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ORIGINAL ARTICLE

Soil acidification and nutrient sustainability of forest ecosystems in the northeastern German lowlands – Results of the national forest soil inventory

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Abstract

Between the first and second national forest soil inventory in the northeastern German lowlands a significant soil acidification took place with regionally varying intensity. It manifests itself in a reduced base saturation in the whole rooting zone. This applies to the base cations magnesium and calcium. For potassium, however, no significant changes were detected.

The acidification dynamic is the strongest in the southern part of Brandenburg. The specific immission situation in this region during the past four decades explains this. Particularly in southern Brandenburg high dust depositions (fly ashes from brown coal-fired power stations) buffered the acid components and enriched the soil with base cations in the 1970s and 1980s. Since the reduction of these atmospheric depositions, the bases were obviously totally incorporated in the biomass or leached out with seepage water.

Currently, the majority of the forest sites in Mecklenburg-Vorpommern and Brandenburg are poor in basic nutrient elements (Ca, Mg, K). Especially the element magnesium is assumed to be lacking. This paper presents an assessment of the long-term availability of the nutrients Ca, Mg und K on the basis of calculated nutrient balances for various forest management scenarios (e.g. full-tree harvest). The results show that the sustainable supply is critical especially for intensive forest use on numerous sites.

Key words

forest soil inventory, forest soil condition, soil acidification, base saturation, nutrient balance, full-tree harvest, magnesium deficiency

Introduction

The forest soil inventory is part of the German- and Europe-wide forest monitoring system. In the northeastern German states Brandenburg and Mecklenburg-Vorpommern it was first done in 1991–1992 on a systematic 8 × 8 km grid and repeated after about 15 years in 2005–2007. Overall, the soil condition was assessed on 206 inventory plots. The data of this inventory gives an impression of the actual forest soil condition, rep-

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resentative for the area of the northeastern German lowlands especially with regards to the degree of soil acidification and its change trends.

By definition, soils acidify if base cations (Ca, Mg, K, Na) are displaced from the cation exchanger and leave the system with seepage water or with the harvest-related biomass export; in the case that this loss cannot be compensated by the release of nutrients from silicate weathering or by atmospheric deposition acidification takes place (Rehfuess 1990). Since the first investigations of forest soil acidification were carried out (Ulrich 1986), many authors assume that the actual acidification and nutrient leaching status were largely caused by acid atmospheric deposition (Veerhoff et al. 1996; Gryschko and Horlacher 1997; Heisner et al. 2003).

Since the 1980s in most German states liming measures of varying degrees were carried out to buffer the atmospheric acid input, however, the German states Brandenburg and Mecklenburg-Vorpommern take a special position on this topic. Here were previously carried out any liming measure for soil protection.

A sensitive indicator of soil acidification is the base saturation, which was calculated in this study as percentage of the base cations Ca, Mg and K in the effective cation exchange capacity (CEC). As recommended by the German working group of the national soil survey the element sodium was not considered. Due to very low contents the measurement of Na is often not sufficiently accurate.

Besides the descriptive analysis of the acid-base-status and its spatial and temporal variability, the present paper contains a scenario-based examination of the nutrient sustainability for various management scenarios.

DESCRIPTION OF THE INVESTIGATION AREA

The investigation area is situated in the transitional zone of oceanic and continental climate. The annual average temperature varies regionally between 8–9°C. The annual climatic water balance ranges from minimum values of about –70 mm in central Brandenburg to maximum values of about +60 mm in the north of Mecklenburg-Vorpommern.

The parent materials are quaternary sediments. In the topsoil mainly glacial cover sands (60% of the inventory sites), glacial fluvial sand (17%), aeolian dune sand (10%) and glacial loam (5% in 10 cm depth; 10% in 100 cm depth) occur. Glacial drift appears in the subsoil of less than 5% of the sites.

The most common soil type is the podzolic brown-earth (WRB: spodic arenosol). The brown-earths differ in various degrees of the development of the spodic horizon. In addition, podzols occur on the nutrient-poor dune sands and luvisols on glacial loam. Sites close to groundwater (gleysols and peat soils) and strongly anthropogenic influenced soils (e.g. backfill) were excluded from this analysis.

The inventory sample consists of 78% pine, 4% oak and 6% beech stands; 8% are other deciduous stands and 4% other coniferous stands (stocking type according to Wellbrock et al. 2006), which also corresponds roughly to the surface percentages of the tree species in the total forest area.

As already described in previous reports, the chemical topsoil condition is strongly affected by the atmospheric deposition situation (Riek et al. 2007). This has changed dramatically since the early 1990s, i.e. since the realization of the first German forest soil inventory (Tab.1). Until the first soil inventory, particularly southern Brandenburg was one of the regions of central

Tab. 1. Comparison of atmospheric element deposition rates at the time of the first and second forest soil inventory in the federal state of Brandenburg

Element	Brandenburg (north)		Brandenburg (south)	
	1986–1989[1]	1996–2004[2]	1986–1989[1]	1996–2004[2]
Sulfur [kg/ha,a]	27.2	4.2	63.0	5.3
Calcium[kg/ha,a]	23.8	4.5	50.9	4.9
Total acidic [eq/ha,a]	486.0	327.0	505.8	379.1

[1] Measurements of deposition by Simon and Westendorf (1991).

[2] Measurements on Level II intensive monitoring plots.

Europe most influenced by immissions. Different deposition intensities of acid sulphur compounds and ashes from brown coal-fired power stations with buffering capacities overlapped in a regionally varying pattern.

After the reunification, the atmospheric deposition strongly decreased due to decommissioning of industrial plants, introduction of flue gas cleaning systems and the use of low-emission energy sources. Of particular note is the elimination of the basic dust input, with the result that the importance of the acid deposition for the acid-base-status of the top-soils increased. Based on element balances of intensive monitoring sites ("level II" sample plots of ICP-forests programme) it was shown that the base stocks of sites previously affected by fly ashes are now nearly exhausted (Riek et al. 2006). Using the data of the second forest soil inventory it can be checked whether these individual findings from case studies are representative for the total forest area or which sites are affected.

MATERIAL AND METHODS

Field and laboratory methods of the German forest soil inventory are documented in detail in Wellbrock et al. (2006).

For the estimation of nutrient sustainability, the following assumptions and computational algorithms have been applied:

- Estimation of deposition:

  The basis is the mean Ca- and Mg-deposition of eight intensive monitoring sites for the period 1997–2009. Canopy processes (element leaching) were taken into account by correction factors according to Riek et al. (2006). The regional adjustment was carried out with the help of the mean annual precipitation rates, which were interpolated for all soil inventory plots from data of the German Weather Service.
- Estimation of silicate weathering:

  First, modelling was required for exemplary aeolian sand and glacial loam soils with the model PROFILE (Bolte and Wolff 2001). The transfer on the total inventory sample was carried out using pedotransfer functions. On the basis of the stock of exchangeable base cations in the subsoil (30–90 cm depth) and their percentage share in the cation exchange capacity it was interpolated between the expected minimum (sand) and maximum (loam) weathering rates.
- Estimation of nutrient eluviation rate:

  First, using relationships between soil solid phase and soil solution phase (derived from measured data from Level II plots) element concentrations of the soil solution were estimated. The computation of average annual element leaching rates was made by multiplying the soil solution concentrations with the seepage of each inventory plot, which was estimated using the water budget model of Wessolek et al. (2008).

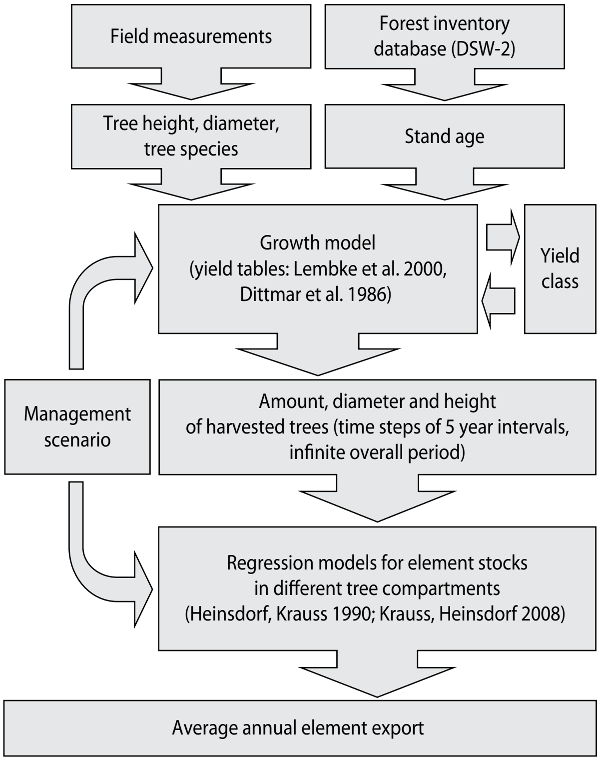

Fig. 1. Model components and input parameters to derive the element export by harvesting

- Estimation of element export by harvesting:

  For each inventory plot forest yield data are available (stand age, tree heights, diameters in breast height), obtained from field surveys. From these measurements, the yield class could be calculated for each stand. The determination of height, diameter and number of trees to be harvested, was derived from relevant yield tables for 5-year thinning intervals on the basis of the current yield class (Lembke et al. 2000; Dittmar et al. 1986). Using regression equations of Heinsdorf and Krauß (1990) and Krauß and Heinsdorf (2008), the element stocks of each tree compartment were derived from tree height and tree diameter. The determination of the average annual nutrient removal was based on an "infinite period" of use for three different management scenarios. An overview of the described approach is shown in Fig.1.

The used balancing approach simplified assumes that the various components (particularly the deposition) will remain constant until the target year 2100.

STATUS AND DYNAMICS OF THE BASE SATURATION

The analysis of the base saturation in different soil depths, stratified by soil types, indicates that the current values are in a low range, especially in the podzols and strong podzolic brown earths. Up to at least 150 cm depth, no significant increase in base saturation was detected in these soils. In contrast, the base saturations of moderate podzolic brown-earths increase at about 100 cm depth and reach medium values in 150 cm depth. In contrast, the slight podzolic brown-earths and Luvisols reach moderate high base saturations already in about 120 cm respectively 100 cm (Riek 2011).

From the frequency distributions of the base saturation clearly a shift toward very low values is evident in 0–60 cm depth between the first and second inventory (Fig.2).

Looking at the individual element concentrations, it appears that the reduction in base saturation between the first and second inventory is due to the decrease of magnesium and calcium, while potassium remained largely constant. The decrease of Mg and Ca affects the upper soil and subsoil equally. The Mg-concentrations in the subsoil of about a quarter of the total inventory samples are below the detection limit (values < 0.1 mmol_c/kg). These very low Mg- contents relate in particular to the strong podzolic brown-earths and podzols, which have the largest decreases in comparison to the first inventory. For the luvisols and slight podzolic brown-earths, however, no significant difference of Ca- and Mg- concentrations in the subsoils can be detected (Riek 2011).

Below, the changes in base saturation are evaluated stratified by immission areas. The following regions can be distinguished along a north-south gradient (see map, Fig. 3):

- North: low acid and base deposition rates
- Centre: medium acid and base deposition rates
- South: very high Ca-, Mg-, K-deposition rates in the 80′s (ashes from brown coal – fired power stations)

The depth-gradients of the base saturation stratified by the immission regions are shown in Fig.4. It is obvious that in the sample "North" no decrease between the first and second soil inventory took place. In the sample "Cen-

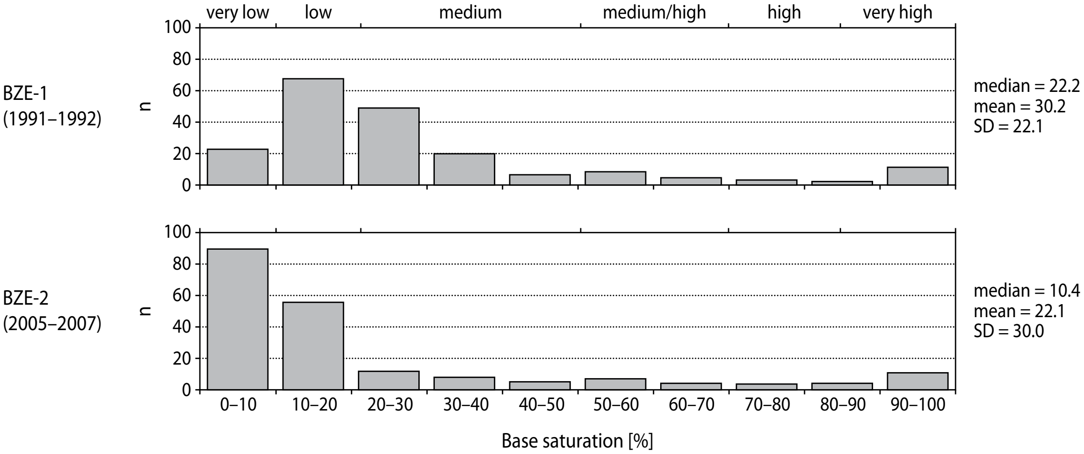

Fig. 2. Base saturation in 0–60 cm soil depth – comparison of the first (BZE-1) and second (BZE-2) forest soil inventory; base saturation = (stock of Ca + Mg + K / stock of Ca + Mg + K + Al + Fe + Mn + Fe + H) × 100%

tre" a decrease is evident but not statistically significant for each soil depth. The decrease in the sample "South" can be seen very clearly and is significant in all depths.

The decrease in base saturation during the period between the first and second forest soil inventory must be seen against the background that the values of the first inventory on a national scale were remarkable high (Wolff and Riek 2007). Mean base saturations of nearly 40% for strong podzolic brown-earths and podzols at that time were explained by the atmospheric deposition situation in the 70´s and 80´s. The basic ash input from brown coal – fired power stations in south Brandenburg was comparable to a large-scale fertilization. The deposited bases were obviously exhausted or leached out during the years from 1992 to 2006. Therefore, it is questionable whether the tendency of base depletion will continue so drastically in the future. It seems more likely that an equilibrium state has been reached which is at a very low level, correspond-

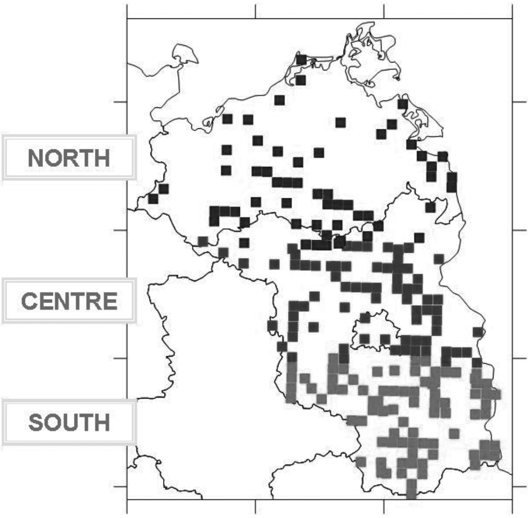

Fig. 3. Spatial differentiation of the deposition situation (north: low, centre: medium, south: very high deposition in the 80´s)

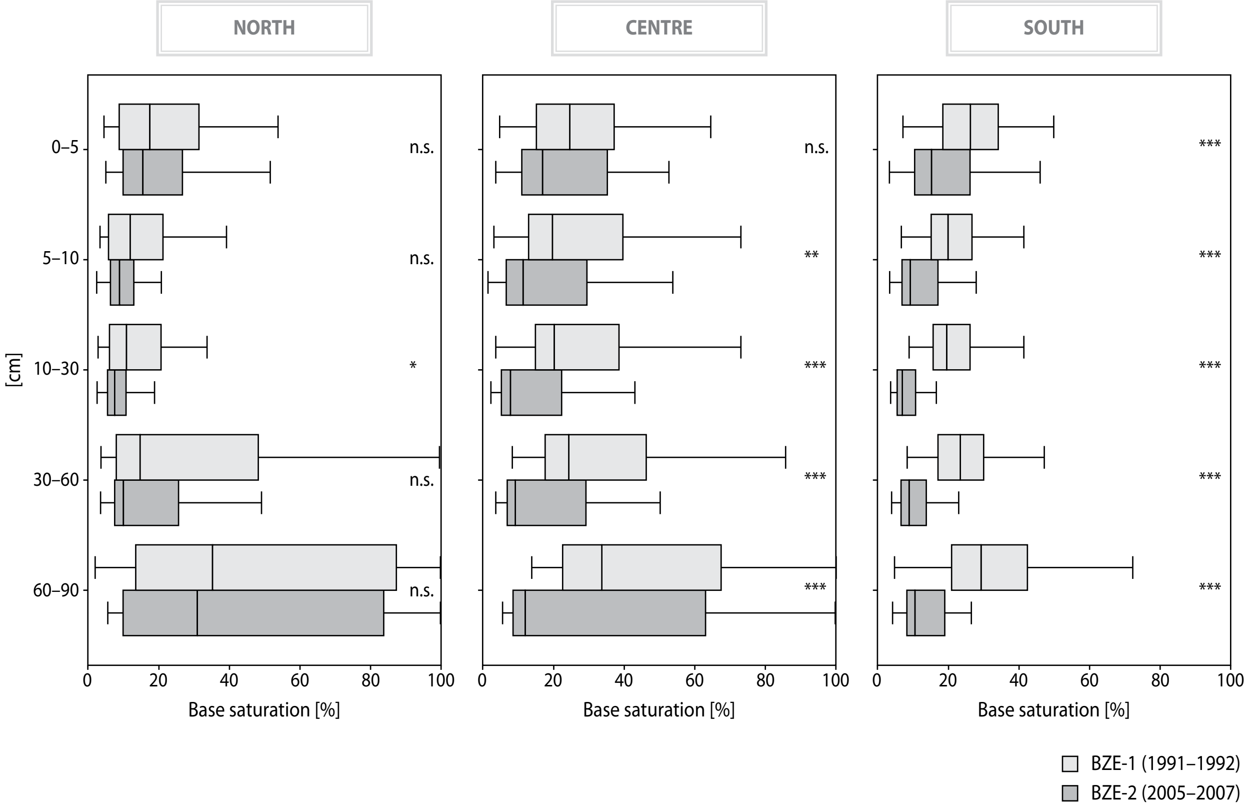

Fig. 4. Box-plots of base saturation in various depths stratified by deposition areas (BZE-1: first national forest soil inventory; BZE-2: second inventory; significance levels using non-parametric Mann–Whitney-U-test: * $p < 0.5$, ** $p < 0.1$, *** $p < 0.001$)

ing to the naturally poor sandy soil sites with podzols. Finally, this can be assessed only after a further soil condition inventory, which is planned to take place in about 10 years time.

NUTRIENT BALANCES AND ELEMENT SUSTAINABILITY

For the assessment of nutrient sustainability of forest sites several approaches exist. These differ greatly in theoretical concept, complexity and required input data. Meiwes et al. (2008) proposed a simple quotient of nutrients stored in soil and vegetation. Rademacher et al. (1999), Joosten and Schulte (2003) and Hagemann (2008) calculated simple budgets, while Lemm (2010) used a combined approach of budget calculations and nutrient-quotients similar to the approach in this study. Finally Verburg and Johnson (2001) presented a spreadsheet biogeochemical model and Sverdrup et al. (2005) applied the complex process-based dynamic soil chemistry model SAFE to Swedish forest soils.

The nutrient balance is derived from nutrient input and nutrient output per time-unit. Element inputs result from the weathering of the parent material, and from atmospheric deposition of dust or precipitation (dry and wet deposition). The element output results from nutrient losses with seepage water and with element removal from timber harvesting.

In the case of negative balances of nutrient input and output, this leads gradually to the exhaustion of the plant available nutrient reserves in forest soils. The soils acidify and the site fertility decreases. The lower the soils buffering, meaning, the fewer exchangeable nutrient cations the soil contains bonding to soil colloids (humus, clay minerals), the shorter the period until the theoretically complete leaching of the soil. However, it can be assumed that this point is never quite reached, as with decreasing resources, tree growth falls (e.g. Sterba 1988; Meiwes 2009), and consequently the nutrient stock incorporated in the biomass decreases as long as a new equilibrium between nutrient availability and nutrient uptake is set at a lower level.

In Fig. 5 the plant available amounts of Ca, Mg and K – computed from deposition and weathering minus seepage discharge – are presented as annual average of all inventory plots.

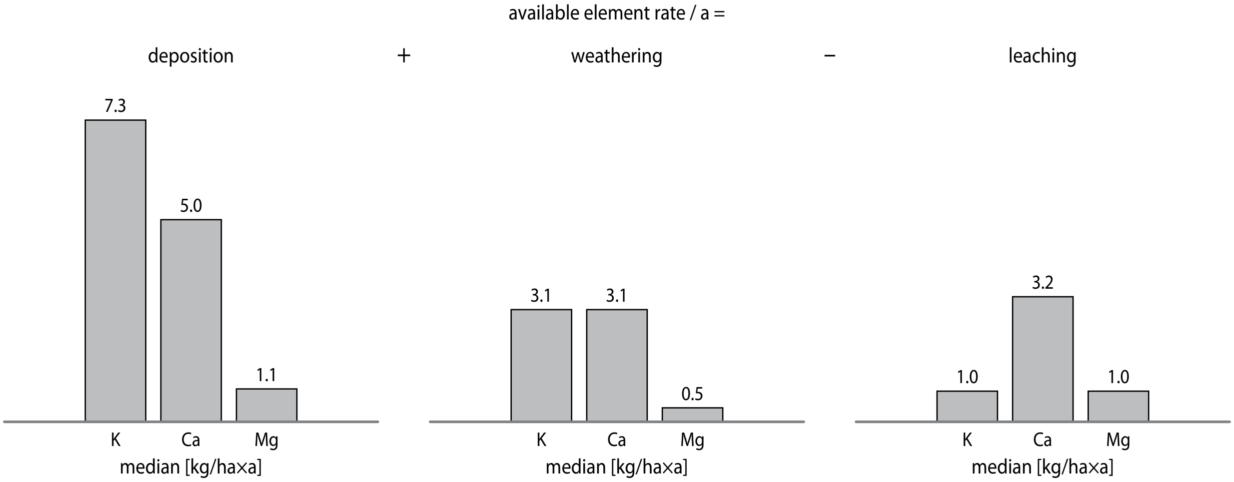

Fig. 5. Modelled deposition, weathering and seepage of the elements K, Ca and Mg as medians of all inventory plots

These calculated values were compared with the average annual element export by harvesting for various forest management scenarios. Three scenarios were distinguished with the following increasing forest use:

- Management scenario 1 (low intensity of use):
  Harvest of trunks (bark removed); first harvest at 15 m canopy height; excluding 5 older trees per ha each rotation time

- Management scenario 2 (moderate intensity of use):
  Harvest of trunks (wood and bark); first harvest at 12 m height
- Management scenario 3 (high intensity of use):
  Full-tree harvest (trunk, branches, needles), all harvests proposed by a growth model.

The evaluation of the soil inventory data shows that in particular for the main nutrients Mg and Ca – depending on the specific site conditions and the scenario-based use intensities – negative balances can occur. For the also examined elements of potassium and nitrogen currently no shortages are expected. To assess the nutrient sustainability for each inventory plot, it was first checked whether the individual balances of the elements Mg and Ca are positive or negative. In the case of negative balance it was examined whether the deficiency can be compensated until the target year 2100 by the current plant available element stock in the forest soil. Thus, three categories of sustainability have been distinguished as follows:

- Sustainability group I:
  Positive balance for all nutrients; nutrient sustainability for the particular management scenario secured beyond the year 2100
- Sustainability group II:
  Negative balance for at least one nutrient element; nutrient supply from the plant available reserve in the forest soil secured at least until 2100; critical nutrient sustainability
- Sustainability group III:
  Negative balance for at least one nutrient element; nutrient supply from the plant available reserve in the forest soil not secured until 2100; nutrient sustainability definitely not given

The classification of all inventory plots into one of the sustainability groups depending on the management scenario is shown in Tab.2. The table indicates that at some inventory plots the nutrient sustainability is not guaranteed even for a low intensity of use. This affects 11% of the sample. The affected sites are supplied very poorly with magnesium and / or are sites with a strong negative Mg-balance. The later can be a result of high seepage rates or of strong growth (integration of large Mg-amounts into the biomass). On the affected sites, it is expected in the long term, that the soil fertility degrades and the current (partially high) growth rates will be reduced permanently.

With increasing intensity of use the number of inventory plots for which this type of use is regarded as unsustainable increases considerably. For management scenario 3 (full tree harvest), it is the case for 42% of the inventory plots; for further 21% the nutrient sustainability is assessed as critical (Tab.2). This reflects the generally known fact, that in particular those components have high nutrient contents, which are additionally harvested in this use scenario (branches, twigs, needles).

On the other hand, the presented data analysis also indicates, that high intensity of use are possible on more than a third of the forest area, without any occurrence of soil overexploitation. This mainly concerns sites with relatively nutrient-rich soils, for which higher weathering rates can be assumed. When deriving maximum acceptable use intensities it is important to note that extreme high intensity of use also affect these nutrient-rich sites. For example, intensive uses have negative effects on the humus state and consequently on the soil structure, the cation exchange capacity and available water capacity. Therefore, in this case a certain proportion of the biomass should remain on the site.

Tab. 2. Percentage of inventory plots in the sustainability groups I – III for different use intensity and nutrient elements (Ca, Mg)

Management scenario	Calcium			Magnesium		
	Sustainability group			Sustainability group		
	I	II	III	I	II	III
1 (low intensity of use)	96.7%	2.5%	0.8%	69.6%	19.0%	11.4%
2 (moderate intensity use)	82.6%	15.7%	1.7%	57.0%	25.6%	17.4%
3 (high intensity of use)	52.0%	32.2%	15.8%	37.2%	20.7%	42.1%

CONCLUSIONS

The changed element input rates by atmospheric deposition induced the decrease of base stocks of forest soils in the northeastern German lowlands. As a result, many sites returned to their naturally nutrient-poor status, which corresponds to the silicate-poor parent material. On these naturally acidic sites liming measures are not recommended. In combination with increased requirements of use, therefore the application of element budget studies seems to be necessary for the sustainable forest management.

In principle, the nutrient budget should be balanced in the long-term, even with intensive timber harvesting. Before proceeding full-tree harvest, therefore an individual site assessment should be carried out to check whether the element sustainability is ensured.

For the inclusion of deeper nutrient-rich soil layers into the nutrient cycle, in the frame of the forest conversion programs suitable tree species should be included in the existing stands (use of “base pump effects”).

For all nutrient-poor sites suitable adapted use strategies (e.g. use of trunk without bark if necessary) must be derived. In principle it is to ensure that an appropriate proportion of the biomass always remains in the forest as a nutrient pool and humus developer.

Intensive uses that go beyond the traditional level should always be documented by the forest administrations.

On selected forest monitoring sites with different use intensities the changes in the nutrient budget should be observed exemplarily. The continuation and possible intensification of the existing soil and nutritional monitoring program is strongly recommended for this purpose.

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