biomass of the lifted two-year-old (1–1) plants (that were chosen as the initial planting stock for the NGSS production) is reduced by up to 50%. The aim is to shorten the skeletal roots and thereby reduce the risk of root system deformation during following nursery and forestry processes, and to achieve a compact and fibrous root system. The cut end diameter of the pruned roots should not exceed 6 mm. After root pruning, the plants are transplanted back into a nursery bed.

The singling and formative pruning of the NGSS is conducted to produce a straight stem and to ensure a dynamic height growth. It is the removal of a stem fork or multiple terminal buds, if these occur. Formative pruning should reduce the occurrence and growth of coarse lateral branches. These operations are performed during the vegetation period after the spring growth has terminated.

Producing the NGSS from seed altogether lasts from three to six years depending on the species and target dimensions (semi-saplings or saplings). Root-pruned plants (1–1) are used as the initial planting stock for further cultivation. The production time in the nursery after transplanting that is required to achieve the finalized planting stock differ among species. The following points summarize the recommended schemes for the production of different forest tree species in the dimensions of NGSS:

- **Oaks** (*Quercus robur* and *Quercus petrea*): The bare-rooted transplants of oaks reach the dimension of NGSS most commonly at the age of four years. The recommended way of production is: two-year-old, root-pruned plants transplanted and grown for two more years as transplants.
- **European Beech** (*Fagus sylvatica*): The bare-rooted transplants of beech reach the dimension of NGSS most commonly at the age of four or five years. The recommendable way of production: two-year-old, root-pruned plants transplanted and grown for two or three years as transplants.
- **Limes** (*Tilia cordata* and *Tilia platyphyllos*), alder (*Alnus glutinosa*), wild cherry (*Prunus avium*), ash (*Fraxinus excelsior*), maples (*Acer pseudoplatanus* and *Acer platanoides*), birches (*Betula* ssp.) and rowan (*Sorbus aucuparia*) The bare-rooted transplants reach the dimension of NGSS most commonly at the age of three years. Typically, two-year-old, root-pruned plants are transplanted and then grown for one

year as transplants. Generally, it is recommended to lift the NGSS in autumn, after the first night frosts occurred.

3.6. Tree species used for experimental planting

3.6.1. Small-leaved lime

Small-leaved lime (*Tilia cordata* Mill. 1768; 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, 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, 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, HAUBOLD-ROSAR 1996; VACEK et al. 2018b), and for the transformation of Norway spruce monocultures (JAKOBSEN, 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). BARTOŠ et al. 2019 confirmed positive ameliorative effect of lime interplanted in silver fir plantation, but also worsened slenderness coefficient and overall growth of the target species (silver fir) was reported. Therefore, silvicultural measures are necessary in such type of cultivation.

Thus, the use of lime in Czech forestry is mainly as soil-improving and stand enriching species (FALTL et al. 2016; MZe 2017a) in mixed stands, especially in forests of lower and middle altitudes (PODRÁZSKÝ, REMEŠ 2005; VACEK et al. 2019b). Its share in forest cover is relatively low; the recent national inventory does not recognize the species individually, it is incorporated within the group of soft-wood broadleaves, which occupies approximately 4.6% of the forest area (FMI 2016). Ministry of Agriculture reported that the percentage of *Tilia* was 1.1% (MZe 2017*b*) or 1.2% of total forest cover without distinguishing between *Tilia* species, with natural percentage being 0.8% and recommended 3.2% (MZe 2019).

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, HAUBOLD-ROSAR 1996; DAUGAVIETE et al. 2015).

3.6.2. Wild cherry

Wild cherry (*Prunus avium* L. 1755) is considered a valuable tree that does not require a long rotation to provide good quality wood (BARTOŠ et al. 2015). It occupies a large Eurasian range; in Central Europe, it occurs scattered and rather in the lower and middle elevations. It forms at most small groups in the stands, most often growing as individual admixture. It prefers deeper, nutrition-rich and well-watered soils (but not illimerized, wet or drying). The litterfall has a favorable chemistry improving soils. Growth is quite fast in favorable conditions in youth, later it slows down significantly. It is demanding on light, in order to grow successfully, it must occupy a dominant position in the stand at an above-level storey, otherwise it will not bear fruit and loses in growth. In the sub-level position, it withers and dies (MUSIL, MÖLLEROVÁ 2005; ÚRADNÍČEK, MÖLLEROVÁ 2005).

For its quality wood, especially for furniture, cherry is classified as noble hardwood (PODRÁZSKÝ et al. 2002; SPIECKLER et al. 2009). Due to the light-loving (photophilous) nature, the crown tends to spread. Thus, the cultivation of a high-quality knotless trunk is usually not possible without pruning. However, it must be done in a timely manner and with reasonable intensity so that the cutting areas are not too large and the negative effect on growth is minimized (KUPKA 2007; SPRINGMANN et al. 2011). Wild cherry has been the subject of breeding programs for the purpose of growing a quality strain (KOBLIHA 2002). Logging is often organizationally problematic due to the dispersion of individuals in the rotation age (PODRÁZSKÝ et al. 2002). In the Czech Republic, cherries are purposefully grown only very rarely. Numerous examples are, for example, long-term cultivated quality cherry admixture in beech stands around the Vlára pass (KULHANOVÁ, LUKÁŠOVÁ 2015), or newly established stands in the vicinity of Židlochovice (STEJSKAL, DOVRTĚL 2016). Cherry also has a very good amelioration effect on the soil and with optimal representation, a stabilizing function can be considered (PODRÁZSKÝ, KUPKA 2011). The aesthetic and ecological function (increasing biodiversity) is also important. It is therefore desirable to test the cherry for use in spatial and species diversification of forest stands.

It is a fast-growing pioneer tree species suitable for afforestation of former agricultural land. To prevent cherry trees from stem sprouting, the growing in mixed stands is recommended (BARTOŠ et al. 2015). According to KACÁLEK et al. (2015), the most suitable mixtures contain tree species that do not overgrow the cherry trees. Also, to prevent cherry trees from stem sprouting, the cherries should share the stand with side-sheltering understorey.

3.6.3. European beech

European beech (*Fagus sylvatica* L. 1753) is a widely distributed tree species. With 8% of the reduced forest area in the Czech Republic (MZe 2015), it is the most common of all broadleaved forest tree species; it is also commercially important. Beech is nowadays used as an ameliorative species in coniferous forest stands and also for reforestation of abandoned agricultural lands (PODRÁZSKÝ, REMEŠ 2007, 2008; HOLUBÍK et al. 2014). Therefore, artificial plantations of beech are very common. ŠPULÁK, KACÁLEK (2016) reported significantly increased topsoil pH and bases content in old-growth Norway spruce stand when enriched by European beech. The species serves as a stand stabilizing species, and an additional of 10–20% in a mix is enough to significantly improve stability of forest stands (SCHÜTZ et al. 2006). As a result, the forest area of European beech in the Czech Republic has been steadily increasing in the last 10–20 years (PODRÁZSKÝ et al. 2014).

3.6.4. Common oak

Common oak (*Quercus robur* L. 1753) belongs to the family *Fagaceae*. The genus *Quercus* associates approximately 320 species with an area across the Northern Hemisphere, from Europe through East Asia to North America. This genus represents about twenty species in Europe (KLIKA 1947). There are eight species of oak in the Czech Republic. Of these, only two species, sessile oak (*Quercus petraea* (Matt.) Liebl.) and common oak dominate the representation and economic importance (ÚRADNÍČEK et al. 2009). The enlargement area extends across almost Europe, except for southern Europe, where it does not occur in the southern part of the Iberian Peninsula, Sicily, Sardinia and the southern part of Greece. The northern border is the southern part of the Scandinavian Peninsula (ÚRADNÍČEK et al. 2009). Vertically, *Quercus robur* is limited to the lowland and upland areas and only reaches over 1000 m a.s.l. in the western and southern parts of its area (KLIKA 1947). Common oak is a light-demanding species. The demands for light are higher than in sessile oak (KACÁLEK et al. 2017). He is able to endure a slight shade only in the lowest stage of development, up to five years of age (KYZLÍK, MICHÁLEK 1963). However, MAUER 2001 reported that seedlings were only able to survive under maternal growth for one year; in the case of loose growth to 0.5, the survival time was extended to two years. Especially on the basis of water requirements, two oak ecotypes are distinguished – floodplain oak and forest steppe. The floodplain ecotype is adapted to the habitats of the floodplain forest. It requires an elevated moisture in soil, optimally permanently higher groundwater level and is resistant to the regular floods typical of hard liquor in which the skeleton forms the stands. Soils prefer deep, loamy and nutrient-rich (SLÁVIK 2004). The forest-steppe ecotype is adapted to shallow, drying soils to forest-steppe habitats and is therefore similar to winter oak in terms of water regime (ÚRADNÍČEK et al. 2009). In contrast to winter oak, it prefers acid soils, where winter oak displaces for its higher competitive ability. Summer oak. Common oak typically does not form monocultural stands, as it is usually accompanied by other broadleaves and Scots pine in mixtures (SVOBODA 1955).

3.7. Methods of afforestation with NGSS

There is not an attempt to replace common-sized planting stock by NGSS in situations where it is not necessary (BALÁŠ et al. 2018*a*). The use of NGSS can be a suitable option as an additional method of forest regeneration in situations where the benefits of large-sized planting stock are obvious, and where common sized planting stock reaches its limitations under the unfavourable site conditions. Although the possibilities of using NGSS are wider, this thesis focuses on three examples and builds on one previous research:

- stands with vigorous weeds (*Calamagrostis*, *Rubus* etc.), i.e. stands on nutritionally rich soils, former agricultural land, old clear-cuts difficult for afforestation

– first phase of afforestation on reclaimed sites where the NGSS are used for the creation of stand skeleton, which will be subsequently completed by other types of tree species and other types of planting stock.
– afforestations under different abiotic disturbances (waterlogging, wind disturbance, late frost episodes)
– it also builds on previous research on climatically exposed sites in frost hollows (BALÁŠ et al. 2011; KUNEŠ et al. 2014a)

There is a general requirement that the width and depth of planting hole must correspond with the proportions of the root system of the planted trees. Planting hole can be dug in a common way using hand tools (axe-mattock). However, using portable earth auger is more appropriate. The autumn planting period of NGSS is assumed to be preferred (over spring) almost exclusively for the reasons of broadleaf tree physiology, suitable climatic conditions and work organization.

3.8. Examples of use of NGSS

The thesis presents model locations with examples of plantations where technology of NGSS was used as follows: Reclamation sites after sand mining, afforestation former agricultural lands, habitats with strong weed competition and potential to dry-out and the use in mountain conditions is briefly summarized as it is part of previous research.

3.8.1. Reclamation sites

The experiments with NGSS on reclamation sites were done in locations Planá nad Lužnicí and Týniště nad Orlicí. The purpose of using NGSS technology on reclaimed sites is that the stage of "established plantation" is achieved faster. This has an importance for shortening the time period during which the protection against game and weed is needed (BALÁŠ et al. 2018*b*). The result should be a considerable reduction in the maintenance costs. The planting stock of the NGSS dimension can be used in the first phase of afforestation for the creation of the stand skeleton, which will be subsequently completed by other types of tree species and other types of planting stock. Potential extent of NGSS technology in the nationwide scale was estimated to be about 2.5% of the total production of broad-leaved planting stock (BURDA et al. 2015; BALÁŠ et al. 2018a). For this potential scope of application of this technology (i.e. about 200 to 250 ha per year), the expected annual savings within the Czech Republic are about CZK 12 million and consists mainly of: (1) elimination or important reduction of costs for weed control; (2) reducing the costs of repeated regeneration (beating up of plantations); (3) shortening the time to achieve the stage of an established plantation in the average of years, thereby reducing the cost of game protection (maintenance of fencing or repellent protection); (4) reducing the average time period of the forest land being rejected from production due to failure of afforestation or slow growth of the plantation by 2 years.

3.8.2. Former agricultural lands

Another important beneficial use of NGSS is on abandoned agricultural land, which is represented in this thesis by locations Truba Research Station and Raspenava. 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, 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. 2014a; BALÁŠ et al. 2016 or GALLO et al. 2018*a*). The initial size of plants can influence the performance 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).

3.8.3. Habitats with strong weed competition and potential to dry-out

Nutrient rich sites with strong weed competition and potential to dry-out are represented in this thesis by Truba Research Station and Vintířov-Sedlec.

3.8.4. The use in mountain regions – previous research

The thesis partly builds on previously published (e.g. BALÁŠ 2014) results from mountain regions: Jizerka-Panelka. The site represents a habitat that is greatly influenced by the freezing stress during the growing season, but also by weed competition of grasses and hard grasses. The occurrence of so-called "frost hollows" is connected with a specific terrain configuration (shallow valleys with a low lengthwise slope). Strong frost hollows usually occur in mountainous locations, but under corresponding terrain conditions, they can be found even in the middle and lower altitudes. The occurrence of sub-zero temperatures, dangerous especially for sprouting trees, is more frequent in the zone near the ground than in the higher zones (above 1 m).

Therefore large-sized planting stock should be preferred in frost hollows, and frost-resistant species should be selected. It is desirable to plant the trees under the crown shelter of trees that are already growing on the site. Another way is to apply multiphase afforestation when the most resistant species are planted in the first phase, and more sensitive species are planted later – after at least partial development of crowns of the trees planted in the previous phases of afforestation.

In previous experiments in mountain frost hollow, the planting stock size (saplings vs. common-sized transplants) significantly influenced the growth performance of rowans (KUNEŠ et al. 2014*a*). The height growth of saplings was more rapid than that of common-sized transplants. As for growth, neither the saplings nor common sized transplants did significantly respond to initial fertilizing. The extreme temperature events during growth seasons as well as snow and ice-coating deformations might be the decisive factors influencing growth performance of rowans under extraordinarily harsh environmental conditions. On the frost-exposed site the height of taller saplings might at least partly compensate for the shelter of a missing forest stand.

3.9. Possible economic benefits of new generation saplings and semi-saplings

The NGSS (taller than 80 cm) planned and produced for the use in forestry and tested in the presented experiments must fulfil high quality standards (BURDA, NÁROVCOVÁ 2009; KUNEŠ et al. 2011a). They have to be also substantially cheaper than a comparable planting stock for amenity purposes. The specially adopted machine technology enables to intensify the production of saplings and thus keeps the production costs low (depending on the species approx. 1–2 EUR per tree). The quality saplings are not intended for common forestry situations. In the extraordinary cases, such as frost-exposed or extremely weeded localities, their use might bring more satisfactory results than use of common-sized planting stock (KUNEŠ et al. 2014a). Work and time samples published by BALÁŠ et al. (2016) suggest that considered that total time required for complete planting of one sapling is around 69 s when related to one worker, and the work costs with the device depreciation of one sapling are approximately 4 CZK (0.16 EUR) without the price of plant.

The economic benefit of using the presented technology is ultimately the result by reducing the afforestation costs (or achieving a secured culture) on some specific habitats that are difficult to standard procedures, and therefore very costly, woodland. Using NGSS technology at sites with the assumed failure to adopt and grow standard-sized planting stock to reduce the overall costs of achieving a secured culture. The proposed system will contribute to a reduction in post-planting shock, and so to accelerate the growth of cultures (KUNEŠ et al. 2007; BALÁŠ et al. 2018a).

For the potential scope of NGSS application (200 to 250 ha per year) the expected savings within the Czech Republic would amount to CZK 12 million annually and would consist of especially in (taken from BALÁŠ et al. 2018a):

– Reduction (to the full elimination) of the cost of weeding (when considered annual cost of weeding of CZK 8 000 ha an annual saving CZK 1.8 million);
– Reducing the cost of repeated renewal (at the annual cost considered for an improvement of CZK 16 000 ha the annual savings would be CZK 3.7 million);
– Reduce the time to achieve a guaranteed crop by an average of 2 years, thereby reducing it costs of gamekeeping (maintenance of the fence, or protection with help repellents), (at the estimated annual cost of gamekeeping of CZK 9 000 per hectare would have an annual financial savings of CZK 4.1 million);
– Reduction of the average time by 2 years when the forest land is actually decommissioned due to failure of afforestation or slow growth of culture (in the case of the average annual toll increase of 4 m^3 ha and average monetization of wood 1 500 CZK/m^3 would be an annual increase in the income from the sale of timber in the whole Czech Republic at the owners of the forest was CZK 2.8 million).

The economic benefit of using the presented technology is ultimately the result by reducing the afforestation costs (when assessing the cost of the stage of achievement protected cultures) at some specific habitats that are standard processes that can only be relied on with difficulty and hence also with considerable (increased and repeated) costs (BALÁŠ et al. 2018*b*). Use of NGSS technology at habitats and management units with anticipated failure to pick up and grow seedlings of standard (custom) dimensions leads to a reduction in total costs in the secured culture stage (e.g. by exclusion) additional costs of repeated forest renewal. In addition, NGSS technology on some problem sites (large calamities) can represent one of the few ways to achieve successful afforestation in real time clearing and forest. A semi-mechanized method of digging holes through a motor jammer leads to increased work performance, resulting in direct labour costs savings at planting. But perhaps even more important is the opportunity to save some of the work forces, with which the forestry sector is currently facing a lack, and thus to streamline the organization of work. Afforestation can be managed in a shorter time, planting it is possible to find time in the climatically optimal periods. This aspect is gaining especially in drier areas and in colder rain years. Use NGSS assumes the autumn planting date. This allows the deforestation to be decomposed tasks on managed forest property by moving their part from the workplace exposed and often climatically less suitable springtime until autumn period. The real work performance of the motor auger, and thus the cost of making the well (or whole planting), they are always dependent mainly on field conditions and other circumstances that are difficult to predict (and quantify) and which are for each individual location. The work performance is particularly influential soil properties. In particular, the presence of skeleton, roots or branches in the soil and then cover (buckwheat, blackberries) complicates work with the hammer and reduces working performance. At the same time, the larger diameter of the drill (for larger seedlings) means on a given site, a lower number of wells produced per unit of time. At the same time note that the size of the drill bit is less effective at the work performance than the effect of soil properties. Installing the motor jammer means twice up to three times the time savings when making holes compared to hand tools. The time for the planting of the tree is practically identical. Total time savings so it can be about 30–50%.

The following are the general summaries of the NGSS projected aspects overview, processed in the sense of SWOT analysis (BALÁŠ 2018a):

Strengths – Increase in work performance (shift performance during preparation planting holes), improving ergonomics of work for forest workers, improving planting quality, reducing the cost of follow-up care on forest-based culture.

Weaknesses – limited use of motor augers in unfavourable soil and forest conditions, a considerable cost of acquiring a motor auger with accessories and the necessity of its maintenance, the requirement of responsible access to work, lack of responsible and qualified workers (forest workers for cultivation);

Opportunities – widening the range of possible forest foundation practices, positive manifestations organisationally and biologically more favourable autumn plantings, increased qualification of workers in cultivation, modernization of afforestation.

Threats – formal obstacles (requirements in competitions etc.), general the preference of short-term financial savings irrespective of the possible long-term positive effects, conservatism and reduced competitiveness of forestry companies when introducing new technological procedures for the establishment of forest stands, negative popularization of technology after its inappropriate application. It is expected that the positive effects of applying the technology of NGSS in forestry will be manifested in particular in:

- reduction of the necessary costs of care for the established forestry culture, especially weeding
- reducing the cost of improving crops (reducing the share of the failure of initial afforestation)
- shortening the time to reach a secure crop, thereby shortening the time it takes need to apply gamekeeping (repellents, fencing)
- shortening the time when the clear-cut area is out of production due to the failure of afforestation or slow growth of the newly established forest culture.

If we assume the expected effects and quantify their economic aspects, then at the presumed average price of CZK 24.00 for nursery category NGSS makes the expected increase in annual sales to planting stock producers total CZK 36 million. Significantly smaller dimensions of root systems NGSS (which allow reducing the size of the planting holes compared to the predominant sizes of holes 35 × 35 cm for a large-sized planting stock) may mean a reduction of planting costs by about 10%. Reducing forest recovery losses from the usual 15% to 7.5% for the used NGSS is about 100 thousand pieces per year will reduce forestry requirements to the amount of forest tree planting material for repeating forest regeneration, which can generate savings in the order of millions of units within the Czech Republic CZK per year. The benefit of the user (the owner of the forest) is also assumed reducing the direct costs of forest management (especially for post-planting care or coatings of repellents) by 30–40%, i.e. by an amount of 3 000 to 3 600 CZK/ha. When using calculated amount of 1.5 million pieces of NGSS planting stock annually, with an area of about 1 200 ha (400 ha of summer oak and winter oak stands, 660 ha of beech forests, 140 ha of reduced species representation of other deciduous trees) is potential savings of costs for secured culture total amount up to 4 million CZK per year.

3.10. Spacing and density of planting

Only in relatively rare cases are the trees (seedlings, transplants or root-pruned seedlings) planted irregularly on the regenerated plot (POLENO et al. 2009). This usually occurs when planting on small areas and when filling gaps in natural regeneration. In most cases, the trees are planted at regular intervals to form a certain geometric pattern called spacing. Spacing is an important parameter for plantation establishment. It defines the number of trees that are planted on a defined area, total available free space around each tree, and the distribution pattern of the individuals within the final plantation. The spacing should be carefully chosen with, having the design of the final forest stand in mind (NEUMANN 2003). A universally regular spacing of seedlings occurs with a triangular and square clip. Due to the frequent strip preparation of the soil, the planting of seedlings is carried out in such a way that the distance between the rows is greater than the distance between the trees in the rows so that a rectangular (row) spacing is formed. In the case of a square and a rectangular clip, the area defined by the clip is identical to the theoretically derived one available area per seedling, which in older forestry literature was referred to as bed of seedlings, in older age a bed of a tree – in the case of a square spacing it is (a^2), in the case of a rectangular one ($a \times b$). The triangular spacing is using the available space more effectively (NEUMANN 2000).

3.11. Other supplementary experiments with saplings and semi-saplings

3.11.1. Brassinosteroids

Brassinolides are plant hormones that were first isolated from *Brassica napus* L. pollen by GROVE et al. (1979). There are many types of artificially synthesized analogues to the natural brassinolide, which are named brassinosteroids (BRs), (BACK, PHARIS 2003). Brassinolides are considered as prospective stimulants of performance and growth of plants (BAJGUZ 2011). They naturally occur in various parts of plants (KRISHNA 2003; BAJGUZ, HAYAT 2009), and they are present in young tissues in higher concentrations (RAO et al. 2002). BRs also influence a range of physiological and morphological reactions in plants (e.g. SASSE 2003). Some experiments have showed that the application of BRs had positive effects on germination, growth, vitality and stress resistance of agricultural and woody plants, e.g.: increased number of fruits in commercial yellow passion fruit (*Passiflora edulis f. flavicarpa* L.) (GOMES et al. 2006), enhancement of seedling growth of sorghum (*Sorghum vulgare* Pers.) under osmotic stress (VARDHINI, RAO 2003), cell elongation of rice (*Oryza sativa* L.) seedlings under low temperatures (FUJII, SAKA 2001), seed germination and seedling growth enhancement of maize (*Zea mays* L.) (HE et al. 1991; SINGH et al. 2012) and cucumber (*Cucumis sativus* L.) (KHRIPACH et al. 1999) under chilling stress, increased freezing tolerance of *Bromus inermis* Leyss. (WILEN et al. 1995), and increased sugar beet (*Beta vulgaris* L.) yield (HRADECKÁ et al. 2009). BRs were also reported to improve seed germination of forest trees (LI et al. 2005) and promote the initiation of embryogenic tissue formation of coniferous trees (PULLMAN et al. 2003). Further, KHRIPACH et al. (1999) suggested that, for practical application, the general ability of BRs to increase the resistance of plants to unfavourable environmental factors, such as extreme temperatures, drought, salinity, or pesticides could be crucial.

In the conditions of Central Europe, late frosts are an abiotic factor causing substantial damage in forest plantations. The adverse effects of sub-zero temperatures are accentuated in late spring, when the young buds and leaves have not yet fully matured. The frost damage susceptibility differs among the tree species. For instance, the threshold when sprouting spruce and pine buds are injured is around –3 °C and –6 °C, respectively (CHRISTERSSON, VON FIRCKS 1988). European beech is generally known as a frost-sensitive species, although dormant winter buds are well-resistant to the Central European climate extremes, and even the mature foliage is considered to show fairly high frost tolerance (KREYLING et al. 2012). There is only a short time period, directly after leaf flushing, when beech becomes highly sensitive to frost (KREYLING et al. 2012; MENZEL et al. 2015; LENZ et al. 2016). DITTMAR et al. (2006) specified the temperature threshold value of –3 °C for late frost damage at the beginning of the vegetation period, which can negatively affect the radial increment. It is apparent that any visible leaf damage which is able to regenerate and has no effect on the increment can also appear after minor frost. Furthermore, it is not only the absolute minimum temperature value, but also the duration of the frost event (temperature sum), which is important in determining the severity of frost injury (LANGVALL et al. 2001).

Extraordinary temperature extremes are primarily reached during clear (cloudless) nights and days (e.g. OKE 1970; GALLO et al. 2011; LESLIE et al. 2014). The spatial distribution of low temperatures corresponds with local terrain forms, and frost events are more frequent in so called frost hollows, i.e. shallow valleys and immersed basins (LINDKVIST, LINDQVIST 1997;). The zone near the ground is particularly threatened (ŠPULÁK, BALCAR 2013). The height and diameter increments deteriorate, and mortality rate increases (KUNEŠ et al. 2014a). Some tree species are more susceptible to late frosts than others – beech is counted as predisposed (STRASSER 2011) among other common broadleaves. The susceptibility increases following the cumulation of more negative factors such as drought and heat during the day

(GEIGER 1950; STEYRER 2011), and the sensitivity to late frosts vary across the distribution range (KREYLING et al. 2012; NOVOTNÝ et al. 2015).

3.11.2. Chlorophyll analysis

Besides measuring total height and root collar diameter, the tree vitality was assessed by measuring the chlorophyll content in case of small-leaved lime plantation at Truba Research Station. 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). A non-invasive optical method using the Opti-Sciences CCM-300 chlorophyll fluorometer (OPTI-SCIENCES 2011) was used.

4. MATERIAL AND METHODS

4.1. Experimental sites

Broadleaved saplings, semi-saplings, and seedlings in different ratios were planted on selected middle-elevated sites to compare their growth performance and overall vitality. The sites are marked on Fig 4.1.1. and summarized in Table 4.1.1. There are five sites in different regions with different numbers of plots on each site.

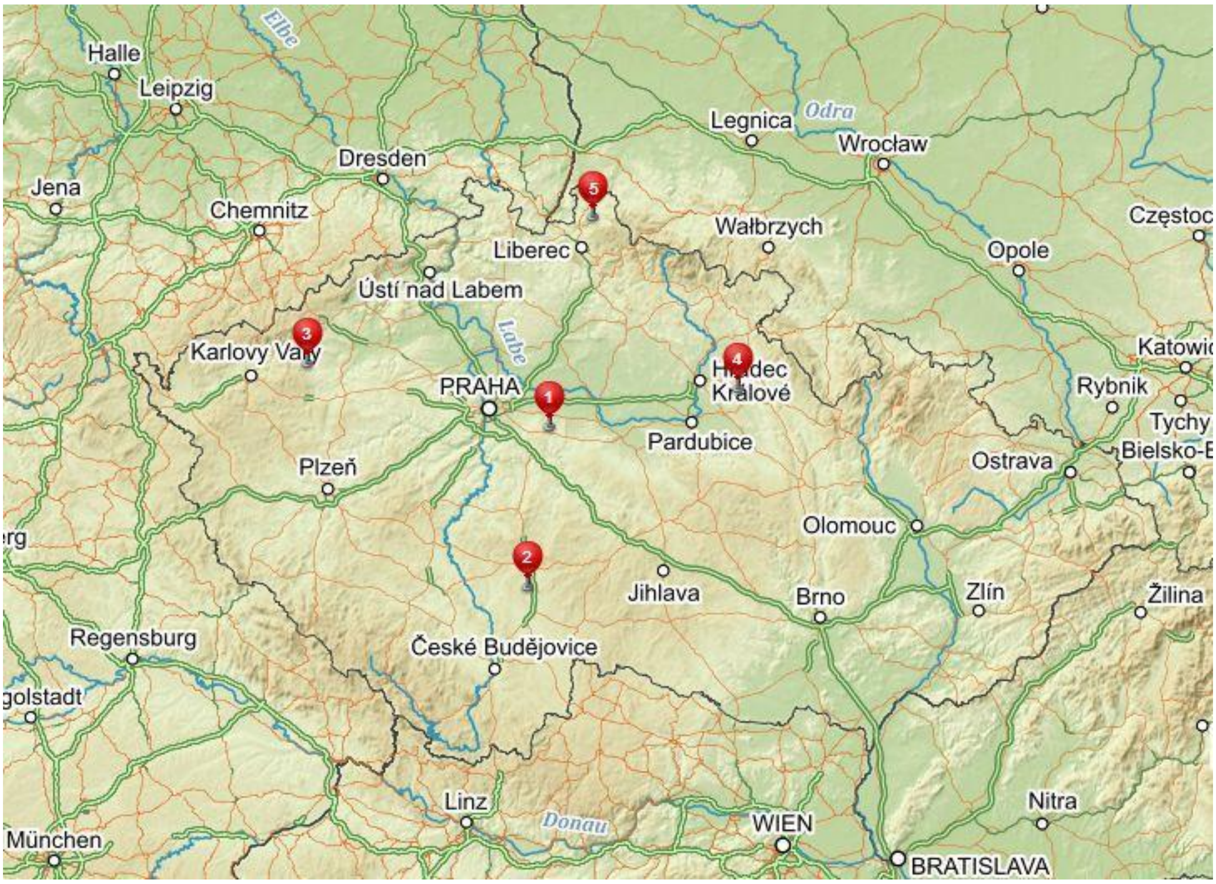


Fig. 4.1.1.: Geographical positions of experimental sites. 1 – Truba Research Station, 2 – Planá nad Lužnicí, 3 – Vintířov-Sedlec, 4 – Týniště nad Orlicí, 5 – Raspenava (Source: Mapy.cz). Complete GIS map of sites and plots is in Attachments (Attachment 1).

Table 4.1.1.: Coordinates of experimental sites in different regions and risk factors

Site name	GPS	Risk factors
Truba	N50°0.36'; E14°50.25'	drought-heat stress, weed competition
Planá	N49°19.48'; E14°41.95'	reclaimed site – poorly developed soil, temperature extremes
Vintířov	N 50°16.5', E 13°14.93'	weed competition, seasonal droughts
Týniště	N 50°10.2', E 16°4.93'	waterlogging, wind disturbance, poorly developed soil, droughts (according to particular plot)
Raspenava	N 50°53.16', E 15°7.93'	Weed competition (abandoned agricultural land), partial waterlogging

The large-sized planting stock proved useful and successful in the conditions of mountain frost hollow (BALÁŠ 2014, KUNEŠ et al. 2014a). The aim of this thesis was to extend the verification of the advantages/disadvantages of this type of planting stock at middle elevations on different type of bedrock and soils:

1. Truba Research Station – abandoned agricultural soil. Two plantations: (1) European beech (*Fagus sylvatica* L.) (*N* = 655; large-sized planting stock (LST)); (2) small-leaved lime (*Tilia cordata* L.) LST (*N* = 704) + standard-sized transplants (SST) (*N* = 799).
2. Planá nad Lužnicí – reclamation on former sand mines with poorly developed soils. Two plots: Lime (*Tilia cordata* L.) NGSS (*N* = 319) and standard-sized transplants (SST) (*N* = 179), and Common oak (*Quercus robur* L.) NGSS (*N* = 146) and standard-sized transplants (SST) (*N* = 155) (all within the same game exclosure).
3. Vintířov-Sedlec – forest stand with problematic regeneration of target species, on volcanic, nutrient-rich soil. Two plots: European beech (*Fagus sylvatica* L.) (NGSS (*N* = 500) and transplants (*N* = 450)) and wild cherry (*Prunus avium* L.) (NGSS (*N* = 300) and transplants (*N* = 300)).
4. Týniště nad Orlicí – type of sites in pine silviculture stands, where the target is to diversify the stands and increase their stability. Three plots (in three different locations): U Glorietu – lime (*Tilia cordata* L.); Štenclova alej – small-leaved lime and wild cherry; Písník – common oak (*Quercus robur* L.).
5. Raspenava – mid-elevation sites on acidic rocks representing former agricultural lands. Numbers and species are specified further.

The use of planting stock was in all cases determined by site suitability and by availability of desired species. Mostly used species were European beech, small-leaved lime, wild cherry, and oaks.

Table 4.1.2.: Overview of planting stock, species and numbers of individuals planted on each plot (site).

Site	Plot	Plantation	Planting stock	Number
Truba Research Station	Truba	BK	transplants – BRs	310
			transplants – control	345
		LP	semi-saplings	704
			transplants	799
Planá nad Lužnicí	Planá	LP	semi-saplings	319
			transplants	179
		DB	semi-saplings	146
			transplants	155
Vintířov-Sedlec	Vintířov	BK	semi-saplings	500
			transplants	450
		TR	semi-saplings	300
			transplants	300
Týniště nad Orlicí	U Glorietu	LP	semi-saplings	192
			transplants	196
	Štenclova alej	LP	semi-saplings	272
			transplants	222
		TR	semi-saplings	10
	Písník	LP	semi-saplings	219
			transplants	215
		DB	semi-saplings	40
Raspenava	Raspenava	BK	semi-saplings	specified according Blocks A–G
		BK	transplants	
		DB	semi-saplings	

4.2. Characteristics of research sites

Following is the detailed description of research sites (and plots within sites), plantations and the planting stock used.

4.2.1. Truba Research Station

4.2.1.1. General 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 site is an example of afforestation of former agricultural land. The plantation was established on abandoned agricultural land formerly cultivated for a long time and then used as a forest nursery. It is a typical site where trees grow under heavy weed competition.

A general recommendation for artificial regeneration on such sites says that the initial height of the planting stock should not be considerably smaller than the height of the weeds. Therefore, it is suitable to use large-sized planting stock. Forest type was mapped as 3S2 – fresh oak-beech forest with *Galium scabrum*. Forest types in the vicinity were 3P1 – acidic fir-oak forest with *Luzula Pilosa*, 3K2 – acidic oak-beech forest with *Carex pilulifera*, 2M1 – nutrient-very poor beech-oak forest with moss and lichens (ÚHÚL 2018; VIEWEGH 2003b). The area was stock fenced (protection from deer, hares and rabbits).

Climatic characteristics were measured by an LEC 3010 datalogger (produced by Libor Daneš Co., Czech Republic). Monitored parameters included hourly temperatures at three heights above the ground, soil temperature (10 cm below ground) and precipitation. Averages and totals were calculated (Table 4.2.1.1.). Average temperatures were calculated (according to standards) as weighted arithmetic mean from daily values (at 7, 14, and 2 × 21 h). Temperatures near the ground were, on average, lower than those recorded at a higher level above the ground. Long term climatic data (1941–2018) from nearest meteorological station in Ondřejov operated by the Czech Hydrometeorological Institute – CHMI (GPS: N 49°54.63333', E 14°47.01667' altitude 528 m a.s.l.) suggest that the average temperature was rising (Table. 4.2.1.2.). Between 1941 and 1950 the mean of average annual temperature was 7.3 °C and it reached 8.9 °C between 2011 and 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. 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 4.2.1.1.). 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). On the other hand, also typical frost episodes occurred (GALLO et al. 2017), similarly to mountain frost hollow sites (GALLO et al. 2014), although with flattened extremes (Fig. 4.2.1.2.). Such effects can have an important negative influence on growth of young trees, on European beech in particular (STRASSER 2011).

Table 4.2.1.1.: Climatic data on the experimental plot Truba.

	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
2018	10.9				389
2019	10.2				528

*Data missing – technical problems

Table 4.2.1.2.: Long term climatic data from meteorological station Ondřejov (ca 10 km south from Truba), source: CHMI.

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

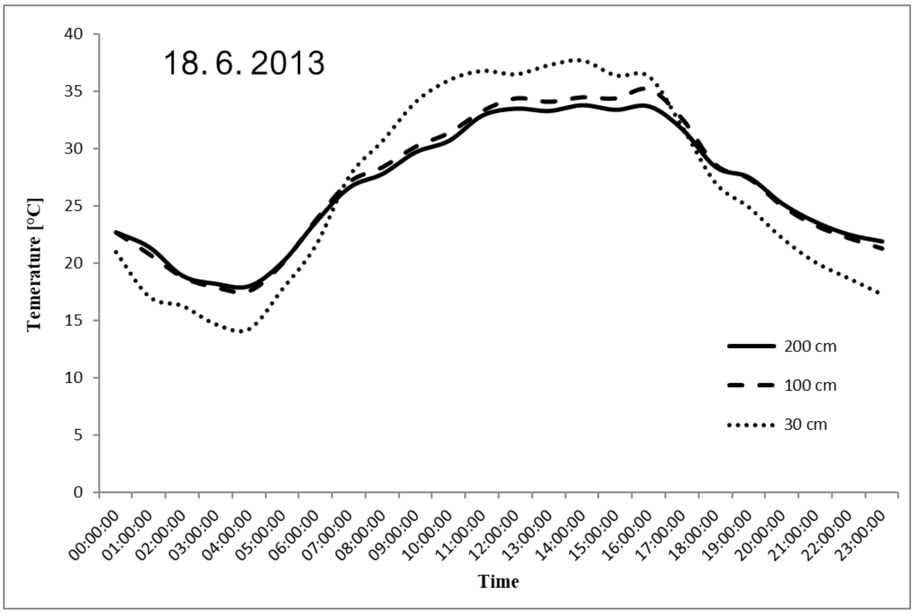


Fig. 4.2.1.1.: Dynamics of a typical heat wave event on 18 June 2013 on the experimental plot Truba. A higher amplitude of temperatures (more extreme course) at the lowest level above the ground was clearly observed.

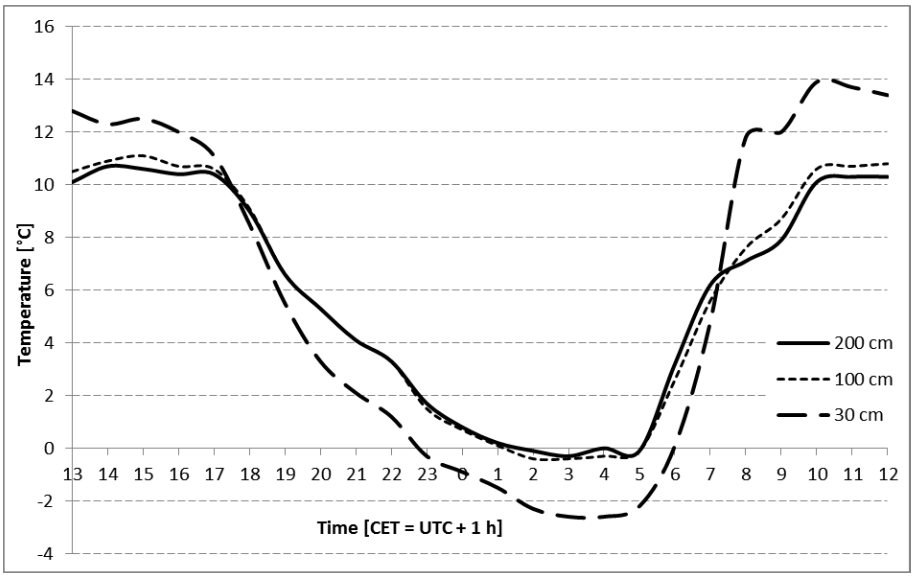


Fig. 4.2.1.2.: Dynamics of a frost event on 4–5 May 2014 on the experimental plot Truba. A higher amplitude of temperatures (more extreme course) at the lowest level above the ground was clearly observed.

4.2.1.2. Soil characteristics

To determine principal soil characteristics at Truba research plot, 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, base saturation, hydrolytical acidity and exchangeable H^+, Al^{3+}.

Soil physical and chemical characteristics are shown in Table 4.2.1.3. 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). The tests were performed in laboratories of VÚLHM Opočno by Ing. Josef Tomáš, as in the cases of other soil and nutrient analyses.

Table 4.2.1.3: Soil characteristics on investigated experimental plot Truba. SBs – sum of soil bases, CEC – cation exchange capacity, BS – base saturation, sd – standard deviation. The available soil nutrients were determined using the Mehlich III extraction method.

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

4.2.1.3. Lime (*Tilia cordata* L.) semi-saplings and standard transplants experiment

The experimental plantation of small-leaved lime was established in autumn of 2012 with a spacing of 1 × 1.5 m. The experimental plot was situated in the area of Truba Research Station near Kostelec nad Černými lesy, the Czech Republic. The surface was flat, the soil of a sandy-loam character, and the area exposed to direct sunlight for most of the day. The upper layers of the soil have the character of an orchard of granularity corresponding to the sand-clay type.

Generally, the stand conditions represented afforestation of abandoned agriculture land. The area was protected by a fence. The aim was to compare the dynamics of the growth of the planting stock of different initial sizes, namely in the dimensions of the saplings and seedlings. These two height classes were arranged in rows, alternating by three rows, the planting holes were made using an earth auger (drill), the influence of the game was eliminated by fencing.

Since 2013, an automatic meteorological station has been installed in the immediate neighbourhood of the experimental plantation (datalogger type: LEC 3010, designed and produced by Libor Daneš company, www.libordanes.cz). The overview of basic climatic conditions in years 2013–2019 is shown in Table 4.2.1.1. Precipitation during whole year was measured by a standard non-heated tipping bucket rain gauge with circular surface of 500 cm^2, i.e. diameter ≈ 25.3 cm.

4.2.1.4. 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. Two types of bare-rooted planting stock sizes were compared, 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) (STIHL 2006). 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 standard sized transplants and saplings were bare-rooted, originated in the eastern part of the Czech Republic (Region: Českomoravské mezihoří, Předhoří Hrubého Jeseníku). Saplings were characterized by a height class of 80–120 cm, root collar diameter 11 mm, while it was 36–50 cm and 8 mm respectively in the case of standard-sized transplants. Both types of planting stock were three years old, root-pruned and transplanted (1−1+1) during nursery production.

4.2.1.5. Beech resistance to frost and the use of brassinosteroids

Initial growth of a young plantation of European beech treated by a brassinosteroid compound prior to planting was measured and compared with a control treatment: we assessed heights, root collar diameters and mortality rate during the period of 2012–2015. The trees showed a posterior damage by near-ground frost after a substantial late frost event on the night of 4–5 May 2014. Therefore, we evaluated the post-stress vitality of trees, subsequent height increment from spring to August, and the height range of the damage.

4.2.2. Planá nad Lužnicí

The site represents an example of afforestation on reclaimed area after the mining of raw materials (the sand-quarry in this case). The soil environment is described as an anthroposol, which is unfavourable for the growth of planted forest trees. An extensive variability of soil characteristics within the research area was recorded (sandy-gravel, sand, clay; chemical characteristics in Table 4.2.2.1.). Forest site type was mapped as 1M3 – nutrient-very poor pine-oak forest with *Vaccinium myrtilus* (ÚHÚL 2018). Forest types in vicinity were 1M2 – nutrient-very poor pine-oak forest with *Avenella flexuosa*, 0P1 – acidic fir-oak-pine forest with *Vaccinium myrtilus*, 0P5 – acidic fir-oak-pine forest with *Picea abies* and *Abies alba* (VIEWEGH 2003*a* p. 135), 0G2 – humid spruce-pine forest with *Molinia coerulea* on serpentine, 3S3 – fresh oak-beech forest with *Carex digitata*, and 2L5 – stream floodplain forest (bank of the Lužnice river).

The experimental plot was situated at reclamation site near Planá nad Lužnicí, Czech Republic (GPS: N49°19.476', E14°41.950', altitude 398 m a.s.l.), on anthropogenic soils developed after sandstone mining. The surface was flat, soil character was sandy, and the area was exposed to direct sunlight for most of the day. The area was protected by a fence.

The sandpit is situated about 2 km south of Planá nad Lužnicí (N49 ° 19.48 '; E14 ° 41.95', elevation about 400 m), 3rd LVS (forest vegetation zone) on the border of PLO (natural forest region) 15 (Třeboňské pánve) and PLO 10 (Central Bohemian Hills, see Attachment 3). The average annual temperature in Planá nad Lužnicí is around 8–9 °C; and the average annual rainfall is around 550 mm (TOLASZ 2007). The research area is located on the internal dump of Planá nad Lužnicí and consists of several sub-plantations of NGSS with pedunculate oak (*Quercus robur* L.), small-leaved lime (*Tilia cordata* Mill.) and black alder (*Alnus glutinosa* L.), established in several stages in 2012–2015. For the purposes of the research, one fenced research plot with lime and oak was chosen to be monitored. Two species, small-leaved lime and common oak, and two sizes of planting stock, were planted, i.e. four variants inside the fenced area. NGSS were 81–120 cm in terms of height class, compared to 36–50 in case of standard-sized transplants. Natural forest regions of the planting stock were 10 – Central Bohemia in case of oaks and 16 – Czech Moravian Highlands in case of limes (in both cases same for both planting stock types). Cultivation formulas were 1−1−1+1 for lime NGSS, 1−1 for standard-sized limes, 1−1+2 for oak NGSS and 0,5−1,5 for standard-sized oaks.

The land for the mining of the sand is being gradually deforested and the loose soil together with other material (e.g. excess excavations from the road construction) is stored in the excavated area. The resulting internal ditches are gradually reclaimed, in particular by forestry reclamation (LEHEČKA 2006). The research area is located in the south-eastern part of the dump where the sediments from the pond Jordán in Tábor were used for final reclamation, where the dehumidification took place between 2012–2014. The total area of the sandpit was about 44 ha in 2017 (KUNEŠ et al. 2017). Changes can be interestingly monitored from aerial maps (mapy.cz) between individual years.

The purpose of the experimental plantings of small-leaved lime and pedunculate oak described here was to compare the dynamics of the growth of the planting stock to different initial sizes, namely in the dimensions of new generation semi-saplings (81–120 cm) and standard-sized transplants (36–50 cm). The plantation was established in autumn 2014 in a spacing of 1 × 1.5 m, the height classes of the planting stock are arranged in rows, the planting holes were made using an earth auger (STIHL 2006; STIHL 2014), the influence of the game was eliminated by fencing.

4.2.2.1. Soil characteristics

Analysis of soils was carried out for the plot Planá-Hůrka (Table 4.2.2.1.). The soil environment can be characterized as anthroposol. It is quite unfavourable for the growth of woody plants and its features vary greatly within the research area. When digging the planting holes, the soil substrate consisting of a material of different properties ranging from heavy plastic clays to coarse-grained gravel was found.

Table 4.2.2.1.: Soil characteristics on investigated experimental plot Planá nad Lužnicí in 2016. SBs – sum of soil bases, CEC – cation exchange capacity, BS – base saturation. The available soil nutrients were determined using the Mehlich III extraction method.

Soil characteristic	Unit	Value
pH/H2O	-	4.9
pH/KCl	-	4.3
SBs	[mval/100g]	0.8
T–S	[mval/100g]	3.5
CEC	[mval/100g]	4.3
BS	[%]	17.8
Humus (Springel-Klee)	[%]	1.7
Oxidizable Carbon	[%]	1.0
Nitrogen (Kjeldahl)	[%]	0.07
P	[mg/kg]	48
K	[mg/kg]	49
Ca	[mg/kg]	590
Mg	[mg/kg]	96

Apparently due to the occurrence of less permeable clay layer deeper under the surface and also due to insufficient climbing occurs on the part of the area in the period with higher precipitation to a significant freezing, indicating the abundant coverage of the rust (*Juncus* sp.). During the longer season without rainfall, the soil gets dryer and harder. This alternating regime greatly restricts the growth of some tree species.

4.2.3. Vintířov-Sedlec

This site represents an afforestation of an older clear-cut with nutrient-rich soil and intensive weed competition. The soil is enriched cambisol with tendency to drying. Forest site type was mapped as 3C1 – drying oak-beech forest with *Luzula luzuloides* (upper part of the plot) and 3B1 – nutrient-rich oak-beech forest with *Melica nutans* (lower part of the plot).

4.2.3.1. Experimental plantation with beech new generation semi-saplings

Plantation of European beech (*Fagus sylvatica* L.) took place in November 2016. Semi-saplings (81–120 cm) and seedlings (36–50) were used. The PLO of the site is 4 – Doupovské hory, the PLO of the planting stock was 10 – Central Bohemia.

The forest vegetation zone was 3, and forest type group 3B. It was a clearance (clear-cut) within a forest area. The area of 0.15 ha was fenced to protect the plantation from game. The planting itself was carried out by earth auger (BALÁŠ et al. 2016). Beech semi-saplings were tested under the conditions of nutrient-rich forest clear-cut site in Doupovské hory Mts. Region – their suitability for reforestation of clear-cuts and other free sites was compared to standard-sized seedlings. Growth and prosperity characteristics were evaluated – mortality, total height, height increment, and root collar diameter. Vitality throughout the vegetation period was visually assessed.

The area of interest was situated on the eastern edge of the Doupov Mountains, (localization N 50°16.5 ', E13°14.93'; elevation 425 m a.s.l.). The climate characteristic was a slightly warm area (QUITT 1971). The subsoil was a tertiary alkaline basalt (ČGS 2018), the soil could be characterized as eutrophic cambisol, sometimes with a tendency to gleying, or with increased skeletal content. It was located on the historical property of the Thurn-Taxis family, which was given back by restitution during the 1990s. The estate is classified into the LHC Vintířov u Radonic and consists of three units with a total area of around 300 ha.

The research area had the character of an older clearance (clear-cut), created around 2005, where the original afforestation with Norway spruce and European larch (*Larix decidua* Mill.)

was unsuccessful. The clear-cut area was surrounded by adult mixed stands with oak, pine, larch, lime, ash, birch, and other species. The site was heavily weeded, abounding with blackberries, nettles and grass. There were points of deciduous tree regeneration (maple, aspen, birch, oak, cherry tree) up to a height of 4 m. The individuals were mostly very poorly shaped and often damaged by game (browsing, fraying, gnawing, abrasion). Shrubby species were represented by the hazel and red elderberry (*Sambucus racemosa* L.).

Prior to planting, vegetation removal was required (grasses, herbs, and most of the regenerating trees – only those with a trunk not damaged by game were left). The transplants were treated for the first winter season with the Aversol game protector, while about a month after the planting, the fencing was completed.

The significant advantage of the advanced planting stock is its higher resistance to competing vegetation and thus the expected reduced need for weeding. Therefore, in the research planting, in the next few years there is no intention of limiting the growth of the competing weed. Only damping at annual dendrometric measurements at the end of the growing season is assumed. The weed is expected to form an ecological cover for semi-saplings at this site, but it is expected to be more threatening for standard-sized transplants. Any reduction of the competing woody species can be done later as needed.

The planting stock consisted of European beech semi-saplings and transplants of standard size (500 + 450 pcs). Semi-saplings had the following characteristics: origin from PLO (Natural forest zone) 10 – Central Bohemia (see Attachment 2), LVS (forest vegetation zone) 4 (see Attachment 3), growth formula 1–2+2, height class 81–120 cm; standard seedlings: PLO (Natural forest zone) 10 – Central Bohemia, LVS (forest vegetation zone) 4, growing formula 1–1, height class 36–50 cm. The indicated root collar diameter was 11 mm for semi-grown and 6 mm for standard transplants.

These two types of planting stock were planted in alternating rows in a 1.5 × 1.2 m spacing. The total reforested area was around 0.17 ha. Planting holes were prepared using a motor auger (a description of the technology is given in BALÁŠ et al. 2016). Planting was carried out in November 2016. Plantation was protected with against deer with stock fence.

For experimental planting, mortality, tree height, and root collar diameter were evaluated. The height was measured by a scale with an accuracy of centimetres, the root collar diameter with a calliper scale accurate to millimetres.

4.2.3.2. Experimental plantation with new generation semi-saplings of wild cherry (Prunus avium L.)

The second phase of experiments at this location was realized on December 7, 2017 using wild cherry planting stock in the dimensions of semi-saplings and standard transplants. Before planting, the vegetation (grasses and shrubs) was carried out. The competing weed was very vital during the first vegetation season, as the removal did not limit its development during the 2018 vegetation season, while at the peak of the season it reached a height of about 80–120 cm. Trees were treated with a repellent against rodents for the first winter period. Even before the actual planting was carried out high-quality protective fencing, so there was no need to use repellent against ungulate game.

An important advantage of advanced planting stock is its greater resistance to competing vegetation and hence the expected reduced need for weeding. That is why the research planting did not envisage targeted reduction of the growth of competing weed. Only tramping of unwanted vegetation is done during regular measurements (at the end of the growing season). It is assumed that the weed will work as an environmentally friendly cover for the large-sized planting stock in the given habitat, but it will be a harsh competition for standard transplants. Possible reduction of competing woody species can be done later as needed.

Planting stock consisted of new-generation semi-saplings and transplants of the standard size of wild cherry. A total of 320 individuals of standard transplants and 304 individuals of semi-saplings were planted. All these plants were subsequently evaluated before and after the first growing season. Semi-saplings had the following characteristics: PLO (natural forest region) 16 – Bohemian-Moravian Highlands, LVS (forest vegetation zone) 4, cultivation formula 0,5–0,5+1, height class 81–120 cm; standard seedlings then: PLO 29 – Nízký Jeseník, LVS (Forest vegetation zone) 1, growing pattern 1–1, height class 36–50 cm. The reported root collar diameter was 10 mm for semi-saplings and 4 mm for standard transplants.

These two types of planting stock were planted alternately in rows in a 1 × 1.5 m spacing. The total forested area was around 0.13 ha. Planting holes were prepared using a motor auger (a description of the technology is given in BALÁŠ et al. 2016).

The total annual precipitation in 2018 was 440.4 mm. The rainfall in the vegetation season (March – September) was 279.4 mm. The data are shown in Table 1, together with rainfall totals since planting in December 2017. The data were taken from the nearest weather station in Tušimice (In-pocasi.cz 2019).

Table 4.2.3.2.1.: Overview of precipitation sums in the period between outplanting to the end of 2018 on research site Vintířov-Sedlec (In-pocasi.cz 2019). Data were taken from nearest weather station in Tušimice.

Year	Month	Monthly sum of precipitation [mm]
2017	December	28.7
2018	January	51.5
2018	February	3.5
2018	March	34.3
2018	April	20.1
2018	May	111.1
2018	June	39.7
2018	July	14.2
2018	August	19.7
2018	September	40.3
2018	October	31.2
2018	November	22.3
2018	December	52.5

4.2.4. Týniště nad Orlicí

This site represents other example of clear-cut on sandy soils (plots 1 and 2) and reclaimed sand pit with sandy soil (plot 3). Natural Forest Area was 17 ("Polabí", English.: Elbe region). Plantations on three plots (Table 4.3.4.1.) within this location were outplanted in November 2011. Within the experimental site, three different experimental research plots were differentiated. Planted tree species were small-leaved lime (*Tilia cordata*), common oak (*Quercus robur*) and wild cherry (*Prunus avium*), planting stocks used were semi-saplings (81–120 cm) and standard-sized transplants (36–50 cm); in case of wild cherry, only semi-saplings (51–700 cm) were planted.

Table 4.3.4.1.: Coordinates of research plots within Týniště nad Orlicí experimental site.

Location name	GPS
U Glorietu	N 50°10.2', E 16°4.93'
Štenclova alej	N 50°10.15', E 16°6.92'
Písník	N 50°9.28', E 16°6.70'

1. U Glorietu – the plot was characterized as recent clear-cut on a plain site with sandy soil. Planting stock was composed of saplings and standard-sized transplants of small-leaved lime in alternating rows. It was partially (alternately) waterlogged (gleying), abundant occurrence of *Molinia caerulea* (L.) Moench. There was a depression in the centre of the plot, waterlogged for most of the time (there was long-term drought at the time of measurement, no standing water at that time). Forest type was mapped as 2P1 – acidic

gleyic fir-oak forest with *Luzula Pilosa*. Forest types in the vicinity were 2O1 – nutrient-medium fir-(beech)-oak forest with *Sanicula europaea* and 2I1 – compacted-acid beech-oak forest with *Luzula pilosa*.

2. Štenclova alej – this plot was located inside a previously wind-disturbed Norway spruce stand. Soil was characterized as cambisol. Planting stock was composed of saplings, and standard-sized seedlings of small-leaved lime and wild cherry semi-saplings in alternating rows. Forest type was mapped as 2I1, and forest types in the surroundings were 2P1, 2P2 – acidic gleyic oak forest with *Carex hirta* and 2K1 – acidic beech-oak forest with *Avenella flexuosa*.
3. Písník – it is an example of a site reclaimed after sand mining. Soil has a layered anthropogenic character with undeveloped humus layer. At a depth of approx. 15–30 cm there was a very compacted layer of gravel. In the surrounding banks there are pinewoods of Scots pine in the phase of thickets to pole stands with the addition of birch and aspen. Forest type was mapped as 1M0 – nutrient-very poor pine-oak forest, forest type also in the surroundings was 1M3 – nutrient-very poor pine-oak forest with *Vaccinium myrtillus* (VIEWEGH 2003a p. 66). All faces lie flat.

4.2.5. Raspenava

4.2.5.1. General characteristic

This site represented an afforestation on former agricultural soils surrounded by mixed forests. Different blocks (plots) on the site represent different soil conditions and spacing regimes. The plots (blocks of different spacing regimes) at this location were established in spring 2016. The experimental site was located near Raspenava (N 50°53.17', E 15°7.97', elevation 370 m a.s.l.) in the Frýdlant salient, Northern Bohemia, Czech Republic. The site has a character of a large open area surrounded by mature mixed forests with Norway spruce, common oak, limes, red oak and other species. Climate is described as mild-warm (QUITT 1971). Under the conditions of nutrient-rich, formerly agricultural soils, a plantation of European beech (*Fagus sylvatica*) and common oak (*Quercus robur*) was established.

Forest site types on the site were mapped as 3O1 – gleyic nutrient-medium fir-oak-beech forest with *Sanicula europaea* and 3S2 – nutrient-medium oak-beech forest with *Galium rotundifolium*. Other forest site types in the vicinity are 3K1 – acidic oak-beech forest with *Avenella flexuosa* and 1T9 – nutrient-poor wet birch-alder forest with *Picea abies* and *Alnus glutinosa (Piceeto-Alnetum).*

4.2.5.2. Soil characteristics

The soils on this experimental plot were investigated in terms of physical and chemical characteristics. The soil properties are summarized in Table 4.2.5.1.

Table 4.2.5.1.: Soil characteristics on investigated experimental plot Raspenava in 2018. SBs – sum of soil bases, CEC – cation exchange capacity, BS – base saturation. The available soil nutrients were determined using the Mehlich III extraction method.

Soil characteristic	*unit*	1-A	1-B	1-C	2-A	2-B_1	2-B_2	2-C	3-A	3-B_1	3-B_2	3-C
pH/H2O	-	5.2	5.5	5.6	4.9	4.8	5.3	5.3	4.9	5.3	5.7	5.2
pH/KCl	-	4.3	4.4	4.4	4.1	4.1	4.2	4.1	4.0	4.1	4.3	4.2
SBs	*meg/100g*	9.7	4.9	5.4	4.3	2.2	2.3	0.4	5.8	4.6	6.1	3.7
CEC	*meg/100g*	15.6	8.1	8.6	12.7	7.8	5.4	3.0	13.7	10.3	9.6	7.1
BS	*%*	62.2	60.5	62.9	33.8	27.6	43.0	13.6	42.1	45.2	63.7	52.1
Humus (Springel-Klee)	*%*	5.8	1.8	1.4	7.4	3.5	1.0	0.9	6.5	3.6	1.2	0.7
Oxidizable Carbon	*%*	3.3	1.0	0.8	4.3	2.0	0.6	0.5	3.8	2.1	0.7	0.4
Nitrogen (Kjeldahl)	*%*	0.25	0.13	0.11	0.35	0.20	0.06	0.05	0.35	0.21	0.11	0.07
P	*mg/kg*	17	11	20	31	13	21	26	26	18	17	19
K	*mg/kg*	137	59	40	68	36	24	19	84	46	30	21
Ca	*mg/kg*	828	624	566	322	296	506	368	450	440	728	476
Mg	*mg/kg*	111	81	74	60	57	81	65	84	79	98	68

On this experimental site, granularity of soils was also evaluated, and the results are summarized in Table 4.2.5.2.

Table 4.2.5.2.: Granularity characteristics on experimental plot Raspenava according to different soil horizons (A, B and C) and soil pits (1, 2 and 3) in 2018.

Sample	2–0.25 mm *%*	0,25–0.05 mm *%*	0.05–0.01 mm *%*	0.01–0.001 mm *%*	<0.001 mm *%*
1-A	21.7	17.3	39.3	16.1	5.6
1-B	25.2	17.1	34.0	17.8	5.8
1-C	38.6	12.9	23.5	15.5	9.5
2-A	19.9	14.4	44.0	15.0	6.6
2-B_1	29.3	9.2	36.4	19.0	6.2
2-B_2	34.4	13.3	31.0	15.4	5.9
2-C	30.6	11.5	34.4	16.8	6.7
3-A	26.5	14.0	36.5	16.6	6.4
3-B_1	29.7	12.9	32.0	18.9	6.4
3-B_2	36.5	13.3	26.0	14.9	9.3

3-C	33.2	14.0	28.1	17.0	7.7

1 – optimal soil, 2 – pseudogley, 3 – dry soil

Table 4.2.5.3.: Soil physical characteristics on investigated experimental plot Raspenava analysed by Kopecký cylinders in 2018.

Variant	Soil horizon	Function	Momentary soil moisture	Volume density	Bulk density	Soil porosity	Maximum capillary water capacity	Maximum capillary air capacity
			(% vol.)	(g/cm^3)	(g/cm^3)	(% vol.)	(% vol.)	(% vol.)
P	Topsoil	mean	65.7	0.7	2.3	70.5	59.3	11.1
		sd	*1.46*	*0.06*	*0.04*	*2.63*	*2.17*	*4.38*
P	Lower	mean	44.5	1.5	2.6	45.0	40.8	4.2
		sd	*6.50*	*0.15*	*0.14*	*4.65*	*4.02*	*1.39*
O	Topsoil	mean	37.1	1.1	2.5	55.3	45.3	9.9
		sd	*3.40*	*0.11*	*0.02*	*3.98*	*3.27*	*1.97*
O	Lower	mean	24.8	1.8	2.7	33.4	27.3	6.0
		sd	*4.21*	*0.09*	*0.13*	*4.95*	*5.42*	*0.74*
S	Topsoil	mean	36.5	1.2	2.5	51.4	40.2	11.2
		sd	*4.06*	*0.23*	*0.04*	*8.26*	*8.49*	*2.10*
S	Lower	mean	28.6	1.5	2.7	44.1	35.0	9.1
		sd	*1.99*	*0.04*	*0.12*	*1.90*	*1.50*	*1.70*
L	Topsoil	mean	34.8	1.0	2.4	60.3	39.4	20.9
		sd	*6.97*	*0.12*	*0.15*	*3.27*	*5.15*	*4.19*
L	Lower	mean	28.6	1.2	2.7	55.8	36.2	19.6
		sd	*2.00*	*0.10*	*0.21*	*3.24*	*1.55*	*4.56*

Furthermore, the soils were analysed by the method of Kopecký cylinders (Table 4.2.5.3.). It was divided by blocks and soil horizons. Kopecký cylinders were sampled in autumn 2018. For different blocks, 5 samples of topsoil and 5 samples of lower layer were collected. From each 5 samples (according to block and horizon) mean and standard deviation were calculated. Samples were taken from optimum soil (O), pseudogley (P), dry (S) and forest (L) for comparison.

4.2.5.3. Climate in Raspenava

To describe climatic characteristics on Raspenava experimental research site, data from nearest climatic and meteorological station in Liberec–Ostašov (continuous data line since 1938) was utilized. The station is located 15 km from the experimental site. Average long-term values are summarized in Table 4.2.5.4.

Table 4.2.5.4.: Mean climatic characteristics on investigated experimental plot Raspenava. Data from climatic station Liberec-Ostašov (In-Pocasi.cz)

Month	Mean precipitation [mm]	Mean temperature [°C]
January	59	-2.2
February	50	-0.9
March	57	2.6
April	50	7.3
May	80	12.0
June	86	15.3
July	98	17.0
August	94	16.6
September	68	12.7
October	61	8.4
November	63	3.3
December	68	-0.6

4.2.5.4. Planting & planting stock

Two sizes of planting stock were used: new generation semi-saplings and standard-sized transplants. The combinations of species/planting stock were beech semi-saplings, standard-sized beech transplants and oak semi-saplings. The plantation was divided into blocks (Table 4.3.5.1.). The experimental area was fenced and weeded before planting. Regular weeding of the plantation was done every year by weeding machine.

In more detail, the experiment was established in the period from 6 to 21 April 2016, and the verification and demonstration area was established for testing new generation semi-saplings spacing with planting material of a common commercial dimension near Raspenava in northern Bohemia in spacing regimes that seem to be acceptable for the use in forestry. It is used for verification of the dynamics of planting growth in various spacing regimes and monitoring of stand conditions with the prospect that it will serve as a demonstration of the influence of spacing (densities) on habitus and planting interior.

When planting the area, the planting plan was used in eight square blocks. The area of each of them was 625 m^2. In the first four blocks, only new generation beech semi-saplings were used in different spacing regimes (Table 4.3.5.1.). The size of the planting material used was 81–120 cm, the root collar diameter was 11 mm, the origin of the Jizera Mountains, the 4th forest vegetation zone. The cultivation formulas of semi-saplings were: f1+2+1, f1+2–1, or 1–1+2. Oaks were in the size of semi-saplings (1–1–1) mixed with beech transplants (1–1). Semi-saplings of oak in the size of 81–120 cm and a root collar diameter of 11 mm originated from the 4th forest vegetation zone of the Jizera Mountains; the beech transplants originated in the 4th forest vegetation zone of the Drahanská vrchovina.

Table 4.3.5.1.: Overview of plots (blocks) and their content on the experimental site Raspenava.

Block	Species	Planting stock	Spacing
A	European beech	semi-saplings	1 × 1.2 m
B	European beech	semi-saplings	1 × 1.5 m
C	European beech	semi-saplings	2 × 2 m
D	European beech	semi-saplings	1.5 × 1.5 m
E	Alternating two types of rows: 1 – oak semi-saplings and beech transplants; 2 – beech transplants (not measured);	semi-saplings; seedlings	1 × 1 m
F	Alternating two types of rows: 1 – oak semi-saplings; 2 – beech transplants; Rows 1 m from each other, trees in 2 m distance within a row, rows shifted by 1m in relation to each other (false triangle spacing)	semi-saplings; seedlings	1 × 2 m (shifted)
G	Alternating two types of rows: 1 - oak semi-saplings; 2 – beech transplants; Rows 1 m from each other, trees in 2 m distance within a row, rows shifted by 1m in relation to each other (false triangle spacing)	semi-saplings; transplants	1 × 2 m (shifted)

Semi-saplings: height: 81–120 cm; root collar diameter: 11 mm; seedlings = root-pruned seedlings (1–1); height: 36–50 cm; root collar diameter: 6 mm.

4.3. Data collection

Tree height was measured with a scale to the nearest one centimetre. Root collar diameter (stem-base diameter) was measured with Vernier calliper scale to the nearest one millimetre. Other aspects of trees and environment were visually assessed. Annual height (root collar diameter) increments were calculated as difference in height (root collar diameter) in the respective year minus height (root collar diameter) in previous year. Periodic increments were calculated as difference between final value (last monitored term) and initial value in the first year.

In case of lime plantation in Truba, 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. Sample leaves for chlorophyll analysis were collected in second half of August from sun-exposed part of the crown. The chlorophyll foliage content (concentration in mg/m^2 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 August 2013 and 3 June 2014 in the evening to reduce the influence of the sun (DEMAREZ 1999; DAWSON et al. 2003; VAN WITTENBERGHE et al. 2012).

4.4. Data analysis

Primary data was digitalized and analysed in MS Excel using descriptive statistics. Statistical tests were performed in R environment (R Core Team 2018). Overall mortality rate was computed as a percentage of dead trees on each plot related to the number of planted trees. 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, CASTELLAN 1988) as the assumption of normality for ANOVA was not met in all cases. Normality of the data was tested by 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.

4.5. Economic analysis

As an example of a simple economic calculation of NGSS, experimental plantation with *Tilia cordata* L. at Truba Research Station was chosen (GALLO et al. 2020a). A simple comparison of costs was undertaken on the economic effectiveness of the two different reforestation approaches: planting using large-sized planting stock or SST. The costs related to the purchase of planting stock, outplanting 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 an admixture to an existing forest and protect them individually. In this case, the number of large-sized planting stock 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 outplanting location was considered to be equal for both types of planting stock, as large-sized planting stock 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 the 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 outplant one large-sized planting stock and SST to be EUR 0.45 and EUR 0.3 respectively. The fencing costs were estimated to be EUR 4,000, corresponding to a minimum CZK 100,000 per km (in case of ideal terrain and rectangular shape of fenced area), 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 large-sized planting stock and standard-sized planting stock 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 large-sized planting stock initial height), while large-sized planting stock requires no weeding. The weeding needs vary in practice considerably, depending on climate and specific site characteristics.

4.6. Analysis of above-ground and below-ground biomass of planting stock

During outplanting of two plantations and individual admixture (Vintířov-Sedlec, Kozí Hory) in November 2017, 5 sample trees of each planting stock and 5 different species (common oak, wild cherry, wild service tree, service tree and crab apple) were taken for analysis of above-ground and below-ground biomass. The biomass was analysed by the xylometric method on 23/11/2017. Samples were divided into above-ground and below-ground parts, which were then compared. Measurements were done with accuracy to 5 ml. Not all tree species evaluated in this analysis are included in the experimental plantations assessed in the present thesis as crab apples were planted in Kozí Hory (2017), wild service trees in both Kozí Hory and Vintířov-Sedlec, but as part of newer plantations that will be assessed in future, and service trees in Vintířov-Sedlec, also as part of newer plantations.

5. RESULTS

Following part presents the results obtained from individual research plots. It is divided according to research sites and research plots within particular site.

5.1. Truba Research Station

5.1.1. Beech plantation

Data from this particular experiment were published in GALLO et al. 2017. This part is an additional information to the completion of the dissertation thesis.

Mortality rate

In all monitored terms, BR treated plants showed an insignificantly (p = 0.244) lower mortality rate than the control. The high initial mortality in summer 2012 can be ascribed to a transplant shock, as the plantation showed a gradually decreasing total (overall) mortality as the experiment progressed (Fig. 5.1.1.1.), i.e. the increase of the cumulative mortality slowed down.

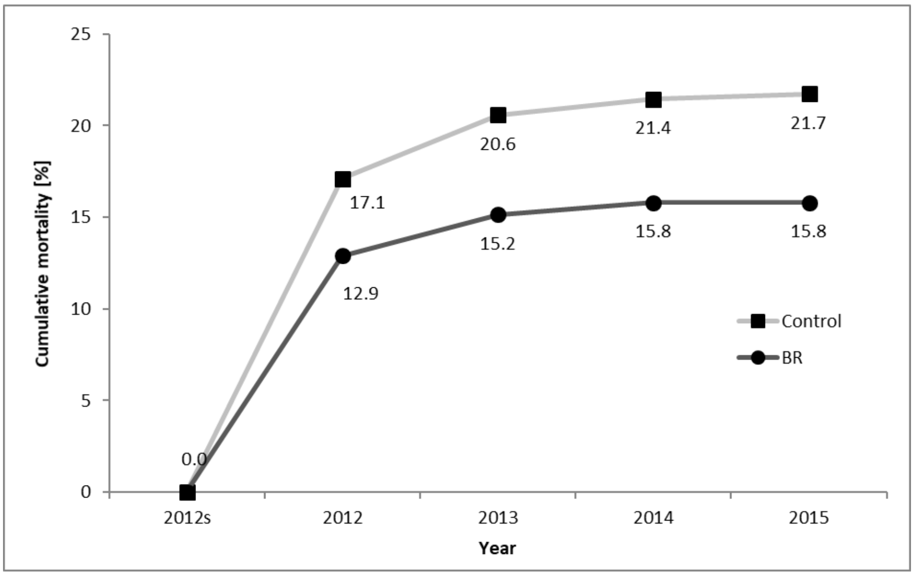
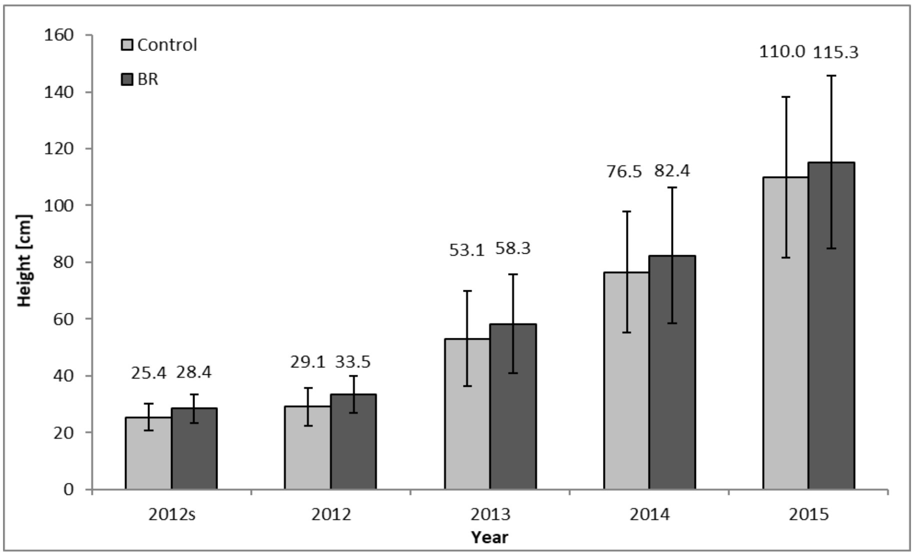


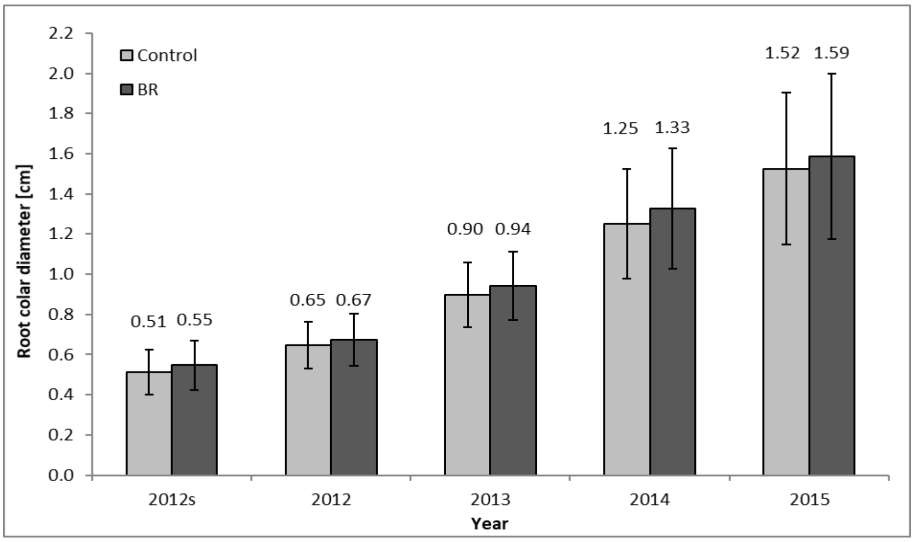
Fig. 5.1.1.1.: Cumulative mortality rate [%] of European beech (*Fagus sylvatica*) transplants recorded in spring 2012 (2012s) and autumn 2012–2015 on experimental plot Truba in the brassinosteroid treatment (BR) and control.

Height, root collar diameter

In all monitored terms, the mean height of the BR treatment insignificantly surpassed the control treatment in absolute numbers. Both treatments showed a stable increment (Fig. 5.1.1.2.a). The differences in the periodical height increment from 2012 to 2015 were not significant ($p = 0.127$).



(a)



(b)

Fig. 5.1.1.2.: Mean heights (a), means of root collar diameters (b) of European beech (*Fagus sylvatica*) transplants on investigated research plot Truba recorded in spring 2012 (2012s) and autumn 2012–2015 in the brassinosteroid treatment (BR) and control. Error bars depict standard deviations.

In the increment of mean root collar diameter (Fig. 5.1.1.2.b), there was a pattern of an advance in the BR set, but the differences were insignificant ($p = 0.434$), as in the case of mean height.

Impact of the frost event

The duration of the frost episode was 7 hours (at 30 cm above the ground) (Fig. 4.2.1.2.). The minimum temperature reached −2.6 °C and the sum of sub-zero hour temperatures was –12.4 °C. At 100 cm above ground, the duration was 4 hours, the minimum temperature reached −0.4 °C and the sum of sub-zero hour temperatures was −1.2 °C. At 200 cm above ground, the duration was 4 hours, the minimum temperature −0.3 °C, and the sum of sub-zero hour temperatures −0.5 °C. The following day, the maximum temperature reached 17.7 °C, 15.0 °C, and 14.2 °C at 30 cm, 100 cm, and 200 cm above ground, respectively. The pyranometer showed this was an almost clear to partly cloudy day. The values of solar irradiance were relatively high, corresponding with direct sunlight (maximum 851 W/m^2 at 10:00), but fluctuated during the day due to clouds.

The characteristics of the plantation one week after the frost event are shown in Table 5.1.1.1. The mean height was higher in BR treatment; however, the absolute upper limit of damage was lower for BR treatment. The mean range of damage was 5% lower in the BR treatment compared to the control treatment. Trees that showed negative increment (breakage, dry terminal) were excluded from the calculation of mean annual increment after frost event.

Table 5.1.1.1.: Characteristics of experimental European beech (*Fagus sylvatica*) plantation after frost event on the night of 4–5 May 2014 on investigated research plot Truba.

	Control	**BR**
Total number of trees	268	253
Number of intact trees	44	44
Number of damaged trees	224	209
Mean height of trees [cm]	61.3	66.6
Sd [cm]	17.4	18.9
Mean annual increment after frost event [cm]	16.3	16.7
Sd [cm]	11.9	12.7
Mean range of damage [cm]	31.2	29.7
Sd [cm]	14.9	14.9
Mean height of lower limit of damage [cm]	11.6	11.9
Sd [cm]	13.3	13.0
Mean height of upper limit of damage [cm]	42.8	41.7
Sd [cm]	12.0	12.1
Maximal range of damage [cm]	75	70

Sd – standard deviation, BR – brassinosteroid treatment

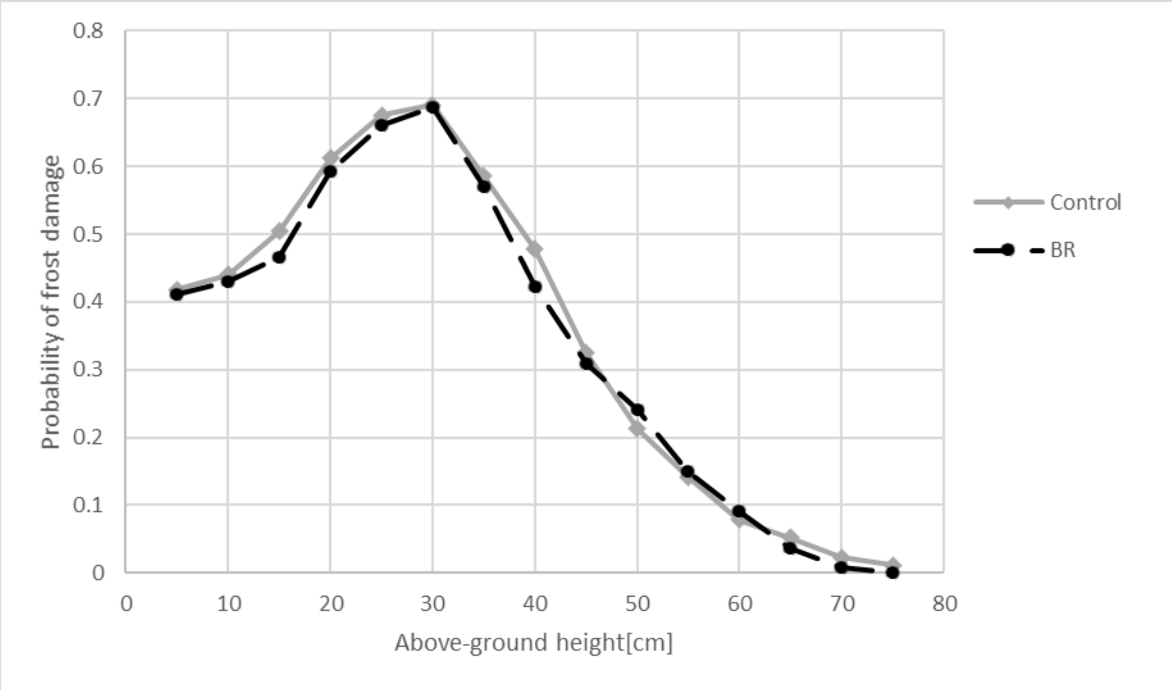


Fig. 5.1.1.3.: Distribution of damage to European beech (*Fagus sylvatica*) transplants among height levels and treatments, showing the frost damage probability on investigated research plot Truba. Each tree was counted according to its range of damage at various height levels. The highest probability of frost damage was at 30 cm above ground level. The graph is not a distribution function *sensu stricto*, as the sum of probabilities of all heights is not equal to 1. As an example, trees damaged at 20–40 cm were used for calculating damage ratios for 20, 30 and 40 cm. Statistical significance was not tested given the very similar values for control and brassinosteroid treatments (BR).

The number of damaged trees according to the level above ground was rising from 5 cm above ground, up to 30 cm with the highest number of damaged trees (Fig. 5.1.1.3.). At higher levels, the number rapidly decreased. No trees were damaged at the level above 70 and 75 cm in the BR and the control, respectively. As the damage of individual trees could possibly infringed more than one height level, the figure does not represent the probability distribution in the statistical sense. The subsequent height increment from spring did not differ between treatments according to the Wilcoxon test (p = 0.8).

When we consider vitality of the trees (A – tree of the best vitality, B – tree of a good health status, C – tree of partially deteriorated health status, D – markedly deteriorated health status, E – dead), both treatments showed a pattern equal with the most abundant average quality ‘B’, followed by ‘C’ and ‘A’ (Fig. 5.1.1.4.). The chi-squared test could not prove any difference in distribution of individuals into categories by their vitality status (p = 0.58).

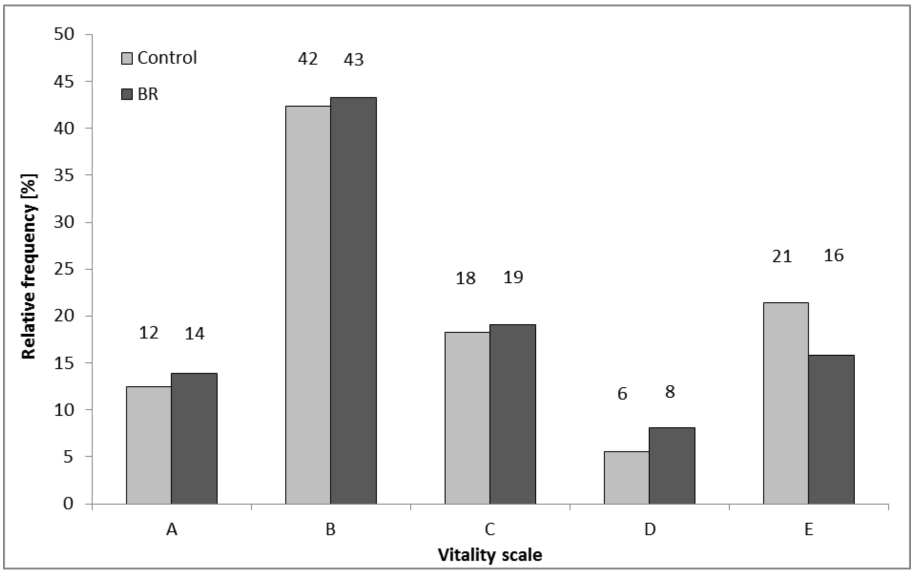


Fig. 5.1.1.4.: Distribution of transplants in brassinosteroid treatment (BR) and control treatments categorized in vitality classes after the late frost event on the investigated plot Truba. Note: A – tree of the best vitality, B – tree of a good health status, C – tree of partially deteriorated health status, D – markedly deteriorated health status, E – dead.

Mean height, root collar diameter, and mortality rate did not show any significantly better performance in the brassinosteroid treatment over the control treatment. Neither the application treatment had a significant positive effect on the resistance of beech to late frosts. The severe frost damage was most intense at 30 cm above ground, and rapidly declined with increased height.

5.1.2. Lime plantation

Data from this experiment were partially published in GALLO et al. 2020a. This part adds more recent data.

Mortality rate

The relative mortality rate (in %) was the highest in the non-weeded standard-sized transplants followed by the weeded standard-sized transplants in the first half of the monitored period. In 2016–2017, the initial mortality in the non-weeded large-sized transplants 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. The non-weeded standard-sized transplants showed worse performance than the other variants in 2015–2017 (Table 5.1.2.1.). Similar low-mortality dynamics continued in following years, which is showed also by the analysis of annual mortality, in which there were no statistical differences in the last 3 monitored years (Table 5.1.2.2.).

Table 5.1.2.1.: Cumulative mortality rate [%] of small-leaved lime (*Tilia cordata* Mill.) on the investigated experimental plot Truba. Values for different planting stocks are in columns, values in different years in rows. Saplings – large-sized transplants, transplants – standard-sized transplants, non-weeded – no weed control regime, weeded – weed control regime. Within each year, different upper-indexed letters in *italics* indicate significant differences (α = 0.05) between treatments.

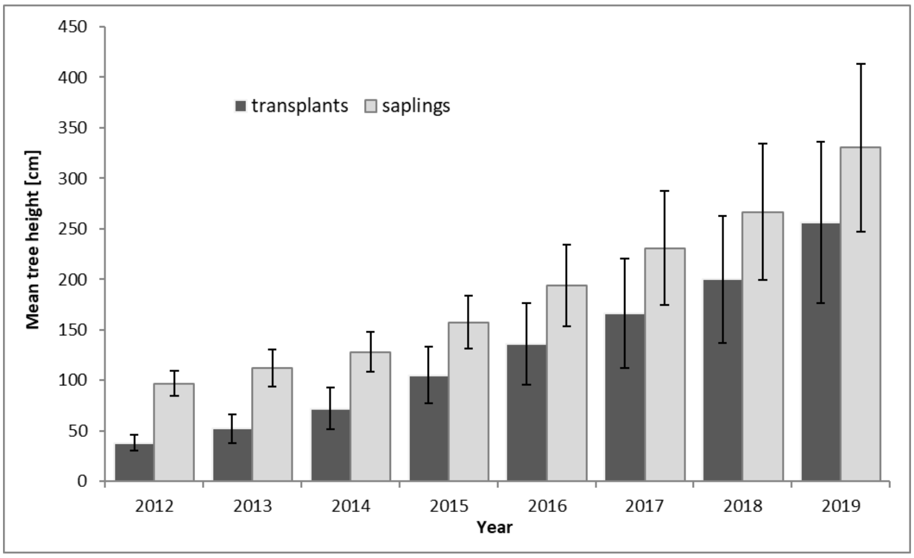
Variant	Year				
	2014	2015	2016	2017	2019
transplants non-weeded	2^{a}	5^{a}	6^{a}	7^{a}	8^{a}
transplants weeded	1^{a}	1^{b}	1^{b}	1^{b}	2^{b}
saplings non-weeded	0^{a}	1^{b}	2^{b}	2^{b}	2^{b}
saplings weeded	0^{a}	0^{b}	0^{b}	0^{b}	1^{b}

Table 5.1.2.2.: Annual mortality rate of small-leaved lime (*Tilia cordata*) [%] on the investigated experimental plot Truba. Values for 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 upper-indexed letters in *italics* indicate significant differences (α = 0.05) between treatments.

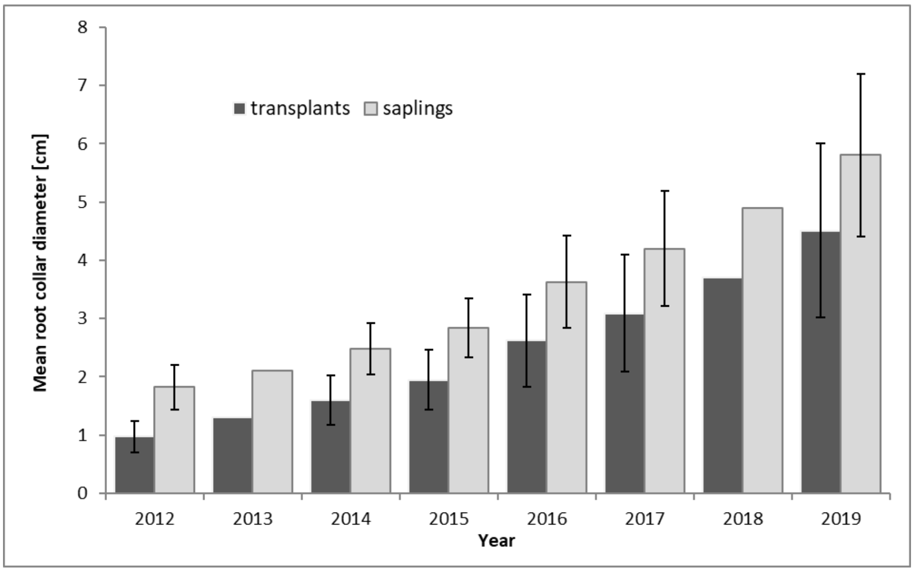
Variant	Year				
	2014	2015	2016	2017	2019
transplants non-weeded	2^{a}	3^{a}	1^{a}	1^{a}	1^{a}
transplants weeded	1^{a}	0^{b}	0^{a}	0^{a}	0^{a}
saplings non-weeded	0^{a}	1^{ab}	0^{a}	0^{a}	0^{a}
saplings weeded	0^{a}	0^{b}	0^{a}	0^{a}	1^{a}

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 last year of monitoring (2019), the median height reached 270 cm in in case of standard-sized transplants and 340 cm in case of saplings. Saplings therefore increased their height margin by 10 cm in 7 years. The median of initial root collar diameter was 1.0 cm in standard-sized transplants and 1.8 cm in saplings. In the final year of monitoring, the median of root collar diameter in standard-sized transplants and saplings reached 4.75 cm and 5.9 cm, respectively. Thus, it is apparent that the saplings have kept an advance over standard-sized transplants 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 5.1.2.1. shows the comparison of *(a)* heights and *(b)* root collar diameters between standard-sized transplants and large-sized transplants (2012–2019).



(a)

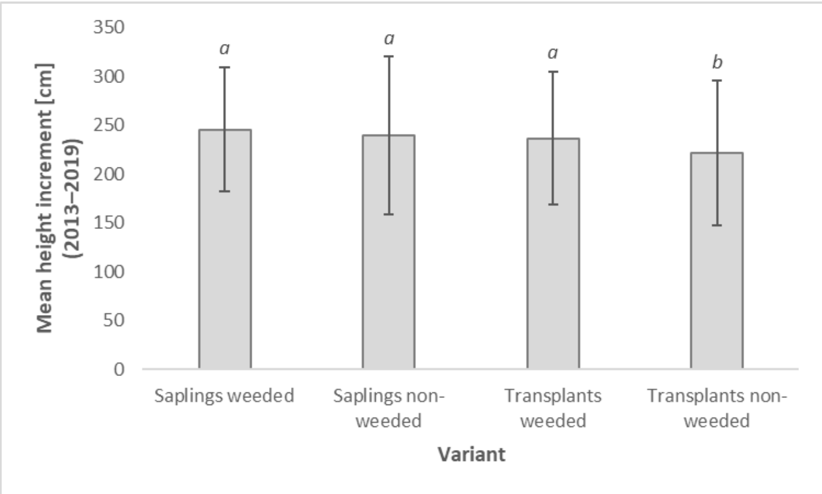


(b)

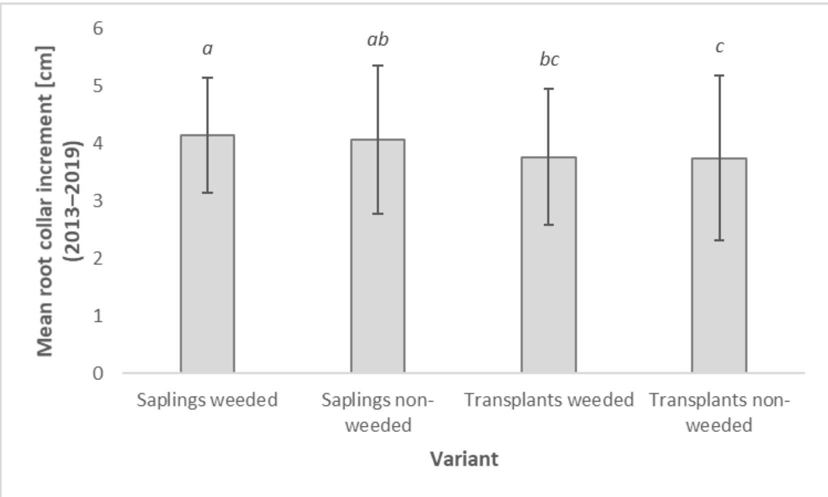
Fig. 5.1.2.1.: Dynamics in development of total height *(a)* and root collar diameter *(b)* of large-sized transplants (LST) and small-sized transplants (SST) of small-leaved lime (*Tilia cordata*) in 2012–2019 on investigated experimental plot Truba. Root collar diameter in 2013 was interpolated from 2012 and 2014 data. Root collar diameter in 2018 was interpolated from 2017 and 2019 data. Error bars depict standard deviation.

Normality test of height increment (2012–2019) showed that the data had normal distribution (Shapiro-Wilk test: W = 0.99758, p = 0.06748), but tested each of four variants separately, the data did not have normal distribution. The non-weeded standard-sized transplants showed significantly lower total height increment than its weed-controlled standard-sized counterpart (221.8 cm (N = 276) vs. 236.2 cm (N = 339)) over the monitored period 2013–2019 (Fig. 5.1.2.2.). At the same time, there was no significant difference in height increment between weed-controlled and non-weeded saplings, although in absolute numbers the weed-controlled saplings showed a higher value of height increment over the whole monitored period (245.6 cm (*N* = 244) vs. 239.9 cm (*N* = 356)).

Non-weeded standard-sized transplants showed significantly lower root collar diameter increment when compared to saplings and weeded-saplings had significantly higher root collar diameter increment than standard-sized transplants (Fig. 5.1.2.2). The weed-controlled LST showed the best results. The non-weeded saplings showed identical results as weed-controlled standard-sized transplants. The lowest root collar diameter increment was found in the non-weeded standard-sized transplants.



(a)



(b)

Fig. 5.1.2.2.: Mean height increment [cm] *(a)* and mean root collar diameter increment [cm] *(b)* of small-leaved lime (*Tilia cordata*) weeded saplings (*N* = 244), non-weeded saplings (*N* = 356) weeded standard-sized transplants (*N* = 339) and non-weeded standard-sized transplants (*N* = 276) plantation in 2013–2019 on investigated experimental plot Truba. Error bars depict standard deviation. Letter indexes in *italics* above columns depict significant differences between respective variants at significance level α = 0.05.

Median height increment over the monitored period 2013–2019 was 240 cm for saplings and 230 cm for transplants. Kruskal-Wallis test showed significant differences between variants. Subsequent Multiple Comparisons *p*-values (2-tailed) showed that weeded × non-weeded saplings performed equally, as well as weeded × non-weeded standard-sized transplants, while saplings under both weeding regimes performed better than non-weeded standard-sized transplants, but only weeded saplings performed better than weeded standard-sized transplants, i.e. there was no significant difference between non-weeded saplings and weeded transplants.

Chlorophyll content

The saplings showed a significantly higher content of chlorophyll than the transplants in 2013 (t-test, t = –3.23, df = 98, *p*-value = 0.002). It reached 446 mg/m^2 in saplings and 378 mg/m^2 in transplants. However, almost no difference in chlorophyll concentration between the transplants and saplings was observed in 2014 (t-test, t = –0.06, df = 58, *p*-value = 0.95), see Fig. 5.1.2.3. The mean values were 403 mg/m^2 in transplants and 404 mg/m^2 in saplings.

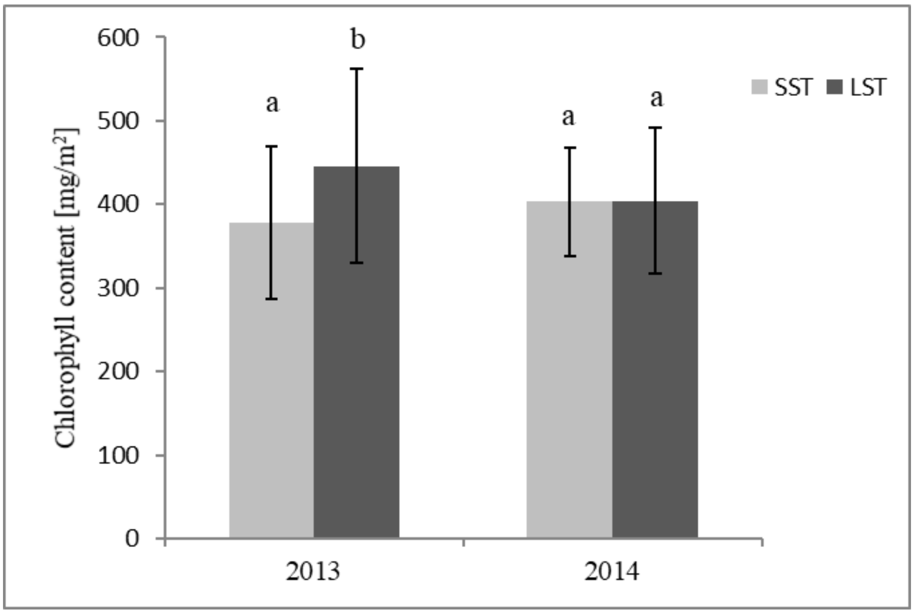


Fig. 5.1.2.3.: Mean chlorophyll content in leaves of large-sized transplants and standard-sized transplants in 2013 and 2014 on investigated experimental plot Truba. Error bars depict standard deviations. Indexes above bars depict significant differences (α = 0.05) between treatments.

5.2. Planá nad Lužnicí

Mortality rate

In case of *Tilia*, 540 saplings and 540 standard-sized transplants were planted; in *Quercus*, there were 284 and 255 saplings and standard-sized plants, respectively. Relative mortality for both species and both planting stock types in the monitored period is summarized in Table 5.2.1.

Table 5.2.1.: Cumulative mortality rate [%] of small-leaved lime (*Tilia cordata*) and common oak (*Quercus robur*) on the investigated experimental plot Planá nad Lužnicí. Values for different planting stocks are in columns, values in different years in rows. Within each year, different upper-indexed letters in *italics* indicate significant (α = 0.05) differences between variants.

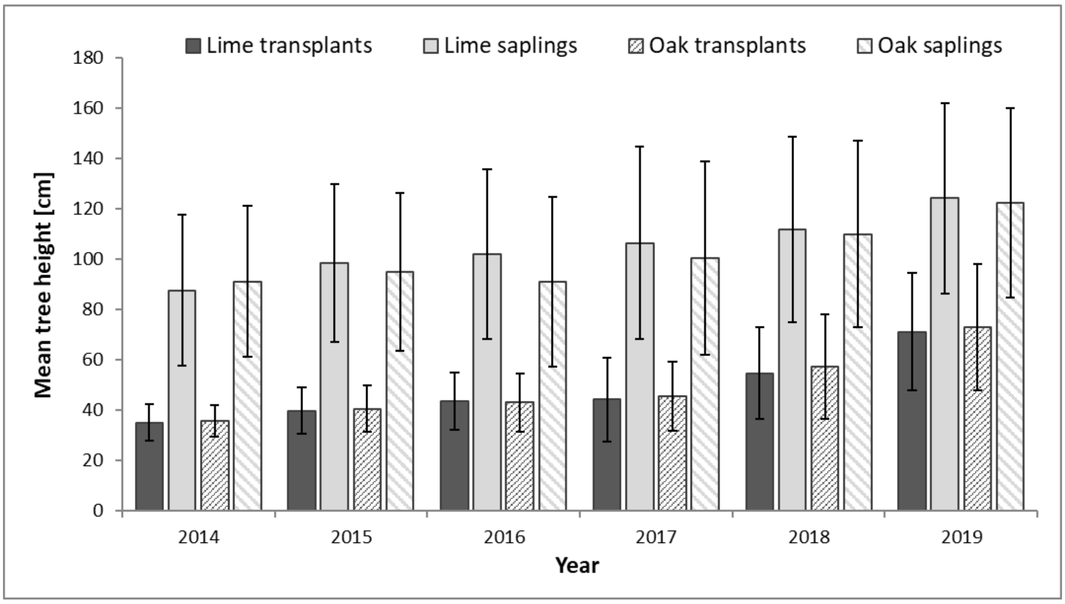
Variant	***Year***				
	2015	**2016**	**2017**	**2018**	**2019**
Tilia saplings	12^{a}	13^{a}	13^{a}	13^{a}	13^{a}
Tilia transplants	32^{b}	32^{b}	33^{b}	33^{b}	33^{b}
Quercus saplings	0^{c}	0^{c}	0^{c}	0^{c}	0^{c}
Quercus transplants	0^{c}	0^{c}	0^{c}	0^{c}	1^{c}

Analysis of annual mortality rate showed elevated mortality of *Tilia* compared to *Quercus* in the beginning of the monitored period. In the last three monitored years, annual mortality equalled zero in case of all variants (Table 5.2.2.).

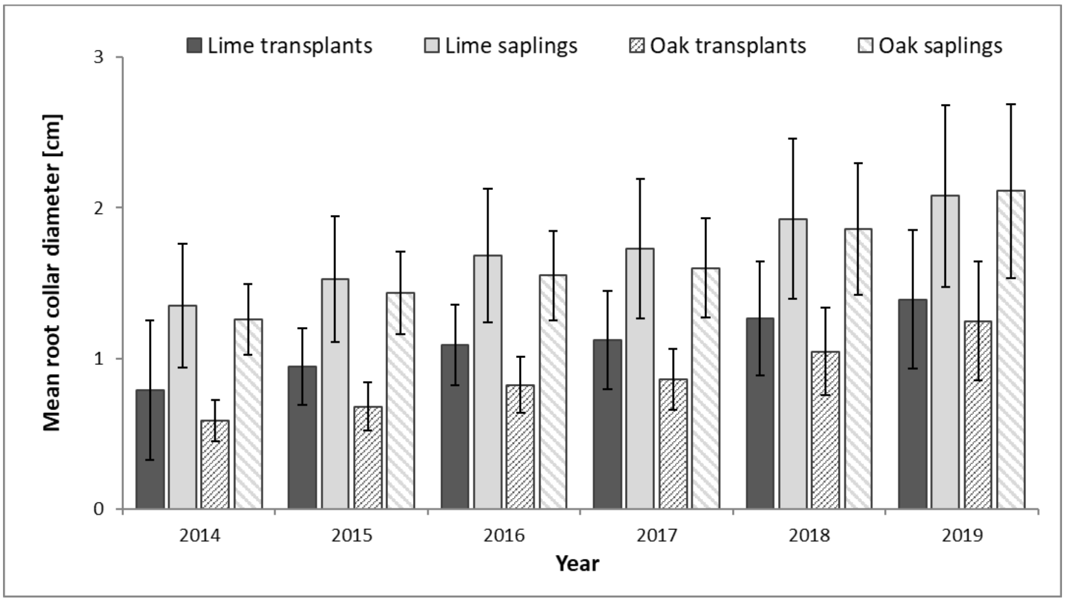
Table 5.2.2.: Annual mortality rate [%] of small-leaved lime (*Tilia cordata*) and common oak (*Quercus robur*) on the investigated experimental plot Planá nad Lužnicí. Values for different planting stocks are in columns, values in different years in rows. Within each year, different letters indicate significant (α = 0.05) differences between variants.

Variant	***Year***				
	2015	**2016**	**2017**	**2018**	**2019**
Tilia saplings	12^{a}	1^{a}	0^{a}	0^{a}	0^{a}
Tilia transplants	32^{b}	0^{a}	0^{a}	0^{a}	0^{a}
Quercus saplings	0^{c}	0^{a}	0^{a}	0^{a}	0^{a}
Quercus transplants	0^{c}	0^{a}	0^{a}	0^{a}	0^{a}

In terms of differences in planting stock, there were initial differences between saplings transplants in *Tilia* in favour of saplings, in contrast to *Quercus*, where there was zero mortality for the whole monitored period (Table 5.2.2.).



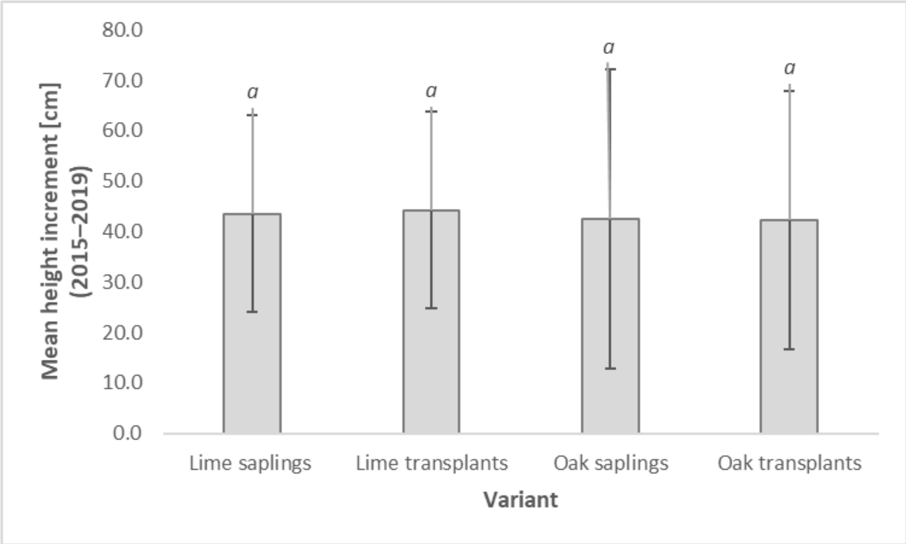
(a)



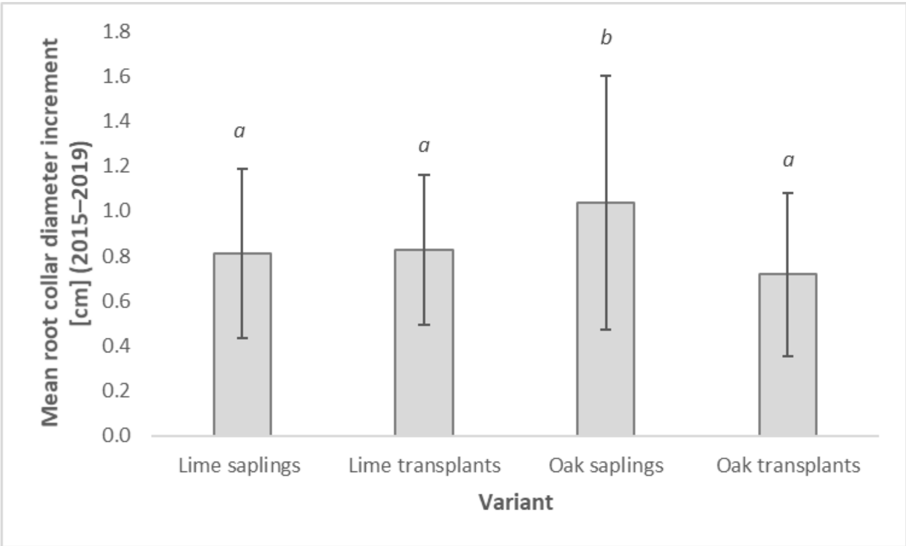
(b)

Fig. 5.2.1.: Mean heights (*a*) and root collar diameters (*b*) of small-leaved lime (*Tilia cordata*) and common oak (*Quercus robur*) transplants and saplings on investigated experimental plot Planá nad Lužnicí between 2014–2019. Error bars depict standard deviation.

Large-sized planting stock in case of both species maintained initial advance during the whole monitored period, regardless of species (Fig. 5.2.1.). Common oak NGSS showed significantly higher increment in root collar diameter in comparison to the other planting stocks during the monitored period (Fig. 5.2.2.).



(a)



(b)

Fig. 5.2.2.: Mean periodic height increment [cm] *(a)* and mean periodic root collar diameter increment [cm] *(b)* of small-leaved lime (*Tilia cordata*) saplings (*N* = 319) and standard transplants (*N* = 179) and common oak (*Quercus robur*) saplings (*N* = 146) and standard transplants (*N* = 155) plantation in 2017–2019 on investigated experimental plot Planá nad Lužnicí. Error bars depict standard deviation. Letter indexes in *italics* above columns depict significant differences between respective variants at significance level α = 0.05.

5.3. Vintířov-Sedlec

In Vintířov-Sedlec, experimental plantations of European beech and wild cherry were evaluated on adjacent plots. European beech plantation has been monitored since 2017, wild cherry plot since 2018. Data from these experiments were partially published in GALLO et al. 2018a, GALLO et al. 2018*b* (European beech) and in GALLO et al. 2019 (wild cherry) and more recent data were added.

5.3.1. European beech plantation

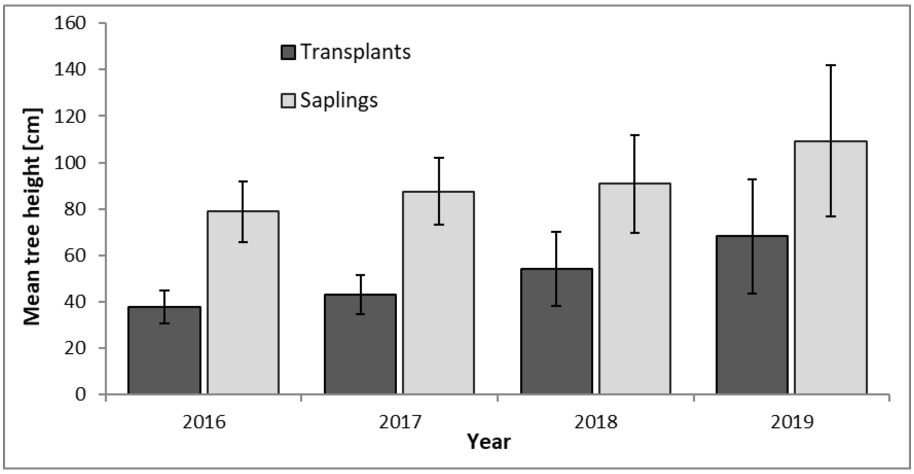
Mortality rate

Cumulative mortality rate [%] after three vegetation seasons is shown in Fig. 5.3.1.1. Overall, it can be considered acceptable as it remained only in percentage units for both types of planting stock, although the spring period (especially May) 2017 was significantly below normal and temperature above normal in the area of interest (CHMI 2018). Semi-saplings achieved lower mortality than standard transplants. On the other hand, in the semi-saplings, the drying-up of the terminal was recorded to a greater extent due to the already mentioned critical lack of moisture in the spring period of the given year. Annual mortality rate was not evaluated, because data from 2018 were not available.

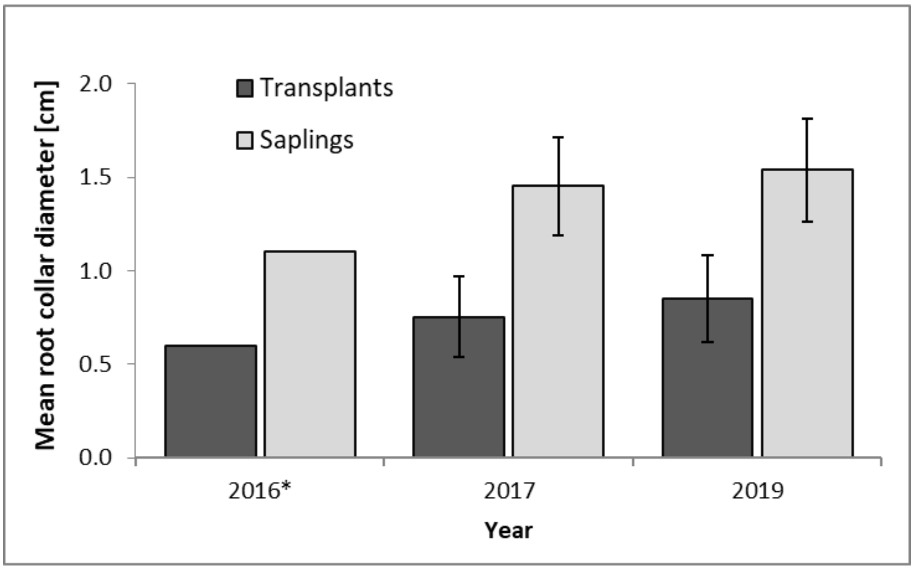
Table 5.3.1.1.: Cumulative mortality rate [%] of European beech (*Fagus sylvatica*) on the investigated experimental plot Vintířov-Sedlec. Values for different planting stocks are in columns, values in different years in rows. Within each year, different letters indicate significant differences between variants (α = 0.05).

Variant	2017	2019
Beech transplants	7^{a}	19^{a}
Beech semi-saplings	5^{a}	12^{b}

A comparison of the mean height values (Fig. 5.3.1.1.*a*) showed that the semi-saplings retained their initial height advantage over standard transplants. The initial average height was 37.7 cm for transplants and 78.7 cm for semi-saplings. After the first year, the transplants reached 43.3 cm on average and semi-saplings 87.9 cm. From this it is apparent that the semi-saplings also showed a higher current increment. The root collar diameter was evaluated after three growing seasons. From the comparison with the input characteristics of planting stock, it is apparent that in both types the root collar diameter increase was recorded, in the case of standard transplants by approximately 1.5 mm, in the case of semi-saplings by approximately 3 mm (Fig. 5.3.1.1.).



(a)

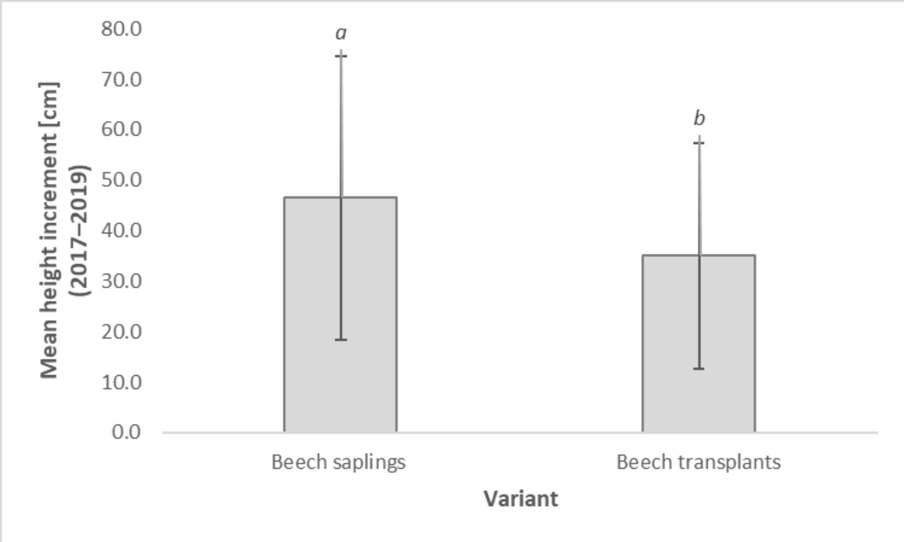


(b)

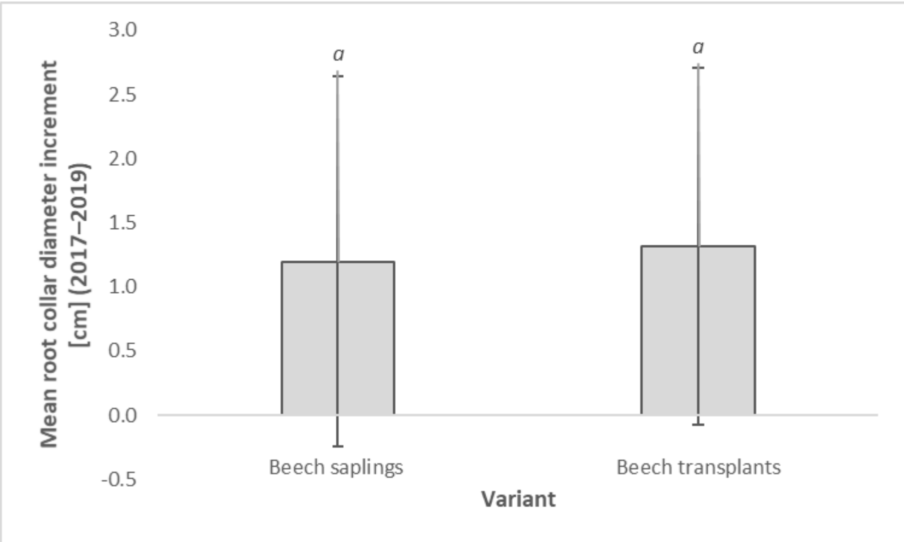
Fig. 5.3.1.1.: Mean heights and mean root collar diameters of European beech (*Fagus sylvatica*) plantation [cm] in 2016–2019 on the investigated experimental plot Vintířov-Sedlec. Error bars depict standard deviation. 2016* initial values are taken from planting stock documentation. In 2018, root collar diameter was not evaluated.

Overall, the course of the 2017 vegetation season can be characterized as rather unfavourable for newly established forest tree plantations. The trees grew very intensively at the beginning of spring, the height increase was completed in June. Then, due to a significant lack of rainfall, there was a visible deterioration in the vitality of most of the trees (late June to late August). At the end of the growing season, the condition of the tree assimilation apparatus improved again in connection with the improved availability of moisture. In the next two seasons, the effect of replanting shock was still evident.

After three seasons, semi-saplings showed significantly higher increment in height, but not in root collar diameter in comparison to standard-sized transplants (Fig. 5.3.1.2.)



(a)



(b)

Fig. 5.3.1.2.: Mean height increment [cm] and mean root collar diameter increment [cm] of European beech (*Fagus sylvatica*) saplings (*N* = 279) and standard transplants (*N* = 314) plantation in 2017–2019 on investigated plot Vintířov-Sedlec. Error bars depict standard deviation. Letter indexes in *italics* above columns depict significant differences between respective variants at significance level α = 0.05.

5.3.2. Wild cherry plantation

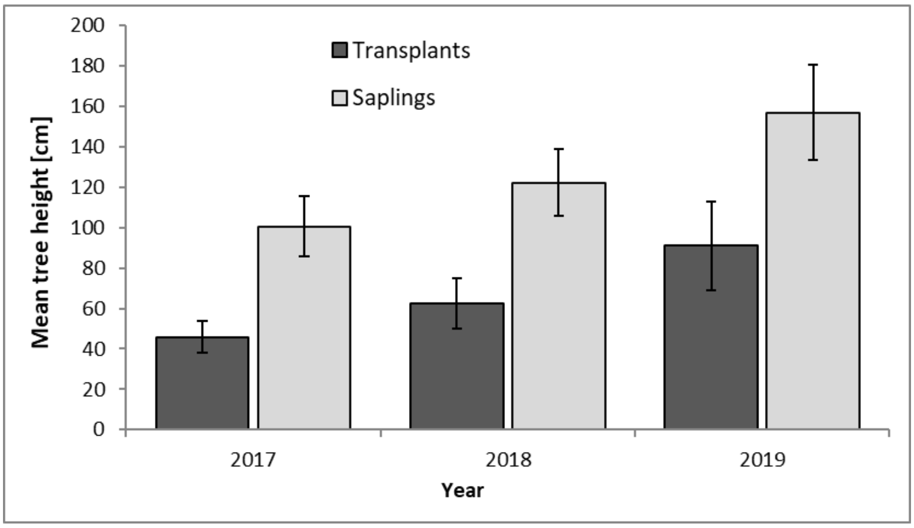
The overall mortality rate after the first vegetation season is shown in Fig. 5.3.2.1. Overall, it can be assessed as very low to negligible. Only 2 (0.6%) semi-saplings and 7 (2.2%) standard transplants were lost. The semi-saplings thus achieved a lower mortality overall than the standard transplants. The number of trees with dried terminal bud was also very low (3 pcs of semi-saplings plants, five pcs of standard transplants), as well as with severe strains of the stem (3 pcs of semi-saplings plants and two pcs of standard transplants). The total proportion of dead or damaged semi-saplings was 2.6% and 4.4% of standard transplants.

Table 5.3.2.1.: Cumulative mortality rate [%] of wild cherry (*Prunus avium*) on the investigated experimental plot Vintířov-Sedlec. Values for different planting stocks are in columns, values in different years in rows. Within each year, different letters indicate significant differences (α = 0.05) between treatments.

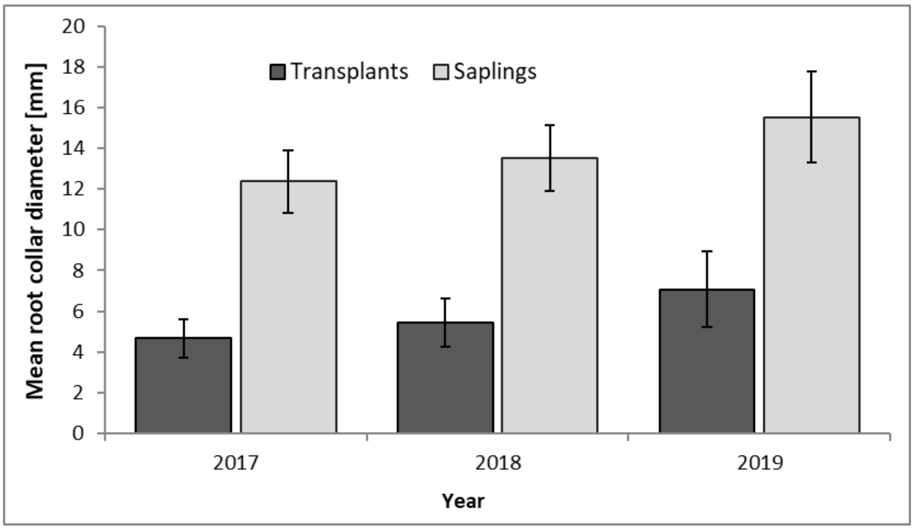
Variant	2018	2019
Wild cherry transplants	2^{a}	4^{a}
Wild cherry semi-saplings	0^{a}	0^{b}

A comparison of the average height values (Fig. 5.3.2.2.) shows that the semi-saplings retained their initial height advantage over the standard transplants during the first growing season. The initial average height was 45.8 cm for standard-sized transplants and 100.6 cm for semi-saplings. After the first year, the transplants reached an average of 62.9 cm, and the semi-saplings reached 122.1 cm. The average height increment was 21.5 cm (standard deviation 12.84) for semi-saplings and 16.8 cm (standard deviation 12.52) for standard-sized transplants. The semi-saplings thus reached a higher increase; the difference was statistically significant ($p < 0.001$).

The root collar diameter was evaluated before the beginning of the first growing season after planting and after the growing season. The comparison with the input characteristics shows that in both types of planting material a measurable root collar diameter increase was recorded, in standard transplants by approximately 0.8 mm (standard deviation 1.36) and in semi-saplings by approximately 1.2 mm (standard deviation 0.96) (Fig. 5.3.2.2.). The difference was statistically significant ($p < 0.001$).



(a)



(b)

Fig. 5.3.2.2.: Mean heights [cm] *(a)* and root collar diameters [mm] *(b)* of wild cherry (*Prunus avium*) semi-saplings (N = 292) and standard-sized transplants (N = 294) in 2017–2019 on the investigated research plot Vintířov-Sedlec. Error bars depict standard deviation.

(a)

(b)

Fig. 5.3.2.3.: Mean height increment [cm] *(a)* and mean root collar diameter increment [cm] *(b)* of wild cherry (*Prunus avium*) saplings (*N* = 292) and standard transplants (*N* = 294) plantation in 2018–2019 on investigated plot Vintířov-Sedlec. Error bars depict standard deviation. Letter indexes in *italics* above columns depict significant differences between respective variants at significance level α = 0.05.

In terms of root collar diameter increment, wild cherry transplants showed significantly higher increment (W = 38848, $p = 0.04292$), which is in contrary to the results of mean height increment (W = 54759, $p = 7.669e^{-09}$) (Fig. 5.3.2.3.).

5.4. Týniště nad Orlicí

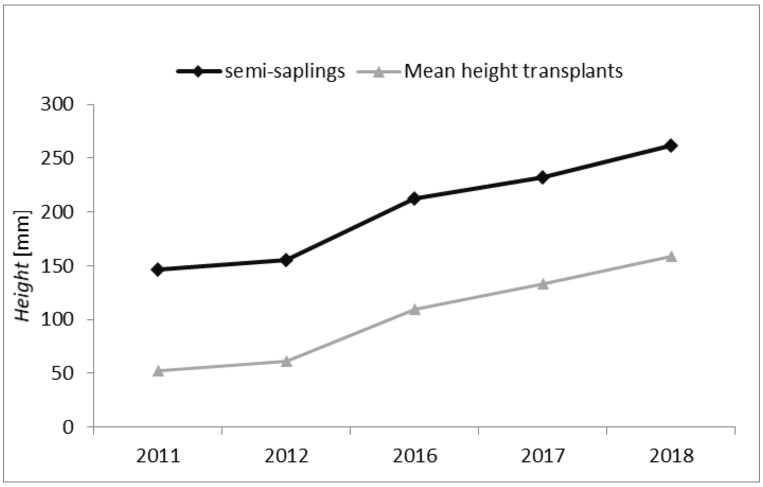
5.4.1. U Glorietu

Mortality rate and damage characteristics in 2018 are shown in Table 5.4.1. Mortality rate of semi-saplings and transplants was 39% and 77% in 2018, respectively.

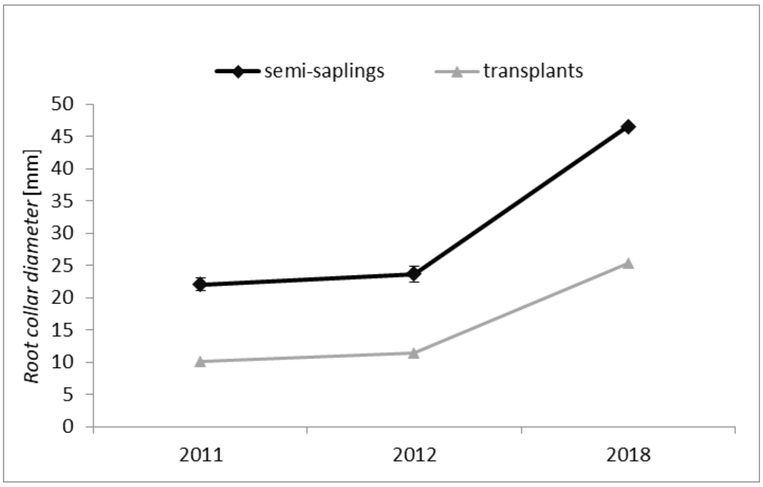
Table 5.4.1.: Cumulative mortality rate and damage of small-leaved lime (*Tilia cordata*) [%] on the investigated experimental plot U Glorietu. Values for different planting stocks are in columns, values in different years are in rows. Within each year, different letters indicate significant differences (α = 0.05) between treatments.

Mortality & damage 2018	Total	Dead [%]	New Terminal [%]	Resprout [%]
semi-saplings	192	39^{a}	14^{a}	19^{a}
transplants	196	77^{b}	2^{b}	6^{b}

Total – Initial (planted) number of trees



(a)



(b)

Fig. 5.4.1.: Mean height [cm] *(a)* and root collar diameter [mm] *(b)* of small-leaved lime (*Tilia cordata*) saplings and standard transplants plantation in 2011–2018 on the investigated plot U Glorietu.

In terms of cumulative (total) mortality semi-saplings showed significantly better results (binomial test: test statistics: 11.522; critical value: 2.7718; $p = 0$). Semi-saplings also showed higher resilience: there was significantly higher number of new terminals (binomial test: test statistics: 6.1049; critical value: 2.7718; $p = 0$), and the percentage of resprouts was also significantly higher in case of saplings (binomial test: test statistics: 5.3197; critical value: 2.7718; $p = 2e^{-04}$).

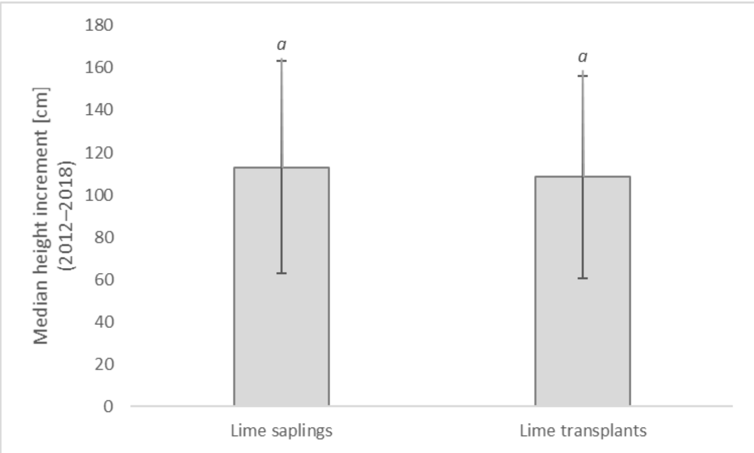


Fig. 5.4.2.: Median height increment [cm] of small-leaved lime (*Tilia cordata*) saplings ($N = 49$) and standard transplants ($N = 26$) plantation in 2012–2018 on investigated plot U Glorietu. Error bars depict standard deviation. Letter indexes in *italics* above columns depict significant differences between respective variants at significance level $\alpha = 0.05$.

NGSS maintained its original advances in height and root collar diameter (Fig. 5.4.1.) Analysis of median height increment showed no significant differences between saplings and transplants (Fig. 5.4.2.).

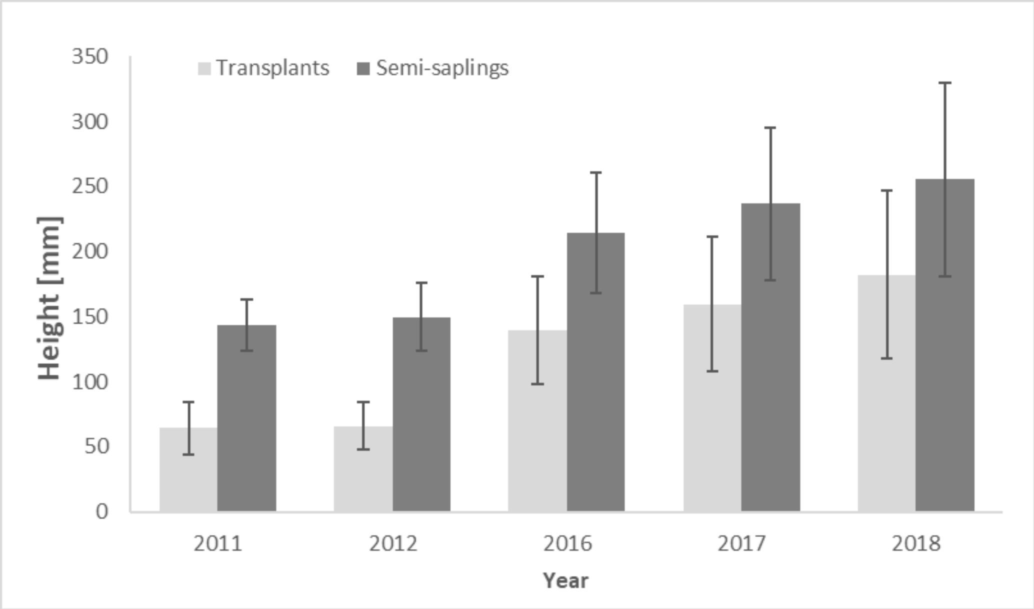
5.4.2. Štenclova alej

On this (wind-disturbed clear cut) site, lime semi-sapling performed significantly better than standard-sized transplants (Table 5.4.2.). Semi-saplings showed, in absolute numbers, lower mortality rate, improved resilience of new terminal bud, and resprouting.

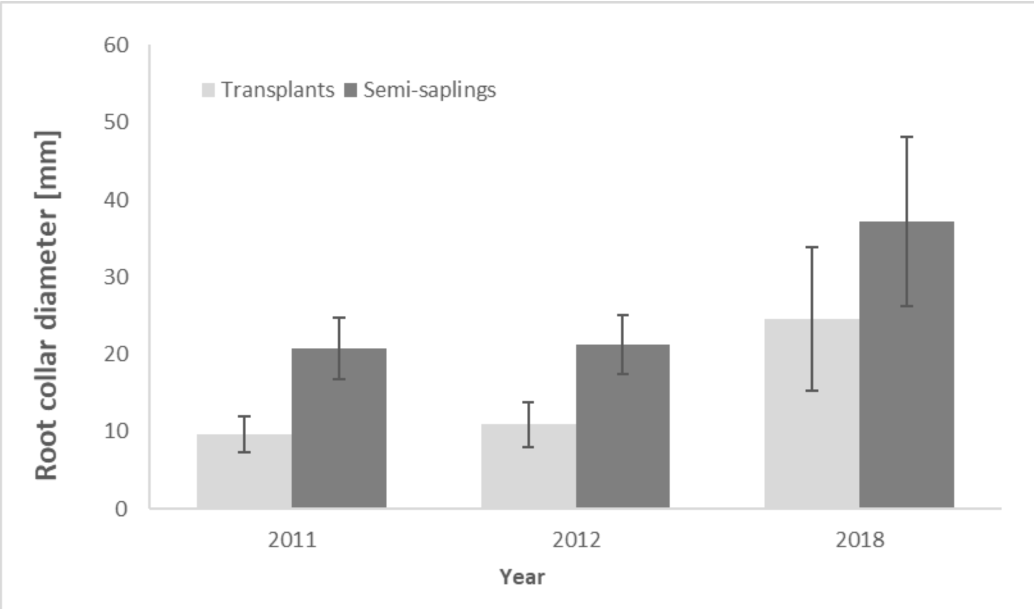
Table 5.4.2.: Cumulative (total) mortality and damage [%] of small-leaved lime (*Tilia cordata*) semi-saplings and standard-sized transplants on experimental plot Štenclova alej (Týniště nad Orlicí).

Mortality & damage 2018	Total	Mortality [%]	New Terminal [%]	Resprout [%]
semi-saplings	272	21^a	8^a	2^a
transplants	222	84^b	4^a	1^a

Total – Initial (planted) number of trees; New Terminal – percentage of newly occurred terminal bud after damage had appeared; Resprout – percentage of trees that resprouted from the ground.

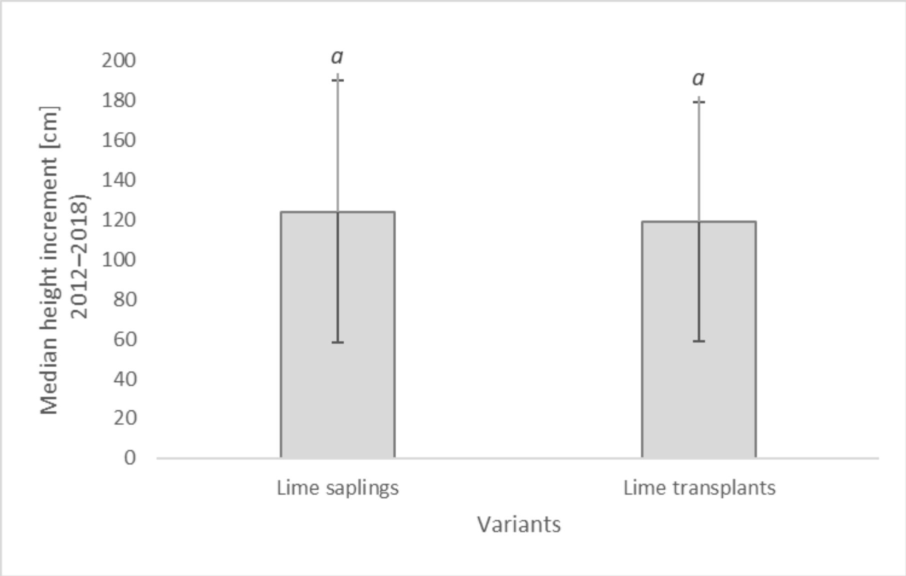


(a)



(b)

Fig. 5.4.3.: Mean height [cm] *(a)* and root collar diameter [mm] *(b)* of small-leaved lime (*Tilia cordata*) saplings and standard transplants plantation in 2011–2018 on investigated plot Štenclova alej. Error bars depict standard deviation.



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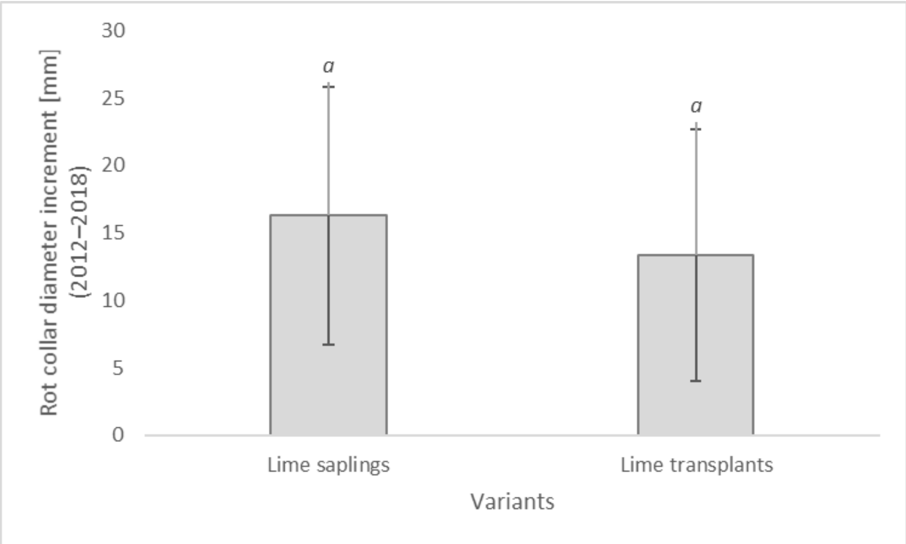


(b)

Fig. 5.4.4.: Median height increment [cm] *(a)* and median root collar diameter increment [mm] *(b)* of small-leaved lime (*Tilia cordata*) saplings (*N* = 171) and standard transplants (*N* = 24) plantation in 2011–2018 on investigated plot Štenclova alej. Error bars depict standard deviation. Letter indexes in *italics* above columns depict significant differences between respective variants at significance level α = 0.05.

NGSS in absolute numbers showed slightly improved results and maintained initial height and diameter advances (Fig. 5.4.3.). In contrast to mortality rates, no significant differences were found for growth dynamics (neither height nor root collar diameter) (Fig. 5.4.4.).

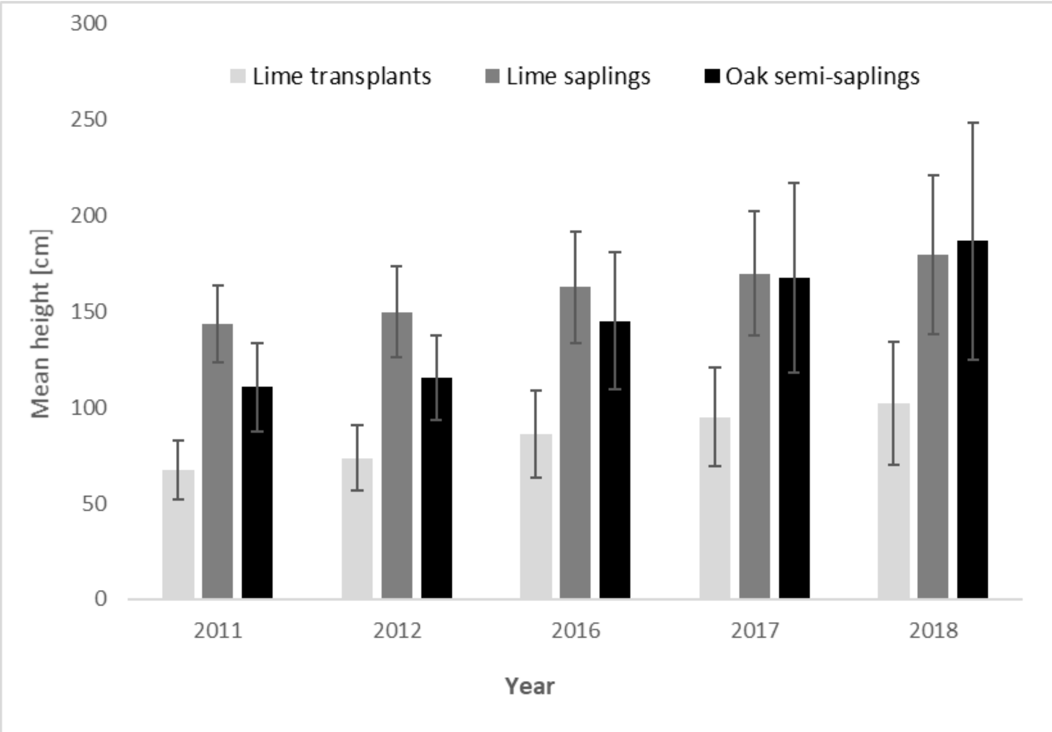
5.4.3. Písník

Cumulative mortality [%] on research plot Písník is summarized in Table 5.4.3.

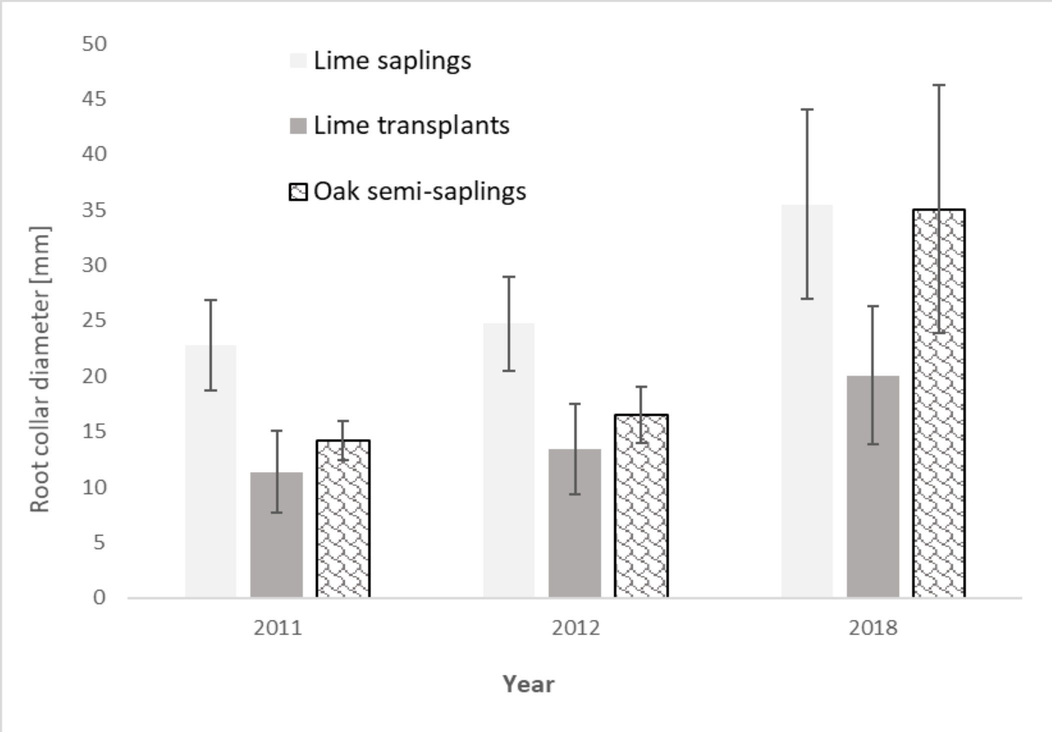
Table 5.4.3.: Mortality and damage of small-leaved lime (*Tilia cordata*) and common oak (*Quercus robur*) semi-saplings and lime standard transplants plantation in 2011–2018. Within each year, different letters indicate significant differences (α = 0.05) between treatments.

Mortality & damage 2018	Total	Dead [%]	New Terminal [%]	Resprout [%]
Lime transplants	219	21[a]	7[a]	40[a]
Lime saplings	215	7[b]	1[b]	20[b]
Oak semi-saplings	40	5[b]	0[b]	3[c]

Total – Initial (planted) number of trees; New Terminal – percentage of newly occurred terminal bud after damage had appeared; Resprout – percentage of trees that resprouted from the ground.



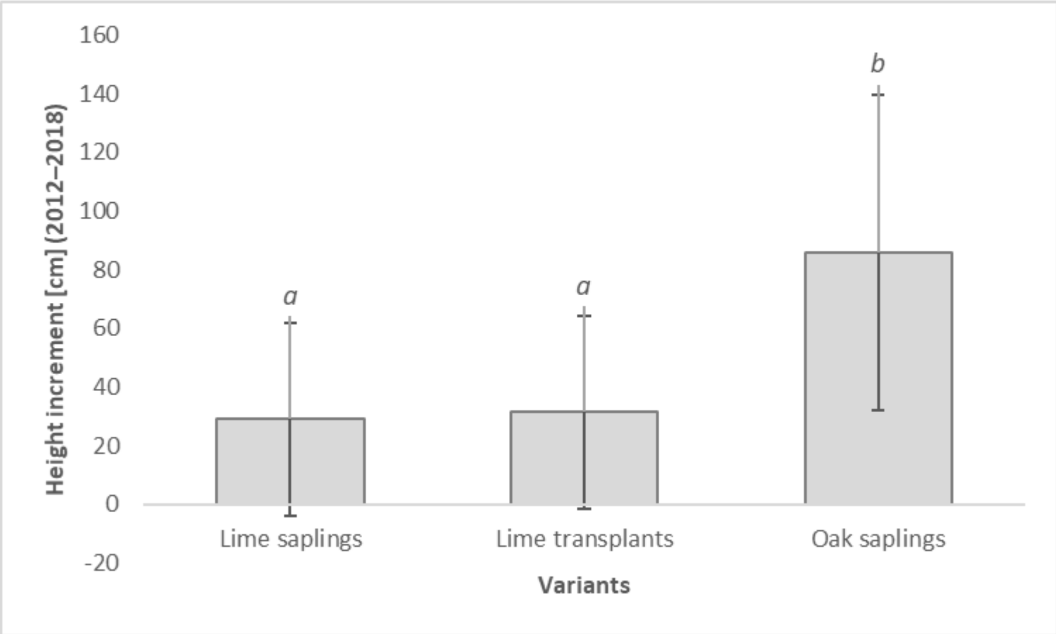
(a)



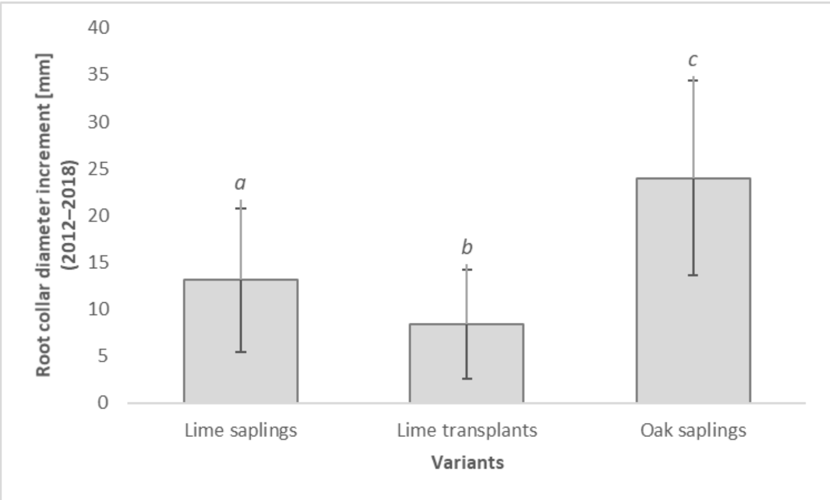
(b)

Fig. 5.4.5.: Mean height [cm] *(a)* and mean root collar diameter [mm] *(b)* of small-leaved lime (*Tilia cordata*) semi-saplings (*N* = 150), oak (*Quercus robur*) semi-saplings (*N* = 38) and lime standard transplants (*N* = 69) plantation in 2011–2018 on the investigated plot Písník. Error bars depict standard deviation.

Fig. 5.4.5. shows the development of mean hight and root collar diameter over the monitored period. Fig. 5.4.6. summarizes calculated increments in height and root collar diameter. NGSS of common oak showed significantly higher increment of height in comparison to small-leaved lime (regardless of planting stock). In root collar diameter, common oak also showed higher increment, but also small-leaved lime NGSS outperformed the standard-sized transplants.



(a)



(b)

Fig. 5.4.6.: Median height increment [cm] *(a)* and median root collar diameter increment [mm] *(b)* of small-leaved lime (*Tilia cordata*) semi-saplings ($N = 143$), common oak (*Quercus robur*) semi-saplings ($N = 35$) and lime standard transplants ($N = 61$) plantation in 2011–2018 on the investigated plot Písník. Error bars depict standard deviation. Letter indexes in *italics* above columns depict significant differences between respective variants at significance level $\alpha = 0.05$.

5.5. Raspenava

Mortality rate

Mortality rate is shown in Table 5.5.1. Cumulative mortality (2018) between all variants did not significantly differ according to multiple-binomial test. Annual mortality (2017–2018) was also not significantly different between variants, nor between couples of variants. When tested two variants individually, statistical differences were found in cumulative mortality (2018) between following variants: Block A – Block E beech ($p = 0.0156$), Block A – Block

F beech ($p = 0.049$), Block A – Block G beech ($p = 0.0023$), Block B – Block F beech ($p = 0.0187$), Block B – Block G beech ($p = 0.0093$), Block C – Block E beech ($p = 0.0156$), Block C – Block F beech ($p = 0.049$), Block A – Block G beech ($p = 0.0023$), Block D beech – Block F beech ($p = 0.0494$), Block D beech – Block G beech ($p = 0.023$), Block E beech – Block F oak ($p = 0.0345$), Block E oak – Block F beech ($p = 0.0276$), Block E oak – Block G beech ($p = 0.014$), Block F beech – Block F oak ($p = 0.0076$), Block F beech – Block G beech ($p = 0.0186$), Block F oak – Block G beech ($p = 0.0037$) and Block G beech – Block G oak ($p = 0.0095$).

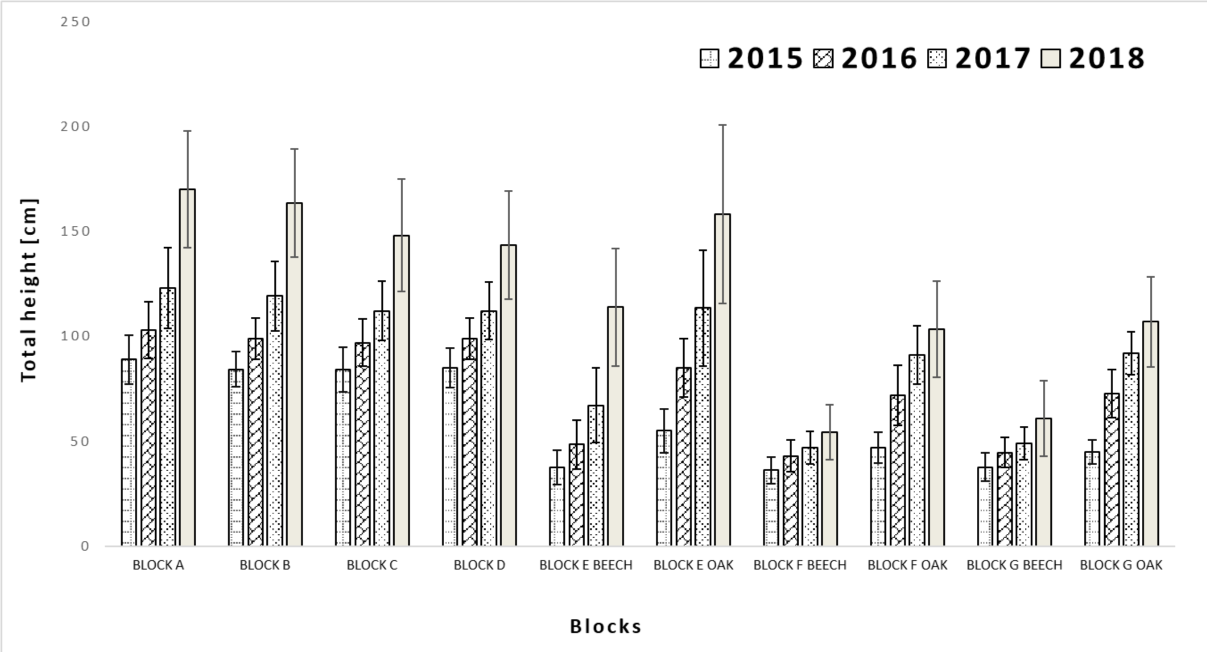
Mortality rate was generally low. However, it was higher for European beech in mixtures with common oak in comparison to pure beech plantation. For oak the mortality was negligible. Elevated beech mortality was probably caused by worsened soil humidity conditions (gleying) in the blocks F and G, with E being a transition to wetter conditions.

Table 5.5.1.: Cumulative mortality [%] of European beech (*Fagus sylvatica*) and common oak (*Quercus robur*) on the experimental plot Raspenava. Blocks A–D: beech semi-saplings; Blocks E–G: common oak semi-saplings + beech transplants.

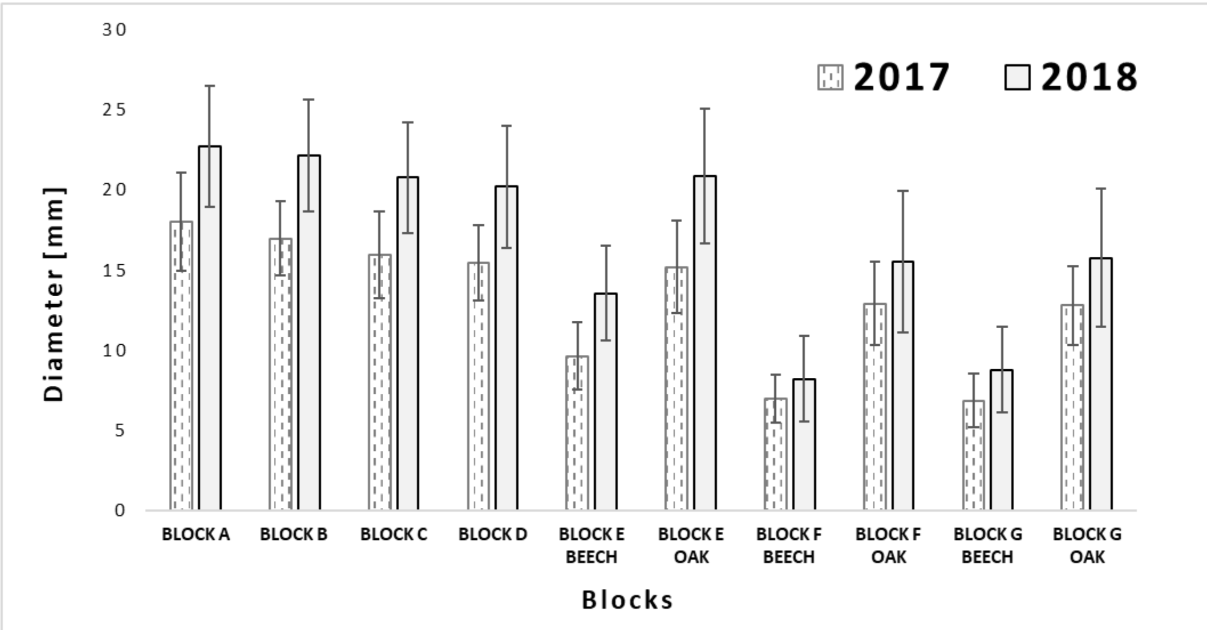
Variant		**2017**	**2018**
	Total	**Dead [%]**	
Block A	104	0	0
Block B	104	1	2
Block C	104	0	0
Block D	108	1	4
Block E beech	104	3	7
Block E oak	112	0	3
Block F beech	52	10	13
Block F oak	70	0	0
Block G beech	52	13	15
Block G oak	42	0	0

Growth characteristics

Tree height and root collar diameter characteristics and their developments in individual monitored years are summarized in Fig. 5.5.1. Fig. 5.5.2. shows the calculated increments in height and root collar diameter during the monitored period.

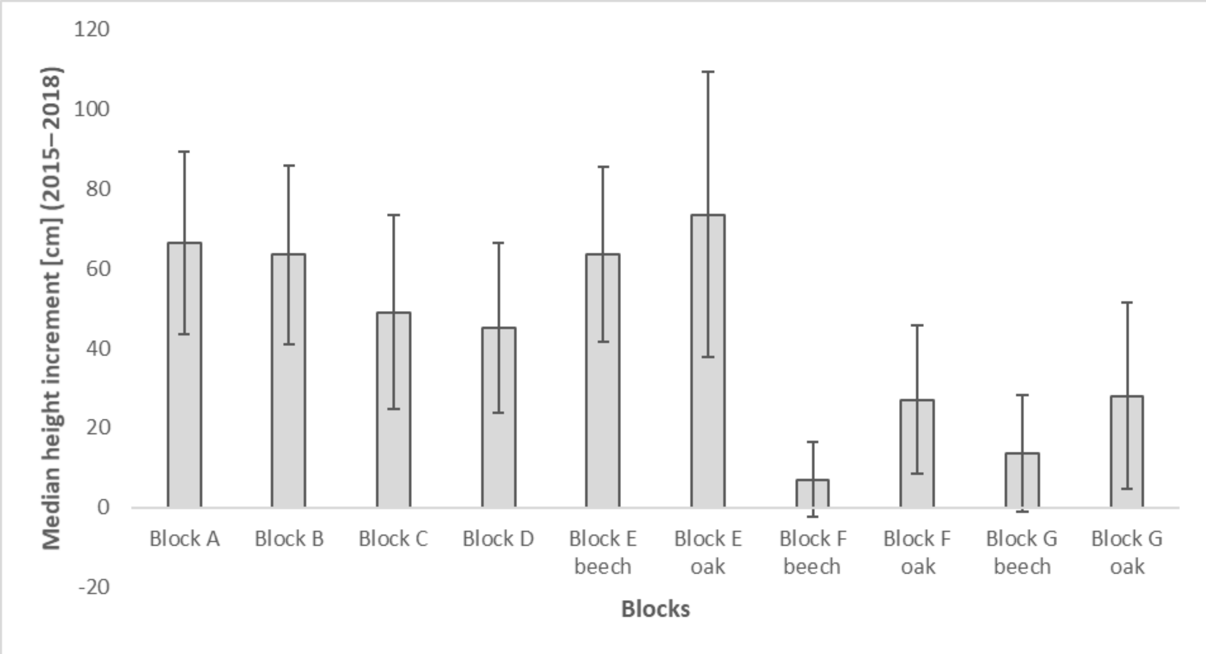


(a)

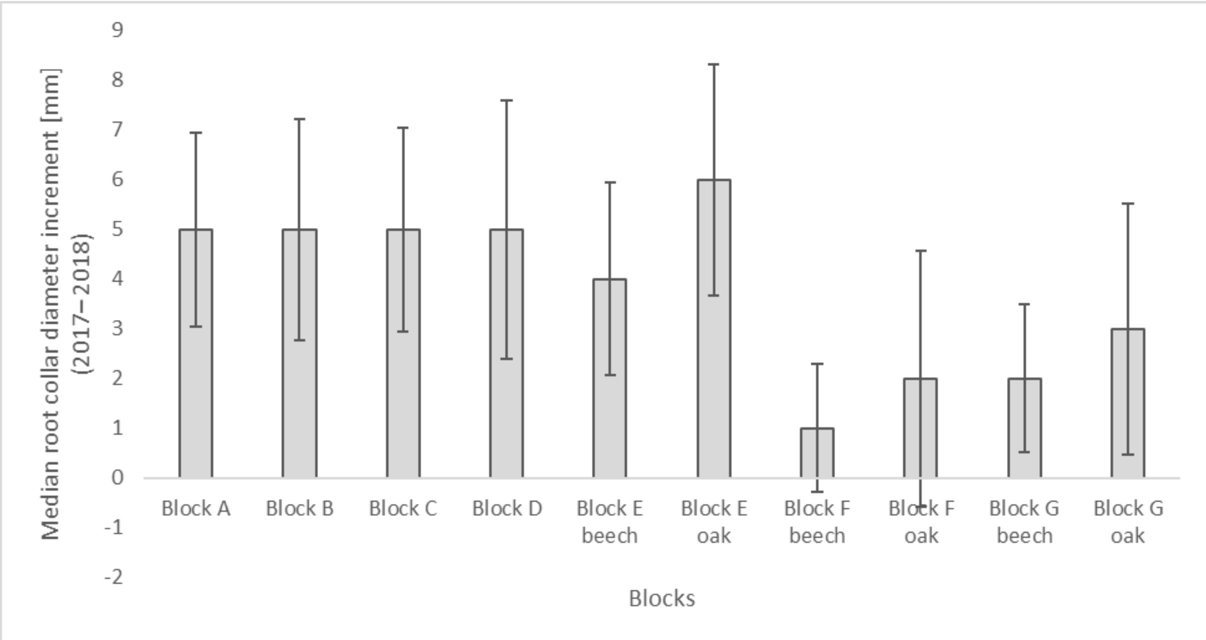


(b)

Fig. 5.5.1.: Mean height [cm] *(a)* and mean root collar diameter [mm] *(b)* of European beech (*Fagus sylvatica*) semi-saplings (Blocks A–D), common oak semi-saplings (*Quercus robur*) (Blocks E–G) and European beech standard transplants (Blocks E–G) in 2017 and 2018 on the experimental plot Raspenava.



(a)



(b)

Fig. 5.5.2.: Median height increment [cm] *(a)* and median root collar increment [mm] *(b)* of European beech (*Fagus sylvatica*) semi-saplings (Blocks A – D), common oak (*Quercus robur*) semi-saplings (Blocks E – G) and European beech standard transplants (Blocks E – G) in 2015–2018 on the experimental plot Raspenava. Error bars depict standard deviation.

Analysis of crown width showed similar dynamics to height and root collar diameter (Fig. 5.5.3.). Beech was best in block A, standard transplants in mixture with oak on water-exposed soil had the smallest crowns.

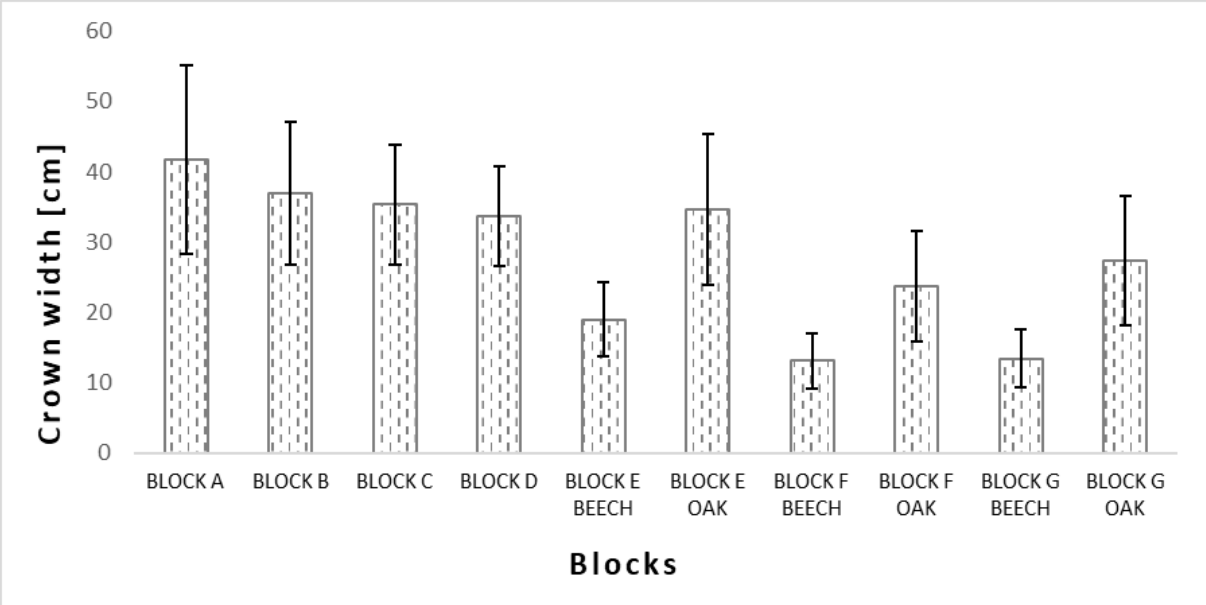


Fig. 5.5.3.: Mean crown width [cm] of European beech (*Fagus sylvatica*) semi-saplings (Blocks A–D), oak semi-saplings (Blocks E–G) and European beech standard transplants (Blocks E–G) in 2017 on the experimental plot Raspenava.

5.6. Economic evaluation of using large-sized stock

Results of economic analysis were taken from GALLO et al. 2020a. Concept 1 of economic analysis (Table 5.6.1.) showed that when the same number of standard-sized transplants (SST) and large-sized transplants (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 5.6.1.: Economic analysis – Concept 1: 4,000 SST (standard-sized transplants) and 3,000 LST (large-sized transplants) outplanted in a fenced area. Weeding was considered necessary only in the case of SST.

	Standard-sized transplants			Large-sized transplants		
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 5.6.2.: Economic analysis – Concept 2: individually protected trees planted as an admixture, comparing SST (standard-sized transplants) vs. LST (large-sized transplants outplanted in a fenced area.

	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 to a reduced number of outplanted trees and therefore a lower number of protective plastic shelters and lower labour costs (Table 5.6.2.).

5.7. Above-ground and below-ground biomass

Results of above-ground and below-ground biomass analysis are summarized in Table 5.7.1. NGSS in comparison to standard-sized transplants tended more to the ratio of 1 in above/under ground biomass, standard-sized transplants showed lower ration, as was the case in weight.

Table 5.7.1.: Mean values of above-ground and below-ground biomass characteristics of used different types of planting stock and species. Assessed planting stock was used for plantations in Vintířov-Sedlec and Kozí Hory (not part of this thesis).

PS	**Ø RCD [mm]**	**Height [cm]**	**Root length [cm]**	**Tree length [cm]**	**Root width [cm]**	**Vol. below-ground**	**Vol. above-ground [cm³]**	**Above-ground dry weight [g]**	**Roots dry weight [g]**	**Dry weight total [g]**	**Ratio above/under weight**	**Ratio above/under volume**
Oak - S	18.8	121.4	28.2	131.6	24	131.4	106.4	59.51	69.74	129.25	0.85	0.81
	4.71	*21.51*	*4.26*	*19.23*	*4.34*	*37.81*	*39.94*	*22.43*	*16.11*	*35.40*	*0.22*	*0.23*
Oak - SS	21.6	95.2	22.4	102.2	19.4	87.4	67.6	40.79	45.83	86.62	0.89	0.77
	3.93	*11.62*	*2.06*	*8.28*	*3.20*	*9.85*	*8.45*	*3.60*	*6.78*	*9.48*	*0.10*	*0.12*
Oak - T	4.8	29.6	15	29.6	9.1	6.5	3.1	1.49	3.91	5.40	0.38	0.48
	1.08	*2.84*	*6.51*	*2.84*	*1.81*	*2.73*	*0.83*	*0.49*	*1.81*	*2.16*	*0.13*	*0.20*
CRA	14.8	104.8	25.2	107	22.4	65.4	45	27.86	32.5	60.36	0.86	0.69
	2.14	*13.32*	*2.04*	*14.52*	*2.42*	*14.80*	*14.95*	*8.36*	*6.42*	*13.80*	*0.18*	*0.23*
WCH	16.8	99	25.8	100.2	26.8	77.8	68.4	36.91	41.48	78.39	0.89	0.88
	1.17	*7.59*	*0.75*	*7.63*	*1.60*	*16.74*	*11.84*	*4.91*	*8.33*	*13.03*	*0.08*	*0.11*
WST	11.4	84.4	26.6	85.2	11.6	46	40	26.23	18.43	44.66	1.42	0.87
	1.02	*9.60*	*1.50*	*9.77*	*2.65*	*9.70*	*7.07*	*5.28*	*3.79*	*7.70*	*0.30*	*0.16*
ST	13	66	28.4	67.6	15.8	42.2	45.8	22.52	21.4	43.92	1.05	1.09
	1.26	*3.16*	*2.73*	*3.26*	*3.54*	*14.82*	*8.18*	*7.98*	*4.59*	*11.83*	*0.31*	*0.28*

Oak – S: common oak (*Quercus robur* L) sapling; Oak – SS: common oak semi-sapling; Oak – T: common oak standard transplant; CRA – crab-apple (*Malus Sylvestris* Mill.); WCH – wild cherry (*Prunus avium* L.) semi-sapling; WST – wild service tree (*Sorbus torminalis* L.) semi-sapling; ST – service tree (*Sorbus domestica* L.) semi-sapling; PS – planting stock; ∅ RCD – root collar diameter. Means are in normal font; standard deviations are in *italics*. Trees used for morphometrical analysis were not part of the research for dissertation, except for wild cherry.

In terms of planting the analysed tree species, oaks and crab-apple were used in Kozí Hory, as part of cooperation with Jerome Colloredo-Mannsfeld forests. Wild cherry, wild service trees and service trees were used in Vintířov-Sedlec as part of research of individual admixture of broadleaved trees in the dimension of new generation samplings and semi-saplings.

6. DISCUSSION

6.1. Forest creation, structure and diversification by artificial regeneration

The thesis focused on the use of new generation saplings and semi-saplings for the purposes of diversification of existing (particularly young) forest stands as well as reclaiming disturbed (wind, bark beetle, mining) forest sites, predominantly on mid-elevation sites.

The basic hypothesis was confirmed, i.e. the results suggest that NGSS showed lower mortality and increased growth under the conditions of strong weed competition (Truba, Vintířov-Sedlec) and performed more or less equally on poorly developed soils (Planá nad Lužnicí). Following text presents particular results for individual research plots representing different both forest and non-forest conditions.

Both creation of new stands and diversifying existing young and pre-mature even-aged stands are driven by the need of more diverse forests both structurally and in terms of tree species. Forest structure in changing conditions requires a transition to diversified forests, and that process is favourable for the decrease of inputs and for the increase of overall stand stability by spreading the risk of disturbances on more species and generations of trees (SCHÜTZ 2001; VACEK et al. 2019c). In Central European forests, there are serious problems with game damage (ČERMÁK et al. 2004; ČERMÁK et al. 2007; CUKOR et al. 2019b). Most damaging species are red deer (*Cervus elaphus* L., 1758), roe deer (*Capreolus capreolus* L., 1758), European hare (*Lepus europaeus* Pallas, 1778) (on young cultures), locally also mouflon (*Ovis musimon* Pallas, 1762), sika deer (*Cervus nippon* Temminck, 1838) and fallow deer (*Dama dama* Frisch, 1775). Moreover, the problems with the regeneration of forests caused by browsing damages of ungulates could be partially solved by a gradual change of tree species composition together with the transition to irregular stands (VACEK et al. 2014; RAYMOND, BÉDARD 2017; GALLO et al. 2020b). Diversification is needed to fulfil multifunctional purposes of forests (YOUSEFPOUR, HANEWINKEL 2014), which is related to today's considerations about climate-smart forestry, which also contains managing biocorridors of key species and connectivity in forest landscapes (BRUNDU et al. 2020). Mixing has overall positive effects on structure, interaction and growth of trees (PRETZSCH et al. 2013b; PRETZSCH, ZENNER et al. 2017). Additionally, monocultures of artificially planted Norway spruce decline on rapid pace on sites where the conditions are no more suitable for its survival (NERUDA 2000; ERBER 2018).

Forest regeneration means the process of exchanging generations of trees in a forest stand. It can take place naturally (seed blight), artificially (planting seedlings, sometimes sowing), or combined. The regeneration can be performed in one or more phases (ŠAFRÁNEK et al. 2018; ŠVÉDA et al. 2020). Natural regeneration is a process where the emergence of a new stand is associated with the direct participation of the parent stand through germination of fallen seeds, or due to sprouting (RADOGLOU et al. 2009; KUNEŠ et al. 2019; MATULA et al. 2019; KUNEŠ et al. 2020). Human participation in the process of natural regeneration may not excluded, but it is only mediated (VACEK et al. 2015). The possibility of applying natural regeneration on calamitous clearings can be supported already during the harvesting of bark beetle-infested trees, by leaving the individuals of interspersed tree species standing (SLÁVIK, KHUN 2014; SLÁVIK, ŠTEFANČÍK 2015; PROKŮPKOVÁ 2020). Mechanical soil preparation after harvesting can also significantly facilitate the emergence of natural regeneration (SUADICANI 2003; NOVOTNÝ, ŠIŠÁK 2016; ULBRICHOVÁ et al. 2017). The advantage of natural regeneration lies especially in the lower initial financial demands as the costs of planting material and its planting are eliminated (ŠAFRÁNEK et al. 2018, GALLO et al. 2020b). The costs of protection (especially against game) may also be partially (but not always) eliminated (SLANAŘ et al. 2017). It is closer to natural processes, which is a positive aspect in localities with nature conservation interests (VACEK et al. 2019c). In stands created by natural regeneration (raid, growth) there is usually a significantly larger number of individuals than in the case of artificially established culture (TOBISCH 2007; MALÍK et al. 2014; GALLO et al. 2020*a*). However, in specific situations, artificial regeneration is needed, but in Central European conditions, particularly standard-sized seedlings and transplants often suffers severe losses in the initial phases of growth (REPÁČ et al. 2020).

The expected benefit of the research summarised in the thesis is the improved knowledge on which species and which planting stock are the most suitable for use in reforestation on different sites with respect to future forest structure and stability. Species-diverse forests are considered more stable under the conditions of intensified abiotic and biotic disturbances (GALLO et al. 2020b; VACEK et al. 2020). It contains resistance and resilience against bark-beetles, rodent, wind and snow. Creating successful forest mixtures is crucial for establishing functioning ecosystems on specific sites like e.g. abandoned agricultural landscape, reclamation sites, or undermanaged forests with weeded old clear-cuts.

One of the options to increase species diversity is the use of admixture of broadleaved trees into existing forest stands that are not diverse enough. The character of the site destined for reforestation needs to be thoroughly analysed and considered for particular planting stock use (SCHMIDT-VOGT, GÜRTH 1969). In some cases, the use of large dimension planting stock can be beneficial. Growth characteristics of different tree sizes were in accordance with previous works, such as VAN DEN DRIESSCHE (1992), who presented growth in Douglas fir. In this case, the relative height-growth rate was higher in smaller trees, but absolute differences increased in favour of larger trees. Also, the suggestion for the reason that this is occurring is given: as the size of a tree increases, the proportion of non-assimilating tissue becomes greater and causes self-shading. The transplant shock was registered for all sizes of bare-rooted planting stock, which was in accordance with previous works (SCHMIDT-VOGT, GÜRTH 1969; VAN DEN DRIESSCHE 1992).

Lower mortality and higher height and root collar diameter increments have already been documented in various planting conditions for large-sized planting stock (VAN DEN DRIESSCHE 1992; STRUVE et al. 2000; KUNEŠ et al. 2014a). However, based on the experience of other plantings, there was a presumption that the situation at the site limited by the amount of precipitation will make the situation more complicated. At the same time, there are factors speaking in favour of and factors speaking against the use of advanced planting stock (NEWTON et al. 1993).

The weed infestation speaks in favour of semi-saplings or saplings. In case of planting semi-saplings and saplings, weeding is usually not needed and not foreseen – this is also one of their main advantages (WATSON 2005; KUNEŠ et al. 2014a). If a weed control has to be applied (in case of extreme weed infestation or combined use of standard-sized plants with the large-sized stock), the semi-saplings and saplings are also better visible than the small trees, thereby minimizing the chopping losses. On the other hand, the larger-sized planting stock is supposed to be more vulnerable in case of insufficient rainfall and low soil and air humidity (WATSON 1985), which, however, was not confirmed by the research studies conducted and presented in this thesis (GALLO et al 2018a; GALLO et al. 2019; GALLO et al. 2020a).

6.2. The effect of saplings and semi-saplings (Truba)

First partial study focused on improving growth performance of European beech plantation by the application of brassinosteroids (BRs). It is discussed first not because of the importance, but stepwise as it was the oldest planting. There are relatively few studies of BRs application related directly to the growth of forest trees. The research of the application of BRs on forest trees has so far less convincing results than other authors investigating agricultural plants: NOVÁKOVÁ et al. (2014) reported a substantially increased mortality rate of Scots pine seedlings planted on abandoned agricultural land after the application of a synthetically prepared analogue of 24-epibrassinolid. BR in that case also slowed the height and radial growth. The effect was significant in two subsequent measurements, which suggest a reaction with long-term effect of BRs. However, in the second study (NOVÁKOVÁ et al. 2015), based on data gathered in a forest nursery, BR treatment decreased the mortality rate of the same species, but general effects on height and radial growth were rather inhibiting again. In the same study, the influence of BR treatment on Norway spruce seedlings was slightly beneficial, depending on chosen concentration, but mostly insignificant. The medium concentration (4 $mg \cdot ha^{-1}$) showed the best results. In relation to our study, we could suggest that the application could have decreased the planting shock in terms of the mortality rate. However, for such a conclusion, more research on various species needs to be done.

Adverse effects of late frosts on European beech were also studied, as it is the principal broadleaved stand-forming tree species on large areas of low, middle and high elevations in Central Europe (PODRÁZSKÝ et al. 2014). The recorded frost event (4–5 May 2014) was the strongest in terms of stress influence with the most serious impact on vegetation during the whole monitored period (2013–2015). Other frost events were either less pronounced or occurred in a period of lower vegetation sensitivity. The lowest temperature (measured at 30 cm above ground) reached –2.6 °C (duration 2 hours, see Fig. 4.2.1.2.). This event caused foliage injury of most trees within the plantation. Subsequently, the damaged trees regenerated, and the annual height and diameter increment did not differ in comparison with previous seasons (GALLO et al. 2017).

During the field reconnaissance, a slightly reduced amount of frost injuries of the BR treatment was noticed. When only the range of damage (lower and upper limits) was assessed, the influence of BR treatment on frost sensitivity was negligible. The process leading to increased frost tolerance involves plasma membrane lipids showing lower phase transition temperature and higher unsaturation degree when treated by a brassinolide, leading to a higher fluidity under low temperature, as found on mango fruit. Therefore “proteins and lipids are involved in brassinolide-mediated responses to cold stress” (LI et al. 2012). Many other physiological changes were also described, for example, increases in leaf water content, relative water content and water potential (LI et al. 2008). In the connection to the phenomena mentioned above, a series of processes including the decrease of intracellular CO_2 was described, which positively influenced the effectivity of photosynthesis under heat stress (THUSSAGUNPANIT et al. 2015).

The frost damage of the lowest parts of trees (i.e. below 20 cm above) was rather reduced, because the shelter, provided by grass and herbaceous weed protected them: where the beech leaves were sheltered in the dense grass, the damage was negligible. Similar shelter effects of the vegetation as grass (less efficient), *Rubus* shrubs and woody shrubs (more efficient) are described by PETRITAN et al. 2011. In our case, the upper limit of frost damage was at about 60 cm above ground, which corresponded with the recorded temperature progress. At the monitored heights of 100 cm and 200 cm above ground, the minimum temperatures reached only –0.4 °C and –0.3 °C, respectively. We may, therefore, deduce the temperature threshold of about –1.5 to –2 °C, which can cause visible but not serious damage of young (sprouting) European beech foliage. The upper above-ground limit of frost damage naturally differs with the intensity of the frost event. In this respect, the zone from 0 to 100 cm above ground is determined by various studies (e.g. GEIGER 1950; ŠPULÁK, BALCAR 2013) as the zone of air layer where the daily temperature amplitude (cold at night but hot in the day-time) is most extended.

The high variability of sensitivity to frost damage in this species, which is not related to climatic conditions of provenances nor species phylogeography, needs to be considered (HOFMANN et al. 2015). The hydraulic frost resistance of European beech is characterized by increased embolism in winter, followed by a decrease before bud flushing, in contrast to, for instance, *Pinus sylvestris*, which is characterized by complete resistance (CHARRIER et al. 2013). GÖMÖRY, PAULE (2011) pointed out the presence of the compromise between two contradictory strategies in terms of the date of bud flushing, which are the effective use of vegetation period and protection against late frost.

The late frost event hit the plantation during bud flushing, when the trees are most susceptible to frost damage (DITTMAR et al. 2006); the course of bud flushing is described by for example ROBSON et al. (2013) and DITTMAR, ELLING (2006). Date of bud flushing in European beech (climax species) is highly determined, besides temperature, by photoperiod (LECHOWICZ 1984; BASLER, KÖRNER 2012; LENZ et al. 2016), namely it is driven by chilling and forcing temperatures with an interaction effect of the photoperiod on forcing rate (photoperiod co-control of leaf-out). It is more pronounced when the chilling requirement is partially satisfied, rather than when buds are fully chilled (VITASSE, BASLER 2013). This dual regulating system minimises the risk of encountering frost event during bud flushing

(CAFFARRA, DONNELLY 2010). When defoliation caused by late frost occurs, European beech can recover by second flushing, but the quality (the content of nutrients, sucralose) is decreased, and that can have a negative impact on growth (GÖMÖRY, PAULE 2011).

6.3. Saplings and semi-saplings under drought-heat stress (Truba)

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). Besides 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. 2011a). In this partial study, standard-sized transplants (SST) were compared with large-sized transplants (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 (ŠAFRÁNEK et al. 2018; ŠAFAŘÍK 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 again costlier in comparison to standard-sized plants. Nevertheless, it might be applied in reforestation or afforestation in many cases (BURDA, 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. 2014a). 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 this case, the afforestation of former agricultural land was monitored. The two different sizes of planting stock were tested 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 the workforce, we might opt for the large-sized planting stock (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 lower compared to those at a higher level above the ground (Table 4.2.1.1.), but with heat extremes in growing period (Figure 4.2.1.1.), which suggests that there are different site conditions for saplings and standard-sized transplants, as their most important part, the terminal bud, was at a different level above the ground. The terminal bud of a large-sized tree is located above the negative influence of early summer weed competition and can thrive (KUNEŠ et al. 2014a).

Under the conditions of generally low mortality of the planted trees, the non-weeded saplings showed similar mortality as the weeded transplants. Weeding had no significant impact on mortality rate of the saplings, but the non-weeded transplants showed increased mortality. The overall differences were not high; the same pattern was registered in height increment of the trees. The saplings were not affected by weed, whereas the standard-sized transplants responded positively to weeding. The non-weeded transplants 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 (STRUVE et al. 2009; WATSON 2005), even a comparable growth pace can be considered a success, because the large-sized plants keep their advance in size. Large-sized transplants can save extra post-planting costs related to protection and weed control. On nutrient-poor sites, the positive effect of reduction in competition might be lower due to less competition by weeds. Therefore, as on specific mountain sites, also on mid-elevation sites, large-sized planting stock is meant be used in specific cases and as a complement to standard-sized transplants (BALÁŠ et al. 2011a; BALÁŠ et al. 2011b). Other negative factors – such as deer browsing, gnawing and fraying – cannot be easily controlled, although the saplings can more efficiently utilize the lifespan of selected deer protection measures such as fencing and individual shelters (KUNEŠ et al. 2011a; KUNEŠ et al. 2011b; GALLO et al. 2020a).

The light sandy-loam soil with a tendency to drying out meant that both standard-sized transplants and saplings 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: common oak (*Quercus robur*) on sandy soil on a site reclaimed after sand mining, as well as European beech (*Fagus sylvatica*) (GALLO et al. 2018a; Gallo et al. 2018b) and wild cherry (*Prunus avium*) on a forest clear-cut (nutrient-rich) site (GALLO et al. 2019). The large-sized transplants are generally considered as more susceptible to water stress than the standard-sized transplants in the initial years after planting (WATSON 1985). However, in all mentioned cases, saplings maintained the initial height advance and lower mortality. This could allow foresters to establish a stable and structured stand sooner and more effectively (GALLO et al. 2020). In Figure 5.1.2.2., a successively increasing effect of weeding on height and root collar-diameter of both sizes of planting stock is apparent.

The chlorophyll content was significantly higher in the large-sized transplants in 2013 but equalled in the following year. This possibly could be ascribed to a larger amount of nutrients still incorporated stored in the tissue of large-sized transplants from a nursery. The reduced content of chlorophyll could also point to the increased stress of plants (VAN DEN BERG, PERKINS 2004). Determining an ideal or universal value is problematic, in any case (LINDA et al. 2019. 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 standard-sized transplants and saplings 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 large-sized planting stock, the costs of establishing a plantation can be significantly reduced.

6.4. Saplings and semi-saplings on reclamation sites (Planá nad Lužnicí)

The importance of the use of saplings and semi-saplings can be seen above all in the fact that they enable to achieve a certain compositional-structural state of the young stand in a shorter time than would be necessary if only standard-sized planting stock would be used. Combination of saplings and semi-saplings with natural regeneration or planting material of common commercial dimension can be spatially diversified from the beginning. Thus, for example, it is possible to create two crown layers, which is a suitable condition for mixing shady and light-wood species. It is also possible to introduce species admixture into already existing vegetation by means of new generation saplings and semi-saplings.

If the established stand is to perform the function of producing organic matter, which will form the soil of the habitat, this task will perform significantly better in the cultivation of the usual commercial size planting stock of pioneer tree species, established in greater density or even sowing these tree species than planting saplings. This statement can be supported by studies of several authors focused on pioneer trees and biomass accumulation in their stands (PODRÁZSKÝ, MORAVČÍK 1992; MORAVČÍK 1994; URI et al. 2002; KUNEŠ et al. 2014b; VACEK et al. 2016*b*). However, another situation may exist in extreme frosty or weed-infested locations, where height may provide a certain advantage to the planting material, especially regarding the climate of the ground layer.

From the presented results, it can be derived that oaks showed improved initial survival compared to limes. This can probably be ascribed to ecological characteristics (silvics) of the different species (SAVILL 2019). Lime is considered mostly climax species in Central European space in the conditions of mixed-broadleaved forest stands of lower to middle elevations. Common oaks, in contrast, regenerate on open sites under more intense supply of sunlight (ÚRADNÍČEK, MÖLLEROVÁ 2005). Reclaimed sandpit, therefore, represents growing conditions for oaks more adequately than for limes. Also, over-layered plateau is prone to waterlogging as well as drying, which is more favourable for oaks than for limes. As a result, initial mortality was significantly lower in oaks compared to limes.

6.5. Saplings and semi-saplings on weed-infested sites (Vintířov-Sedlec)

According to the experience in the area of interest, clear-cutting silvicultural system on a nutrient-rich and drying habitat is very problematic. Failure of afforestation in these conditions is most often caused by the influence of weed competition, lack of water in the soil, or damage by game. If there is a need for clear-cutting (typically an older stand with reduced stocking, where the weed cover has already developed and natural regeneration has failed for various reasons), it is necessary to afforest the area immediately and effectively protect against game. Any delay in the afforestation usually results in a head starts of the weed over the planted-sized trees. This head start results in a need for weeding treatments. A similar situation occurs when losses occur after the first afforestation, for whatever reason (GALLO et al. 2018a; GALLO et al. 2018b). Such clear-cuts are very difficult to afforest, and practically the only real possibility is to use large-sized planting stock in the dimensions of semi-saplings or saplings. Such a situation was also the case of our research plot, which (after several previous unsuccessful attempts of an operational character), we were able to afforest only with the experimental approaches described in the study (GALLO et al. 2018a; GALLO et al. 2018b; GALLO et al. 2019).

It is also worth mentioning the development of weed vegetation in the research area. Following the removal and fencing of the area, the following year saw a significant development of woody vegetation, especially individuals of vegetative origin (resprouts), but apparently also individuals of generative origin, permanently damaged by game over a long period of time. In addition to shrubs (elderberry – *Sambucus* agg., hazel – *Corylus avellana*) among the tree species, the fastest growth was recorded for sycamore, aspen, silver birch, oaks, and elms. The dynamic development of vegetation within the fenced area in comparison to the surroundings is the evidence of considerable game pressure in this locality.

Wild cherry is generally considered to be a more demanding tree species, requiring nutrient-rich and well-watered soil (MUSIL, MÖLLEROVÁ 2005). In an arid climate, it responds very well to artificial irrigation (example from Spain - MOLINA et al. 2016), but does not tolerate heavy, poorly drained soils with stagnant water (example from Sweden – MARTINSSON 2001).

Thus, after planting at a site with reduced availability of soil moisture, a significant manifestation of planting shock was expected. However, in the first year after planting, the cherries in the experimental plantations of both compared initial sizes (standard-sized transplants and saplings) showed high resistance and vitality – with an average height increment of around 20 cm, minimal mortality and a satisfactory condition of the assimilation apparatus in the second part of the vegetation season.

Compared to the previous year (2017), when the neighbouring research planting of European beech was damaged due to drought (GALLO et al. 2018*a*), no significant manifestations of drought damage were recorded in cherry plantations. Occasional tree deaths may have been caused by factors other than drought (e.g. rodent damage). Likewise, overlie by weed occurred only sporadically, if it occurred, and only in places with more abundant blackberry (*Rubus fruticosus* agg.) development. This result was undoubtedly due to the weather course in the vegetation season 2018, which in most areas of the Czech Republic harmed both the adult stands and the planting. In the area of interest, which usually suffers from a lack of precipitation, several heavy showers and storms of local character were recorded in the critical spring season (May and June) with total tens of mm (In-počasí 2019).

The contribution of showers to drought reduction was only temporary, but thanks to a favourable occurrence date, these rainfalls contributed to improving the health condition and growth of trees after planting.

At the same time, however, extraordinary drought tolerance and intensive growth dynamics were recorded in the first year after planting also within the next plantation of the wild cherry, in which the author participated. Initial evaluation of the plantation of common oak and wild cherry in the locality Kozí Hory (MIKOLÁŠEK 2019) showed a very intensive growth of the wild cherry in the first year after planting. In contrast, the oak in the same conditions experienced a growth stagnation (but also with minimal mortality). A similarly intensive growth dynamics in the first year after planting was also described in the case of cherry plantings in the Židlochovice area (STEJSKAL, DOVRTĚL 2016). According to this, though so little and preliminary, experience, the cherry tree can be considered surprisingly resistant to soil drought, which is important in the current period with a predominance of dry years. The coming years will probably be decisive for the overall success of the plantation.

Wild cherry is habitually used in silviculture as a site improving and ameliorative forest tree species (PODRÁZSKÝ, KUPKA 2011). In addition, cherries are very interesting in terms of promoting the usability and attractiveness of the environment for animals (birds, bees), as well as interesting wood, which is used in decoration and industry. For its valuable wood, the species has suffered huge exploitation throughout Europe (GANOPOULOS et al. 2011; DUCCI et al. 2013) – the demand for cherry wood in Western Europe is being fulfilled to a large extent by unsustainable harvests in Eastern Europe.

A more detailed assessment of the difference in the growth of semi-saplings and standard-sized transplants is still premature, but after the second growing season it could be stated that semi-saplings have maintained (even slightly increased) the initial height and diameter lead. Similar results are reported by e.g. DOSTÁLEK et al. (2014), who also observed the growth of cherries with different initial seedling sizes. The described research plantation is established as a small homogenous stand so that it enabled monitoring of the growth dynamics of planting material of different initial size. In real operation conditions of forest management, however, it would probably be desirable, with regard to its ecological characteristics, to grow cherry trees as admixed trees in the main stand of other tree species. It is ideal that cherry represents about 30% of the top-level trees, while it is advisable to support the existence of the undergrowth and to apply pruning if necessary (PODRÁZSKÝ, KUPKA 2011). Better cherry growth in the mixture compared to monoculture was also observed in the exotic conditions of South American Chile (LOEWE et al. 2013). Anyway, due to light resistance, it is necessary to maintain the cherries in a significantly above-level (or at least level) position throughout the individual. If necessary, regular release from competing tree species is therefore necessary (STOJECOVÁ, KUPKA 2009). Furthermore, the need to ensure good protection against game appears to be very important, as cherry is preferentially sought and damaged by game (LÖF et al. 2014).

Based on experience in the area of interest (habitats threatened by the competing weed and droughts) it is advisable to avoid, as far as possible, clear-cutting management. If it has already been necessary to carry out a clear-cut regeneration (older stands with reduced stocking, where the weed has already developed and the natural regeneration failed for various reasons), or the clearing was created by salvage felling, it is necessary to afforest the area immediately and effectively protect it against game.

If for any reason afforestation fails, and also in case of any delays in afforestation on such sites results in an increase in the height of the weed over the planted trees, requiring very expensive weeding treatments. Then, the only real possibility is to use large-sized planting stock in the dimensions of semi-saplings (or saplings). As on adjacent experimental plot with *Fagus sylvatica*, this was also the case in the investigated area, which after several previous unsuccessful operational attempts was afforested only after establishing of the research area.

The planting stock in the dimensions of saplings and semi-saplings would not be fully operational without applying the method of planting the holes using a motor earth auger (STIHL 2006; STIHL 2014). By using the auger, it is relatively easy to create full-fledged holes that provide ample space for the rich and compact root system of the large-sized planting stock, which would be unmanageable in the required quality and speed with the use of hand tools (planting axe hoe) (BALÁŠ et al. 2016).

6.6. Týniště nad Orlicí – complex of various sites

Research site Týniště nad Orlicí contained three different plots representing, in terms of our research, unique temporarily water-logged site on the plot U Glorietu, clearance after wind disturbance on the plot Štenclova alej, and post-mining sandpit in case of last plot, Písník. In all cases, structural and species diversity changes were desirable; in case of the last plot it meant establishing a new forest.

In case of temporarily water-logged site U Glorietu, saplings of small-leaved lime showed significantly increased survival (lower cumulative and annual mortality rates) in comparison to standard-sized transplants (Table 5.4.1.). In terms of height and root collar diameter (Fig. 5.4.1.), NGSS kept the original advance, as the analysis of (height) increment showed statistically insignificant result (Fig. 5.4.2.) The available results obtained from the plantation on this research plot therefore show that the NGSS can be used in temporarily water-logged habitats, due to significantly lower mortality rate of saplings than standard transplants (39 vs. 77 %). This is probably due to the overall larger dimensions. The idea is derived from the fact that big mature trees are not so heavily impacted by temporary water-logging in comparison to small (young) trees (HOOK 1984).

On the wind-disturbed plot, Štenclova alej, NGSS of small-leaved lime as well as individual plantings of wild cherry showed excellent performance, especially in contrast to high cumulative mortality of standard-sized transplants of small-leaved lime (21 vs. 84 %) (Table 5.4.2.). Therefore, NGSS can be recommended for sites suffering from intense weed competition, which is in accordance with studies from Vintířov-Sedlec (GALLO et al. 2018a; GALLO et al. 2019). The difficult character of the site (weed infested) originated in the preceding wind disturbance, as the main tree layer was heavily disturbed, while lower layers and particularly the ground vegetation was left undisturbed and after the release, weed species showed extremely high competition ability. In such case, initial size of trees proved to be crucial in order to perform a successful reforestation. However, vigorous and abundant natural regeneration of silver birch, Scots pine, European larch, Norway spruce, white pine (*Pinus strobus* L.) and European beech. Particularly European beech effectively grew through the competing vegetation, which is in contrast to artificial regeneration of beech in Vintířov-Sedlec (GALLO et al. 2018). The natural regeneration was also (visually) performing better in comparison to standard-sized transplants on the plot, therefore further research of artificial × natural regeneration (and their combination) would be desirable. NGSS of wild cherry were not part of statistical analyses, as there was only small number of them (N = 10), but they all showed excellent growth (detailed data are available from the author).

Based on results from the third research plot in Týniště nad Orlicí, Písník, NGSS can be successfully used also on reclaimed sand-pit sites, which is in accordance with previous study from Planá nad Lužnicí sandpit (KUNEŠ et al. 2017) and also with results presented in this thesis regarding the same research site. NGSS of common oak and small-leaved lime showed significantly lower mortality compared to standard-sized transplants of small-leaved lime (Table 5.4.3.). Differently, oak NGSS significantly outperformed both NGSS and standard-sized transplants of lime in terms of height increment; in root collar diameter the order was –

oak NGSS – lime NGSS – lime SS – significantly from best to worse (both in Fig. 5.4.6.). This result confirmed the better suitability of common oak on sandpit in comparison to small-leaved lime, which can be partially equalled by the use of advanced planting stock of lime (similar mortality, but lower growth; SST: lower growth and higher mortality).

6.7. Raspenava – initial experiment on abandoned land

Plantings on Raspenava research site showed variable growth performance and survival rates between variants on former agricultural lands. European beech was confirmed to have improved performance in monoculture under the conditions of fresh soil. With increasing humidity, both groweth performance and survival rapidly declined (Table. 5.5.1. and Fig. 5.5.1.). Common oak performed equally well on both fresh and humid soils in terms of mortality, the growth decreased with increased soil humidity (Fig. 5.5.2.). Such finding is in accordance with other works (NIELSEN, JØRGENSEN 2003; CUKOR et al. 2017c). Different spacing regimes probably do not affect growth rates in the initial phases of growth (POLENO et al. 2009). Analysis of crown width showed similar dynamics to the tree height increment (Fig. 5.5.3.). As this experiment is mainly focused on spacing regimes, it will be important to analyse the growth dynamics of individual blocks in following years.

6.8. Synthesized knowledge and experience for afforestation, reforestation and silviculture

The main objective of this thesis was to find out about advantages and disadvantages of large-sized (advanced) planting stock (simplified as "saplings") under specific conditions of mid-elevated sites in comparison to standard-sized planting stock of broadleaved forest tree species (in both cases).

On all sites and in all types of climatic and soil conditions, saplings proved to have better or at least the same initial survival and growth performance as standard-sized transplants. Moreover, they showed a practical benefit of improved visibility and therefore decreased the threat of accidental cutting during weeding, which is in case of saplings not even needed in most cases. Furthermore, the economic benefit is reachable according to economic analysis, when the number of individuals is lowered, which is only possible, again, in case of saplings.

The results showed that NGSS can outperform standard-sized transplants that are habitually used in forestry (afforestation, reforestation, reclamation) in initial phases of growth. However, in accordance with JELÍNEK, ÚRADNÍČEK (2010), it is reasonable to make decision regarding the possible use of the large-sized plants based on the specifics of managed site, especially ecological site characteristics and expected treatments.

7. CONCLUSIONS

NGSS showed lower mortality rate and increased growth under the conditions of the relatively dry climate and intense weed competition (Truba, Vintířov) and performed more or less equally on poorly developed soils (Planá nad Lužnicí). The advanced planting stock of selected species (European beech, small-leaved lime, common oak and wild cherry) maintained the initial height and diameter difference. The pros of NGSS are enhanced growth, better visibility on complicated site infested by weed competition. Also, in waterlogged site conditions, survival and growth of NGSS showed far better dynamics compared to standard transplants. The cons are the time-consuming production and more complicated transport, both of which are linked to increased costs. The expected higher sensitivity and vulnerability of larger plants to severe droughts were not confirmed.

The study of growth performance and resistance of European beech plantation to the frost in Truba confirmed that the late frost events were most damaging at 30 cm above the ground in comparison to the other above-ground layers (as in the lower layer above the ground, trees were protected by grass), which is a threatening situation especially for the terminal buds of the standard-sized planting stock.

The large-sized planting stock can shorten the time during which the protection against game and weed is needed. The large-sized plants are, however, costlier, and more laborious for outplanting. Therefore, it can be recommended to use large-sized planting stock for specific sites, where reduction in outplanting density (numbers of trees per areal unit) is not a problem, and where weed control may be difficult.

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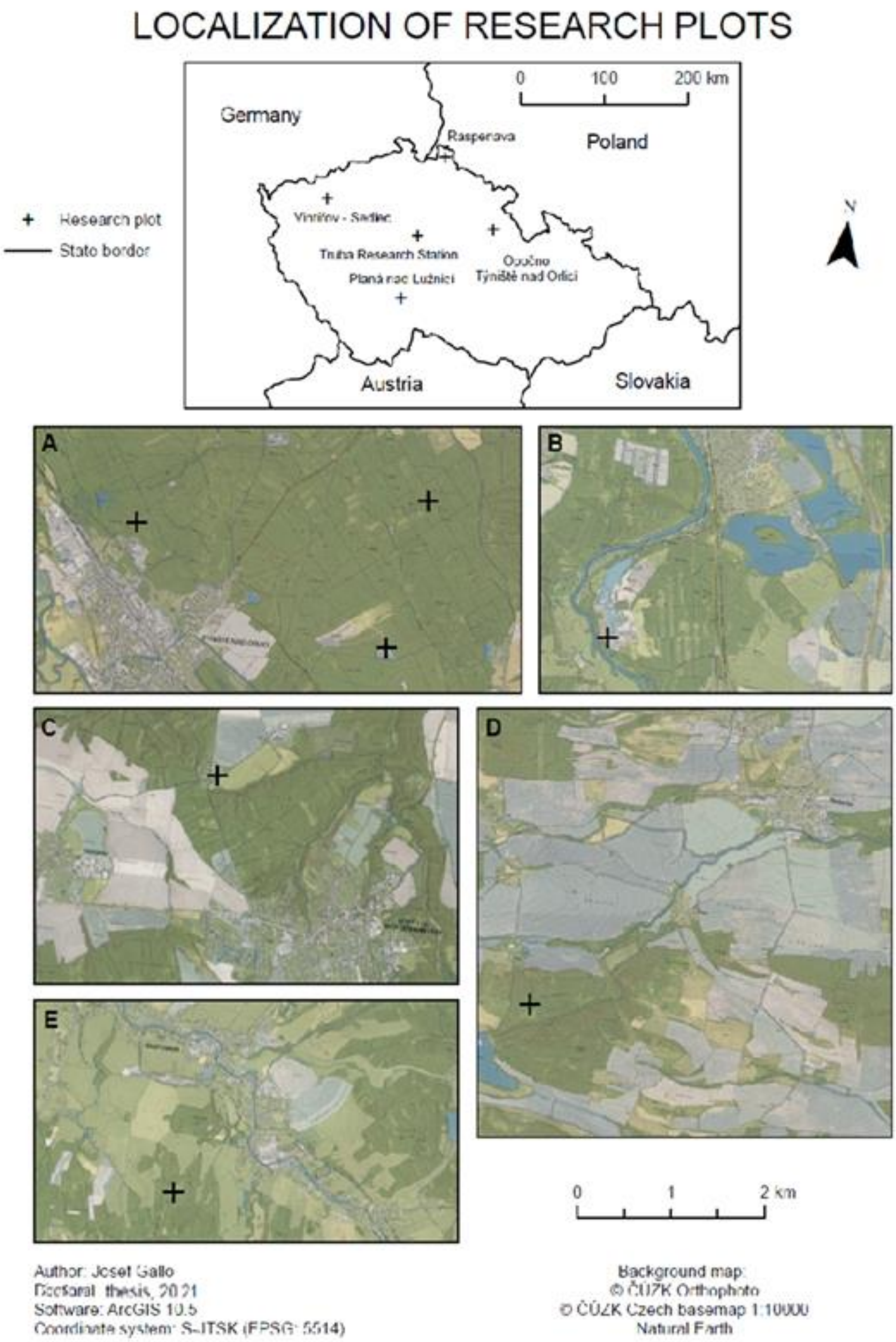
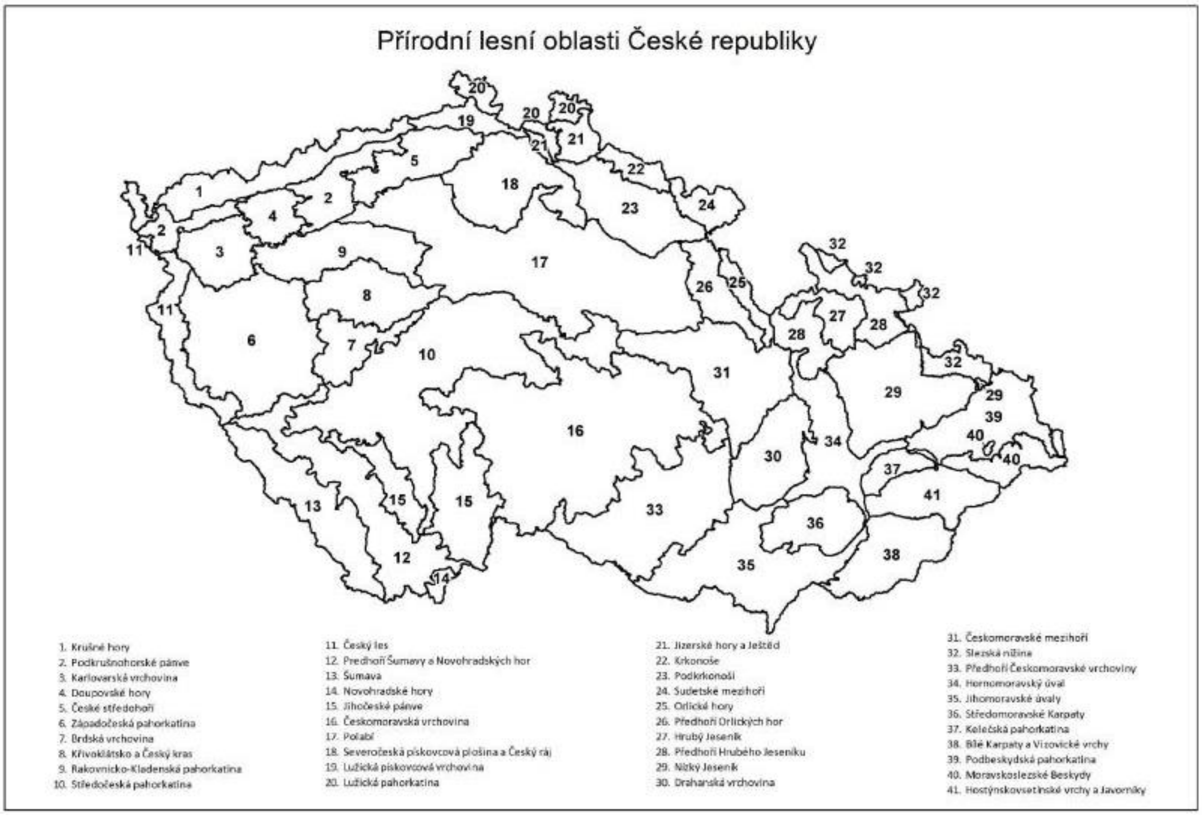
9. ATTACHMENTS

Attachment 1 – Map of research plots (ArcGIS)



A – Týniště nad Orlicí (from left to right: U Glorietu, Písník, Štenclova alej), B – Planá nad Lužnicí, C – Truba Research Station, D – Vintířov-Sedlec, E – Raspenava

Attachment 2



Natural forest zones in the Czech Republic (there are 41 forest zones according to 298/2018 Coll directive). Regionalization is based on natural conditions.

Attachment 3

Site name	Forest site type	Ecosystem classification Natura 2000 or Corine (CHYTRÝ et al. 2010)
Truba Research Station	**3S2 – fresh oak-beech forest with *Galium scabrum***	*Galio-Carpinetum oakhornbeam forests*
	3P1 – acidic fir-oak forest with *Luzula Pilosa*	*Old acidophilous oak woods with Quercus robur on sandy plains*
	3K2 – acidic oak-beech forest with *Carex pilulifera*	*Luzulo-Fagetum beech forest*
	2M1 – nutrient-very poor beech-oak forest with moss and lichens	*Medio-European acidophilous oak forests*
Planá nad Lužnicí	**1M3 – nutrient-very poor pine-oak forest with *Vaccinium myrtilus***	*Subcontinental pine-oak forests*
	1M2 – nutrient-very poor pine-oak forest with *Avenella flexuosa*	*Subcontinental pine-oak forests*
	0P1 – acidic fir-oak-pine forest with *Vaccinium myrtilus*	*Central European lichen pine forests*
	0P5 – acidic fir-oak-pine	*Central European lichen pine forests*
	0G2 – humid spruce-pine forest	*Sphagnum spruce woods*
	3S3 – fresh oak-beech forest	*Galio-Carpinetum oakhornbeam forests*
	2L5 – stream floodplain forest	*Alluvial forests with Alnus glutinosa and Fraxinus excelsior*
Vintířov-Sedlec	**3C1 – drying oak-beech forest with *Luzula luzuloides***	*Galio-Carpinetum oak-hornbeam forests*
	3B1 – nutrient-rich oak-beech forest with *Melica nutans*	*Asperulo-Fagetum beech forests*
Týniště nad Orlicí		
Týniště – U Glorietu (U nádraží)	**2P1 – acidic fir-oak forest with *Luzula Pilosa***	*Old acidophilous oak woods with Quercus robur on sandy plains*
	2O1 – nutrient-medium fir-(beech)-oak forest with *Sanicula europaea*	*Old acidophilous oak woods with Quercus robur on sandy plains*
	2I1 – compacted-acid beech-oak forest with *Luzula pilosa*	*Galio-Carpinetum oak-hornbeam forests*
Týniště – Štenclova alej (Pod Křivinou)	**2I1 – compacted-acid beech-oak forest with *Luzula pilosa***	*Galio-Carpinetum oak-hornbeam forests*
	2P2 – acidic gleyic oak forest with *Carex hirta*	*Old acidophilous oak woods with Quercus robur on sandy plains*
	2K1 – acidic beech-oak forest with *Avenella flexuosa*	*Medio-European acidophilous oak forests*
Týniště – Písník (Rašovice)	**1M0 - nutrient-very poor pine-oak forest**	*Subcontinental pine-oak forests*
	1M1 – nutrient-very poor pine-oak forest with *Festuca ovina* (or degradation stage with *Calluna vulgaris*)	*Subcontinental pine-oak forests*
Raspenava	**3S2 – nutrient-medium oak-beech forest**	*Galio-Carpinetum oak-hornbeam forests*
	3O1 – gleyic nutrient-medium fir-oak-beech forest with *Sanicula europaea*	*Asperulo-Fagetum beech forests*
	3K1 – acidic oak-beech forest with *Avenella flexuosa*	*Luzulo-Fagetum beech forest*
	1T9 – nutrient-poor wet birch-alder forest with *Picea abies* and *Alnus glutinosa (Piceeto-Alnetum)*	*Alder swamp woods*

Forest site types in bold mark those present on research site, normal font represents forest site types in the vicinity of investigated plots. In the first column, alternative name of plot used in previous literature (BALÁŠ et al. 2016) is given in case of research site Týniště.

10. PHOTO GALLERY

10.1. Truba Research Station

European beech plantation


Photo of European beech plantation on investigated research plot Truba after outplanting in 2012 (31/10/2012) *(left)*, and after growing season 2014 (13/02/2015) *(right)*. Photos by Martin Baláš.


Photo of European beech plantation on investigated research plot Truba after growing season 2015 (10/09/2015) *(left)*, and after growing season 2016 (03/02/2017) *(right)*. Photos by Martin Baláš.

European beech plantation on investigated research plot Truba after growing season 2018 (21/02/2019). Photo by Josef Gallo.

Small-leaved lime plantation

Small-leaved lime plantation on investigated research plot Truba in 2013 (20/05/2013) *(left)*, and in 2015 (10/09/2015) *(right)*. Photos by Martin Baláš.

Small-leaved lime plantation during growing season in 2016 (26/05/2016) on investigated research plot Truba. Photo by Josef Gallo


Photo of small-leaved lime plantation on investigated research plot Truba after growing season 2018 (05/10/2018) *(left)*, and in 2019 (07/08/2019) *(right)*. Photos by Martin Baláš.

Measuring small-leaved lime plantation on investigated research plot Truba in summer 2019 (06/08/2019). Photo by Josef Gallo.

10.2. Planá nad Lužnicí


Small-leaved lime plantation *(left)*, and common oak/small-leaved lime *(right)* on the investigated research plot Planá nad Lužnicí after outplanting in 2014 (11/11/2014). Photos by Martin Baláš.

Photo of small-leaved lime plantation *(left)*, and common oak/small-leaved lime *(right)* on the investigated research plot Planá nad Lužnicí during growing season 2015 (02/06/2015). Photos by Martin Baláš.

Photo of small-leaved lime plantation *(left)*, and common oak plantation *(right)* on the investigated research plot Planá nad Lužnicí at the end of growing season 2018 (21/08/2018). Photos by Martin Baláš.

Photo of common oak plantation in comparison to Scots pine *(left)*, and small-leaved lime plantation *(right)* on the investigated research plot Planá nad Lužnicí during the growing season 2019 (22/07/2019). Photos by Martin Baláš.

10.3. Vintířov-Sedlec

European beech plantation

Outplanting of European beech plantation on the investigated research plot Vintířov-Sedlec in autumn 2016 (28/11/2016). Photos by Martin Baláš.

Comparison of European beech semi-sapling *(left)* and standard-sized transplant *(right)* during the first growing season after outplanting in 2017 (04/06/2017) on the investigated research plot Vintířov-Sedlec. Photos by Martin Baláš.

European beech plantation during the second growing season (31/05/2018) *(left)* and after the third growing season (14/04/2020) *(right)* on the investigated research plot Vintířov-Sedlec. Photos by Martin Baláš.

Wild cherry plantation

Photo of wild cherry plantation in the midst of the first growing season 2018 (02/05/2018) *(left)*, and in the beginning of following growing season 2019 (09/04/2019) *(right)* on the investigated research plot Vintířov-Sedlec. Photos by Martin Baláš.

Photo of wild cherry plantation in the midst of the first growing season 2018 (02/05/2018). Photo by Josef Gallo.

10.4. Týniště nad Orlicí

U Glorietu

Plantation of small-leaved lime after growing season (29/10/2013) *(left)*, and after growing season 2018 (14/11/2018) *(right)* on the research plot Štenclova alej in Týniště nad Orlicí. Photos by Martin Baláš.

Štenclova alej

Plantation of small-leaved lime after outplanting in 2011 (01/11/2011) *(left)*, and after growing season 2018 (14/11/2018) *(right)* on the research plot Štenclova alej in Týniště nad Orlicí. Photos by Martin Baláš *(left)* and Josef Gallo *(right)*.

Interior of small-leaved lime plantation after growing season 2018 (14/11/2018) on the research plot Štenclova alej in Týniště nad Orlicí. Photo by Josef Gallo.

Písník

Plantation of small-leaved lime after outplanting in 2011 (01/11/2011) *(left)*, and after growing season 2013 (29/10/2013) *(right)* on the investigated research plot Písník in Týniště nad Orlicí. Photos by Martin Baláš.

Plantation of small-leaved lime/common oak *(left)* and small-leaved lime *(right)* after growing season 2018 (15/11/2018) on the investigated research plot Písník in Týniště nad Orlicí. Photos by Martin Baláš.

10.5. Raspenava

European beech plantation after growing season 2017 (19/10/2017) on investigated research plot Raspenava. Photo by Josef Gallo.


Collecting of soil samples (25/10/2017) on investigated research plot Raspenava. Photo by Josef Gallo.


European beech and common oak plantation after growing season 2018 (07/11/2018) on investigated research plot Raspenava. Photo by Josef Gallo.

10.6. Sample trees for biomass analysis

Morphology of sample trees for biomass analyses taken from lot planted in Vintířov-Sedlec on 07/12/2017 – semi-saplings of wild service tree (*left*) and service tree (*right*). Photos by Martin Baláš.

10.7. Root systems

Typical compact root system of small-leaved lime and common oak semi-saplings planted on the research plot U Glorietu in Týniště nad Orlicí in 2011 (01/11/2011) and in Kozí Hory in 2017 (21/11/2017), respectively. Photos by Martin Baláš.

10.8. Explanation to photo gallery

Dates are in the DD/MM/YYYY format.

Full quality photos and other supplementary materials are available from the author (gallo@fld.czu.cz).

11. LIST OF ABBREVIATIONS

NGSS	new generation saplings and semi-saplings
LST	large-sized planting stock
SST	standard-sized planting stock
MZe	Ministry of Agriculture [Ministerstvo zemědělství]
PLO	natural forest region
PRP	permanent research plot
LVS	forest vegetation zone