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RESEARCH ARTICLE

Long-term assessment of macro- and micronutrients in foliage of European beech (*Fagus sylvatica* L.) in thinned versus unmanaged old-growth stands

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Abstract

Background: Science-based decisions regarding forest management require the knowledge of the impact of thinning regimens on the forests' vitality and resilience. There is no systematic study analysing the role of forest management approaches on the nutritional status of forests, serving as a surrogate for their health and growth.

Aims: We assessed the impact of 'heavy thinning from above' versus 'no management' on the foliar chemistry of old-growth European beech stands on a calcareous site with cambisol/chromic luvisol soil in Thuringia, Germany.

Methods: Macro- and micronutrients were analysed by serial foliar analysis of six trees per experimental plot over 13 years (2009–2021). To assess potential differences of foliar chemistry between the two plots and over time, a linear mixed-effects model was applied.

Results: Foliar concentrations of all macro- and micronutrients were not significantly different between the two plots ($p > 0.05$), demonstrating that the management approach had no relevant impact on the nutritional status of beech trees growing at the calcareous site. Furthermore, all foliar concentrations were dynamic over the 13-year evaluation period. Hence, long-term forest monitoring is crucial to capture the complex interplay between the trees and environmental conditions.

Conclusions: Serial foliar analysis allows for a reliable evaluation of a forest's nutritional status. The results indicate that either regimen, that is, 'heavy thinning from above' or 'no management', shall not pose any risk in terms of growth and stability. Our results add to the understanding of beech forest dynamics and may provide a further piece for science-based strategies of sustainable forest management.

KEYWORDS

calcareous, leaf (foliar) analysis, linear mixed model, no management, nutrition, thinning, unmanaged

1 | INTRODUCTION

While in the past the main purpose of forest management in Europe was timber production, the current sustainability criteria additionally direct management approaches. These are mainly based on the forests' mitigation potential of ongoing climate change by acting as carbon (C) sinks, with the aim of significantly contributing to achieving climate neutrality (IPCC, 2023; Köhl et al., 2021). To sustainably manage forests, effective science-based adaptive strategies considering the entire forest-wood value chain are crucial (Hyyrynen et al., 2023; Köhl et al., 2021; Noormets et al., 2015).

Thinning, especially the 'heavy thinning from above' approach, is currently a common management strategy of European beech (*Fagus sylvatica* L.) forests in Europe including Germany (Thünen-Institute, 2012; ThüringenForst, 2024). In contrast to the thinning regimes, the 'no management' approach implies a reduction/cessation of silvicultural input, thereby relying on the natural succession processes of forest ecosystems. The preservation of unmanaged forests or the back-conversion of managed to unmanaged forests with the aim of mitigating climate change was adopted decades ago and is part of the Convention on Biological Diversity of the United Nations (United Nations, 1992). This was implemented in Germany in the National Strategy of Biological Diversity, defining the aim that 5% of the total forest area shall be unmanaged (Mohaupt-Jahr & Küchler-Krischun, 2008). Consequently, the percentage of unmanaged forest area increased from ≈2% in 2013 to 3.1% in 2020 (Bundesministerium für Ernährung und Landwirtschaft, 2021). However, whether unmanaged forests are advantageous over managed forests regarding their vitality and climate change mitigation potential is still debated (Köhl et al., 2021).

Science-based decisions regarding forest management require the knowledge of the impact of kind and extent of forest management approaches on the forests' vitality and resilience, especially with a view to the changing climate.

It is generally accepted that forest disturbances including thinning can influence the microclimate of a forest ecosystem as a result of, for example, increased availability of light, water, and nutrients for the remaining trees (Aussenac, 2000). However, the effects are complex and depend on factors including soil characteristics and climate so that the net consequences are not always the same and cannot be predicted upfront. Further, the ongoing climate change will likely impact the contribution of forests to mitigation efforts. Observed effects regarding the impact of active forest management on the sensitivity of forests to changing climate are contradictory, being either negative (e.g., Mausolf et al., 2018), inconclusive (e.g., Bosela et al., 2021), or positive (e.g., Bottero et al., 2017).

So far, there is no systematic analysis studying the role of forest management approaches on the nutritional status of forests, in particular beech trees. The nutritional status is determined by both macronutrients, required in large amounts, and micronutrients, of which only small amounts are needed. Maintaining adequate nutrient concentrations and ratios of nutrients in plants is critical for their health and growth; thus, imbalances in nutrition may result in impaired growth and reduced stability of forests (Marschner, 2012), eventually leading to reduced capacity for C sequestration and increased sensitivity to climate change (Jonard et al., 2015; Oren et al., 2001).

To explore the impact of the forest management approach, that is, 'heavy thinning from above' and 'no management', on the long-term nutritional status of European beech trees at a calcareous site and consequently on their vitality, macro- and micronutrients of beech trees growing on two experimental plots with different management were assessed from 2009 to 2021 by means of serial foliar analysis.

2 | MATERIALS AND METHODS

2.1 | Description of the experimental site

We studied an old-growth European beech stand, aged 125 years (in 2023), in the forest district Buchfart, Federal state of Thuringia, Germany. The experimental site is located in forestal climate zone 'hills with humid climate' (Vf) at 390 m altitude asl, in a nutritious and carbonate-rich terrestrial forestal site of humidity level 2 (fresh). The cambisol/chromic luvisol soil type developed from silty loam as parent substrate on middle-triassic limestone (Borys et al., 2013).

In 1959, the beech stand had been separated into experimental plots with different forest management regimes of 0.25 ha size each. In the present analysis, we describe the nutritional status of beech growing at experimental plots with the 'heavy thinning from above' (termed H; coordinates: 50°90'29.5″N 11°34'03.8″E) and the 'no management' regimen (termed N; coordinates: 50°90'34.8″N 11°34'04.7″E).

2.2 | Soil characterization of the experimental plots

The results of the soil characterization from 2009 were reported previously (Borys et al., 2013) and are briefly summarised: the calcareous cambisol/chromic luvisol soil type, as found on both experimental plots, showed the typical order of soil horizons: Ah/Bv-Al/Bvt/cCv-C. The mineral soil horizons are covered by a humus layer (horizons O_l, O_f, O_h). On the two studied experimental plots, the mean pH values of the O_h horizon were 5.4 (plot H) and 5.3 (plot N) and of the A_h horizon 6.7 (plot H) and 4.5 (plot N). The lower pH of the A_h horizon at the unmanaged site may be caused by the less pronounced natural regeneration compared to the managed site. Grain size distributions for the two experimental plots H and N were clay (45.6%/41.6%), silt (51.7%/56.5%), and sand (2.7%/1.9%). Overall, the experimental plots can be regarded as comparable with respect to their chemical and physical soil characteristics, since the observed differences were within the range of normal variance of a given site.

TABLE 1 Development of forest growth at the two experimental plots from 1959 to 2023.

Growth parameters	Heavy thinning from above[a]				No management			
	1959	2009	2011	2023	1959	2009	2011	2023
Stem number (N ha^{-1})	1029	238	175	125	1188	488	480	388
Basal area (m^2 ha^{-1})	18	20	28	20	22	42	43	41
Mean DBH (m)	15.1	38.2	39.1	45.2	15.5	33.6	33.7	36.5
Top height (m)	20.9	37.8	38.4	36.6	22.4	38.4	39.8	40.7
Growing stock/stem volume (m^3)	157	507	534	372	200	810	816	817

[a]According to the beech yield table of 1983 (Dittmar et al., 1986) (stocking level 1.0 for site index 0).
Abbreviation: DBH, diameter at breast height.

2.3 | Management of the experimental plots

The 'heavy thinning from above' plot was managed according to the beech yield table of 1983 (Dittmar et al., 1986) with a thinning rotation period of 5 years. On the 'no management' plot, wood was only removed in terms of duty of care for public safety.

The forest management regimes were evaluated based on growth parameters that had been assessed in 1959, 2009, 2011, and 2023 (Table 1). Forest growth data for 1959 and 2009 were reported previously (Borys et al., 2013). In accordance with the management type characteristics, the 'heavy thinning from above' regimen compared to 'no management' led to a steady decrease of the stem number and growing stock over time. In the years 2009 and 2011, the growing stock area of the managed plot was around 65% of the unmanaged plot growing stock area. Data relating to forest growth were provided by the University of Applied Sciences Erfurt, Erfurt, Germany.

2.4 | Foliar analysis

Leaf samples from six beech trees per experimental plot were characterized in the years 2009, 2011, 2013, 2015, 2017, and 2021. Samples from the sunlight-exposed part of the tree crowns were collected by tree climbing using the single-rope technique. Samples were always taken within several days after 10 August (at full foliation) in accordance with the standard method defined in the soil inventory in forests (Wellbrock et al., 2022) to assure comparability of results, since the leaf nutrient concentrations vary seasonally (Ulbricht et al., 2016). The leaf samples of each tree were processed in the laboratory of the State Office for Agriculture and Rural Area Thuringia (*Thüringer Landesamt für Landwirtschaft und Ländlichen Raum*), Jena, Germany, for the quantification of dry mass and chemical composition per tree using validated standard methods. Fresh sample material was gently dried in convection chambers at a temperature gradient from 50 to 30°C and afterwards ground to particle size <0.5 mm by ultracentrifugation at 18,000 rpm for further analysis (EN ISO 6498:2012). The content of the following macro- and micronutrients was assessed: nitrogen (N) using elemental analysis (combustion analysis [ISO 16948:2015]), and phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S), copper (Cu), manganese (Mn), iron (Fe), and zinc (Zn) using X-ray fluorescence analysis (DIN ISO 15309:2007).

2.5 | Statistical analysis

For each determined nutrient per experimental plot, data from six trees with six repeated measurements were available. To assess potential differences between the two management types over time, a linear mixed-effects model (LMM) was applied. To estimate the LMM, Restricted Maximum Likelihood was used. The covariance matrix of random effects was chosen based on Akaike's information criterion. Possible covariance matrices were (1) compound symmetry, if the variances remained constant at all assessment time points; (2) compound symmetry—heterogeneous, if the variances were heterogenous at different assessment time points; (3) diagonal, if the variances were heterogenous at different assessment time points but without a correlation between the assessment time points. Forest management type and assessment time point were set as fixed effects. Statistical analysis was carried out using IBM SPSS, version 29.0 (Armonk, NY: IBM Corp.).

3 | RESULTS

Leaf nutrition with respect to macronutrients and micronutrients from 2009 to 2021, including the nutrition level thresholds according to Göttlein (2015), is visualized in Figure 1. The results of the LMM regarding differences between the two management types in nutrition levels over time, that is, *p*-values for management type and time point, are summarized in Table 2.

The visual appearance of the mean concentration–time curves (see Figure 1) implies that the trees growing on the two experimental plots with different forest management approaches were largely comparable with respect to leaf nutrition during the observational period of 13 years. The inferential statistical analysis (see Table 2) confirmed this appearance: for all assessed macro- and micronutrients, no statistically significant difference between the 'heavy thinning from above' and the 'no management' approach was obtained (i.e., for the fixed effect of 'management type', all *p*-values were larger than 0.05).

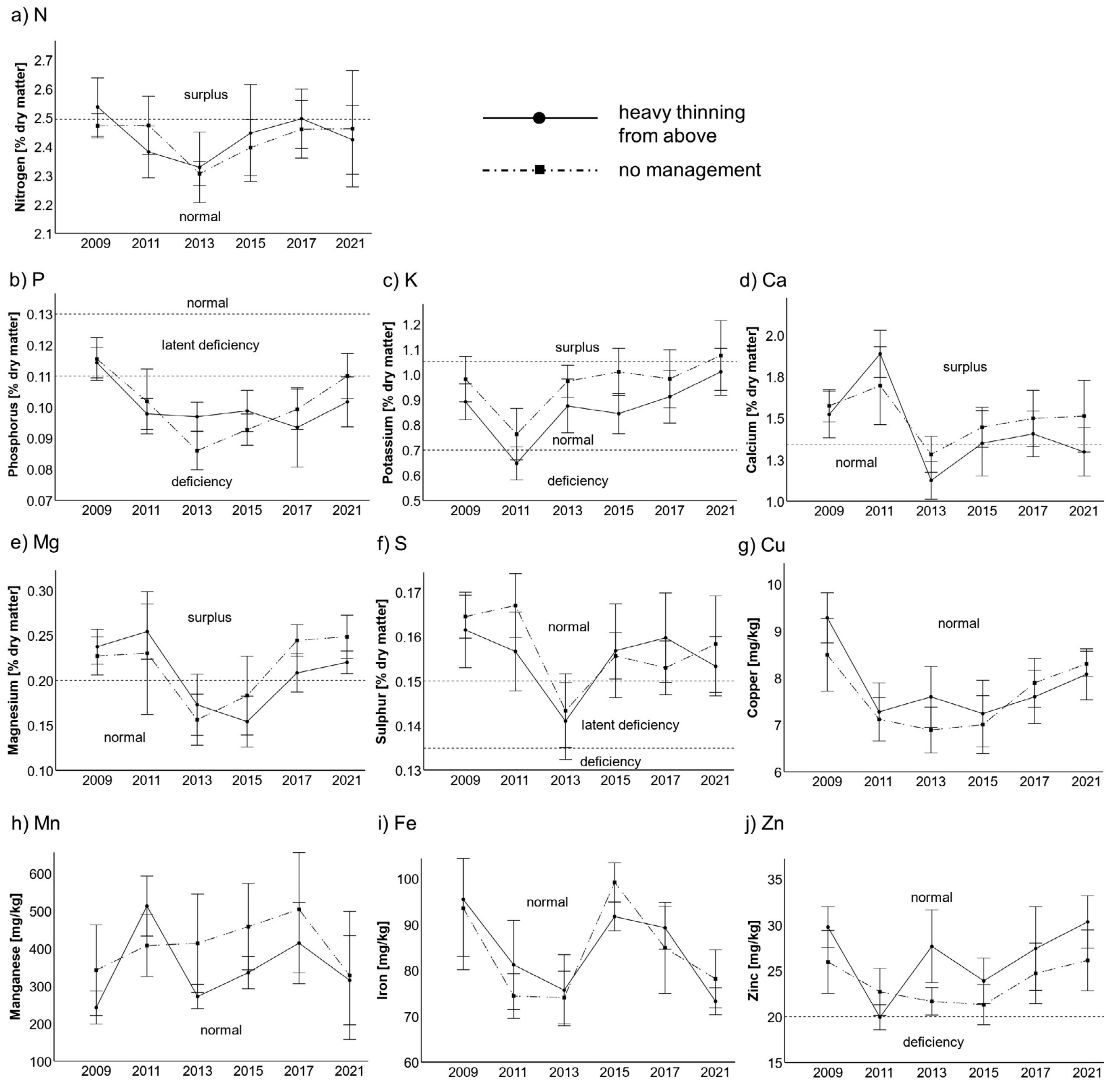

FIGURE 1 Leaf nutrition (macronutrients, micronutrients) by means of serial foliar analysis from 2009 to 2021. Shown are arithmetic means ± standard deviations of six trees per experimental site. Nutritional levels according to critical values for European beech (Göttlein, 2015) are indicated; horizontal dashed lines represent thresholds of nutrition levels. Ca, calcium; Cu, copper; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; N, nitrogen; P, phosphorus; S; sulphur; Zn, zinc.

However, the foliar concentrations of all assessed nutrients were dynamic over time as reflected by significant time effects (i.e., for the fixed effect of 'time point', all *p*-values were clearly smaller than 0.05).

While the mean foliar concentrations of P were in the deficiency range at both experimental plots throughout the observational period, the concentrations of all other nutrients were either in the normal range throughout the study (N, K, Fe, Cu, Mn, and Zn) or fluctuated between two nutritional levels (Ca, Mg: fluctuation between normal and surplus range, S: fluctuation between normal and latent deficiency range).

4 | DISCUSSION

In our study, we compared the impact of two forest management approaches, that is, 'heavy thinning from above' and 'no management', on the foliar nutrition of European beech growing in Central Germany at a calcareous site. Overall, the long-term nutritional status of beech trees did not differ between both sites that were either managed by thinning or unmanaged.

In particular, the nutritional status of forests is best assessed by means of foliar analysis because the nutritional status of the leaves

TABLE 2 Results of linear mixed-effects model.

	p-Values of fixed effects	
	Management type: heavy thinning from above vs. no management	**Time point**
Macronutrients		
N	0.614	**0.005**
P	0.555	**<0.001**
K	0.101	**<0.001**
Ca	0.680	**<0.001**
Mg	0.332	**0.007**
S	0.748	**<0.001**
Micronutrients		
Cu	0.419	**<0.001**
Mn	0.275	**0.024**
Fe	0.595	**<0.001**
Zn	0.052	**<0.001**

Note: The covariance structure of the LMM was chosen based on Akaike's information criterion (N, P, K, Ca, S, Cu, Mn, Zn: compound symmetry; Mg, Fe: diagonal). *p*-Values < 0.05 were considered statistically significant and are indicated in bold.
Abbreviations: Ca, calcium; Cu, copper; Fe, iron; K, potassium; Mg, magnesium; Mn, manganese; N, nitrogen; P, phosphorus; S; sulphur; Zn, zinc.

is not directly proportional to the nutrient content of the soil, since trees have an effective selective ability for nutritional uptake (Bussotti & Pollastrini, 2015; Marschner, 2012). At present, foliar analysis is still associated with large effort, but this may change in the near future due to further development of drone technology.

Importantly, we systematically assessed the nutritional status of beech trees including macronutrients and micronutrients over a long period of 13 years (2009–2021), which allowed us to detect potential trends of deteriorated or improved nutrition: in accordance with our previous results of the long-term nutritional status of two old-growth European beech stands depending on the site factor soil (Borys et al., 2024), the foliar nutrient concentrations in the present study were largely dynamic over time at both sites, which presumably relates to other influencing factors such as climate (e.g., temperature or amount and distribution of precipitation). Trends of improving or deteriorating nutrition were not detected. Comparable results regarding dynamic macronutrient concentrations of European beech tree foliage have been reported previously (Duquesnay et al., 2000; Ognjenović et al., 2020). These and our results underline that serial foliar analysis is advantageous over single assessments, which is especially illustrated by the different covered ranges of nutrition levels according to Göttlein (2015) for Ca and Mg throughout the observational period in our study. Hence, long-term assessment of forest nutrition is crucial to capture the complex interplay between the tree and the environmental conditions.

In line with the general properties of calcareous soils with limited availability of P (Marschner, 2012), the foliage of our studied beech stand was deficient in P throughout the observation period. Deteriorating and thus insufficient P nutrition of several tree species including European beech has been reported previously, which is attributed to anthropogenic impact including atmospheric nitrogen deposition, leading to an unfavorably high N/P ratio (Jonard et al., 2015; Talkner et al., 2015).

Based on our long-term results that the concentrations of all assessed macro- and micronutrients did not show any statistical significance between trees of both experimental sites, it can be concluded that the forest management regime has no relevant impact on the nutritional status of the beech trees growing on that specific calcareous site. About one-third of the potential beech forest area in Central Europe is situated on calcareous soil (Dannenmann et al., 2016). Our result is at least representative for beech forests growing on calcareous sites with cambisol/chromic luvisol soil.

Since adequate nutrition can be regarded as a surrogate for the vitality and resilience of a forest, our results indicate that either regimen, that is, 'heavy thinning from above' or 'no management', shall not pose any risk in terms of growth and stability. Regarding the impact of the management regimes on the C-sequestration potential, we previously showed that the 'no management' approach might be superior over thinning approaches: using a validated process-based forest model, we estimated how much C will be stored in the year 2099, considering various climate scenarios and different management regimes, in a forest district in Thuringia that includes the herein studied experimental plot. The model also included the C stored in wood products resulting from timber harvest. Material and energy substitution were, however, not accounted for, since these are not considered in the Kyoto protocol due to large uncertainties in their estimation. Furthermore, natural disturbances such as increasing storms or fires were not considered in the model (Borys et al., 2016), although extreme events will be more frequent in the future, which would reduce the forests' C sequestration potential (Albrich et al., 2023). The simulated mean C stock (in soil, biomass, dead wood, and wood products) was much larger in the unmanaged stands compared to the managed stands in all climate scenarios. Thus, the 'no management' strategy seems to be superior to the thinning regimen for maximizing C-sequestration in this area, without considering C loss from natural disturbances and without considering material and energy substitution (Borys et al., 2016). These results are in accordance with those of other groups (considering conifer and aspen-birch forests) (Bradford, 2011; Nunery & Keeton, 2010), and the importance of unmanaged forests to mitigate climate change was recently discussed (Kun et al., 2020).

Based on the results of the herein presented study regarding the beech trees' nutritional status and the previous results regarding C sequestration, it is considered justified that defined old-growth European beech stands were recently taken permanently out of forest management in Thuringia, Germany (Thuringia, 2014). This is also in line with a recent report of the European Forest Institute (EFI) on scientific evidence regarding old-growth forests, in which it is concluded that 'the few remaining EU primary and old-growth forests can only be preserved through strict protection, without natural resource extraction'. The definition of old-growth status is not yet unambiguous, but

EFI suggests it to be not too strict and to use levels of naturalness and old-growth indicators to encompass a wider range of forests (O'Brien et al., 2021).

5 | CONCLUSIONS

The foliar nutritional status (macro- and micronutrients) of old-growth European beech stands was largely dynamic during the observational period of 13 years, highlighting the need for continuous, long-term assessments of forest nutrition. The forest management approach, that is, 'heavy thinning from above' versus 'no management', had no impact on the foliar nutrition of beech growing on the calcareous site. Our results add to the understanding of beech forest dynamics and may provide a further piece for science-based strategies of sustainable forest management.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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