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Chemical forest amelioration: Experience from the Czech Republic and other selected countries – A review

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Abstract: This review article summarises the results of research on forest liming, fertilisation, nutrition flows and cycles in selected European and other countries. The presented studies mostly deal with assessing the effect of liming and fertilisation applied during planting or shortly after planting. The sporadic studies on fertilisation in older stands are also presented. The application of crushed limestone, dolomite or other alkaline rocks or their mixtures is usually used to improve the soil conditions on a large area through the adjustment of soil acidity and to supply any deficient elements, especially calcium and magnesium. These amendments are typically used on naturally nutrient-poor soils or as a curative technique to neutralise the soil chemistry affected by anthropogenic acidification. Artificial fertilisers are usually applied on small spots to individual trees on the surface of the soil shortly after planting or into a planting hole during planting. The purpose is to give some initial support to young trees to better overcome the post-planting shock and to accelerate the height growth. Less frequently, artificial fertilisers are used on large areas of forest stands for the purpose of increasing stem growth. The methods and the extent of forest fertilisation substantially vary in individual countries and different time periods.

Keywords: afforestation and forest regeneration; forest fertilisation; macronutrients; tree growth; soil and foliage chemistry; soil remediation

Chemical soil amelioration (reclamation) in forestry is a set of measures to improve the chemical and, as a result, biological and physical properties of soils (Podrázský et al. 2003; Abdi, Deljouei 2019). The general goal of fertilising is to optimise the biomass production, and environmental and economic goals (Smethurst 2010). It is carried out by adding mineral additives (amendments) to the soil (Glaser et al. 2002; Jandl et al. 2003). Amelioration means either adding deficient nutrients directly (fertilisation) or influencing the soil chemistry in a way that ensures that soil nutrients are more available to plants [for example, adjusting the soil pH by liming (Katzur, Haubold-Rosar 1996)]. For some treatments, both amelioration effect principles can be combined. Namely, multi-component

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fertilisers with a basic (alkaline) reaction are used in poor acidic habitats with nutrient deficits in the foliage of the target tree species (Aarnio, Martikainen 1995; Aarnio, Martikainen 1996; Jacobs et al. 2005). Alternatively, a wide spectrum of biological reclamation measures is possible (Huss-Danell, Lundmark 1988; Granhall 1994; Myrold, Huss-Danell 2003).

Liming is the most widespread and typical example of land reclamation measures in forest stands. This treatment means the application of crushed limestone, dolomitic limestone and dolomite (Kreutzer 1995; Bošeľa, Šebeň 2010; Šrámek et al. 2012). In the forest stands of Central and Northern Europe, liming was originally used and tested mainly as a treatment to improve the growth or production of forests (Materna 2001; Podrázský 2006a). This would happen through the alleviation of soil acidity and adding calcium, namely in those forest habitats that were naturally poor or degraded by previous inappropriate management practices (Becker-Dilligen 1939; Němec 1956; Kreutzer 1995; Brække 1999; Šrámek et al. 2012; Jansone et al. 2020). Later, liming was used to counteract or compensate for the anthropogenic acidification resulting from fossil fuel combustion (Podrázský 2006b; Kölling 2014).

Forest fertilisation with artificial fertilisers may have various goals and uses different application methods. The application of fertilisers usually provides a site or trees with a wider variety of elements than just Ca and Mg (usually N, P, K, Ca, Mg, and/or some needed microelements). Especially in the past (experience mainly from Sweden – Jacobson, Pettersson 2010), fertilisers were used in larger areas (surface, usually aerial applications) to supply nutrients in middle-aged and older stands in order to improve their vitality and chiefly improve the growth and biomass production.

In contrast to large-scale surface applications (Stetter 2010), the targeted (pointed, local) fertilisation of young plantations is conducted to support the trees in the initial period after planting in order to overcome the post-planting shock more easily. With this method of application, the fertiliser is not applied on the whole surface of the forest stand, but only close to the individual trees or directly into the planting hole (Kuneš et al. 2006). In the case of containerised planting stock, the initial nutrient supply can also be incorporated in the soil substrate. In the past, powders from crushed basic (alkaline) rocks were also used as fertilisers or amendments (Becker-Dilligen 1939; Němec 1956; Materna 1963), but nowadays, advanced fertilisers with a slow or controlled release of nutrients are preferred (Kuneš et al. 2014b; Gallo et al. 2021).

This paper focuses chiefly on the Czech and European scientific literature. Attention is paid to the countries where the chemical amelioration of forests or forest sites traditionally plays, or has played, a significant role, or where individual interesting experiments were conducted (Germany and the Nordic and Baltic countries). Where appropriate, a comparison with papers published outside Europe is included. Considering different approaches and natural conditions across Europe, the review is thematically ordered according to the individual countries.

APPROACH, STUDIES AND EXPERIENCES IN THE CHOSEN COUNTRIES

Czech Republic

Amelioration of sites degraded by previous poor forest management practices. In the beginning of the 20th century, a substantial part of Czech forests was degraded due to the previous poor forestry or 'agroforestry' management practices (coniferous monocultures, litter raking, grass harvest, etc.). From the 1930s to the 1950s, several experiments that focused on forest soil reclamation were conducted (i.e. Němec, Mařan 1937, 1938, 1939; Kozel 1957). According to Němec (1956), crushed basic rocks (limestone, basalt, amphibolite, diabase, etc.) were applied to broadleaved plantations (alder, lime, oak, beech, elm, maple). Sometimes, preparation of the sites by the cultivation of nitrogen-fixing herbaceous plants (*Lupinus* etc.) before replanting was carried out. The crushed rocks were mostly applied to the planting holes or were top-dressed in small circles around the planted trees. In some cases, the amendments were aerially applied on the surface of the plot to be reforested. In most cases, the plantations positively responded to the fertilisation in terms of height and radial growth, reduced mortality, or improved nutrition. The promising results of these experiments inspired many later studies dealing with initial fertilisation methods on degraded sites. This was followed by other review publications (Lhotský et al. 1987; Podrázský 2006a; Gallo et al. 2021).

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Amelioration of sites affected by air pollution (1960–2000). During the period from the 1960s to the 1980s, large areas of forests in Europe were affected by deposition of acidic pollutants (chiefly SO_2 and NO_x) and their health status rapidly deteriorated (Ulrich et al. 1980; Ulrich 1986; Kopáček, Veselý 2005). The tri-border area among northern Czechia, southwestern Poland and eastern Germany formerly belonged to the region most seriously inflicted by pollutants [Black Triangle (Křeček, Hořická 2006)]. In the northern part of Czechia, many forests finally succumbed to the combined stress from pollution and the subsequent insect pest attacks (Lomský et al. 2011b).

In the heavily air-polluted areas of Czechia, chemical amelioration became an important part of the measures aimed at decelerating the process of the disintegration of forests affected by air pollution and improving the soil chemistry in forest sites affected by acidification resulting from the air pollution load (Klimo et al. 2006). In some regions, the practical use of crushed alkaline rocks was connected with intensive research conducted to assess the amelioration effects on forest ecosystems (Kulhavý et al. 2009; Šrámek et al. 2012), as liming may have questionable (negative) side effects and some desired effects may not always manifest (Hruška, Cienciala 2001).

The first use of chemical amelioration of this type in Czech forestry dates to the 1960s in the Trutnov region (foothills of the Giant Mountains – Krkonoše), affected by air pollution emitted by the coal power plant in Poříčí. The crushed basic rocks (limestone, dolomite, amphibolite, etc.) were applied alternately to the planting holes at a dose of 1 kg of limestone and 4 kg of diabase. By fertilising experimental plantations of beech, larch and spruce, higher survival and growth rates of transplants were achieved. Almost 90% of the cost of fertilisation was reimbursed through a reduction in the cost of afforestation. Within two to three years after application, the plantation achieved a better health status of assimilation apparatus and higher vitality. The effect of land reclamation measures on growth ceased to be obvious in the spruce after about ten years and after five years in the larch. A longer beneficial effect was observed in the beech (Tesař et al. 2011).

The targeted fertiliser application into the planting hole sometimes raises concerns about the deteriorated penetration of the roots into the soil surrounding the planting hole. This phenomenon was reported by Tesař et al. (2011) on spruce. Initially, the fertilised trees grew faster, but after seven years, the height increase of the spruce was surprisingly the highest in the control trees. The root systems of the fertilised trees were accumulated in a small area of the fertilised holes. The trees apparently showed a disproportion between the roots and the above-ground parts. In contrast, in the unfertilised variant, the spruce roots grew out of the planting holes, which later allowed them to draw nutrients from a larger area. Nevertheless, later studies from mountain conditions (nutrient-poor podzolic soils) did not confirm this concern; the roots spread out from the fertilised planting hole without any problems (i.e. Kuneš et al. 2014a).

In the beginning of the 1970s, crushed basalt rocks were experimentally used for the individual fertilisation of spruce plantations on peat gleys and peat soils in the locality of Nové Město in the Ore Mountains (Ferda, Čermák 1979). The amendment was applied in combination with individual liming and nitrogen fertilisation. The effectiveness manifested only in the first years after planting. Trees fertilised with crushed basalt showed a reduction in mortality by 15% and an increase in growth compared to the variant treated only with a combination of individual liming and nitrogen fertilisation without the basalt. However, in the period of fourteen years after the application, the basalt fertilisation did not achieve such an effect as the treatment with liming and that with complex fertilisation using industrial fertilisers.

Between 1978 and 1991, 62 000 ha of forest stands were limed in the Ore Mountains, 8 000 ha in the Jizera Mountains, 7 400 ha in the Giant Mountains (Krkonoše), and 2 800 ha in the Orlické Mountains (Šrámek et al. 2003). Lime was also used in the Jeseníky and Beskydy Mountains (Balek et al. 2001; Drápelová, Kulhavý 2012). The applications were mostly realised by planes and helicopters. Terrestrial machinery was especially used in the Ore Mountains, on flat terrains after bulldozer site preparation. The projected dose of crushed limestone usually ranged between 2 $t \cdot ha^{-1}$ to 4 $t \cdot ha^{-1}$.

Materna (2001) summarised some outcomes of the assessment of aerial liming in the Ore Mountains (applied dolomitic limestone, usually 4 $t \cdot ha^{-1}$). In a part of the limed areas, increased calcium concentrations in the organic horizon and slight changes in the soil reaction were detectable several

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years after the application. To some extent, calcium also got into the mineral soil. The dispersion of aerially applied limestone was not uniform. Sites with very high concentrations of Ca in the soil were found, indicating that, in some places, the projected dose was exceeded several times. On the other hand, patches with no elevated Ca concentrations were detected.

In the Ore Mountains, some injudicious and counterproductive treatments also took place, such as site preparation using a bulldozer that consisted in the removal of grass turf and the upper humus layer and uploading the material into windrows. The habitat between the windrows was thus deprived of organic matter and key nutrients. The preparatory (temporary) forest plantations were planted in almost sterile mineral horizons. Later, in some places, the windrows were spread out with the subsequent afforestation (Podrázský et al. 2003). The organic material partially decomposed during the period of its deposition in the windrows, which improved the chemical properties, especially in terms of higher organic matter content and the value of cation exchange capacity. The C : N ratio remained less favourable, as did the phosphorus content, which suggests that the process of nutrient depletion also continues after the windrows have spread out (Vavříček et al. 2008).

During the 1990s, there was a decline in liming due to optimistic predictions regarding the further development of forest health and the condition of the forest soils caused by a significant decrease in emissions (Šrámek et al. 2003). Nonetheless, the forestry practice and research still faced the very difficult task of reforesting habitats after the disintegrated forests, often in climatically highly exposed areas and with degraded, acidified soil. The use of crushed alkaline rocks and other amendments thus became the subject of interest again. In contrast to previous aerial applications, this time, the amendments were applied locally into the planting holes or on the soil surface close to the planted trees. Chemical amelioration would again serve as direct support for the newly planted trees (Balcar 1998). Due to the low concentration of nutrients and the high transport and application costs (Kuneš et al. 2011; Kuneš et al. 2013), the extensive use of crushed alkaline rocks was found to be uneconomical. For the fertilisation of young tree plantations on a wider scale, artificial fertilisers with a higher concentration of nutrients were thus recommended.

Measures to counteract the yellowing of spruce. In the surroundings of the Czech-Slovak-Polish tri-border, a serious and specific decline event of Norway spruce forest stands occurred at the turn of the millennium. First yellowing and then the decline and dieback of spruce stands began to appear here, even in the situation after a significant decrease in the air-pollution load. The poor health of forest stands was undoubtedly related to nutritional disorders, but the symptoms also varied in different areas according to the chemistry of the bedrock. It was also unclear whether the nutritional disorder was a cause or a consequence of some other factors reducing the stand vigour. On naturally poor soils on acidic rocks in the higher parts of the Hrubý Jeseník, a significant lack of nutrients was recorded in the soil and in the assimilation apparatus of individual trees with deteriorating health. Simultaneously, the individuals in good health were often found in the same place (Šrámek et al. 2008). These healthy trees showed a higher (but still suboptimal) foliage nutrient content than the damaged ones (Pecháček et al. 2011). In areas with nutrient-richer bedrocks (Beskydy flysch), the forest decline was probably related to a disruption in the nutrient intake; it was probably not a direct consequence of nutrient deficiencies in the soil. The research at that time (Holuša, Liška 2002) revealed that the foliage and soil nutrient content did not reach optimal values, but was without serious deficits. The degradation of epicuticular waxes caused by acute air pollution was not identified as a direct cause either. The study at the time speaks only of non-specific nutrition disorders (Bednářová 2008). To date, an extensive area of the forest stands affected by the mentioned nutrient disbalance has been destroyed by the bark beetle dieback.

The main goal of the application of liming and other ameliorative materials after the year 2000 was to prevent or reduce the symptoms of repeated and widespread yellowing and decline of spruce stands in the Krušné (Ore) Mountains and Orlické (Eagle) Mountains (Šrámek et al. 2003, 2012). Between 1999 and 2012, almost 50 000 ha of forests were limed, of which more than 33 300 ha occurred in the Ore Mountains. The aerial application method was used. Dolomitic limestones with a higher proportion of Mg were preferentially applied (MoA 2004). Additionally, slowly soluble magnesium fertilisers were also applied at some sites, as well as foliar fertilisation by Mg-fertilisers (Šrámek et al. 2014).

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The aerial application of crushed rocks was considered a fast and economically advantageous method, but there might be substantial local differences in the amount of deposited material (Bošeľa, Šebeň 2010). Due to the slower solubility, crushed silicate rocks were recommended in habitats where classical liming posed a higher risk of the nutrient or heavy metals leaching [e.g. in drinking water protection zones (von Wilpert, Schäffer 2000)].

From 2011 to 2013, the aerial liming and fertilisation of forest stands from public funds was almost stopped. The main reason was the austerity measures due to the previous economic crisis (MoA 2012, 2013, 2014). Despite the slowdown in the implementation of amelioration interventions, the results of previous research surveys evaluating the effects of liming on the soil environment and the growth (health status) of forests were published.

Advanced anthropogenic soil acidification gradually led to the destruction of the sorption complex. Subsequently, aluminium is released into the soil solution, and it enters the mineral horizons below (Mládková et al. 2006). Liming is a measure that can start the soil regeneration process. The effects of liming typically manifest with a decrease in the soil acidity and by an increase in the soil nutrient element content (especially Ca and Mg in case of dolomitic lime use). This improves the ratio of basic cations (Ca + K + Mg) to the aluminium content, which indicates a reduction in the toxicity of aluminium to the root systems of trees (Bakker et al. 1999; Šrámek et al. 2006). On the other hand, changes in the chemistry are most pronounced in the upper soil horizons (Musil, Pavlíček 2002), often only in the overlying humus (Šrámek et al. 2012). Mineral soil horizons are usually unaffected by liming (Mládková et al. 2006).

Several years after liming, an increase in the Ca and Mg in the foliage chemistry (needles of Norway spruce) is usually detected (Šrámek et al. 2006). A more significant increase in the content of nitrogen and other elements in needles after liming is manifested only in favourable cases, sometimes the increase in the content is only weak, or is not apparent at all (Kulhavý et al. 2009; Vavříček et al. 2010). Although, in some cases, the effect of liming is only short-term, on other sites (i.e. the Beskydy Mountains, Bílý Kříž), it lasted for several decades (improvement of nutrition by basic elements, but not nitrogen), regardless of the application dose (Truparová, Kulhavý 2011).

Some tree species may show a specific response to liming (fertilisation). An example is the planting of Carpathian birch in the air pollution area of the Jizera Mountains. The fertilisation of crushed dolomitic limestone (point application during planting) had a significant negative effect on the growth of Carpathian birch, but an even higher content of the main nutrients in the leaves was recorded (Kuneš et al. 2007). In contrast, the same treated beech plantation initially showed a slightly positive growth reaction, but without affecting the content of most nutrients. Only in the case of phosphorus (quite deficient in the locality), a higher content was recorded (Špulák et al. 2011).

Application of artificial fertilisers in forests. Contrary to liming, mostly applied in large areas by the aerial method, artificial fertilisers are usually applied at planting in Czech forests to particular trees on the surface of the soil (Kuneš et al. 2009; Vavříček et al. 2010) or into a planting hole [initial fertilising (Kuneš et al. 2006; Kuneš et al. 2014b)]. Aerial applications were conducted only rarely, e.g. to counteract the yellowing of forest stands or improve their nutrition (Lomský et al. 2006); see the previous text.

The tabletting of artificial fertilisers enables the precise application in terms of the dose and place. Tabletted fertilisers, intended for fertilising forest plantations, began to be tested more extensively in the 1980s in the Czech Republic (Lokvenc 1987; Materna, Ledinský 1987). Preform fertiliser was developed and used in Czechia, and Dukofert fertiliser in Slovakia. However, the field testing of neither of the fertiliser types fully met expectations, which should have consisted in a significant intensification of growth of the plantations, especially on the large air-pollution clear-cuts (Nárovec 1992; Nárovec 2004). After 1993, the production of Preform and Dukofert fertiliser tablets was terminated.

In the forest environment, it is desirable for nutrients from the applied fertiliser to be released gradually so that they can be absorbed as much as possible by the vegetation and not leached out, as is the case of fast-release mineral fertilisers primarily intended for agriculture (Insam, Merschak 1997). Therefore, slow-acting fertilisers (or slowly soluble fertilisers; slow-release fertilisers) are particularly suitable for forestry. The rate of fertiliser dissolution, and thus the release of nutrients, depends on a number of factors such as moisture, temperature and the activity of soil microorgan-

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isms (Jahns, Kaltwasser 2000). Ideally, the fertiliser should release the nutrients only when the soil temperature and humidity are sufficient. This should ensure that the largest possible proportion of nutrients can be absorbed by plants (trees). In Czech forestry, the products by the Silvamix brand are probably the most common fertilisers belonging to the group of slow-release artificial fertilisers.

Slow-soluble Silvamix fertilisers are produced mainly in a tabletted form. The beginning of their practical use falls into the period of reforestation after the air pollution forest dieback (1980s). Gradually, the technological principles of the application of fertiliser tablets in forests, especially on clear-cuts after air pollution, were determined (Kubelka 1987). When using the Silvamix fertiliser tablets, there was a certain shift in the view of the fertilisation aim, which was also reflected in the method of application. Older tabletted fertilisers were intended for application directly into the planting hole, either into its bottom or to its edge (initial fertilisation). On the other hand, it was recommended to rather apply the Silvamix fertiliser tablets on the soil surface around the perimeter of the crown or to squeeze them into the soil surface only by pressing (Kubelka 2001). This form of application corresponded to the philosophy of 'storage fertilisation', which was used in Germany (Nárovec 2004).

The advantage of artificial fertilisers (not only slow-release Silvamix) rests in the ability to adapt their nutritional composition according to the need to supply a specific missing element. In the case of Silvamix, several types of fertilisers with different proportions of nutrients are produced, designed for typical situations that can be encountered most often in practice. The nutrient ratio can be easily chosen to achieve the best possible approximation of soil properties at a given habitat to a nutrient-balanced state (Vavříček et al. 2010; Pecháček et al. 2017).

There are some typical examples of habitats, where the specific fertiliser formulations are useful, e.g. the mountain areas on acidic bedrocks, especially on former air-pollution clear-cuts, where an insufficient supply of Ca and Mg were usually detected in the past (Šrámek et al. 2006; Šrámek et al. 2012). Later, the deficiency of phosphorus and some other macro- and micronutrients was manifested in these areas (Špulák 2009; Kuneš et al. 2011). Phosphorus is often also missing on air-polluted sites after bulldozer soil preparation, while the supply of other elements is significantly better or sufficient. Therefore, the soil deficit of phosphorus often remains hidden for a long time, because its deficit in the assimilation apparatus is usually not as significant, and also the observable deterioration of health in the absence of phosphorus is often practically not manifested. The health status of Norway spruce stands is rather problematic when there is a lack of phosphorus with a simultaneous excess of nitrogen (atmospheric deposition). The N : P ratio can then be used as a good indicator of nutritional status (Lomský et al. 2011a). The fertiliser composition and formulation type must respect the specific features of the given habitat.

When assessing the efficiency of liming or fertilisation, there are several factors which must be considered. The altitude and the dominant species of forest cover may influence the soil properties similarly to the treatment (Mládková et al. 2006). Habitat characteristics play a significant role in the effectiveness of fertilisation. An example is the planting of beech, sycamore maple and fir on a wet site in the 7th forest vegetation zone [beech-spruce (Viewegh 2003)] in the Orlické (Eagle) Mountains. The thing that had the greatest influence on the survival and increment was the technology of planting (mound planting). The effect of fertilisation with Silvamix was not evident, but a positive effect of limestone and amphibolite dusts on the survival and increment was observed (Černohous, Kacálek 2008).

When using fertilisers, including slow-releasing products, the recommended dosage and method of application must be followed to reduce the risk of adverse effects. A special slow-release organic fertiliser (Frisol series), recommended for forest reclamation and revitalisation of undeveloped and degraded soils, containing the extract of a soil fungal biomass, was used in the recultivated area in the North Bohemian brown coal basin. Very good growth, but also the high mortality of transplants (European ash) occurred. The causes of the disproportions reflected in the prosperity of woody plants probably lie in the incorrect dosing of the preparation (Bulíř 2007), while the specific 'correct' dose depends on the soil conditions of the habitat.

In relation to soil fertilisation, another question is the influence of the optimal to luxurious fertilisation of transplants during growth in a forest nursery on the morphological parameters of the

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planting stock. Research showed that the optimal fertilisation (beech seedlings, slow soluble fertiliser Plantacote) accelerates the overall growth of the seedlings; on the contrary, the luxury fertilisation has a positive effect especially on the height increment of the aboveground part. The diameter increment and root biomass are less affected. Therefore, in the case of luxury fertilisation, the ratio of aboveground and belowground biomass may deteriorate (Nárovcová, Jurásek 2007). After planting in a forest habitat (7th forest vegetation zone in Hrubý Jeseník), the transplants grown in a nursery with luxury nutrition were not deteriorated. Four years after planting, the post-planting shock is still evident, but it is not greater than with the standard fertilised transplants. The height increment does not differ from the optimally fertilised seedlings, i.e. luxuriously fertilised plants maintain their initial lead in absolute terms, even though they are declining in relative terms. The possible luxury fertilisation (over-fertilisation) did not improve the prosperity of transplants after planting, but also did not cause major difficulties in their growing (Bartoš et al. 2008).

It must be emphasised that forest fertilisation is generally not a universal cure to resolve all the problems caused by wrong silviculture techniques or by the anthropogenic impact. With the help of fertilisation, it is possible to partially mitigate the negative impacts. However, the decisive importance still lies in the gentle handling of the planting stock, respectively, the subsequent fertilisation should not be a guide to careless handling (e.g. Grossnickle 2005).

Germany

In Germany, liming (eventually combined with other amendments) has been an important method of chemical amelioration in forests. As reported by Materna (2001), the first experiments with liming in Germany date back to the turn of the 19th and 20th centuries. The first documented experiment was mentioned by Seibt (1977), which was established in Erdmannshausen in 1907. Extended liming was used for production purposes from the 1930s until 1950s (Seibt, Wittich 1977; Gussone 1983). Later, other concepts supported the use of this treatment to a large extent (Hüttl 1987).

In some federal states of Germany, liming has become part of the long-term forest management concept, with a total of 2.5 million ha limed between 1984 and 1998 (Meiwes et al. 2002) and by 2009 the limed area reached about 3 million ha, i.e. more than one third of the total forest area in Germany (BMELV 2009). The approach to liming differs among the federal states of Germany, not only due to the specific natural conditions and different acidification pressure, but also reflects the different emphasis that particular federal states place on the benefits and risks of liming.

Federal states where large areas of forest are limed include Baden-Württemberg, Rhineland-Palatinate, Hesse, Lower Saxony, Saxony, North Rhine-Westphalia and Saxony-Anhalt. Dolomitic limestones are used in doses of 3–4 $t \cdot ha^{-1}$, usually applied once per decennium (Reif et al. 2014). In some regions, liming is considered a medium to long-term strategy. In Baden-Württemberg, for example, liming is planned for 2050, with about 21 000 ha being annually limed in the next years. The total area, which should be limed by 2050, would therefore be approximately 680 000 ha [i.e. 45% of the forests of this federal state (Janssen 2014)]. At the same time, there is a principle not to lime on those habitats where the application of limestone would be unnecessary, inappropriate or too risky. Such localities include habitats saturated with nitrogen (risk of nitrogen leaching), peat bogs, moorlands, surroundings of watercourses and water bodies or, on the contrary, dry, extremely rocky and stony habitats, and of course localities where nature conservation interests predominate (Badalík, Řezáč 2001; Kölling 2014). On the other hand, in some federal states (e.g. Bavaria, Brandenburg and Mecklenburg-Western Pomerania), liming is used only in very exceptional cases (Reif et al. 2014).

Since the late 1970s, the surface liming of forests has been widely used as a reclamation and curative technique after undesirable interventions (e.g. litter raking) and also for the compensation of the acid deposition, which was associated with the acidification of soils by anthropogenic air pollution (Ulrich et al. 1980; Tichý 1992; Klose, Makeschin 2004; Stetter 2010; Baumann et al. 2019). The acidification of forest soils is mostly connected to a deficit of magnesium and other soil basic elements. Therefore, the liming aimed to slow down the acidification of the soil and to mitigate the insufficient nutrition of forest trees.

In this context, the term compensatory liming (Kompenzationskalkung) was used in Germany

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during the 1980s (see Gussone 1987; Brahmer 1994; Höcke 2006; Schaaf, Hüttl 2006, etc.). Dolomitic limestone or dolomite has been used as a source of magnesium which has become a deficient nutrient in many forest habitats due to acid deposition (Evers 1991; Feger 1997; Landmann et al. 1997; Baumann et al. 2019). Liming increases the tree growth and additional N of anthropogenic origin can be retained by the vegetation (Greve et al. 2021). Although lime treatment has notable positive effects on the soil property recovery, the site characteristics must be taken into account when one decides to apply the reclamation measure (Jansone et al. 2020).

The response of forest soil to fertilising or liming may vary substantially depending on the stand conditions. Next to the positive effects, the potential negative impacts of liming also play a role (Kreutzer 1995). The risks must also be considered, including, e.g. a reduction in the soil organic matter (Aarnio, Martikainen 1995; Kreutzer 1995; Aarnio, Martikainen 1996; Seitz 2014) followed by nutrient leaching (Marschner, Wilczynski 1991; Köling 2014) and the subsequent eutrophication of the surface water, mobilisation of copper and lead in the soil (Brahmer 1994; Kreutzer 1995) or shifting of the fine roots towards soil surface layers and increased root rot (Kreutzer 1995). Seitz (2014) compares the liming of forest soils to a powerful drug that can help, but also often has risks and side effects. The assessment of the benefits, potential risks or side effects and the financial costs is crucial when deciding on the use of such treatments.

After the input of acidifying pollutants into forest ecosystems has fallen rapidly over the past two decades, liming is increasingly attributed to a 'regenerative' function and is justified by efforts to restore natural (anthropogenic acidification of undeformed) soil processes resulting in the natural status of soils (von Wilpert 2014). The need for liming in a certain forest habitat (with the exception of localities where liming is excluded for some reason) is assessed here according to the value of the soil exchange reaction (pH_{KCl}) and the level of base saturation of the soil sorption complex in the upper soil layers. According to von Wilpert (2014), sites where amelioration intervention is highly needed include sites with soils where the base saturation (BS) is less than 5% and where the value of the soil exchange reaction (pH_{KCl}) has fallen below 3.0 in the upper organomineral and mineral soil horizons.

The amount of mobile aluminium in the lower mineral horizons of the soil profile is used as a quantity indicator to derive the total required dose of limestone, which should ensure the restoration of the natural soil reaction and adequate nutrient content. In naturally acidified soils, exchangeable aluminium occurs mainly in the upper part of the soil horizon. Its larger amount in the lower mineral horizons is usually the result of anthropogenic acidification (von Wilpert 2014).

In connection with the significant improvement of the air pollution situation, it is appropriate to argue in favour of protective (regenerative) liming. In the monitored habitats, even in non-limed localities, the decrease in the soil reaction stopped or a slight increase was detected (von Wilpert 2014). However, in limed habitats, the increase in the value of the soil reaction was significantly higher. Clear differences in the rate of regeneration (increase) of the soil reaction values were recorded up to a depth of 30 cm (Jansone et al. 2020). The amelioration intervention is of great importance for adjusting the base saturation of the soil sorption complex. While, in limed areas, the saturation values began to increase, in non-limed areas, the leaching of soil bases continued (albeit at a much slower pace than in the past), thus also decreasing the saturation values of the sorption complex, due to the nitrogen input, which, especially sulphur, fails to decrease significantly (von Wilpert 2014).

Liming should thus shorten the time required for the soils to regenerate to their original state before massive anthropogenic acidification begins. While, on limed sites, the soil will need about 40 to 80 years to regenerate (simply assessed using the soil reaction), on non-limed sites, the regeneration of soil will take at least 250 years. Using the base saturation as a criterion, the regeneration time in limed localities will also be about 40 years (von Wilpert 2014).

Liming induces the soil microbial activity (Lorenz et al. 2001). The improved conditions for the ammonia-oxidising bacterial community causes the mineralisation of the organic matter with the risk of nutrient (especially nitrogen) leaching (Bäckman et al. 2003). The dynamics of the content of organic matter in the soil and the content of nitrogen compounds can be a problem after liming (Kreutzer 1995).

There are potentially negative impacts on mosses and some insect species, the levelling of habitat

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properties by surface aerial application of limestone (after previous levelling by acid deposition), loss of calciphobic plant species, favouring ruderal species (humus mineralisation), and the unnatural influence or damage to soil biota (Seitz 2014). On the other hand, the changes in the ground vegetation after fertilisation may be favourable as a result. The increase in the available nutrients after fertilisation can suppress some competitive oligotrophic species to support the growth of the nutrient-demanding vegetation, including the natural regeneration of tree species. The accelerated decomposition of the above-ground organic soil horizons after liming may improve the conditions for the development of the natural regeneration of tree species (Bauhus et al. 2004).

Nordic and Baltic countries

Denmark. In Denmark, liming and forest fertilisation have been and are being carried out mainly on an experimental level. Pilot testing in forestry practice was also performed in some cases (Vejre et al. 2001). Although these experiments have mostly not resulted in more extensive practical applications, the Danish experience with fertilising forests in poor acidic habitats is a source of very interesting information for Central European forestry.

As in other countries, also in Denmark, the goals and expectations that liming and fertilising of forest stands should meet gradually developed over time (Ingerslev et al. 2001). In connection with previous experiments with nitrogen fertilisation, which was to mainly serve for the amelioration of poor soils on heaths, in the second half of the 20th century, fertilisation was focused on a direct increase in the growth and production. Attention was focused on young plantations and stands (up to 15 years) and on middle-aged stands.

Nitrogen fertilisation in poor heathland habitats in western Denmark elicited a positive response, while the response to phosphorus and potassium application was not clear. Furthermore, the duration of the effects of nitrogen fertilisation, its timing, and the possible risk of causing imbalances in the nutrition of cultures (secondary deficiency in the supply of other nutrients) were also studied. However, no clear conclusion was reached on these issues. Over time, however, there has been some shift in the positive response to fertilisation with nutrients other than nitrogen. From the point of view of production (not curative) fertilisation, two general theses were formulated: (*i*) The strategy of increasing the production of young stands by supplying only one element is wrong. In order to prevent unbalanced nutrition, it is better to supply a wider range of nutrients; (*ii*) Each experiment or treatment should be evaluated individually with great regard to the site in which it took place. Generalisation to a larger area should be very careful (Vejre et al. 2001).

In the mid-aged stands, attempts to apply fertilisers in Denmark began around the mid-1960s, and their results were often quite different. On the one hand, positive effects of nitrogen fertilisation at doses of 200–600 kg·ha^{-1} were recorded. In other cases, a highly variable reaction of individual trees to fertilisation of Norway spruce at a nitrogen dose of 120 kg·ha^{-1} was recorded, from a significant increase in growth to the poisoning of some trees.

In 1976, an extensive pilot programme with combined NPK fertilisation was launched in the western part of the Jutland peninsula. In general, the experiments showed that the reaction of forest stands fertilised with a high nitrogen content in the mixture (N : P : K = 23 : 3 : 7) was rather negative, while in the case of the application of a fertiliser mixture with a lower nitrogen content (N : P : K = 14 : 4 : 7) the reaction was mostly positive. Overall, however, the results were rather inconsistent, and the possible positive response was not convincing enough. Therefore, the programme was terminated in 1989 (Vejre et al. 2001). Experiments established at that time were later evaluated in detail, not only in terms of the effects on the forest stand production, but also on their nutrition and soil chemistry. The results show that liming in combination with NPK fertilisation had a significant effect on improving the chemistry of the upper soil horizons, but no increase in growth (spruce) was recorded, and, in addition, the surface water was negatively affected by leaching nutrients from fertilisers (Ingerslev 1999). Fertilisation also had a minimal effect on the needle chemistry (Ingerslev, Hallbäcken 1999).

Over time (1980–2000), there has also been a significant shift in Denmark in the perception of the importance of fertilisation and liming for forest ecosystems. The impetus was the deteriorating condition (decline) of European forest stands (Larsen 1995), the so-called 'the new type of forest damage', which was attributed to acidification. Although, at least initially, significant production motivation

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persisted, over time the role of fertilisation to support the vitality of stands and their balanced nutrition in conditions of anthropogenic acidification prevailed (Ingerslev et al. 2001). The annual deposition of acidic pollutants has decreased significantly since the 1980s, namely from the 25–30 kg·ha^{-1} for sulphur and 18–35 kg·ha^{-1} for nitrogen (Vejre 1999), to the current ca. 1/3 of the then peak value for sulphur (Kaae et al. 2022) and to the 1/2 for nitrogen, respectively (Strandberg et al. 2012). Nevertheless, at least, in some localities in Denmark, nitrogen gradually moved from the role of a deficient nutrient to the position of a nutrient in excess. Moreover, the excess nitrogen supply induces a deficit in nutrition of other elements. This corresponds to the declining response of the stands to nitrogen fertilisation and increased nitrogen leaching (Vejre et al. 2001); concurrently, the authors point out that the generalisation of their findings to other sites should be considered very carefully, depending specifically on the stand condition.

In relation to the philosophy of compensatory liming and fertilisation (Hüttl 1988), the importance of assessing the nutritional status and possible deficiencies or imbalances of individual nutrients began to be emphasised in Denmark also. The decision on the application of chemical amelioration and the selection of a suitable fertiliser should then correspond to the results of the nutritional analyses of the given stand and forest site. Attention should also be paid to the solubility of fertilisers, which must correspond to the ability of the fertilised vegetation to uptake the released nutrients. Furthermore, fertilisation and liming have been shown to be able to have a curative effect against some of the causes of soil degradation or against the symptoms of wasting, including extremely low concentrations of certain nutrients. So far, however, it has not been possible to carry out such targeted and balanced chemical land reclamation that would be able to continuously maintain the optimal nutrition, vitality and growth of forest stands even in problematic habitats, thus preventing signs of decline caused by nutritional imbalances (Vejre et al. 2001).

Despite some shortcomings (or lower consistency) of fertilisation treatments in Denmark, or more precisely for the need to find ways to eliminate them, Vejre et al. (2001) saw the great importance of experiments dealing with forest nutrition. Attention should also be paid to some specific situations where chemical amelioration may prove desirable over time, with persistent acidification pressure highlighting the need for amelioration. These include support for nutrition during the conversion of coniferous monocultures to deciduous or mixed stands, fertilisation with intensive use of biomass for energy purposes, which is associated with increased nutrient removal from forest ecosystems, etc.

Increasing the values of cation exchange capacity, base saturation and pH was observed in the 44-year-old Norway spruce plantation on nutrient-poor soil. In a short time (2 years after application), the chemistry changes occurred only in the hummus soil horizons, not in the mineral horizons (Ingerslev et al. 2014).

Sweden. Extensive experimental and practical experience with the fertilisation of forest stands comes from Sweden (Nohrstedt 2001). In many cases, nitrogen or magnesium are limiting elements in the nutrition of Swedish forests, which is why amelioration measures have generally been aimed at adjusting the availability of these two essential nutrients.

It is estimated that, from the 1960s until the turn of the millennium, nitrogen fertilisation was carried out at least once on approximately 2 million ha of forest, i.e. about one-tenth of the area of Swedish commercial forests (Nohrstedt 2001). Nitrogen fertilisation reached its greatest extent at the end of the 1970s (approximately 190 thousand ha per year). Furthermore, the extent of fertilisation decreased to 20 thousand ha in the 1990s. The reason for the decrease was both the streamlining of the fertilisation regime (more careful selection of suitable forest stands and the extension of the application interval) and concerns about side effects, supported by, among other things, worries about increasing the anthropogenic nitrogen inputs and the deposition of other acid pollutants (Jacobson, Pettersson 2010). These concerns are confirmed, for example, by a study from neighbouring Norway, which also shows the risk of P and Mg deficiency in the case of excessive fertilisation with a nitrogen fertiliser (Nilsen, Abrahamsen 2003).

Initially, nitrogen fertilisation in Sweden was carried out using pure urea or ammonium nitrate; later, ammonium nitrate with finely crushed limestone was used. As a rule, the fertiliser was applied at a dose of 150 kg·ha^{-1}, mostly two to four times per rotation, usually at ten-year intervals

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(Nohrstedt 2001). However, the ten-year interval is too long for the effective application of the fast-release fertilisers (the used dose is high). To reduce nutrient leaching, it would be optimal to apply fertilisation more often (preferably every 2 years, economically optimally once every 3 years) and in smaller doses (Bergh et al. 2008). The ten-year interval is suitable when using slow soluble fertilisers.

In connection with anthropogenic depositions, issues related to the circulation of other nutrients have arisen here as well, because excess nitrogen (not only) in boreal forests can cause a lack of basic nutrients by the increased uptake and leaching (Aber et al. 1989; Nohrstedt 2001; Nohrstedt 2002) or restriction of the phosphorus accessibility. Phosphorus can be added by applying a fertiliser with a suitable composition (Fransson, Bergkvist 2000). However, generally, fertilisation with nutrients other than nitrogen has not received much attention in Sweden. Especially in the southern part of the country, there is mostly no acute need for liming. Therefore, only minor effects of fertiliser additions on the growth and leaf chemistry were recorded, as resulted from the study of Sikström (2002), which dealt with the effect of fertilisers with Ca, N, P, K content in a Norway spruce stand.

Liming or fertilising usually accelerates the organic matter mineralisation (Aarnio, Martikainen 1995; Kreutzer 1995; Bäckman et al. 2003; Köling 2014). Some new outcomes found in a mature Scots pine stand on the podzolic soil in Northern Sweden show that long-term use of an ammonium nitrate fertiliser (an average annual amount of net N reached 75 kg·ha^{-1} for 12 years) suppresses the enzymatic white-rot lignin mineralisation, which could lead to a selective accumulation of lignin-derived compounds in the soil organic matter (Hasegawa et al. 2021).

Due to the soil conditions, there is wide potential in Sweden to use nitrogen fertilisers as a tool to increase the forest production. The wood production in older stands is, on average, increased by 15 m^3 per decade and 1 ha after nitrogen fertilisation. In addition, the higher stem diameter growth of fertilised trees is reflected in a higher share of sawn timber and valuable assortments. Larger dimensions of fertilised trees also reduce the cost of skidding (Jacobson, Pettersson 2010). If fertilisation is applied to young stands, the increase in biomass supply can be roughly doubled in two decades (Stockfors et al. 1997).

However, there are also studies with the opposite results. In the case of the highly productive Norway spruce stand in western Sweden (Jacobson et al. 2000), an insignificant growth increase was observed after a repeatedly applied nitrogen fertiliser (urea). Despite the high nitrogen addition, there were no obvious residual changes in the nutrient concentrations in the above-ground parts of the trees.

Liming and fertilising may be also problematic from the point of view of nature protection. The ameliorative treatment usually affects the ground vegetation of herbs and mosses. The effect may be evident for almost two decades after the application of the nitrogen fertiliser, as results from a study performed in southern Sweden (Olsson, Kellner 2006).

Norway. In Norway, several long-term experiments on forest fertilisation can be observed. A young pine stand in south-east Norway was limed in 1959 with a dose of 3 t·ha^{-1} of limestone and in 1970 with granulated ammonium nitrate (200 kg N·ha^{-1}). Changes in the nutrient content of the needles (increase in Ca and decrease in Mn, Al, and Fe) have emerged, but no significant effect of liming on the tree growth was detected (Børja, Nilsen 2009). In general, liming often had no effect, or had negative effects on the tree growth on mineral soils (Nilsen 2001). On the other hand, a positive growth reaction after fertilisation with nitrogen fertilisers in old pine stands of poorer quality was recorded in another experiment (Haveraaen, Frivold 2015).

A study assessing the effect of liming with P and Cu fertilising (row phosphate and copper sulfate) on a poor heathland in Norway (Erstad 2006) showed a gradual, but visible beneficial effect on the vitality of woody plants and ground vegetation, and the simultaneous decline of nutrient-poor species (e.g. *Nardus stricta* and *Vaccinium uliginosum*) after fertilising.

A combination of liming and other fertilisers has been tested in a young Scots pine stand (33 years) on a sandy, nutrient-poor soil in southern Norway. The effects of liming are determined mainly by the type of liming material, its solubility and doses. The chemical changes were manifested especially in the humus layer. Lime affects the soil more deeply than dolomite, due to better solubility. After 4 years, about 30% of the added amounts of N, K, and Mg were leached, but only about 10% of the Ca.

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In contrast to nitrogen, calcium is considered an element with low mobility in the soil (Frank, Stuanes 2003).

On the peatland soil in south-central Norway, the effect of a limestone and NPK fertiliser application was studied. An obvious increase in the soil parameters (N, P content) was recorded only up to a depth of 20 cm in the case of the fertiliser application. After liming, an increased Ca content, pH, and base saturation could be detected rather deeper [up to a depth of 30–60 cm (Brække 1999)].

Finland and Baltic countries. There are frequent concerns about the organic matter loss and the nitrogen and other nutrients leaching after fertilisation in boreal forests. In southern Finland, a slow soluble nitrogen fertiliser based on ureaformaldehyde (UF) was tested in a Scots pine stand. The use of the UF-derived fertiliser increased the availability of nitrogen on acidic forest soils, but did not accelerate the nitrification activity. Fertilising did not accelerate the organic matter mineralisation, which is usually connected with the risk of nutrient leaching (Aarnio, Martikainen 1995, 1996). A similar author team (Aarnio et al. 2003) further successfully tested the application of apatite rock powder in the Scots pine stand in southern Finland. The goal was to ensure the supply of phosphorus in a safe way, i.e. without the risk of leaching. The positive effect on the phosphorus content was noticeable even after 10 years.

An experiment on wood ash recycling was established on nutrient-poor sandy soils in a mid-aged Scots pine stand in Lithuania. The application of ash and nitrogen fertiliser was evaluated. The results showed an increase in the Ca and Mg content and a decrease in the acidity in the upper layer of the forest soil (humus) already four months after the application of wood ash in the pine stands (Ozolincius 2006). Later studies originated from this experiment showed the following: Fertilisation only with ash had a minimal effect on the pine vitality and soil and foliar chemistry, while nitrogen fertilisation increased the concentrations of N and other elements in the pine needles and soil (Varnagirytė-Kabašinskienė 2008). The complex ash plus nitrogen treatment is the most effective in increasing the vitality, namely in the increase of the dry-mass of the current-year's needles (Varnagirytė-Kabašinskienė et al. 2015).

In Finland, some negative effects of liming and fertilisation were revealed. The lack of accessible boron was repeatedly registered in a Norway spruce stand in Central Finland (Lehto 1994; Lehto, Mälkönen 1994). Necrosing of fine roots in the spruce stand in Finland was observed as a consequence of soil chemical changes after a fertiliser application (Helmisaari, Hallbäcken 1999). In most cases, the liming of forests is not considered appropriate in Finland (Saarsalmi, Mälkönen 2021).

Other selected examples

Artificial fertilisers are used in forestry worldwide in a variety of conditions. Below is a selection of some application examples:

The above-mentioned studies from Scandinavia can be compared with a study from Canada (Québec), realised in analogous conditions. The experiment was performed in the stands of *Abies balsamea* and *Picea mariana* in the boreal habitats that are naturally very poor in nitrogen and with minimal deposition. The increased nitrogen deposition was simulated by the periodical application of ammonium nitrate. In both stands, nitrogen additions regularly caused a substantial increase in the inorganic nitrogen content in the soil solution. However, it was estimated that more than 95% of the added nitrogen was retained above the rooting zone without leaching to the deeper soil horizons. The nitrogen addition increased the N, Ca, Mg, and Mn foliar concentrations at the black spruce site, but had no effects at the balsam fir site. A significant growth response was observed in the case of the balsam fir, but only in the first 3 years after application; the growth response of the black spruce was negligible (Houle, Moore 2008).

The application of a polymer-coated fertiliser into the planting hole was successfully tested to alleviate the transplanting shock and to initiate the growth of planted deciduous trees (black walnut, American ash, and tulip tree) in the United States (Jacobs et al. 2005). Positive effects of the initial fertilisation with this type of fertiliser have also been reported in Iceland for the downy birch, Siberian larch and Sitka spruce (Óskarsson et al. 2006).

On the other hand, the unfavourable response after the application of the polyurethane-coated fertiliser sometimes occurs, as has been referred to in North America in the case of Douglas-fir seedlings planted in a drought area. The fertilised plants showed less root growth, lower root biomass and, as a result, less collar root diameter. This unfavourable phenomenon was probably partly caused

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by an inappropriate method of applying the fertiliser material. Prior to planting, the fertiliser was poured onto the bottom of the planting hole, and it was not mixed with the soil. In the dry and warm period, when the most intensive nutrient output from the fertiliser capsules took place, the concentration of active fertiliser in the soil solution inside the continuous layer of fertiliser probably increased, which probably led to the dehydration of the roots (Jacobs et al. 2004).

Nitrogen fertilisation or nitrogen deposition (example from Switzerland) can also mean an increased risk of trees (spruce, beech) being attacked by fungal pathogens (Flückiger, Braun 1999).

Fertilisation is often also carried out on plantations of fast-producing woody plants. An example from the temperate zone can be a study from Slovakia (Kohán 2002), focused on the evaluation of the effects of fertilising a poplar stand (hybrid poplar No. I-214) in the Latorica river basin with a fast-release fertiliser (NPK). For the fertilised variants, a faster increase was recorded, especially in the diameter. Another example, in this case from subtropical conditions (Chile), is a study evaluating the fertilisation of *Pinus radiata* plantation. There, several options with a combination of different doses of nitrogen, phosphorus, boron and potassium were established. In poorer habitats, the fertilisation had a positive effect on the leaf nutrient content and growth, but, in richer habitats with heavier clay soil, the effect was minimal (Ramírez Alzate et al. 2016).

The study by Brais et al. (2015), performed in a 53-year-old forest stand on a sandy, acidic soil in Québec (Canada), shows that only a wood ash application improves the soil acid-base status, but has no effect on the foliar nutrition in the short period. The relative stem growth (measured by diameter at breast height – *DBH*) increased only in the case of *Pinus banksiana* in the option with N fertilisation by urea; the growth response of *Picea mariana* even shows a slight decrease in the relative growth in the highest dose of wood ash (8 $t \cdot ha^{-1}$).

An experiment with young trees of *Platycladus orientalis* assessed the relationship between N-fertilisation and drought tolerance. The results of a study from Iran indicate that the urea fertiliser, especially in a higher amount (150 mg per kg of substrate), improved the growth and quality of seedlings under different soil moisture conditions and increased their survival under severe drought (Aliarab et al. 2020).

CONCLUSION

The approach to forest soil amelioration may substantially vary in the individual countries, especially due to the different natural conditions and other specifics. In the Czech Republic, surface liming in air-polluted areas has been practised for several decades. Despite the intensive research, the practical use of artificial fertilisers remained only on the local level. Similarly, in Germany, surface liming has been extensively used to compensate for the anthropogenic deposition of acidifying substances. In Denmark, nitrogen or complex fertilisation has been tested mostly on the experimental level. Later, compensatory fertilisation and liming prevailed to counteract the acidifying deposition, however, especially on an experimental level. In Sweden, the extensive practical use of nitrogen fertilisation to increase wood production has been practised in the past. Experimental liming often did not lead to the desired effects on growth, similar to Norway. N-free fertilisation had a chiefly experimental characteristic. In Norway, experiments on liming and nitrogen and complex fertilisation were performed, but the practical use of chemical soil amelioration was negligible. Complex and nitrogen fertilisation could have the potential to stimulate forest production on mineral soils. However, the nutrient balance may be influenced by the anthropogenic nitrogen deposition. More recently, fertilisation experiments, therefore, often addressed potential nutrient imbalances due to acidification. In Finland and the Baltic countries, nitrogen fertilisation on peatlands has been practised to increase production. Liming of forests has not been considered an appropriate method in Finland.

Despite the various and often contradictory experiences, generally, it can be stated that liming or fertilisation has the potential to change the soil chemistry and improve the nutrition status of trees, which finally can result in an increase in tree growth and vitality. Desirable results of liming on soil include a reduction in the soil acidity, an increase in the availability of Ca and Mg, a reduction in the mobility of toxic forms of aluminium, and an improvement in the soil humus quality.

Surface fertiliser applications can improve the nutrient status of the soils and then the health status of the stands. The initial point fertilisation effectively reduces the post-planting shock of seedlings to accelerate their initial growth without having an extensive impact on the soil chemistry.

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Sometimes, the expected effects did not occur, or the negative effects prevailed. The efficiency of the fertiliser application to increase tree growth increment tightly depends on the type of fertiliser, nutrient content proportion, solubility, and dosage, as well as on the soil conditions and tree species. All these conditions must be considered to reduce the risk of adverse effects.

The increase in tree growth after fertilisation may lead to higher C sequestration. On the other hand, the accelerated decomposition of soil organic content increases the emissions of CO_2, especially after liming.

The assessment of the benefits, potential risks or side effects and the financial costs is crucial when deciding on the use of such treatments. Liming and fertilisation are followed by the risk of loss of the soil organic matter and the leaching of excessive nutrients. Attention should be paid to the dosage and solubility of the fertilisers, which must correspond to the ability of the fertilised vegetation to uptake the released nutrients. To reduce nutrient leaching, slow-soluble fertilisers are recommended on forest sites. The desired advantage of artificial fertilisers is the possibility to formulate their composition according to the need to supply specific missing elements. The chemistry changes after the surface application are usually restricted to the upper soil horizons, which often causes the shifting of fine roots towards soil surface layers.

Generally, forest fertilisation is not a universal cure. With the help of fertilisation, it is possible to partially mitigate the negative conditions caused by natural or anthropogenic impacts. Anyway, the assessment of the benefits, potential risks or side effects and the financial costs is crucial when deciding on the use of such treatments.

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