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The most significant results of long-term research on silviculture experiments focusing on spruce and beech in the territory of the former Czechoslovakia

Igor Štefančík[1]*, Stanislav Vacek[2], Vilém Podrázský[2]

[1]*National Forest Centre - Forest Research Institute, T. G. Masaryka 2175/22, SK – 960 92 Zvolen, Slovak Republic*
[2]*Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 1176, CZ – 165 00 Prague 6 – Suchdol, Czech Republic*

Abstract

This work summarizes the history and development of the research on silviculture in the former Czechoslovakia. A different approach of the silviculture research reflecting various site conditions was presented separately for the Bohemian area (later Czech Republic) and Slovakia (later Slovak Republic). The research focused especially on spruce forests in the Czech Republic, and on pure and mixed beech stands in the Slovak Republic. The attention was also paid to the history of research institutions before and after the dissolution of Czechoslovakia. The results achieved so far have been analyzed with particular focus on silviculture of the two most significant tree species in the former Czechoslovakia, namely the Norway spruce and the European beech. At present, the two species dominate the tree species composition of both countries. The spruce comprises 50.5% of the forests in the Czech Republic, and 23.1% in Slovakia. The share of beech is 33.5% in Slovakia, but only 8.3% in the Czech Republic. In both countries, the share of these tree species has changed, in comparison with their original proportion. It is more evident in the Czech Republic than in Slovakia, especially in the case of spruce. For the two tree species, the most important results of a long-term research (including developed original thinning methods) were evaluated separately for each country.

Key words: silviculture; Norway spruce; European beech; tending, thinning; production

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1. Introduction

Hundred-year long development of silviculture in the former Czechoslovakia – in the Czech Republic (CR) and the Slovak Republic (SR) – reflected specific natural and socioeconomic conditions. Czechoslovak forests occupied 4.601 million hectares (ha), i.e. a forest percentage of 36%. From this area, 2.627 million hectares were situated in the CR (a forest percentage of 33.3%) and 1.974 million hectares in the SR (a forest percentage of 40.2%) – (Poleno 1990). Former Czechoslovakia thus belonged to the most forested states of Europe (Poleno 1990). All forest land was subject to delimitation both from the ecological and economic point of view. Since 1960, all forests have been economically regulated irrespective of size and use. Forests in the CR and SR differ profoundly in their species composition. Coniferous species (especially *Picea abies* [L]. Karst.) prevailed in the CR, while in the SR, broadleaved species predominated, especially *Fagus sylvatica* (L). All forests in the former Czechoslovakia were of exceptional importance as an irreplaceable component in the environmental conservation and formation, i.e. forests fulfilled their economic and non-market forest functions (Poleno et al. 2007a).

An extensive expansion of the Norway spruce (*Picea abies* [L.] Karst.) outside its natural range in the past was determined by its favorable characteristics such as rather undemanding silviculture, fast growth, high production and quality of wood augmented by permanent demand for spruce timber (Poleno et al. 2009). In addition, it was a popular species for afforestation of clearings and artificial regeneration after clear-fellings. These facts resulted in its high representation in the species composition of the former Czechoslovakia forests and accounted for more than 40% of the forest area. According to the forest inventory in 1980, the spruce represented 56% of forests in the Czech Republic and 26% in Slovakia (Mráček & Pařez 1986). Podrázský et al. (2013) state that natural proportion of spruce for the CR is 11.2%, but its current share is 50.5% (Green Report 2017). An increase in the spruce

**Corresponding author. Igor Štefančík, e-mail: stefancik@nlcsk.org*

percentage in the past – at the expense of other tree species, especially beech – became evident mainly in Bohemia. In the CR forests, the beech natural proportion was 40.2% (Podrázský et al. 2013), while the current share is 8.3% (Green Report 2017).

In Slovakia, the difference in the share of spruce and beech was not that prominent as in the Czech territory. First of all, no significant increase in spruce percentage was ascertained in comparison with its natural proportion of 5.7% (Vladovič 2003) and its present share of 23.1% (Green Report 2017). In the case of beech, its natural and actual percentage was 47.9% (Vladovič 2003) and 33.5% (Green Report 2017), respectively.

The aim of this paper is to outline the history of silviculture in the former Czechoslovakia with an emphasis on the research of spruce and beech stands cultivation in the CR and the SR.

2. History of silviculture in Slovakia

In Slovakia, silviculture has had a notable tradition since the times of the Austro-Hungarian Empire, i.e. even before the establishment of the Czechoslovak Republic. Its reputation was confirmed by the founding of the "Central Forest Research Station" at the Banská Štiavnica Academy and of four other external research stations in 1898. The beginnings of research were initiated by owners of the forest and non-forest land in an effort to obtain information on how to establish and grow forests. Research carried out at these stations focused mainly on the issues of forests establishing, their regeneration, tending, acclimatization of exotic species (foundation of the arboretum in Kysihýbel in 1900), afforestation of non-forest soils etc. In 1923, it was officially renamed the State Forest Research Institute in Banská Štiavnica. Consequently, the Institute for Forest Silviculture and Biology and Experimental Forestry Station in Kysihýbel were established within the State Forest Research Institute's structures.

Silviculture conformed to the legislation of that time (forest law, guidelines, recommendations, guides, etc.). The book by a Czech forester J. Konšel (1931) – "A brief outline of the forest formation and silviculture" – helped Slovak foresters deepen their theoretical knowledge of silviculture (especially tending). After World War II, silviculture and tending were paid even more attention to. In practice, the Schädelin crown quality thinning (1934), which was recommended mainly for broadleaved (especially beech) stands, arouse interest. From 1946 to 1947, S. Kriška wrote an university textbook "The Science of silviculture with forest aesthetics". However, the textbook was not published, so only a few foresters knew it and applied in practice. In 1952, J. Kňazovický published the book "Cleanings and thinnings", which was actually the first Slovak book of its kind.

In 1952 – a significant milestone for silviculture in Slovakia – the University of Forestry and Wood Technology (UFWT) was established in Zvolen. At the Faculty of Forestry, the Department of Silviculture employed important forestry experts (H. Bezačinský; A. Sokol; S. Kriška) who contributed significantly to a new textbook (Silviculture 1956). At the turn of the 1950s and 1960s, systematic research on silviculture in Slovakia began thanks to the researchers at the Faculty of Forestry of UFWT (Š. Korpeľ, J. Réh) and the Forestry Research Institute (L. Štefančík).

During this period, several permanent research plots were established to serve as the bases for the theoretical and practical development of silviculture in Slovakia. It was crucial to obtain knowledge on silviculture of particular tree species to maximize their production. Slovakia is characterized by very variable site and natural conditions. It was essential to take these differences into account and apply appropriately differentiated silviculture methods (Štefančík et al. 1985) on a site classification basis. Thus, management units were created that these presented parts of the forest with uniform natural conditions, stand conditions and same functional focus (Hančinský 1977).

Since the 1970s, forests dieback, caused by air pollution, has become more evident, a phenomenon the silviculture research had to reflect (Grék et al. 1991). In the early 1990s, after the dissolution of the Czechoslovak Republic, silviculture research began to focus on close-to-nature methods of forest management and on intensive research of natural forests (M. Saniga), whose founder was a prominent Slovakian forestry researcher of international importance Prof. Š. Korpeľ.

Climatic change and its impacts have also been reflected in silviculture (Čaboun et al. 2008) resulting in development of methods to mitigate the impacts of climate change, with respect to the specific site and natural conditions of Slovakia.

3. History of silviculture in Bohemia, Moravia and Silesia

When the Czechoslovak Republic was established, the state became an owner of a considerable area of forests, the charge of which was entrusted to the Czech State Forests and Properties in Bohemia, Moravia and Silesia. This enterprise started to restrict spruce silviculture on unsuitable sites and to convert monocultures into mixed stands (Valdhauser 1926). Research activities in forest stands were carried out by the state research stations in Prague and Brno, established in 1886 and 1888 to provide experimental background for spruce silviculture in Bohemia, Moravia and Silesia. For example, the research institutes from Prague participated in the study of silviculture of mixed spruce and beech stands situated in the Rezek experimental district in the Giant Mountains (Krkonoše) from 1886 until 1947 (Vacek 1996).

In 1923, the Institute of Silviculture was established in Brno. Managed by Prof. J. Konšel, the Institute developed various methods of spruce cultivation, from establishing of stands, through their regeneration to tending (Zahradník 2001). In 1947, a research station for forest species breeding was set up in Kostelany, focusing on the silviculture of fast-growing tree species (willows and poplars). Consequently, the Research Institute for Silviculture, Seed production and Nursery management was established in Opočno in 1951. In 1952, the stations and the Institute merged into the Forestry Research Institute in Zbraslav-Strnady.

After the World War II, thanks to outstanding forester Hugo Konias (Mottl et al. 1956; Poleno 1996), we observe significant development of the close-to-nature forms of forest management in CR, collectively referred to as the shelterwood system (Anderle 1949; Polanský 1961; Mezera 1963; Čížek & Stone 1963; Peřina et al. 1964). At this time, considerable attention was paid to systematic research on forest stands tending (Chroust 1965; Pařez 1972).

Throughout the Eastern bloc, the period of 1965–1985 can be described as an era of favouring technology over ecology and the central harvesting model over decision-making in particular stands (Poleno 1996).

Air pollution calamity culminating in the 1970s and 1980s provoked forestry research to act and publish numerous analyses of the pollution causes, undesirable development in progress and management proposals (Tesař 1976; Materna 1978; Peřina et al. 1984; Vacek & Lepš 1987).

After 1990, multiple works were published, reflecting current ecological knowledge as well focusing on the issue of shelterwood, selection and close-to-nature management (Poleno 1997; Průša 2001; Poleno et al. 2007a, 2007b, 2009; Souček & Tesař 2008; Bílek et al., 2016). After 2000, considerable attention was also paid to the silviculture of forests in close connection with global climate change (Slodičák & Novák 2007a; Vacek et al. 2016).

4. History of silviculture research on spruce stands in Slovakia

In Slovakia, research on silviculture of spruce stands started at the turn of the 1960s and 1970s, much later than in other European countries, e.g. in Germany, Austria, but also in the Czech Republic, where the attention was paid to the silviculture of spruce stands at the end of the 19th century (Slodičák & Novák 2007b).

The experiments in Slovakia, carried out in 1965, monitored spruce stands production (biomass) using various methods and mechanization of tending measures, especially in the small pole and pole stages (Korpeľ 1992). The impact of traditional, predominantly biologic-production-oriented thinning methods (taken from abroad) with regular and relatively frequent (short) repetition of measures – following the rule: in time, moderately and more frequently – was monitored. At the same time, a new approach was examined as well. The approach was based on few concentrated measures leading to maximum technical and operational effect – following the rule: early, heavier and less frequently. The new methods of spruce stands tending were required by the contemporary social situation (labour shortage, demands on higher efficiency and practicality of the tending activity). Moreover, methods to achieve the best possible result not only in terms of production but also of economic efficiency, by means of suitable tending method in spruce stands, were sought. The research was focused on questions of the type and intensity of thinnings (Saniga 1985, 1996; Korpeľ 1992).

The first results of long-term research (a 22-year observation) in Slovakia were published by Korpeľ (1992), who compared the following thinnings in a 26-year old spruce stand at an altitude of 500 m a.s.l. (a forest type group *Querceto-Fagetum*): moderate low thinning (B grade according to German Forest Research Institutes of 1902), heavy low thinning (C grade according to the German Forest Research Institutes of 1902), Schädelin crown quality thinning (1934) and the control plot without any measures taken. In the comprehensive assessment, ***heavy low thinning*** was the most suitable as it maintained a relatively high volume and value production. In addition, it also effectively increased the spruce resistance to abiotic factors. The author recommended the heavy low thinning to be applied as a first measure after the previous cleaning.

The moderate low thinning, which was often recommended in the past, proved to be insufficient, especially from the aspect of static stability of the stand. Moreover, stability parameters (crown length, $h/d_{1.3}$ ratio) were approaching the values found on the control plot (without measures). But in terms of volume production, it showed to be advantageous. ***Schädelin crown quality thinning*** also proved to be very suitable. The important aspect of this thinning is the number of target trees in favor of which the measures are carried out. At 400–500 target trees per hectare, the thinning interval depended on the thinning grade (thinning intensity) to these trees, ranging from 5 to 10 years. Schädelin crown quality thinning showed that thinning intensity of more than 20% (by volume) with an 8–10 year thinning interval, can be applied without any greater risk in the 3rd age class. This thinning method also had a beneficial effect on static stability to abiotic injurious agents and was also advantageous in view of diameter, height and spatial differentiation of the stand structure.

Korpeľ (1992) concluded that the crown thinning with positive selection is effective in terms of stand stability but poses a greater risk for the stand immediately after the measure, because there is a significant proportion of relatively unstable trees from the 3rd tree class (intermediate trees) or other individual trees in the stand structure with their limited growth space.

Similarly, Saniga (1985) obtained nearly identical results after 20 years of applying the different tending method. Saniga proved that heavy low thinning had an apparent effect on the stand stability as early as in 10 years time (two tending measures) and the stand sustained its stability in the following period. The impact of the crown quality thinning was positively reflected on the spruce static stability even after 14 years (three tending treatments). Moreover, the stand stability significantly improved in the following period. For Slovak conditions, the author recommended applying of ***the crown quality thinning with the rationalization variant – the target (crop) tree method***. This method allows applying a combined measure into the crown level and partially into the suppressed level, not only to support target trees, but also to remove the unstable parts of the stand and thereby increase its stability. The 1st thinning should be carried out immediately at the beginning of the small pole stage (a mean stand diameter of 10 cm), by 25 years of the stand age at the latest. However, preceding tending of spruce stands by cleanings is a prerequisite for the proper thinning efficiency.

The above-mentioned procedures (methods) for stand tending were recommended in systematically tended stands, where favorable conditions had been created by thicket tending (cleanings) to achieve the demanded structure and ensure functional efficiency. However, heavier thinnings were not recommended for stands with neglected tending and with one layer structure.

In the late 1970s, research on spruce stands tending in Slovakia was carried out on several research plots in the framework of an IUFRO international experiment.

Since the 1970s or the 1980s, a modern phenomenon of the 20th century began to manifest itself prominently – as continual damage and decline of spruce stands caused by air pollutants. This phenomenon significantly affected forest stands not only in the CR and Slovakia but throughout Europe.

It should be stressed that this was a grave issue because of lacking experience in the management of such affected stands in Slovakia. Later, thanks to international scientific dialogue (especially with Germany and the Czech Republic), early results from the domestic research (Štefančík et al. 1987) and knowledge gained from the practice, the awareness and understanding of complex air-pollution issues deepened, which resulted in the initial proposals (instructions) for the management of forest stands affected by air pollutants (Grék et al. 1991; Kamenský 1993; Štefančík & Štefančík 1993).

In the early 1990s, almost all forestry research addressed a sole issue – how to minimize the negative impacts of polluted air on the forests of Slovakia. Heretofore, it was the most comprehensive research involving specialists from multiple scientific disciplines and forestry fields. It was necessary to reflect the fact of the great diversity of site and natural conditions of forests in Slovakia. "Management models by forest areas of Slovakia" (Kamenský et al. 1996) resulted from the synthesis of the most comprehensive scientific knowledge and practical experience of forest management, or, to be more precise, the forest management planning and management principles in forests affected by air pollutants. Štefančík et al. (1999) published the final report – the second comprehensive work dealing with forest-based preventive, adaptation and remedial measures aimed at reducing negative anthropogenic and abiotic injurious agents. The principles of tending and regeneration of forests affected by air pollutants (Štefančík & Kamenský 1999) formed a significant part of the results from the mentioned research. Results of the research conducted in the CR, summarized in the publication (Peřina et al. 1984), served as a valuable source of knowledge in those principles formulation. The extensive research helped to create an original tending method for young spruce stands, ***air pollution selection cleaning***. Consequently, ***air pollution selection thinning*** was developed for small-pole and pole-stage stands (Štefančík in Grék et al. 1991), which was derived from the free crown thinning (Štefančík 1984) supplemented with the principles of tending in the air pollution areas (Štefančík in Grék et al. 1991).

In the late 1990s, the situation significantly improved thanks to dramatical reduction of emissions in Slovakia (Štefančík & Kamenský 2010). Nonetheless some areas of Slovakia witnessed a massive dieback of spruce stands, probably caused by a complex of harmful agents (abiotic, biotic) and effects of ***a global climate change***, which manifests itself through extreme temperature fluctuations and intense weather changes during the year, among other things (Kulla & Sitková 2012). The phenomenon called ***modern spruce dieback***, forced researchers to seek new or to modify existing tending methods of spruce stands. New methods help eliminate or reduce large-area dieback (decomposition) of spruce monocultures. In addition to that, another major issue occurred – game-induced damage, compelling the researchers to amplify their focus. Currently, the issue of game-induced damage is the most urgent forestry problem in Slovakia (Štefančík & Kamenský 2010, 2011; Kamenský & Štefančík 2011; Štefančík 2012).

Štefančík & Kamenský (2009, 2010, 2011) published recent research results on young spruce stands (16-year-old thicket) situated in the areas struct by massive dieback, where three variants of the tending measure were verified. First, 400 target trees per hectare were marked on one plot. Crowns of those trees were released by removal of competing individuals (Fig. 1). Stems of these target trees were protected by wire netting. The rest of the plot remained untreated. In the other two variants, the number of remaining individuals was reduced to 1,600 trees.ha^{-1} and 2,000 trees.ha^{-1}. The aim of this experiment was to verify whether such a radical measure in thickets does not cause subsequent stand damage in terms of abiotic but also biotic (game) injurious agents. Therefore, it is important to emphasize *that protection against the game* (wire mesh for the stem protection), which usually damages the thickest and most vital trees forming the skeleton of the stand, *is an inevitable part of such radical measures*.

One year after applying the measure, the stands showed a favorable sign: strengthened static stability, which is of prime importance in spruce thicket when applying any measure. The values of the slenderness quotient (h_{100}/d_{100}) were 0.720 for the plot with the amount of 1,600 trees ha^{-1} of the remaining stand, or 0.731 for the plot with 2,000 trees ha^{-1}.

After **two years**, the stands faced a significant attack of the game (damage by browsing and stripping). The least affected was the plot where only target trees had a preference during the measure. The worst damage was on the plot with density of 1,600 individuals per hectare. The number of damaged trees increased with the layer – it was the highest in the upper layer, lower in the middle layer and the lowest in the lower layer, as ascertained on all the plots.

Fig. 1. Plot with 400 target trees per hectare released by an

intervention; the rest of the plot remained untreated. (Photo: Igor Štefančík).

The number of target trees was reduced (reflecting bark-miner damage, snow-induced crown breaks, windthrows and game-induced damage that occurred despite mechanical protection), on all plots in the course of **tree years after carrying out the measure**.

It should be concluded that reducing the number of trees to about 1,600 pieces per hectare appears to be too radical under the given natural and stand conditions.

Reduction to 2,000 or to 2,500 trees ha^{-1} rather than to 1,600 trees ha^{-1} appears to be more appropriate for the first tending measures in spruce stands when the thicket transforms into the small-pole stage. In view of the damage in the reduced stand, the method, which releases about 400 target trees per hectare all over the crown's perimeter and the remaining area is left untreated, appears to be more suitable. A timely, consistent and systematic tending of the thicket growth is an inevitable precondition for the use of the target trees method.

5. History of silviculture research on spruce species in the Czech Republic

In the Czech Republic, the history of silviculture research in its broadest sense dates back to the 16th century, when different experiments of artificial regeneration of the spruce were carried out (Zahradník 2001).

Continuous long-term silviculture research into spruce stands started after the founding of the Research Institute for Silviculture, Seed production and Nursery management in Opočno in 1951, carrying on a long tradition of spruce silviculture research. In Opočno region, numerous experiments with spruce silviculture were realized by V. V. Havelka (*1780, †1847), J. Bohutínský (*1850, †1930) and a co-founder of the research institute, a forest counsel H. Konias. Later, his collaborators (Mottl et al. 1956) evaluated the results of his varied methods of forest management. These results contributed significantly to increasing stability of largely unstable spruce stands.

In the following text, the history of spruce silviculture research is outlined by following sectors: forest seed production, nursery management, afforestation, tending, forest stand regeneration and silvicultural environmental research. Forest seed production covers the following issues: quantity and quality of spruce fructification in air polluted areas; methods of determining the quality of spruce seed; pre-sowing preparation of the long-term stored spruce seed; influence of the spruce seed origin and sorting on the seed quality and the dynamics of seedlings growth (Hrabí 1990; Procházková 2009). Nursery management research was focused mainly on various technologies of silviculture of bare-rooted and container-grown planting stock of spruce (generative and vegetative) from seedlings to saplings in various environmental conditions; irrigation and fertilization technology; verification of different types of packaging; quality of substrate for container filling and handling planting stock from the forest nursery to planting locality (Lokvenc 1965; Dušek 1980; Jurásek 1988). These results helped to develop more efficient technologies of forest seedling and production of bare-rooted and containerized planting stock of Norway spruce.

Within afforestation, the research initially focused on the following issues: mountain locations and mountain forest/tree line; considering different types of containerized planting stock for different site and stand conditions; and on root system deformation during afforestation with containerized planting stock. Later the research focused on technologies of afforestation of areas affected by intro-skeletal erosion; fertilization of forest cultures; morphological variability and diversity of mountain spruce populations; variability of the Norway spruce clones growth in mountain conditions; morphological and physiological parameters of spruce planting stock growing using intensive technologies (Lokvenc 1963; Nárovec 1991). These results significantly facilitated more efficient technologies of spruce afforestation in various environmental conditions.

A number of authors such as Vicena (1964), Pařez (1972), Chroust (1980), Slodičák (1987) dealt with possible influencing the stability of spruce stands through their tending and then with the increase of the threatening risk of snow and wind damage to spruce stands caused by neglected tending.

Models of stand tending represent a practical output of current research on the tending of spruce and other major tree species stands. These models represent a set of instructions for carrying out improvement cuttings from the first tending measure to the end of tending (Slodičák & Novák 2007a). Models of stand tending in their present concept were first defined in Germany in the late 1960s (Abetz 1969); in our countries, Chroust (1976) contributed significantly to their introduction into practice. The first summarizing publications of these models appeared in Czechoslovakia in the late 1980s (Pařez & Chroust 1988). These works were followed by tending models designed on the basis of the evaluation of long-term thinning plots at the Research station in Opočno (Slodičák & Novák 2007a). Current models are based on the differentiation of the tending by target management units (TMU) and their degree of threat by abiotic agents.

In addition to the essential influence of tending on stand stability and resistance to abiotic factors, it is important to mention its fundamental influence on the change of stand environment which results from changed radiation, thermal and water regimes of the stands. The most comprehensive overview of the so-called "ecological effects" of tending measures carried out in spruce stands in the Czech Republic conditions is given in Chroust (1997). The influence of tending on the nutrient cycle through the change in the litter amount and the rate of decomposition of organic horizons in spruce stands is the subject of intensive research (Podrázský et al. 2005; Dušek et al. 2009). These results contributed significantly to streamlining policies and procedures of tending and stabilization of spruce stands from juvenile to upcoming mature growth phases with emphasis on quality and safety of production and fulfillment of ecological forest functions.

The existing knowledge on the positive influence of tending on the health status of spruce stands was primarily obtained in the areas of spruce decline, under the influence of air pollutants (Tesař 1976; Slodičák 1988). Although the air pollution rate has decreased considerably since the turn of the 1980s and 1990s (Hůnová et al. 2004), the state of forest soils affects negatively the health status of forests until present (Vacek et al. 2015c).

However, radical tending measures at young age had an identically positive influence on the increment and stands health status (Tesař 1976; Slodičák & Novák 2000) in all the experiments with tending of spruce stands and under the influence of air pollutants in danger zones C, B and A, at the 5th, 6th and 7th forest altitudinal zone (Fig. 2).

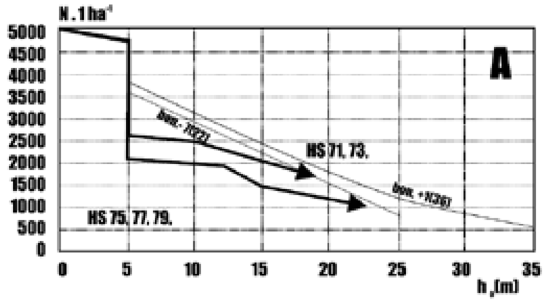


Fig. 2. Tending program for spruce stands (stand density versus upper hight) in the air pollution danger zone A, differentiated by management units (MU 70, 72) for the 1st and 7th site class (Slodičák & Novák 2000).

Increased air pollution load at juvenile stages when Norway spruce is sufficiently vital does not usually cause significant damage or growth depression. Owing to the rapid growth of spruce thicket, penetration of air pollutants decreases until the crowns create a canopy. At later stages, when the vitality of trees is decreasing, it is again necessary to utilize the effect of mutual shading (Slodičák & Novák 2000).

Research on forest stands regeneration initially focused on conversion of spruce monocultures into close-to-nature stands on the basis of a typological survey. Prior to the spruce monocultures conversion, H. Konias tried to create a stand skeleton through crown thinnings. This stand skeleton consisted of strong trees with developed crowns, subsequently enabling him to work on regeneration from the inside without any serious risk. However, the attention was paid to the care of standing volume as it was an important part of the silvicultural system (Mottl et al. 1956). The knowledge on standing volume care confirmed that the absolute amount of current increment depends on the crown size and structure. V. Zakopal continued in the pioneering work of Konias, who dealt with the conversion of the forests managed by clear-felling system to the selection forest, in a number of studies. Zakopal emphasized the wood production and continuous reproduction of the forest in his research and development of silvicultural techniques. At the same time, he elaborated shelterwood systems for managing spruce stands with maximum application of selection principles (cf. Zakopal 1965).

In the context of the increasing air pollution load, considerable attention was paid to the silviculture of stands with dominant spruce and under various conditions of damage, threats and tolerance, especially in the Trutnov region (Tesař 1976; Tesař et al. 2011), in the 1950s–1960s. During the 1970s and 1980s, the damage to spruce stands was increasing rapidly in the Sudeten Mountains. In connection with the experience from the Trutnov region, the health status, damage dynamics and stands decline, in relation to the air pollution ecological conditions, were studied. The acquired knowledge helped to define the symptoms of damage (Vacek 1992), manifestations of insufficient fructification (Jurásek et al. 1982) and possibilities of artificial forest regeneration (Lokvenc 1978). The primary task was to enhance provision of basic ecological functions resulting from the simple existence of a forest (Vacek & Lepš 1996). There were also significant soil changes, resistant to traditional silviculture techniques of ensuring ecological stability of forest stands (cf. Peřina et al. 1984). In particular, liming and fertilization (Podrázský et al. 2003) and technologies based on gentle treatment of soil surface that do not cause intro-skeletal erosion (Šach 1990; Vacek et al. 2003) have been tested. These results contributed significantly to optimizing the regenerative processes in spruce forest stands, extending their life in anthropogenic environmental conditions, and to alleviating various types of disturbances in forest ecosystems.

First of all, it was necessary to stabilize forests and ensure ecological and environmental functions in mountain forests (Vacek et al. 2013). This necessity resulted from the economic problems primarily caused by air pollution effect. Practical foresters expected scientific assistance in dealing with provision of forest water management functions. Under the direction of V. Krečmer and V. Peřina, an extensive demonstration object was built in the catchment area of Šance water reservoir (Krečmer 2007). A unique ecological silvicultural experiment managed by P. Kantor came from the same initiative and was located in the Orlice Mountains (Kantor 1983). He monitored the hydric effects of spruce and adjacent beech stands, from the mature stand to juvenile stages. Based on numerous experiments, methods for the management of forests with water management functions were developed (Šach et al. 2007). For the sake of nature conservation, site and stand conditions as well as methods on close–to-nature forest management were studied in specially protected areas (Vacek et al. 2012). These results served as the basis for the creation of differentiated silvicultural practices in spruce forest stands, especially in mountainous areas, with an emphasis on priority of ecological and environmental functions of the forest.

Moreover, the damage dynamics of spruce stands caused by rime in the Orlice Mountains (Kadlus & Říha 1971) was studied in detail, which laid a partial basis for the stabilization of the natural spruce management. Podrázský & Remeš (2005), Podrázský et al. (2011), Kacálek et al. (2013) dealt with negative impact of spruce monocultures on the soil environment compared to other coniferous or deciduous tree species. These results incited a new approach in stabilizing of spruce management, especially in juvenile growth phases consisting primarily in the care of long enough crown with rich assimilation apparatus.

6. History of the silviculture research on beech stands in Slovakia

In Slovakia, professional tending of beech stands has a shorter tradition than, for example, in France, Denmark, Switzerland or Germany (Štefančík 1964, 1966, 1974, 1978, 1985). Tending of beech stands was virtually carried out only on the basis of foreign knowledge, creating the need to verify it under our conditions, and to establish domestic research. This intention was realized only in the late 1950s. A program of systematic research on beech stands tending was prepared at the Research Institute for Forestry (RIF) in Zvolen, in cooperation with UFWT in Zvolen.

The aim of this research was to obtain exact knowledge of natural conditions of Slovakia. In the case of thinnings, the main objective was to find out which selection and thinning method is the most suitable for beech stands under domestic conditions. Initially, research focused on unmixed beech thicket which was systematically neglected in tending (Réh 1968, 1969), or more precisely, on the small-pole and pole stage (Šebík 1969; Štefančík 1974). Within the research, all the basic silviculture and production issues of thinnings started to be investigated. At the beginning, this was mainly the question of *the type of thinning* (low thinning, crown thinning); *the selection method* (positive, negative) and the structure of unmixed beech stands; later, researchers concentrated on of the thinning intensity, i.e. strength, intensity and time intervals between thinnings.

In our economic conditions, the tending effect of two grades of the low thinning (B and C grade according to German Forest Research Institute from 1902) and two crown thinnings (Schädelin quality thinning and free crown thinning by Štefančík [1984]) were examined.

In Slovakia in the 1960s, Prof. Dr. L. Štefančík developed an original thinning method – **free crown thinning** (Štefančík 1984), which started to be applied in research in 1958, and successful testing facilitated its pathway into forestry practice as well. It became known as Štefančík's free crown thinning (Poleno et al. 2009) and is included among modern (new) methods of thinning in beech stands (Korpeľ et al. 1991). This method has also received favorable response and recognition abroad (Assmann 1978; Poleno et al. 2009).

The free crown thinning (Štefančík 1984) showed to be especially suitable for pure beech stands in Slovakia. Typically for this method, the measure is carried out in the crown and suppressed layer, i.e. throughout the stand profile (Table 1), which differs, for example, from the Schädelin quality thinning (1934).

The main objective of this method is cultivation (supporst) of the so-called ***trees of selective quality***, i.e. promising and target trees. Nevertheless, trees in the crown

Table 1. Silvicultural analysis of the free crown thinning according to Štefančík (Štefančík 1984).

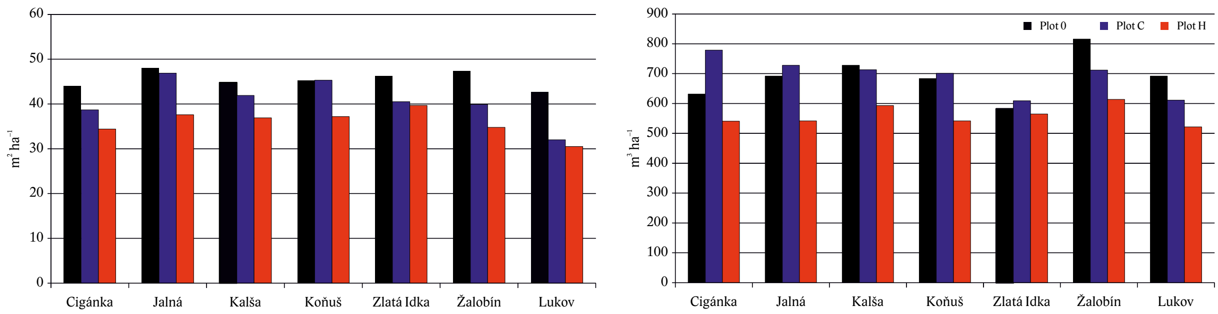
Selection method	Object of treatment in the stand layer (tree class)	Purpose of treatment	
Positive in the crown layer	dominant and co-dominant trees (1–2) sub-dominant trees (3) suppressed trees (4–5)	cultivation of trees of selective quality	– release of lateral space of their crown – release of the space of lower part of their crown – removal of individuals lashing their stem
Positive in the suppressed layer	sub-dominant and suppressed trees (3–5)	Removal of undesirable trees from the viewpoint of	– their mutual spacing, i.e. thinning of supressed layer, assurance of tenting and protective function of this component
Negative	dominant, co-dominant, sub-dominant and suppressed trees (1–5)		– the quality of their stem and crown; improvement of the mean mass quality and assurance of potential substitutes for cancelled trees of selective quality
Sanitary			– health state; increasing of the stand resistance
Relatively mature			– tree species; increasing of the production of tree species desirable from economic aspect

and suppressed layer of the stand are provided for as well. Thinning combines five independent methods of selection. The positive (basic) selection in the crown level preceeds other four selections – positive in the suppressed layer, negative, sanitary and mature, which cultivate trees throughout the stand (Table 1). The number of target trees is set by a model and refers to the rotation age.

The results from the long-term experiments in beech stands, where Štefančík's free crown thinning was applied, were summarized by Štefančík (2015). It is evident from the last measurements that the highest values of quantity production (basal area, merchantable volume) were found on the control plots (without treatments) and on the plots with the heavy low thinning (C grade according to the German Research Institute of Forestry in 1902) (Fig. 3).

In terms of quality production, which is best represented by the number and production of target trees, the best results were definitely achieved by Štefančík's free crown thinning (Fig. 4).

7. History of the silviculture research on



Explanatory notes: 0 – control plot; C – low thinning; H – Štefančík's free crown thinning.

Fig. 3. Stand parameters (basal area – left) and (merchantable volume – right) of the main stand after the last measurement on seven experimental plots.

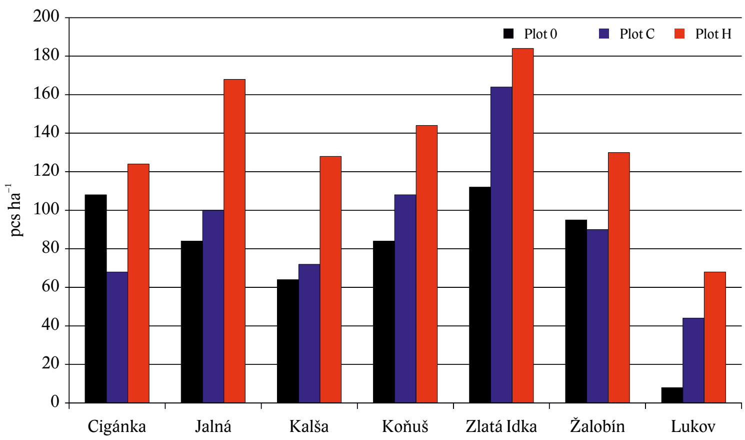


Fig. 4. Number of target trees per hectare aged between 83 and 105 years on seven experimental plots.

beech stands in Bohemia

Initially, natural regeneration of pure and mixed beech stands with dominant European beech was researched, in particular (Peřina et al. 1964; Kadlus 1967). Attention was also paid to the conversion of clear-cutting system to the selection one; not only to regeneration felling and natural regeneration development, but also to the study of increment and obtaining promising material for growing valuable beech and oak assortments and increasing of the total production of deciduous stands (Zakopal 1968; Mareš 1970; Peřina et al. 1978). There was a need to address nursery issues, especially of growing rich-root-system planting stock material and container-grown plants as well (Dušek 1963; Lokvenc & Skoupý 1967).

Interest in research of pure and mixed beech stands with beech increased in connection with the significant impact of air pollutants on forest stands in the 1970s, especially with efforts to increase ecological stability of forest stands. At that time, a number of research projects addressed research of the beech in the following fields: forest seed production, nursery management, afforestation, tending, regeneration, structure and development, health status and forest functions in various site and stand conditions (cf. Peřina et al. 1984).

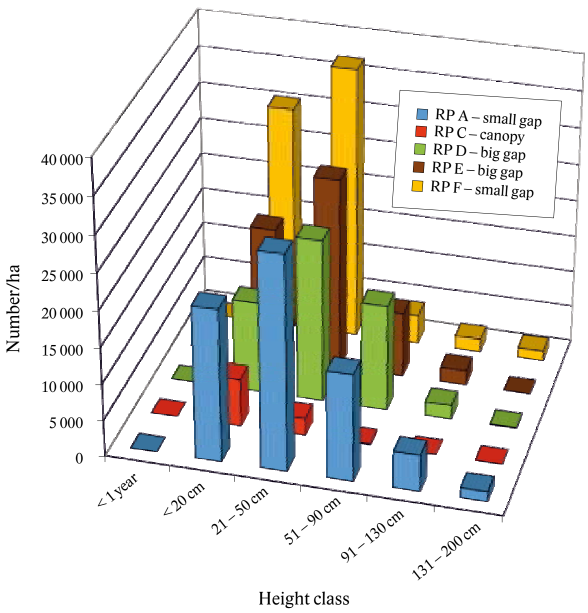
Researchers examined the quantity and quality of beech fructification (Procházková et al. 2002; Vacek & Hejcman 2012) and also the pre-sowing preparation of beechnuts (Hrabí 1992). In forest nursery management, mainly issues of various methods of growing beech planting stock in forest nurseries, including its succeeding growth monitoring in plantations, were investigated (Jurásek 1990; Nárovcová & Jurásek 2007). Attention was also paid to the technology of beech propagation by cuttings, their artificial planting and succeeding growth (Jurásek & Leugner 2009). The results helped to streamline the technology of forest seedling and nursery production in times of considerable lack of beech seed during air pollution calamity, when beech trees were infertile for almost 15–18 years.

Within the context of afforestation, research focused on different beech populations and planting technologies and on the protection of different types of planting stock material and support of its growth in the clearing areas and under the stands (Lokvenc & Vacek 1991; Balcar & Hynek 2000; Špulák et al. 2010). In the case of beech stands tending, researchers tested various methods of tending of predominantly young stands with emphasis on their spatial distribution, coenotic position, quality of production and radial growth (Novák et al. 2015; Remeš et al. 2015). These results contributed to the optimization of specific silviculture procedures for beech stands in different habitat and stand environmental conditions.

In the study of structure, production and regeneration of beech stands, the research focused mainly on five areas: quantity and quality of beech production (Souček 2007), structure and biodiversity of beech stands (Vacek et al. 1996a, 2014b, 2015; Dobrovolný 2016), modelling of structural parameters in relation to beech stands management (Sharma et al. 2016, 2017), natural regeneration of the beech (Vacek et al. 1999, 2017; Špulák 2008; Dobrovolný & Tesař 2010; Bílek et al. 2014) and game damage of regeneration (Vacek et al. 2014a; Ambrož et al. 2015).

A detailed analysis of beech natural regeneration was carried out in the Voděrady beechwoods, National Nature Reserve (NPR), located in the University Forest Kostelec nad Černými lesy. There are close-to-nature beech stands, which were left to self-development in the 1950s. At present, we observe an emerging decay of the upper stand storey and the appearance of gaps and suitable conditions for the natural regeneration of these stands as well. An emphasis was placed on the analysis of the heterogeneity of the micro-site conditions and the competition of ground vegetation in gaps, which originated from the natural dynamics of the studied stands. Both the greatest coverage of natural regeneration and the highest density of individuals from regeneration were found in small gaps. A slightly lower regeneration density was found in big gaps, while the regeneration density under closed canopy was 5–10 times lower than in small gaps (Fig. 5). The coverage of the beech natural regeneration and the diameter and height of the beech dominant individuals were positively correlated with the relatively scattered sunlight, but negatively correlated with the coverage of the ground vegetation.

Fig. 5. Height classes of the beech natural regeneration under the canopy and gaps of various sizes (Bílek et al. 2014).



Research on the optimization of ecological and economic parameters of beech stands tending confirmed not only the crucial importance of the coenotic position of trees in the stand to their diameter increment, but also the importance of selected climatic factors. The results confirm that crown tending of the beech is not only a suitable means for an increase in value increment, but also a suitable measure to reduce the negative impacts of extreme climatic events (Remeš et al. 2015).

Significant research attention was also paid to the study of site conditions and functions of forests in stands with the dominant European beech. Podrázský (1996); Matějka et al. (2010); Špulák et al. (2016) researched soil and vegetation conditions in beech stands. Podrázský et al. (2003, 2005); Vacek et al. (2009); Černohous & Kacálek (2008) studied the problems of fertilization, liming and various methods of amelioration of forest stands. Vacek & Jurásek (1985); Králíček et al. (2017) investigated the health status of beech stands. Kantor (1981, 1984); Kantor et al. (2009); Švihla et al. (2012) studied hydric regime issues in beech stands. These results significantly contributed to the strengthening of production, ecological and environmental functions of forest stands in the context of specific technologies of silvicultural management.

8. Conclusion

The analysis of spruce stands tending in Slovakia and the Czech Republic implies that tending must start during the youngest growth stages. Tending of the thicket, decisive for building the stand static stability, as well as for the arrangement of the species composition (in mixed stands), is particularly necessary. Research results showed the importance of early and sufficiently intensive tending for achieving the desired structure and ensuring favorable static stability, or more precisely forest stands protection against anthropogenic and abiotic injurious agents. Crown thinnings with positive selection proved to be the best.

A long-term systematic research (for more than 50 years) on phytotechnics and silviculture-production issues in beech tending in Slovakia proved crown thinnings to be the most suitable measure from the selective methods, or, more precisely, the thinnings based on the positive selection from the crown level. These thinnings are the most suitable from the view of cultivation the quality production and of the stands safety during the thinnings periods. The free crown thinning (Štefančík 2015) proved to be the best for tending of beech stands under Slovak conditions. Low thinnings showed to be less suitable for beech stands, especially from the qualitative point of view. The verification of the tending results of beech stands in the Czech Republic was based on long-term results from Slovakia with similar findings.

In conclusion, we might sum up that the main silvicultural research topics in the Czech Republic have been investigated at the Research Station in Opočno, following extensive practical experience and experiments of H. Konias who advanced close-to-nature methods of forest management. Here, in cooperation with other institutions and forestry faculties, a unique forest silviculture school began to form, significantly influencing silviculture of forests in both countries. Owing to this, a number of key monographs have been published, inspiring and determining silviculture of forests in the Czech Republic and, within the cooperation of both nations, in Slovakia as well.-

It is gratifying that even after the splitting of Czechoslovakia on December 31, 1992, after 74 years together, cooperation in the silviculture research between two countries has continued very closely, as evidenced by numerous workshops and the annual joint conferences of silviculturalists.

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