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SHORT COMMUNICATION

Derivation of threshold values for the sulfur nutritional status of European silver fir from a cumulative concentration distribution

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Abstract

For European silver fir (*Abies alba* (Mill)), reliable threshold values for the sulfur nutritional status are not available. Because European silver fir is an important coniferous tree species in Central Europe and due to the fact that by reduced S emissions, S is becoming a more and more critical nutrient this knowledge gap should be closed. From the interpretation of the cumulative distribution of sulfur concentrations in first-year needles, the respective threshold values for the range of normal nutrition as well as the threshold for deficiency could be derived. When knowing these thresholds also the range of harmonic nutrition, which is the range for the optimal relation of two nutrients, could be calculated. As compared to the very few literature data available and compared to the respective values of the two most important European conifers Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), the values derived for S nutrition of European silver fir are very reasonable. With respect to the S nutritional thresholds, European silver fir is very close to the values of the other two conifers, whereas the harmonic range of S in relation to N is a bit shifted to higher values indicating that European silver fir has a slightly higher demand for S (in relation to N). There is a certain time lag between the reduction of SO_2 emissions in Europe and the reduction of S concentrations in needles, suggesting that S stored in the soil during periods of high emissions is relevant for S nutrition of trees for a longer period of time.

KEYWORDS
Abies alba, nutritional limits, nutrient ratios

1 | INTRODUCTION

As sulfur has become a (potentially) deficient nutrient in many regions after the significant reduction of S emissions in the years between 1985 and 2000 (Göttlein & Mellert, 2018), the lack of corresponding threshold values for European silver fir is unsatisfactory. According to Göttlein (2020), this knowledge gap regarding the sulfur nutritional status of European silver fir can be closed by evaluating the cumulative frequency function of as many needle analyses as possible.

2 | MATERIALS AND METHODS

For deriving threshold values for the nutritional status of European silver fir from first-year needle's concentrations it is necessary to use a rather big data set covering all situations of nutritional supply, from deficiency to surplus. One important data source was the database of the "International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests" (ICP Forests), containing in total 224 datasets from nine countries (Table 1). Here, about half

TABLE 1 Number of datasets obtained from different sources and countries.

	ICP Forest	Inventory	Others
France	119		
Germany	48	83	430
Italy	2		
Spain	2		
Austria	22		
Switzerland	3		
Slovakia	1		
Croatia	23		
Czech Republic			102
Slovenia	4		
sum	224	83	532

Note: Order of countries according country code in the ICP Forest database.

of the available values came from France. Another important data source were the two German forest soil inventories BZE1 and BZE2, which were conducted in the years 1987 to 1993 and 2006 to 2008 and also contain tree nutritional data, giving in total 83 values. The biggest amount of data (532 datasets) came from several individual sources from Germany and the Czech Republic. Here, some people allowed access to original measurement data already used in publications (Novotný et al., 2010; Rodenkirchen, 1998). Also, the forest services of the German federal countries Niedersachsen and Sachsen provided some unpublished data. Total 839 values originating from the years 1961 to 2022 could be used in this study, mainly from the central European part and not from the margins of the distribution area of European silver fir (Caudullo et al., 2017).

The threshold values were derived from a cumulative frequency distribution of S concentrations (Göttlein, 2020). According to this procedure, a higher-order polynomial function is fitted to the cumulative distribution and the first and second derivatives of this function are calculated. By interpreting the curvature of the cumulative function, the nutritional thresholds can be deduced. The range of harmonic S nutrition expressed as molar ratio to nitrogen was calculated by crosswise division of the values of normal nutrition according to Goettlein (2016).

3 | RESULTS AND DISCUSSION

The evaluated data set is heterogeneous in space (10 countries; Table 1) and time (time span 61 years). SO_2 emissions, and in consequence S input to forest ecosystems, strongly depended on the intensity of using S-containing coal, especially lignite, for energy production (UBA, 2021) as well as on the intensity of the use of flue gas desulfurization technologies. In consequence, hot spots of SO_2 emission were located in countries with big lignite deposits, like the former German Democratic Republic, the Czech Republic, or Poland. Because the exact location of the sampling points is not available in the dataset, a separate evaluation of high- versus low-input regions is not possible. However, over time there is a general trend in SO_2 emissions in Europe, with high values in the 1990s (and before) and low values in the years after 2010 (EEA, 2023). As shown in Figure 1, this trend can also be seen in the S concentrations in first-year needles, but with a certain delay. This delay is caused by the fact that in times of high S input, sulfate was stored in the soil by sorption or precipitation (Alewell, 1995). This stored sulfate is released in times of lower S input, thus keeping S availability high for a certain time span. At the intensive forest monitoring site Höglwald, the time of releasing soil stored sulfur after reduction of sulfur input lasted about 25 years (unpublished data). As shown by the boxplots of Figure 1, the upper whisker of needle's S concentration from 1993 to 2022 is strongly falling due to reduced S availability while the lower whisker is nearly constant. The latter shows that there is a nutritionally important lower threshold for S concentration in needles, the deduction of which is one important aim of this short communication.

Figure 2 shows the cumulative frequency distribution of S concentrations in first-year needles of European silver fir from the described dataset. According to Göttlein (2020), a 10th-degree polynomial function was fitted to the cumulative distribution. The point of the strongest left curvature of the fitted function (= maximum of the second derivative) gives the deficiency threshold (DT), the point of the strongest right curvature (= minimum of the second derivative) the upper threshold of the range of normal nutrition (UT). The lower threshold of the range of normal nutrition (LT), which is the border to latent deficiency, results from the intersection of two tangents, tangent 1 at the deficiency threshold and tangent 2 at the inflection point of the curve (= maximum of the first derivative).

The threshold values for S nutrition of European silver fir derived from Figure 2 are given in Table 2, as well as for comparison the respective values of the most common central European conifers Norway spruce (*Picea abies)* and Scots pine (*Pinus sylvestris)* (Göttlein, 2015; Göttlein & Mellert, 2018). To determine the harmonic, that is the well-balanced range of S in relation to N, the molar ratio was calculated on the basis of 100 N (S_{per}100N) using the values for normal nitrogen nutrition of European silver fir from Göttlein et al. (2011).

The derived thresholds for first-year needle's S concentration of European silver fir for deficiency as well as for the lower and upper border of the range of normal nutrition are very close to the respective values of the two most important conifers. For the assessment of the nutritional status of trees in addition to foliar nutrient concentrations, also nutrient ratios can be used (Fiedler & Höhne, 1984), especially the ratio to nitrogen, which is the most important nutrient in terms of quantity. For ratios outside the "harmonic range," the supply with the respective nutrient in relation to nitrogen is either too low or too high. Looking at the molar S_{per}100N ratio, the range of harmonic nutrition is shifted to higher values, indicating that the demand of European silver fir for S, relative to N, is a bit higher than for the other two species. Also, when looking to the harmonic range of other element to N ratios (Goettlein, 2016), European silver fir shows a shift to higher values, for Ca and Mg at the lower and upper border, for P and K only at the upper border. It is known for long time that European silver fir in

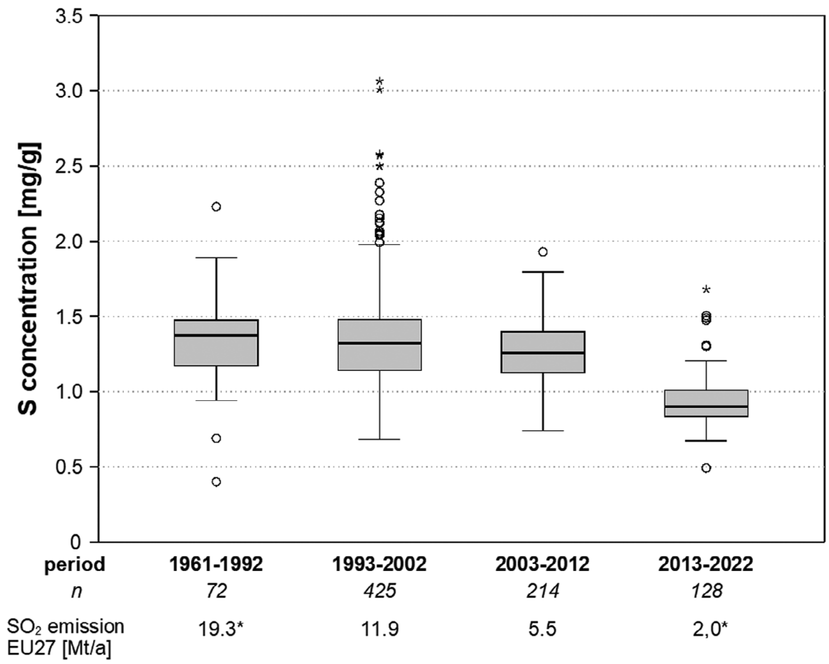

FIGURE 1 Boxplot of the data set in four time periods. Data for SO_2 emission of the EU27 states given as annual average in mega-tons per year for each period from the data available from 1990 to 2021 by the European Environmental Agency (EEA, 2023). Values with * do not cover the whole-time segment.

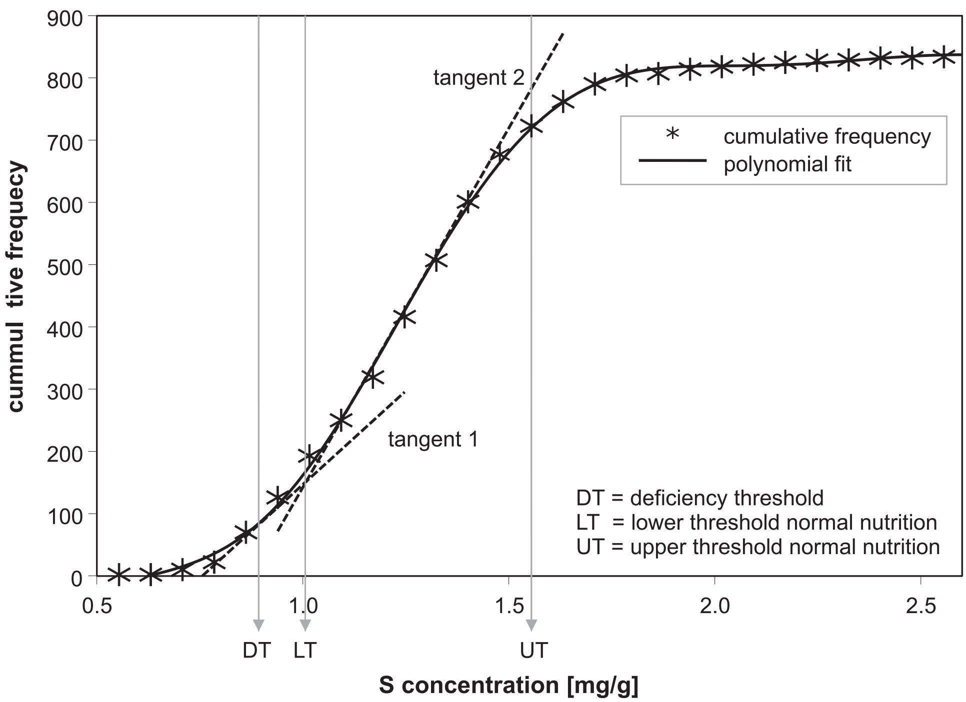

FIGURE 2 Derivation of nutritional threshold values from the cumulative frequency distribution of S concentrations in first-year needles of European silver fir according to Göttlein (2020).

TABLE 2 Nutritional thresholds for S in first-year needles of European silver fir (*Abies alba)* derived from Figure 2 in comparison to the respective values of the two most common central European conifers Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*).

	DT	LT	UT	Molar ratio
	S (mg g^{-1})			S_{per} 100N
Abies alba	0.88	1.01	1.55	2.59–5.51
Picea abies	0.80	1.00	1.60	2.10–4.29
Pinus sylvestris	0.95	1.00	1.60	2.38–4.83

For abbreviations, see Figure 2.

comparison to Norway spruce and Scots pine on comparable sites often has higher nutrient levels in terms of concentration and/or nutrient ratios (Fiedler et al., 1973). This is why European silver fir is classified as a more demanding tree species (Stinglwagner et al., 2005).

In the huge collection of nutritional data for tree species made by van den Burg (1985, 1990), for S nutrition of European silver fir only four data sets are available, which are solely characterizing the range of normal nutrition. Here the values range from 0.9 to 1.2 mg/g for the lower threshold of normal nutrition (LT) and from 1.2 to 1.8 mg/g for the upper threshold (UT). Thus, the thresholds derived according to Figure 2 fit well into the expected range. For the deficiency threshold, in van den Burg's collection no value is available.

4 | CONCLUSIONS

The approach of deriving thresholds for the S nutritional status of European silver fir from the cumulative frequency distribution provides reasonable values. The obtained smooth, s-shaped curve is a good indicator for a homogeneous data set. The derived values are in the range observed for the two main central European conifers Norway spruce and Scots pine. As shown by the slightly higher values for the range of harmonic nutrition (molar S-to-N ratio), European silver fir in comparison to the other two conifers has a slightly higher demand for sulfur, relative to N.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as third-party data were analyzed by permission and no new data were created or analyzed in this study.

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