EVALUATION OF SOIL AMENDMENT EFFECT ON FOLIAR NUTRIENT COMPOSITION AS BASIS FOR DEVELOPING PREDICTIVE TECHNOLOGIES FOR FOREST STAND RESPONSE

Guna Petaja[1], Zaiga Anna Zvaigzne[1], Dana Purvina[1], Andis Lazdins[1, 2]
[1]Latvian State Forest Research Institute "Silava", Latvia; [2]Latvian Academy of Sciences, Latvia
guna.petaja@silava.lv, zaiga.zvaigzne@silava.lv, dana.purvina@silava.lv, andis.lazdins@silava.lv

Abstract. This study evaluated the impact of soil amendments – ammonium nitrate (NH_4NO_3) and wood ash – on the chemical composition of tree needles and leaves, focusing on essential macro- and micronutrients (nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg)) critical for forest growth. Tree crown material from Scots pine, lodgepole pine, Norway spruce and silver birch was collected after fertilizer application. Foliar samples were taken from multiple experimental plots, with three first-stratum trees sampled in each plot, concentrating on the upper third of the tree crowns. This approach ensured representative data for nutrient concentration changes over time. The response varied depending on the forest site type and fertilizer type. The statistically significant differences observed in conifer forests with drained organic soils indicate that NH_4NO_3 fertilization could affect N concentrations in plant tissues, possibly as a result of the nutrient dilution effect, where higher biomass may lead to a decrease in N concentration in the needles. Wood ash, either alone or combined with NH_4NO_3, had a more pronounced positive effect on K and P in conifer stands, with its impact remaining site-specific. It also increased Ca concentrations, particularly in conifer forests on dry upland and drained mineral soils, while its effect in deciduous stands was limited to forests with drained mineral soils. Mg concentrations in fertilized plots were higher in deciduous stands with drained mineral soils, whereas coniferous stands showed more varied responses. Given the role of nutrient availability, soil properties, and dilution effects in determining foliar nutrient concentrations, ongoing monitoring and repeated sampling before thinning are recommended to assess long-term fertilization impacts and prevent nutrient imbalances.

Keywords: forest fertilization, ammonium nitrate, wood ash, foliar nutrients.

Introduction

Nutrients are classified into macronutrients and micronutrients based on the amounts required by organisms. Nitrogen (N), phosphorus (P), and potassium (K) are considered primary macronutrients because they are needed by plants in the largest quantities [1]. According to the Law of the Minimum, formulated by German chemist Justus von Liebig, plant growth is limited by the resource available in the smallest amount, rather than by the total amount of resources [2]. N limitation is commonly observed in boreal and temperate conifer forests, whereas phosphorus limitation is more frequent in tropical, subtropical, and temperate broadleaved forests [3]. In addition to N and P, other nutrients such as calcium (Ca), magnesium (Mg), and potassium (K) may also be deficient in forest soils, limiting tree growth and forest productivity. This highlights the importance of considering these nutrients in fertilization strategies [4-6].

A key advantage of forest fertilization compared to other methods of enhancing stand growth is its rapid effect – additional growth reaches its peak as early as 2-3 years after fertilization [7]. N fertilizers and wood ash are commonly used for this purpose. In Norway, forest fertilization is one of the primary strategies for mitigating climate change in forest management and is funded by the state [8]. In contrast, in Denmark, forest fertilization is limited due to the need to reduce overall mineral fertilizer consumption in the country, with priority given to agricultural production [9]. Nutrient supply thresholds have also been established; for instance, in Finland, the need for fertilization is determined through needle analysis of trees felled during thinning operation [7].

Foliar analysis is a practical and cost-effective method for assessing forest nutrient status. It directly reflects nutrient availability in the soil by measuring the nutrients absorbed and utilized by trees, often providing a more accurate representation of soil fertility than soil measurements alone. Combined with reference values for foliar and soil nutrient contents, as well as nutrient balance assessments, this approach can help forest managers determine whether additional fertilization is required [11]. A study in Finland shows that fertilization of Scots pine stands with N and P mineral fertilizers and wood ash significantly increased foliar nutrient concentrations over 26 years [12].

The aim of the study was to evaluate the short-term effects of NH_4NO_3 and wood ash fertilization on foliar nutrient concentrations in coniferous and deciduous forest stands in Latvia by comparing control and fertilized plots. In modern forestry, predictive technologies such as forest growth models, remote sensing, and geographic information systems (GIS) are essential for forecasting forest stand responses to interventions like soil amendments. By integrating foliar nutrient data into these tools, forest managers can more accurately predict how nutrient availability will affect tree growth, enabling better decision-making for fertilization and resource management.

Materials and methods

A total of 50 coniferous (Scots pine *Pinus sylvestris* L., Norway spruce *Picea abies* (L.) H.Karst., Lodgepole pine *Pinus contorta* Dougl. var Latifolia Engelm.) and 10 silver birch (*Betula Pendula* Roth) stands were selected for the study. These stands represented four forest site types: forests with drained mineral soils, forests with wet mineral soils, forests with drained organic soils and dry upland forests. The selected forest stands were managed by JSC "Latvia's State Forests," the Forest Research Station, and other landowners. Fertilization treatments involved a one-time application of NH_4NO_3 at a rate of 0.44 $t \cdot ha^{-1}$, between December 2016 and July 2017, and wood ash applied from November 2014 to July 2017 at a rate of 3-8 $t \cdot ha^{-1}$. In seven spruce stands, wood ash was applied alone, while in 10 conifer and six birch stands, it was applied in addition to NH_4NO_3. Fertilizers were applied manually or using agricultural tractors (Valtra P 191 equipped with an Amazone mineral fertilizer spreader, Belarus 952 equipped with a conical mineral fertilizer spreader), depending on the area's accessibility.

Crown material was collected after fertilizer application. Sampling was conducted in all experimental plots, with samples gathered from three first-stratum trees in each plot. Samples were collected from the upper third of the tree crowns, focusing on well-lit branches. In total, 2064 leaf and needle samples were collected for the study. Climbing equipment was used for sample collection. The sampling and analysis were performed in accordance with the ICP Forests forest health monitoring methodology [13]. The analysis methods are summarized in Table 1. Total nitrogen (N_{tot}) analysis was not conducted for deciduous stands in forests with drained mineral soils.

Table 1

Methods of foliar chemical analyses

Parameter measured	ISO standard	General method description
Total carbon (C_{tot}) concentration	ISO 10694	Elemental analysis, Elementar EL Cube.
Total nitrogen (N_{tot}) concentration	LVS ISO 13878:1998	Elemental analysis, Elementar EL Cube.
Phosphorus (P) concentration	LVS EN 14672:2006	Spectrophotometry, Shimadzu UV-1900.
Potassium (K), calcium (Ca), magnesium (Mg) concentration	ISO 11466	Flame atomic absorption spectrophotometry, Thermo Fisher Scientific iCE3500

The Shapiro-Wilk test was used to assess the normality of the data. Since the data did not meet the assumption of normality, the Wilcoxon rank-sum test with continuity correction (a non-parametric test) was used to estimate differences between the control and fertilized plots at the individual forest stand level.

Results and discussion

Conifer stands

When evaluating the average concentration of total carbon (C_{tot}) in needles following the application of soil amendments, no significant differences were observed between control and fertilized plots regardless of the forest site type and fertilizer type (Fig. 1a).

For total nitrogen (N_{tot}, Fig. 1b), slightly higher average concentrations were observed in NH_4NO_3-treated plots compared to control plots in forests with drained mineral soils and dry upland forests, while in forests with drained organic soils, the opposite pattern was found, with statistically significant differences ($p = 0.0013$). For wood ash application, N_{tot} concentrations were lower in fertilized plots compared to control plots in forests with drained mineral soils. However, in dry upland forests and forests with drained organic soils concentrations were higher in fertilized plots. NH_4NO_3 provides nitrogen (N) in a readily available form, which may explain the differences in N_{tot} concentrations in needles [14], while wood ash could stimulate microbial activity, accelerating organic matter decomposition and nitrogen release [15]. The lower N_{tot} concentrations in NH_4NO_3-treated plots on drained organic soils may result from differences in initial N availability or the nutrient dilution effect, where increased biomass leads to a lower concentration of N in plant tissues despite higher total N availability [16; 17]. When wood ash and NH_4NO_3 were applied together, N concentrations in fertilized plots were higher than in control plots in both forests with drained mineral and drained organic soils, possibly due to the combined effects of organic matter decomposition promoted by wood ash and the direct nitrogen input from NH_4NO_3.

Potassium (K), along with phosphorus (P), calcium (Ca) and magnesium (Mg), is a key element contained in wood ash. In conifer stands, K concentrations were higher in fertilized plots treated with combined soil amendments or NH_4NO_3 alone compared to controls. However, when wood ash was applied alone, K concentrations varied by the forest site type: they were slightly lower in fertilized plots compared to controls in forests with drained mineral and organic soils but slightly higher in fertilized plots in dry upland forests (Fig. 1c). This variation can be attributed to differences in the forest site properties, nutrient leaching, and plant uptake. In forests with drained mineral and organic soils, fertilization may have altered soil pH and microbial activity, potentially increasing K leaching or affecting its retention. Plant nutrient leeching from wood ash has been described in several studies [18]. The nutrient dilution effect could also help explain the lower K concentrations observed in fertilized plots. Conversely, in dry upland forests, lower moisture levels might have reduced K mobility, allowing it to accumulate more in fertilized plots. A study on Scots pine stands on peat soils demonstrated that wood ash application can help mitigate K deficiency for up to nine years after application [19].

P has lower solubility than other nutrients, affecting its availability to plants [20]. When wood ash was applied alone, P concentrations in fertilized plots were higher than in control plots in forests with drained organic soils and dry upland forests (Fig. 1d), but lower in forests with drained mineral soils. When combined with NH_4NO_3, the effect on P concentrations reversed: in forests with drained mineral soils, P concentrations were higher in fertilized plots, indicating enhanced P availability, while in forests with drained organic soils, concentrations were lower. Surprisingly, when NH_4NO_3 was applied alone, P concentrations in fertilized plots were higher across all forest site types. This could be attributed to indirect effects on root growth and microbial activity, as nitrogen fertilization can stimulate root development, improving the plant's ability to access P [21].

Ca is another element whose deficiency can be mitigated by applying wood ash. In dry upland forests and forests with drained organic soils, Ca might be more limited, therefore trees responded positively to wood ash application, leading to increased Ca concentrations in needles in fertilized plots compared to control plots (Fig. 1e). However, in forests with drained mineral soils, the opposite effect was observed, with slightly lower Ca levels in treated plots. When wood ash was applied together with NH_4NO_3, Ca concentrations in fertilized plots were slightly lower than in control plots, though the difference was minimal. When NH_4NO_3 was applied alone, Ca concentrations were lower in the fertilized plots. This can be explained by the fact that NH_4NO_3 releases ammonium (NH_4^+), which competes with Ca^{2+} for uptake by plant roots. This competition reduces Ca absorption [22].

Mg showed variable effects depending on the forest site and fertilizer type (Fig. 1f). When NH_4NO_3 was applied alone, Mg concentrations in fertilized plots were lower in forests with drained organic soils and dry upland forests, likely due to competition between ammonium (NH_4^+) and Mg ions (Mg^{2+}) for root uptake [23]. In forests with drained mineral soils, Mg concentrations in fertilized plots were slightly higher than in control plots, potentially due to soil properties or natural variation. When wood ash was applied alone, Mg concentrations were higher in fertilized plots of forests with drained organic soils and dry upland forests, likely due to the direct source of Mg and improved soil pH. In contrast, fertilized plots in drained mineral soils had lower Mg concentrations, likely reflecting the absence of Mg limitation. In forests with both drained mineral and organic soils, Mg concentrations were lower in fertilized plots when wood ash and NH_4NO_3 were combined. In dry upland forests, however, Mg concentrations were higher in fertilized plots, suggesting stronger Mg limitation or site-specific factors that enhanced Mg uptake.

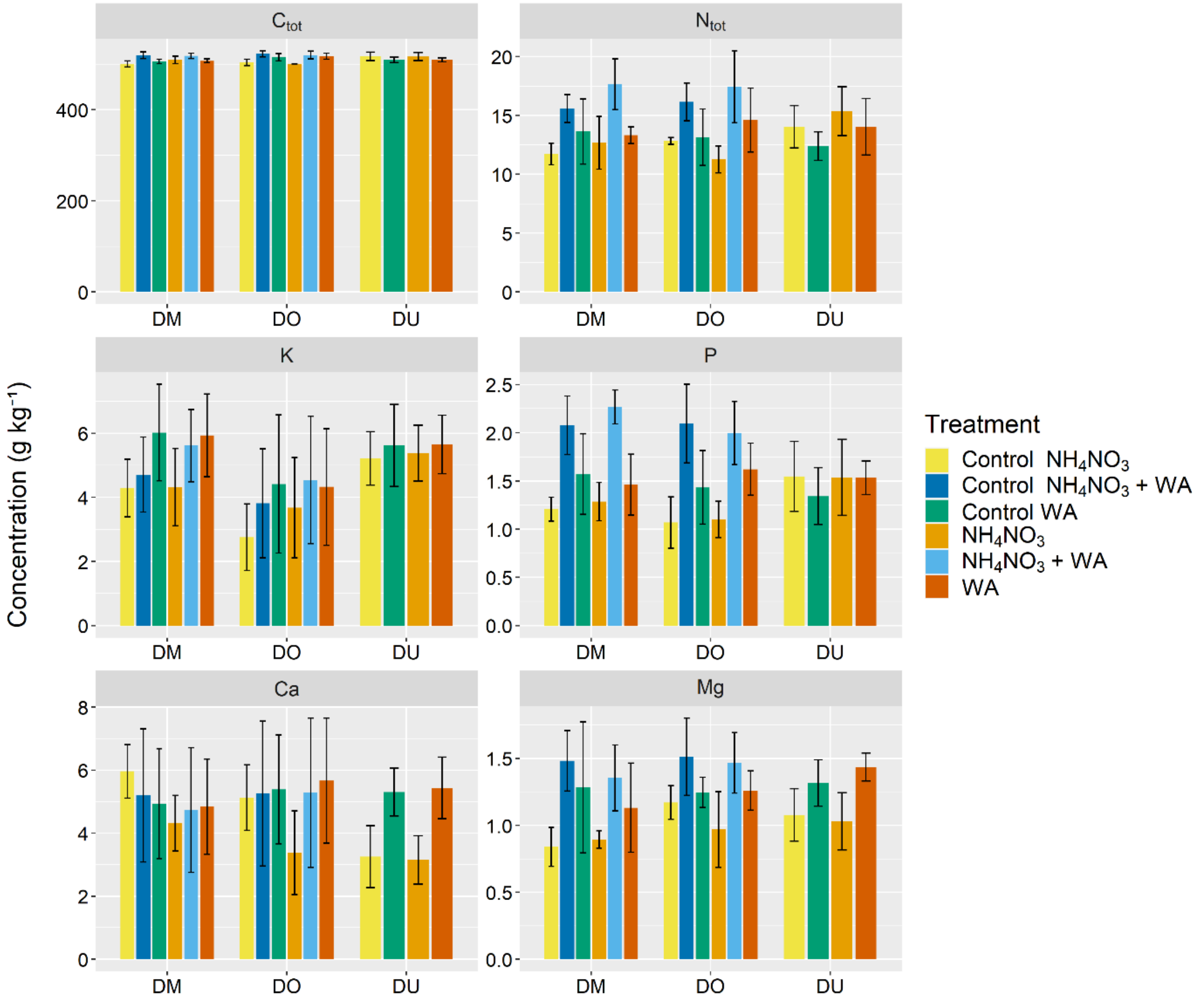

Fig. 1. **Element concentration in conifer needles depending on forest site type and fertilization treatment:** C_{tot} – total carbon; N_{tot} – total nitrogen; DM – forests with drained mineral soils; DO – forests with drained organic soils; DU – dry upland forests; WA – wood ash; NH_4NO_3 – ammonium nitrate

Deciduous stands

In silver birch stands differences in foliar C_{tot} concentrations across treatments and forest site types were negligible (Fig. 2a). For foliar N_{tot} (Fig. 2b), NH_4NO_3-treated plots had slightly higher concentrations in forests with wet mineral soils and slightly lower concentrations in dry upland forests compared to controls, possibly due to site-specific factors such as moisture levels and soil properties. In drained mineral soils, N_{tot} concentrations in fertilized plots were slightly lower when NH_4NO_3 and wood ash were applied together, potentially due to nutrient competition or changes in nutrient balance. A dilution effect may have also contributed if increased biomass in fertilized plots led to lower N concentrations in birch leaves. When wood ash was applied alone in dry upland forests, differences between fertilized and control plots were minimal, suggesting limited effects on N cycling.

K concentrations in birch leaves suggest improved K availability in fertilized plots of forests with drained mineral and organic soils treated with NH_4NO_3 and wood ash together, as well as in forests with wet mineral soils treated with NH_4NO_3 (Fig. 2c). However, in dry upland forests where wood ash was applied alone, K concentrations were lower in fertilized plots. Due to the small number of replicates, conclusions about wood ash effects should be drawn with caution. Additionally, NH_4NO_3 did not lead to higher K concentrations in dry upland forests or drained mineral soils.

For P, the combined application of NH_4NO_3 and wood ash resulted in a response similar to K but less pronounced (Fig. 2d). When applied separately, both fertilizers were associated with lower foliar P concentrations in fertilized plots, possibly due to a dilution effect, where increased biomass led to lower P concentrations in foliage.

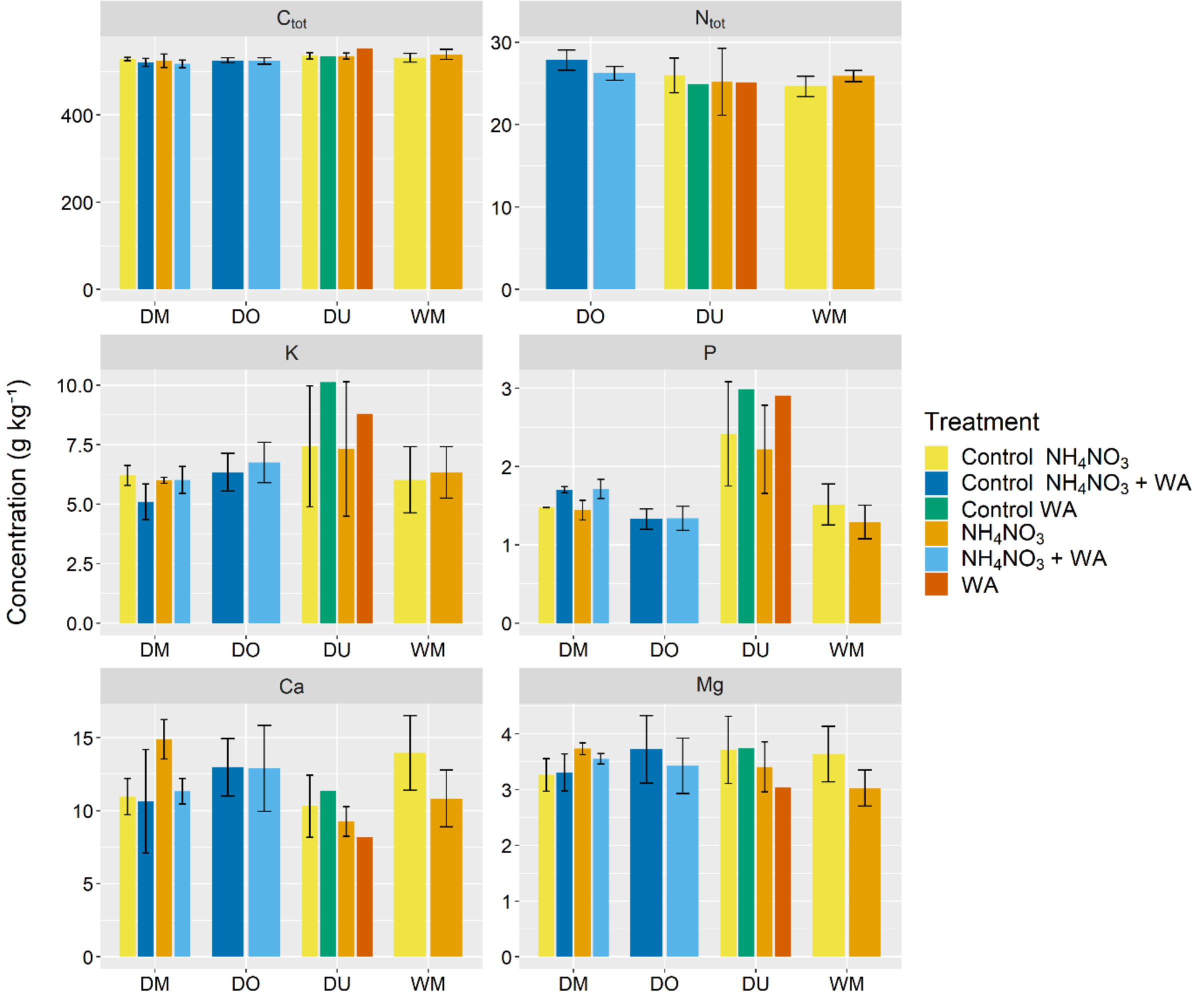

Fig. 2. **Element concentration in deciduous (silver birch) leaves depending on forest site type and fertilization treatment:** C_{tot} – total carbon; N_{tot} – total nitrogen; DM – forests with drained mineral soils; DO – forests with drained organic soils; DU – dry upland forests; WM – forests with wet mineral soils; WA – wood ash; NH_4NO_3 – ammonium nitrate

For Ca, NH_4NO_3, whether applied alone or with wood ash, was associated with higher foliar concentrations in forests with drained mineral soils, while differences between control and fertilized plots were minimal in drained organic soils (Fig. 2e). In dry upland forests, neither treatment caused notable differences in foliar Ca concentrations, likely due to soil properties, initial nutrient availability, pH changes, and cation competition. A dilution effect may have occurred with wood ash application, while NH_4NO_3 does not directly supply Ca.

For Mg, a response was observed only in forests with drained mineral soils (Fig. 2). In forests with drained organic soils and dry upland forests, differences between control and fertilized plots were minimal, possibly due to nutrient competition or limited Mg availability. Foliar Mg concentrations can also be influenced by leaf position and light exposure, which may explain why wood ash did not consistently increase Mg concentrations [24]. Overall, differences in foliar nutrient concentrations between fertilized and control plots were not statistically significant.

Conclusions

Our findings suggest that fertilization effects on foliar nutrient dynamics are site- and tree type-specific. In coniferous stands, NH_4NO_3-treated plots in forests with drained organic soils had significantly lower N_{tot} concentrations compared to controls (11.26 ± 1.15 g·kg^{-1} vs. $12.84 \pm$

0.29 g·kg^{-1}, $p = 0.0013$), likely due to a dilution effect or differences in initial availability. The combination of NH_4NO_3 and wood ash resulted in higher N_{tot} concentrations in fertilized plots compared to controls. Use of combined fertilizers also resulted in higher K concentrations compared to controls, while wood ash alone had variable effects. NH_4NO_3-treated plots had higher P concentrations than controls, but wood ash effects both alone or combined with NH_4NO_3 were again more variable. Fertilization with wood ash resulted in higher Ca concentrations in dry upland forests and forests with drained organic soils, while NH_4NO_3 application resulted in lower Ca concentrations compared to controls. Plots treated with wood ash alone had higher Mg concentrations than controls, except in forests with drained mineral soils, while the combined application of wood ash and NH_4NO_3 resulted in slightly lower Mg concentrations than controls. In deciduous stands, N_{tot} concentrations showed high variability, with no consistent differences between fertilized and control plots. K concentrations were higher in fertilized plots of forests with drained mineral and organic soils treated with NH_4NO_3 and wood ash but lower in dry upland forests treated with wood ash alone. The combination of NH_4NO_3 and wood ash had a similar effect on P concentrations, though less pronounced than for K. All fertilization treatments resulted in higher Ca concentrations compared to controls in forests with drained mineral soils but had minimal effects in other site types. Positive Mg responses were limited to forests with drained mineral soils. These results highlight the need for ongoing monitoring and pre-thinning sampling to assess long-term impacts of fertilization, particularly in underrepresented deciduous stands.

Acknowledgements

The study was funded by Latvia Council of Science national research programme project: “Forest4LV – Innovation in Forest Management and Value Chain for Latvia’s Growth: New Forest Services, Products and Technologies” (No.: VPP-ZM-VRIIILA-2024/2-0002). Data used in the study were partly acquired in the project “Monitoring of forest fertilization effect” No. 5-5.5.1_001j_101_23_55.

Author contributions:

Conceptualization, A.L., methodology, A.L. and G.P., validation, D.P., formal analysis, G.P., investigation, Z.A.Z., D.P. and G.P., writing – original draft preparation, G.P., writing – review and editing, G.P. and A.L., visualization, G.P., project administration, A.L. All authors have read and agreed to the published version of the manuscript.

References

[1] Essential nutrients for plants. [online] [27.01.2025]. Available at: https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/General_Biology_(Boundless)/31:_Soil_and_Plant_Nutrition/31.01:_Nutritional_Requirements_of_Plants/31.1C:_Essential_Nutrients_for_Plants
[2] Allaby M. A Dictionary of Ecology. 4th edition. Oxford: Oxford University Press, 2010. 672 p.
[3] Du E., Terrer C., McNulty S.G., Jackson R.B. Nutrient limitation in global forests: current status and future trends. In: McNulty, S.G., editor. Future Forests. Amsterdam: Elsevier, 2024, pp. 65-74.
[4] Chen B., Fang J., Piao S., Ciais P., Black T.A., Wang F., Niu S., Zeng Z., Luo Y. A meta-analysis highlights globally widespread potassium limitation in terrestrial ecosystems. New Phytologist, vol. 241, 2024, pp. 154-165.
[5] Katzensteiner K., Glatzel G. Causes of magnesium deficiency in forest ecosystems. In: Magnesium Deficiency in Forest Ecosystems, Vol. 1, 1997, pp. 227-251.
[6] Minocha R. Calcium fertilization effects on leaf biochemistry of northern hardwood trees dependent on elevation. Project Title: Effects of Calcium Silicate Fertilization at Watershed 1 of Hubbard Brook Experimental Forest, N.H. on the Foliar Biochemistry and Physiological Function of Conifer and Hardwood Trees. U.S. Forest Service Northern Research Station, 2004. [online] [27.01.2025]. Available at: https://nsrcforest.org/project/calcium-fertilization-effects-leaf-biochemistry-northern-hardwood-trees-dependent-elevation
[7] Saarsalmi A., Mälkönen E. Forest fertilization research in Finland: A literature review. Scandinavian Journal of Forest Research, vol. 16, 2001, pp. 514-535.

[8] Norwegian Ministry of Climate and Environment. Norway's National Plan related to the Decision of the EEA Joint Committee No. 269/2019 of 25 October 2019. [online] [27.01.2025]. Available at: https://www.regjeringen.no/contentassets/31a96bc774284014b1e8e47886b3fa57/norways-national-plan-related-to-the-decision-of-the-eea-joint-committee-no.-269-2019-of-25-october-2019.pdf

[9] Danish Forest and Nature Agency. The Danish national forest programme in an international perspective. [online] [27.01.2025]. Available at: https://naturstyrelsen.dk/media/nst/Attachments/dnf_eng.pdf

[10] Brockley R.P. Foliar analysis as a planning tool for operational fertilization. Proceedings of Enhanced Forest Management: Fertilization & Economics Conference, March 1-2, 2001, Edmonton, Alberta, Canada, pp. 62-67.

[11] Fernández-Moya J., Alvarado A., San Miguel-Ayanz A., et al. Forest nutrition and fertilization in teak (Tectona grandis L.f.) plantations in Central America. New Zealand Journal of Forestry Science, vol. 44, Suppl. 1, 2014, pp. S6.

[12] Moilanen M., Hytönen J., Hökkä H., Ahtikoski A. Fertilization increased growth of Scots pine and financial performance of forest management in a drained peatland in Finland. Silva Fennica, vol. 49, no. 3, 2015, article ID 1301, 18 p.

[13] Rautio P., Fürst A., Stefan K., Raitio H., Bartels U. Part XII: Sampling and Analysis of Leaves and Needles. UNECE ICP Forests Programme Co-ordinating Centre: Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests. Thünen Institute of Forest Ecosystems, 2020, p. 20. [online] [12.02.2025]. Available at: http://www.icp-forests.org/manual.htm.

[14] Samuel A., Dines L. Fertilisers and manures. In: Lockhart and Wiseman's Crop Husbandry Including Grassland. 10th edition. Cambridge:Woodhead Publishing, 2023, pp. 81-114.

[15] Insam H., Franke-Whittle I.H., Knapp B.A., Plank R. Use of wood ash and anaerobic sludge for grassland fertilization: effects on plants and microbes. Bodenkultur, vol. 60, 2009, pp. 39-51.

[16] Jarrell W.M., Beverly R.B. The Dilution Effect in Plant Nutrition Studies. Advances in Agronomy, vol. 34, 1981, pp. 197-224.

[17] Braun S., Schindler C., Rihm B. Foliar Nutrient Concentrations of European Beech in Switzerland: Relations With Nitrogen Deposition, Ozone, Climate, and Soil Chemistry. Frontiers in Forests and Global Change, vol. 3, 2020, Article 33.

[18] Callesen I., Ingerslev M., Raulund-Rasmussen K. Dissolution of granulated wood ash examined by in situ incubation: Effects of tree species and soil type. Biomass and Bioenergy, vol. 31, 2007, pp. 693-699.

[19] Hytönen J. Effects of wood, peat and coal ash fertilization on Scots pine foliar nutrient concentrations and growth on afforested former agricultural peat soils. Silva Fennica, vol. 37, no. 2, 2003, article ID 503.

[20] Karltun E., Saarsalmi A., Ingerslev M., Mandre M., Andersson S., Gaitnieks T., Ozolinčius R., Varnagiryte-Kabasinskiene I. Wood ash recycling - possibilities and risks. In: Röser D., Asikainen A., Raulund-Rasmussen K., Stupak I., editors. Sustainable Use of Forest Biomass for Energy, Vol. 12. Dordrecht: Springer Netherlands, 2008, pp. 79-108.

[21] Du M., Zhang W., Gao J., Liu M., Zhou Y., He D., Zhao Y., Liu S. Improvement of root characteristics due to nitrogen, phosphorus, and potassium interactions increases rice (Oryza sativa L.) yield and nitrogen use efficiency. Agronomy, vol. 12, 2022, article ID 23.

[22] Bonomelli C., de Freitas S.T., Aguilera C., Palma C., Garay R., Dides M., Brossard N., O'Brien J.A. Ammonium excess leads to calcium restrictions, morphological changes, and nutritional imbalances in tomato plants, which can be monitored by the N/Ca ratio. Agronomy, vol. 11, 2021, article ID 1437.

[23] Mulder E.G. Nitrogen-Magnesium Relationships in Crop Plants. Plant and Soil, vol. VII, no. 4, 1956, pp. 341-376.

[24] Leegood R.C. Photosynthesis. In: Lennarz, W.J., Lane, M.D., editors. Encyclopedia of Biological Chemistry. 2nd edition. Academic Press, 2013, pp. 492-496.