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Estimation of Nutrient Exports Resulting from Thinning and Intensive Biomass Extraction in Medium-Aged Spruce and Pine Stands in Saxony, Northeast Germany

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Academic Editors: Scott X. Chang and Xiangyang Sun
Received: 31 August 2016; Accepted: 19 November 2016; Published: 30 November 2016

Abstract: A growing interest in using forest biomass for bioenergy generation may stimulate intensive harvesting scenarios in Germany. We calculated and compared nutrient exports of conventional stem only (SO), whole tree without needles (WT excl. needles), and whole tree (WT) harvesting in two medium aged Norway spruce (*Picea abies* L. KARST.) and Scots pine (*Pinus sylvestris* L.) stands differing in productivity, and related them to soil nutrient pools and fluxes at the study sites. We established allometric biomass functions for each aboveground tree compartment and analyzed their nutrient contents. We analyzed soil nutrient stocks, estimated weathering rates, and obtained deposition and seepage data from nearby Level II stations. WT (excl. needles) and WT treatments cause nutrient losses 1.5 to 3.6 times higher than SO, while the biomass gain is only 1.18 to 1.25 in case of WT (excl. needles) and 1.28 to 1.30 in case of WT in the pine and spruce stand, respectively. Within the investigated 25-year period, WT harvesting would cause exports of N, K^+, Ca^{2+}, and Mg^{2+} of 6.6, 8.8, 5.4, and 0.8 $kg \cdot ha^{-1}$ in the pine stand and 13.9, 7.0, 10.6, and 1.8 $kg \cdot ha^{-1}$ in the spruce stand annually. The relative impact of WT and WT (excl. needles) on the nutrient balance is similar in the pine and spruce stands, despite differences in stand productivities, and thus the absolute amount of nutrients removed. In addition to the impact of intensive harvesting, both sites are characterized by high seepage losses of base cations, further impairing the nutrient budget. While intensive biomass extraction causes detrimental effects on many key soil ecological properties, our calculations may serve to implement measures to improve the nutrient balance in forested ecosystems.

Keywords: spruce; pine; thinning; aboveground biomass; energetic use; stand growth; nutrient contents; nutrient accumulation

1. Introduction

In order to mitigate fossil carbon dioxide emissions for energy generation, renewable energies such as bioenergy are being promoted as an alternative to fossil fuels. In Germany in 2013, renewable sources accounted for 12.3% of total energy consumption, of which biomass accounted for 7.6% [1]. Within the biomass sector, forest residues have been identified as a large underused source for potentially increasing the raw material supply. Already, about 11 million$\cdot m^3$ of wood has been used directly for energy purposes, which accounts for about one fifth of the total annual harvest from forests. The potential for increasing forest biomass for energy (at a sustainable rate) is estimated to be between 12 and 19 million$\cdot m^3 \cdot year^{-1}$, which could be achieved by increasing the utilization of forest residues and currently underused hardwood stands [2].

The process of extracting harvesting residues from forests, or whole tree harvesting, has a number of technological and ecological constraints. On the technological side, there is a high expenditure for the logistics due to the scattered location of the biomass and its low density, and thus transportability [3,4]. Advanced technologies and management practices could help to improve both feedstock quality and cost efficiency in the future [3,5]. The biomass market situation, and thus the actual price paid by biomass combustion facilities per unit of feedstock, will eventually determine economic feasibility of the utilization of forest residues for bioenergy.

On the ecological side, there is a threat of potentially high nutrient exports when extracting the nutrient-rich crown material, and thus a loss of productivity [6–10]. Also, if large parts of the harvesting residues are exported from the site, there will be fewer habitats for decomposer fauna and flora and less input material to refill the site-specific humus stock [11,12]. The nutrient issue could be attenuated by returning nutrients into the forests from sources such as wood ash from biomass combustion facilities [13–16]. Implementing wood ash recycling systems into practice would require thorough knowledge regarding the actual amounts of nutrients removed in management scenarios of various intensity [14]. Additionally needed is an estimation of the available soil nutrient pool, which plays a major role in assessing the impact of harvest-induced nutrient losses on site productivity, and thus on management sustainability in terms of maintaining nutrient reserves. Finally, site specific nutrient balances are needed to evaluate the impact of different harvesting intensities and to draw conclusions for adapted forest management.

Estimating nutrient fluxes associated with the extraction of aboveground biomass compartments under intensive management scenarios requires knowledge and estimation methods about the distribution of biomass and nutrients of all tree compartments. Yet yield tables and forest growth models typically used in forest management and planning in Germany concentrate on just the volume of the marketable round wood, which is typically the tree trunk up to a certain diameter (e.g., 7 cm over bark), depending on the current market situation. Information about the distribution of the biomass to above-ground tree compartments, such as the stem with a diameter smaller than 7 cm, branches, foliage, and dead branches is needed in order to estimate the profitability and the impact on the nutrient budget of going from classic stem-only (SO) harvesting to more intensive scenarios, such as whole tree without foliage (WT excl. needles) or whole tree (WT) harvesting [17,18]. Some studies on the impact of nutrient removals in intensive scenarios focus on the final felling and harvesting at the end of a stand's rotation time and its impact on the growth of the next stand generation [7,10]. The rationale for this approach is that the biomass and nutrient fluxes in final fellings, such as clear cuts or shelterwood cuttings, are especially large. Alternately, other studies have concentrated on the impact of intensive biomass exports in thinning operations of medium aged stands [10,19–22], which happen at a stage of stand development when the remaining trees exhibit high productivity, and thus require large amounts of nutrients for the buildup of aboveground biomass.

In our study, we aimed at quantifying the nutrient exports of thinning operations with variable intensities of biomass removal in two medium-aged coniferous stands representing typical site and stand conditions in the region of Saxony in northeast (NE) Germany and evaluating the impact of such treatments on the nutrient budget of the stands. We hypothesize that intensive harvesting scenarios (1) impose a strong negative effect on the nutrient balance of forest stands, even in the thinning stage; and (2) will lead to a more negative nutrient balance in the highly productive stands than in less productive stands, due to larger absolute amounts of biomass and thus nutrients removed. Therefore, we developed single-tree biomass equations to predict the dry mass of all aboveground tree compartments based on the tree's diameter at breast height (DBH) and analyzed nutrient contents of these compartments. Based on this knowledge, we estimated the biomass and nutrient extraction by thinning with three different management intensities: conventional SO, WT (excl. needles), and WT harvesting, which refers to aboveground biomass only. In all scenarios, stumps and roots are left in the stand. Also, we calculated the nutrients required to build up aboveground biomass within the examined time span. Finally, we set the amount of extracted and stored nutrients in relation to the site-specific nutrient stocks and fluxes in order to estimate the sustainability of intensive management scenarios.

2. Materials and Methods

2.1. Study Area and Sites

The study area was the Oberlausitz in Saxony, NE Germany. In the northern lowlands, the typically nutrient poor pleistocene soils are often covered with Scots pine (*Pinus sylvestris* L.) stands. Depending on the site potential which varies on a small scale, forests could be dominated by Scots pine, sessile oak (*Quercus petraea* (Mattuschka) Liebl.), pedunculated oak (*Q. robur* L.), silver birch (*Betula pendula* Roth), European beech (*Fagus sylvatica* L.), and various mixtures of these species. Of these species, pines are the most dominant in the study region, covering 69% of the forested area. In the hills in southern Oberlausitz, site conditions are generally more suitable for forestry, as soils are derived from weathered granodiorite bedrock overlain with a loess layer of variable thickness (often 10 to 40 cm). Many forest stands here are pure Norway spruce (*Picea abies* (L.) Karst.) plantations or spruce dominated, and spruce accounts for 13% of the forest cover, while under natural conditions most sites consist of beech dominated mixed forests. We selected two study stands to represent these contrasting stand types: a pine stand on a nutrient-poor Podzol-type soil with a low water holding capacity derived from pleistocene gravel and sand in the lowlands, and a spruce stand on a deep Cambisol-type soil in the southern hills (Table 1). Although the soil conditions at the spruce site were nominally more favorable than at the pine site, the base saturation of the mineral soil was substantially lower (Table 1), which was caused by atmospheric acid inputs from recent decades (notably from 1970 to 1990). Both stands were 38 years-old in 2013. At this age, thinning operations are carried out once or twice in ten years to increase stand stability and promote growth of the most favorable trees by reducing stand density.

Table 1. Site and stand characteristics of the studied Scots pine and Norway spruce stand in Saxony.

Ecosystem Component	Parameter	Unit	Scots Pine (Laußnitz)	Norway Spruce (Neusalza-Spremberg)
Site characteristics	Mean annual temperature	°C	9.4	8.1
	mean annual rainfall	mm	757	910
	altitude	m above sealevel	190	405
Soil characteristics	Soil type		Dystric Arenosol on pleistocenic sediment	Cambisol on weathered granodiorite overlain with loess
	Profile depth (root zone)	cm	35	60
	field capacity	$mm \cdot dm^{-1}$ ***	8.5	18.8
	Base saturation in the organic layer (mean ± SD)	%	30.4 ± 14.9	68.4 ± 43.5
	Base saturation in the mineral soil	%	8.2–3.4	4.5–1.7 ± 5.2–1.2
Stand characteristics in 2013	Age	Year	38	38
	Stand density	$N \cdot ha^{-1}$	1850	725
	Stock density **		0.89	0.97
	Growing stock	$m^3 \cdot ha^{-1}$	199.0	400.5
	Average DBH *	cm	14.3	24.5
	Average height	m	13.9	23.8
	Mean annual increment	$m^3 \cdot ha^{-1} \cdot year^{-1}$	10.2	16.2
	Basal area	$m \cdot ha^{-1}$	29.9	34.1
	Average slenderness coefficient		0.95	0.97

* DBH: diameter at breast height; ** ratio of actual growing stock to potential maximum growing stock (according to yield table); *** mm or water per dm of soil depth.

2.2. Stand Biomass and Treatment

In 2013, inventories of the pine stand and the spruce stand were carried out on representative 0.2 ha subplots, determining the number of trees, the DBH, and the height of 10 trees representing the largest 10% of each stand. This data was used to model current stand properties and stand development for 25 years, using the individual tree based forest growth model BWinPro-S [23]. In this time span, forest management will focus on the process known as 'stand qualification', which is selective cutting to promote the growth of the healthiest trees. According to current management practices, we assumed moderate to heavy thinning from above in the spruce stand, and heavy thinning from below in the pine stand. The thinning intensity in terms of removed volume per hectare was adjusted in such a way to keep the degree of stocked area as well as the current increment constant, which resulted in the removal of about 60 m^3 every 5 years in the spruce stand and 45 m^3 every 10 years in the pine stand. This was done in order to maximize stand stability, and to achieve a high growth rate at the stand level as well as a reasonable DBH increment of the single trees.

Based on the inventories, nine to ten trees were selected across the range of DBH values in order to investigate the relative mass distribution as well as nutrient contents in the aboveground biomass compartments. The selected trees were felled and separated into the following compartments in the field: (1) stem wood (diameter > 7 cm) including bark; (2) tree top wood (diameter < 7 cm) including bark; (3) branches including bark and needles; (4) dead branches (Table 2). The fresh mass of these compartments was determined using a hanging scale mounted in the stand. Subsamples of each compartment were taken to the lab and dried at 60 °C until weight was constant. For the stem wood including bark compartment, we collected three 5 cm thick discs from the following tree heights: 1.3 m, 1/2 of the length of the stem wood, top of the stem wood. For the branches including needles, we collected one entire branch from each third whorl, starting at the youngest whorl. For the tree top wood we collected one 5 cm thick slice from the middle of the section, and for the dead branches we randomly collected three to five dead branches per tree. This resulted in relatively large amounts of sample material for the most important tree compartments in terms of mass and nutrient contents (i.e. stem wood, bark of the stem wood, branches and needles). In the lab, the subsamples were further divided into the following target compartments: stem wood, bark of the stem wood, tree top wood including bark, branches including bark, needles and dead branches (Table 2). During the drying and separating process, the water content of each compartment was determined as well as the wood/bark ratio and the branches/needles ratio. Thus, we were able to determine the dry mass of each compartment of each tree by simple ratio calculations. This data was used to fit allometric biomass models of the dry mass of each biomass compartment (M_{bc}) of the type $M_{bc} = a \times DBH \ (\mathrm{cm})^b$, where a and b are specific coefficients and the explaining variable is the DBH (cm), by using non-linear regressions of the original data. As our emphasis was to estimate nutrient stocks in each biomass component, we used the described independent biomass models for each component, instead of an approach focusing more on the additivity of the biomass equation.

Table 2. Partitioning of the aboveground biomass into tree compartments in the field and in the lab, number of samples taken per tree and compartment.

Compartment		Number of Samples
Field	**Lab**	**Samples/Tree**
Stem wood incl. bark	Stem wood > 7 cm	3
	Bark of stem wood	3
Tree top wood incl. bark	tree top wood incl. bark	1
Branches incl. bark and needles	Branches incl. bark	4–7, depending on tree size
	Needles	4–7, depending on tree size
Dead branches	Dead branches	3–5, depending on tree size

2.3. Nutrient Contents

Prior to chemical analysis, one composite sample per tree and compartment was created and ground to 0.25 mm (needles: 0.08 mm). For C and N analysis, aliquots of 10 mg of sample material were analyzed using a Vario EL III (Elementar Analysensysteme GmbH, Hanau, Germany).

Nitrogen contents of low N biomass compartments (stem wood, bark, tree top wood, branches, dead branches) were determined with a Vario Max cube (Elementar Analysensysteme GmbH, Hanau, Germany) using 300 mg aliquots of sample material. The contents of P, K, Ca, and Mg contents were analyzed after HNO_3 digestion using a CCD-ICP Spectrometer CIROS (Spectro Analytical Instruments, Kleve, Germany).

2.4. Soil Nutrient Stocks and Nutrient Balance

Soil profiles were dug and characterized in both stands, and each mineral soil horizon was sampled using metal rings, so that bulk density could be determined in addition to chemical analyses. We calculated the stock of exchangeable Ca^{2+}, K^+, and Mg^{2+} based on the cation exchange capacity (CEC_{eff}) after percolating 5 g subsamples with 1 M NH_4Cl and subsequent analysis in the CCD-ICP spectrometer CIROS (Spectro Analytical Instruments, Kleve, Germany). Total concentrations of N and P were determined after digestion in HNO_3, HF, and $HClO_4$, using the CCD-ICP spectrometer CIROS (Spectro Analytical Instruments, Kleve Germany). Based on horizon-wise nutrient contents and bulk densities, the exchangeable and total nutrient stocks per hectare were calculated for the root zone (35 cm at the pine site and 60 cm at the spruce site).

For the nutrient balance, data from the EU-monitoring Level II sites were used to estimate atmospheric deposition inputs and seepage outputs. For the pine stand, the Level II station "Laußnitz" was used, which is only 500 m away from the study site, while for the spruce stand data from the Level II station "Bautzen/Neukirch" was used, which is 15 km away from the study site, but is comparable in terms of site, soil, and stand conditions [24]. The weathering inputs were roughly estimated according to a method by [25]. First, a total weathering rate of 0.4–1.0 $kmol \cdot ha^{-1} \cdot year^{-1}$ was estimated according to literature values [26]. Then, the share of K^+, Ca^{2+}, and Mg^{2+} was determined in relation to their share in base saturation. Due to data scarcity, we could not set up nutrient budgets for P.

3. Results

3.1. Forest Development

Both the pine and the spruce stand are very productive. Thus, they exhibited a relatively high current increment which decreased slightly during the modeled period from 14.4 to 13.1 and 27.5 to 26.7 $m^3 \cdot ha \cdot year^{-1}$ at the pine and spruce site, respectively. The high productivity can be attributed both to proper forest treatments before the beginning of the study period, and to the favorable growing conditions. Figure 1 shows the development of the total aboveground biomass and the impact of the thinnings that were modeled to be carried out once in 10 years in the pine stand and once in 5 years in the spruce stand.

In both stands, the volume increment over the study period was slightly lower than the volume harvested in thinnings (132.5 vs. 141.1 $m^3 \cdot ha^{-1}$ in the pine stand and 277.1 vs. 318.9 $m^3 \cdot ha^{-1}$ in the spruce stand, Table 3). With regard to the further stand development after the study period, we set a slightly lower stocking density (Table 3). After the qualification phase focused in this paper, the pine stand will reach the dimensioning phase, in which no more thinnings are carried out and the trees are left to grow until they reach the target DBH (40 cm). Due to its high productivity, the spruce stand will more or less skip the dimensioning phase, because the largest trees will have already reached the target DBH (40 cm) after the qualification phase. Once they have reached it, forest management will focus on harvesting the mature trees and at the same time initiating stand regeneration.

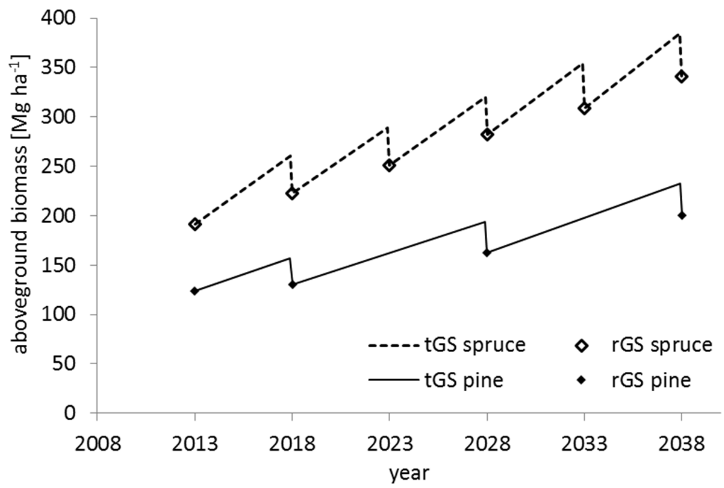

Figure 1. Development of total aboveground biomass (t·ha^{-1}) of the pine and spruce stand. tGS: total growing stock, rGS: remaining growing stock after thinning. Thinning of the pine stand in 2018, 2028, and 2038; thinning of the spruce stand is carried out in 2018, 2023, 2028, 2033, and 2038.

Table 3. Development of the remaining stand and sum of extracted volume in thinnings. Scots pine stand: three thinnings, Norway spruce stand: five thinnings during a 25-year period.

Date / Period	Current Increment	Stocking Density	Growing Stock	Extracted Volume
Pine	m^3·ha^{-1}·a^{-1}		m^3·ha^{-1}	m^3·ha^{-1}
2013	14.4	0.89	200.2	
2038	13.1	0.84	332.7	
Σ thinnings 2018–2038				141.1
Spruce				
2013	27.5	0.97	400	
2038	26.7	0.93	677.1	
Σ thinnings 2018–2038				318.9

3.2. Biomass and Nutrient Distribution in Tree Compartments

We achieved a satisfactory fit of the allometric biomass equations to our data for most of the biomass compartments. As an example, Figure 2 shows the biomass equation of the total aboveground biomass of the spruce stand. The equation parameters and the coefficients of determination are given in Table 4.

The coefficients of determination of the biomass functions were generally high, indicating a strong correlation of the DBH and the mass of the biomass compartments, especially in the case of stem wood, bark, branches, and needles, which are the most important aboveground biomass compartments with respect to their share of total aboveground biomass (Figure 3) and nutrient storage.

The development of the share of the biomass compartments in total aboveground biomass is shown in Figure 3, based on the biomass equations in Table 4. Obviously, the tree top wood incl. bark is relevant only for trees with a DBH < 20 cm, because a relatively large part of the stem is smaller than the defined 7 cm diameter. In larger trees, the stem wood with a diameter > 7 cm including bark accounts for 79% in both spruce and pine. The most important difference between the pine and spruce is the share of branches and needles, with pine trees having a larger share of branches at 14% and a smaller share of needles at only 4.4%, compared to 11.0% and 8.2% in spruce trees, respectively, due to their species-specific crown architecture and physiology. Figure 3 clearly shows the larger relative importance of low quality crown material in small trees, and thus in young stands. This probably makes whole tree harvesting for bioenergy purposes especially attractive in younger stands in order to increase the overall economic outcome of thinning operations.

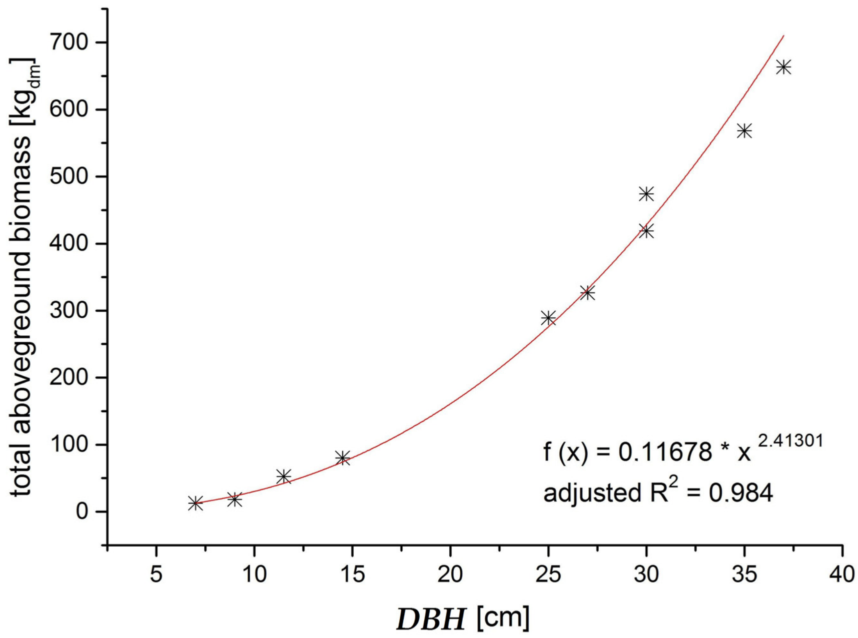

Figure 2. Relation of total aboveground biomass of the sampled spruce trees to DBH and biomass equation.

Table 4. Equation coefficients (a, b) and coefficients of determination (R^2) of the biomass equations $M_{bc} = a \times DBH\ (\mathrm{cm})^b$ for the aboveground biomass compartments of the pine and spruce stand.

Compartment	Pine Stand			Spruce Stand		
	a	*b*	R^2	*a*	*b*	R^2
total aboveground biomass	0.0786	2.539	0.98	0.11678	2.41301	0.98
stem wood	0.0075	3.2281	0.98	0.033	2.68382	0.98
bark of the stem wood	0.0052	2.5924	0.98	0.00926	2.3432	0.98
tree top wood incl. bark	174.34	−1.526	0.89	50.69505	−1.02053	0.78
branches	0.0008	3.3992	0.99	0.00542	2.66276	0.96
needles	0.0015	2.8154	0.94	0.01253	2.35013	0.94
dead branches	0.0002	3.3465	0.88	0.01722	1.91842	0.86

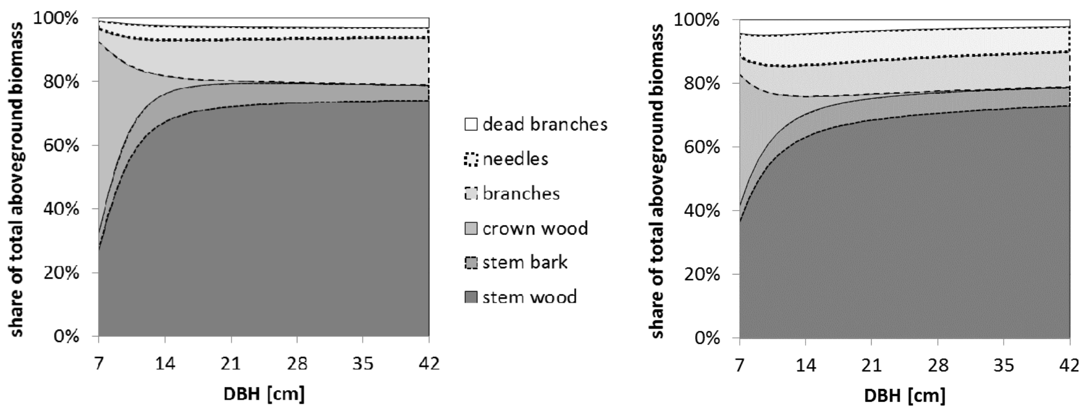

Figure 3. Share of aboveground biomass compartments of the examined Scots pine (**left**) and Norway spruce (**right**) stand at a DBH-range of 7 to 42 cm.

3.3. Nutrient Contents in Aboveground Biomass Compartments

Although nutrient contents for aboveground tree compartments were measured in various other studies, the results are often only partly comparable, because of differences in the defined compartments, in stand age and soil conditions [27]. Thus, with respect to the purpose of this study, we performed our own measurements of nutrient contents (Table 5).

Table 5. Nutrient contents (g·kg^{-1}) of aboveground biomass compartments of pine and spruce trees at the trial sites in East Saxony. Means and standard deviation, n = 5.

	Stem Wood		Stem Bark		Tree Top Wood		Branches		Needles		Dead Branches	
						Scots Pine						
N	0.72	(0.3)	2.76	(0.5)	1.98	(0.6)	4.24	(1.1)	16.4	(2.6)	2.24	(0.7)
P	0.04	(0.4)	0.26	(1.3)	0.17	(1)	0.40	(1.7)	1.41	(7.2)	0.09	(1.1)
K	0.36	(0.4)	1.25	(1.6)	0.91	(1.2)	1.78	(2.1)	6.06	(7.8)	0.26	(1.3)
Ca	0.72	(0.4)	6.86	(1.6)	1.34	(1)	3.11	(2.3)	4.03	(6.8)	2.06	(0)
Mg	0.17	(0.3)	0.46	(1.2)	0.35	(0.9)	0.50	(1.9)	0.74	(5.4)	0.21	(0)
						Norway Spruce						
N	0.80	(0.3)	3.78	(0.8)	2.07	(0.3)	4.49	(0.7)	13.2	(1.6)	1.86	(0.3)
P	0.06	(0)	0.54	(0.1)	0.31	(0.1)	0.60	(0.1)	1.36	(0.2)	0.10	(0)
K	0.46	(0.1)	2.70	(0.5)	1.23	(0.3)	2.73	(0.5)	5.10	(0.7)	0.28	(0.1)
Ca	0.90	(0.1)	7.55	(0.9)	1.27	(0.2)	3.16	(0.3)	4.16	(0.4)	2.98	(0.4)
Mg	0.14	(0)	0.98	(0.1)	0.34	(0.1)	0.63	(0.1)	0.90	(0.1)	0.29	(0.1)

The highest concentrations of all nutrients are generally found in the needles, with the exception of Ca, which shows the highest concentration in the bark. Magnesium concentrations differ between pine and spruce. In the pine trees, Mg concentrations are highest in the needles, followed by branches and bark; while in spruce trees, Mg is distributed similar to Ca with the highest concentrations in the bark, followed by needles and branches. The nutrient contents of the dead branches range somewhat in between those of branches and stem wood.

3.4. Biomass, Nutrient Extraction, Uptake, and Storage

Relative to the increment of the remaining stand, the harvested biomass in the thinnings of the 25-year study period are larger in the spruce stand compared to the pine stand (Table 6). While the biomass extraction in the WT scenario in the pine stand is lower than the biomass ingrowth (129 vs. 114 t·ha^{-1}), it exceeds the ingrowth in the spruce stand (150 vs. 201 t·ha^{-1}) due to a higher overall productivity of the spruce stand, and thus heavier and more frequent thinnings. When intensifying the biomass extraction from conventional stem only (SO) harvesting to whole tree harvesting (WT), the factor of increase is slightly higher in the pine stand compared to the spruce stand (factor of increase 1.30 in the pine stand compared to 1.28 in the spruce stand), due to the smaller dimension of the harvested pine trees, and thus a relatively larger proportion of crown material (see Figure 3). The difference in the factor of increase of WT (excl. needles), with a higher biomass extraction in case of pine compared to spruce (factor of increase 1.25 vs. 1.18), results from the higher share of branches in pine trees compared to spruce trees.

The relative loss of nutrients in intensive scenarios far exceeds the biomass gain, with factors of increase in whole tree harvesting between 1.7 (Ca, pine and spruce) and 3.6 (P, pine) to 3.4 (P, spruce), respectively. If needles are allowed to fall off before extracting crown material (WT excl. needles), the increase in nutrient exports is generally higher in pine trees than in spruce, which goes along with the relatively larger biomass extraction due to the higher share of branches in pine trees in the WT (excl. needles) scenario.

Table 6. Aboveground biomass increment and nutrient uptake/storage in the remaining stand.

Scots Pine Stand		**Biomass**	**N**	**P**	**K**	**Ca**	**Mg**
		t·ha^{-1}			**kg·ha^{-1}**		
Remaining stand Δ 2013–2038 (WT)		129	237	18	99	189	32
Σ thinnings	SO *	88	80	5	39	113	17
	WT (excl. needles) *	110	156	12	69	169	26
	WT *	114	230	18	96	187	30
Ratio Compared to SO							
thinnings	WT (excl. needles) *	1.25	2.0	2.4	1.8	1.5	1.5
	WT *	1.30	2.9	3.6	2.5	1.7	1.8
		Biomass	**N**	**P**	**K**	**Ca**	**Mg**
Norway Spruce Stand		**t·ha^{-1}**			**kg·ha^{-1}**		
remaining stand Δ 2013–2038 (WT) *		150	335	35	172	261	44
Σ thinnings	SO *	157	162	15	99	220	33
	WT (excl. needles) *	185	271	29	161	304	48
	WT *	201	486	51	245	372	63
Ratio Compared to SO							
thinnings	WT (excl. needles) *	1.18	1.7	1.9	1.6	1.4	1.5
	WT *	1.28	3.0	3.4	2.5	1.7	1.9

* SO: stem only, WT (exl. needles): whole tree without needles, WT: whole tree.

3.5. Evaluation of the Nutrient Budget as Influenced by Intensive Harvesting

For evaluation of the impact of the thinning scenarios of varying intensity on the nutrient regime of the study sites, annual rates of nutrient inputs and outputs were estimated and compared to the nutrient pools in the organic layer and the mineral soil in the rooting zone (Table 7). Both sites are characterized by relatively high atmospheric N inputs, which far exceed seepage loss and uptake by the trees. The result is a positive N balance on both stands regardless of the biomass extraction intensity, showing that the studied forest stands currently function as nitrogen sinks. The situation is fundamentally different for the base cations. Moderate atmospheric and weathering inputs are hardly sufficient to compensate for seepage loss and nutrient fixation in the biomass increment of the remaining stand. Even conventional SO harvesting would lead to negative nutrient balances and the more intensive biomass extraction scenarios would impair the nutrient balance even further. The only exception is K in the spruce stand, which would have a negative balance only under the WT scenario. Regardless of the intensity of biomass extraction, both sites are characterized by high seepage losses of base cations, in relation to the atmospheric and weathering inputs. In the case of Ca, soil available pools and seepage losses are both twice as high at the pine site compared to the spruce site, indicating that seepage losses of Ca are coupled to availability. On the other hand, this relation is much less pronounced in the case of Mg, and K does not show such a relation at all.

Table 7. Pools of total N and exchangeable K^+, Ca^{2+}, and Mg^{2+}, annual rates of nutrient inputs and outputs, as well as the nutrient balance under different biomass extraction scenarios (SO, WT excl. needles, WT) of the Scots pine stand and the Norway spruce stand.

	Scots Pine Stand				**Norway Spruce Stand**			
	N	K^+	Ca^{2+}	Mg^{2+}	N	K^+	Ca^{2+}	Mg^{2+}
Soil pools		kg·ha^{-1}				kg·ha^{-1}		
	2955	53	263	13	3599	172	127	34
	N	K	Ca	Mg	N	K	Ca	Mg

Table 7. *Cont.*

		Scots Pine Stand				Norway Spruce Stand			
Inputs		kg·ha^{-1}·year^{-1}				kg·ha^{-1}·year^{-1}			
Deposition		19.3	2.1	3.3	0.7	36	4.8	4.9	1.3
Weathering			4	9.8	0.5		7.6	7.5	1.2
Outputs		kg·ha^{-1}·year^{-1}				kg·ha^{-1}·year^{-1}			
Seepage		1.5	3.1	15.5	3.2	1.9	2.9	7	3.9
Uptake and storage in ingrowth		6.8	2.8	5.4	0.9	9.6	4.9	7.5	1.3
Thinning	SO	2.3	1.1	3.2	0.5	4.6	2.8	6.3	0.9
	WT excl. needles	4.5	2.0	4.8	0.8	7.7	4.6	8.7	1.4
	WT	6.6	2.8	5.4	0.8	13.9	7.0	10.6	1.8
Balance		kg·ha^{-1}·year^{-1}				kg·ha^{-1}·year^{-1}			
	SO	8.7	−0.9	−11.0	−3.4	19.9	1.8	−8.3	−3.6
	WT excl. needles	6.6	−1.8	−12.6	−3.7	16.8	0.0	−10.8	−4.0
	WT	4.4	−2.6	−13.2	−3.8	10.6	−2.4	−12.7	−4.5

4. Discussion

In this study we simulated relatively heavy thinnings in order to sustain stand stability to adapt the stands to climate change in the long term, and make use of the high forest productivity [28,29], which is accelerated by high atmospheric N inputs of about 19.3 and 36.0 kg·ha·year^{-1} at the pine and spruce site, respectively. The large difference in productivity between pine and spruce is both a species and a site effect, because the less demanding pine stands are usually grown on the least productive forest sites [19].

The biomass functions we established in order to model the mass of each aboveground compartment were easy to apply and fit our data very well. Only for the tree top wood of spruce and the dead branches, the R^2 was slightly lower than for the other compartments, probably because the tree top wood is a somewhat artificially defined compartment and the retention of dead branches on a tree depends on factors other than the tree's DBH, such as the actual stand density in the area surrounding the respective tree. Nevertheless, since these two compartments play a minor role for addressing the questions raised in this paper, and the R^2 was still sufficient, we retained the equations for use. The drawback of the biomass functions we established is that they are stand specific, and can therefore only be applied for the DBH range for which they were calibrated. As a result, we concentrated our study on just the thinning phase. In order to create more widely applicable biomass functions, more trees with a wider range of DBH, and from stands representing a wider range of productivity and stand density, would need to be measured. The biomass equations would then need to account for this greater variability by incorporating further explanatory variables such as height and stand density, in addition to the DBH [30].

One option proposed to increase the harvested biomass, and keep nutrient exports relatively low at the same time, is to leave tree tops in the forest for one year to allow the needles to fall off before collecting the tree tops (WT excl. needles scenario) [7,20]. The different pattern of crown biomass allocation between pine and spruce, with a greater share of branches in pine trees versus needles in spruce trees, shows that this method would lead to a greater biomass loss in spruce than in pine trees, when compared to the WT scenario. With respect to biomass feedstock quantities, this procedure would be more viable in pine than in spruce stands. If biomass feedstock quality is also considered, it would be preferable in any case to exclude the needles, as wood is a higher quality feedstock in terms of particle size distribution when chipping at the forest industries [3], as well as the behavior in the burning process.

The nutrient contents in the aboveground biomass compartments match with the findings of previous studies, as far as the compartments are comparable. Jacobsen et al. [31] performed nutrient analyses that are partly comparable, and found similar nutrient contents in the stem wood, bark, needles, and branches of pine and spruce trees. The nutrient contents reported by Weis and Göttlein [9] in the needles, bark, and wood of spruce trees are also within the range of our findings.

Due to the rough estimation method of weathering and the utilization of deposition and seepage values from similar and close-by sites (but not exactly the study sites), the nutrient balance should be interpreted with some caution. Nevertheless, it is still useful for evaluating the impact of biomass, and thus nutrient extraction, in the different thinning scenarios.

Our findings confirm our first hypothesis, that intensive harvesting scenarios impose a strong negative effect on the nutrient balance of forest stands even in the thinning stage. We demonstrated that intensive WT and WT (exc. needles) harvesting causes fairly high nutrient exports in the thinning phase of the trial sites. The biomass gain is far lower than the nutrient expenses, as the biomass gain is only 1.18 to 1.30 times compared to SO, but the ratio of nutrient losses is 1.4 to 3.6 compared to SO. The increase of nutrient losses from SO to WT harvesting are greater for N and P compared to the base cations, reflecting the over proportional abundance of N and P in the crown material, especially in the physiologically active needles. Yet the impact on the site-specific nutrient sustainability is far greater for the base cations than for N, because of excess atmospheric N inputs. We unfortunately have no data for the nutrient balance of P, but as P inputs into the forest ecosystem by weathering and deposition are usually low, a rather negative P balance similar to that of the base cations can be assumed. High seepage losses contribute strongly to the negative nutrient balance of the base cations. The seepage losses of base cations result from sulfur depositions during the 1970s to 1990s, which were greatly reduced by the end of the last century [32]. However, SO_4^{2-} from accumulated S pools still gets washed out of the soil profile, coupled with base cations to neutralize the charge [33]. This leads to negative nutrient balances for Ca^{2+} and Mg^{2+} already at the SO scenario, which decreases further in the WT (excl. needles) and the WT scenario, when K^+ also becomes negative.

According to our findings, we reject our second hypothesis, according to which the negative impact of intensive harvesting is greater in highly productive stands than in less productive stands, due to larger absolute amounts of removed biomass, and thus nutrients. In our study, the higher stand productivity of the spruce stand corresponded with a higher nutrient demand for uptake and storage, as well as higher nutrient losses due to biomass extraction, compared to the less productive pine stand. At the same time, these differences in productivity, and thus biomass-related nutrient fluxes, are balanced out by higher nutrient stocks and inputs through deposition (except for Ca), while seepage losses are equal to or even lower than the pine site. Thus, the relative impact of nutrient exports through intensive biomass extraction is almost equally severe in the spruce and pine stand, despite different absolute levels of biomass extraction.

Our findings should, however, be interpreted with some caution, as they are based on static assumptions regarding the development of forest growth, the nutrient concentrations in the biomass, and the weathering rate. In reality, increased nutrient scarcity due to intensive biomass extraction may cause reduced growth of the remaining stand, as has been shown in studies conducted in North American and Scandinavian forests [7,8,10], while other studies found no clear effect on tree growth [34,35]. A meta-analysis by Achat et al. [36] indicates an average growth reduction of 3%–7% after intensive biomass extraction. Declining pools of available nutrients may also cause reduced nutrient concentrations in the foliage of the remaining trees, which would also alter the nutrient balance. The nutrient balance is also known to be strongly influenced by the rate of mineral weathering [37], which is in practice very difficult to determine and could only be roughly estimated in our study. Furthermore, mineral weathering rates are not static, but mycorrhizal weathering may be accelerated if there are nutrient deficiencies [38]. Despite these uncertainties, our findings underline the possible nutrient balance risk of intensive biomass extraction from thinnings, which brings into question the nutrient balance sustainability of these intensive management practices.

Our study highlights that intensive harvesting scenarios like WT (excl. needles) and WT harvesting can have severe consequences for the nutrient balance of forest sites. Furthermore, intensive biomass removal is known to negatively affect the soil as the basis for biomass production. Reduced residue inputs reduce the organic carbon content [39] and mineralization rates and cause soil compaction and thus a reduced water holding capacity [36]. Based on the analysis of detrimental forest management practices (i.e., litter raking, fuelwood collection), the influence of biomass extraction on soil acidification was highlighted, because the uptake and storage of cations exceeds that of anions during tree growth and biomass buildup [40,41]. In order to mitigate the negative effects of intensive biomass extraction on the nutrient budget, the redistribution of wood ash is frequently discussed and has proven to be suitable to compensate for nutrient losses in forests, with the exception of N [13,42–45], and was previously found to be applicable in the form of bark-ash-pellets at the study sites [14].

5. Conclusions

Our study provides evidence that intensive biomass extraction may cause substantial losses of nutrients in pine and spruce stands, even in the thinning stage of stand development. This is amplified by the high productivity of both investigated stands, which is accelerated by high atmospheric N inputs. Despite the fact that the nutrient balance established in this study contains only a rough estimation of the weathering rate, it suggests that the budgets of base cations are already stressed due to high seepage losses caused by the still ongoing effects of very high S-driven acid deposition which occurred previously in the region. Therefore, the nutrient balance became negative even for SO harvesting in the case of Ca^{2+} and Mg^{2+}. Further intensification of biomass removal clearly impairs the nutrient budget, also for K^{+}, while the N balance remains positive even in the most intensive biomass removal scenario (WT). Even if a further development of the wood energy sector will increase the demand for forest biomass in the future, forest management should take the nutrient balance into account. Intelligent concepts to limit forest biomass extraction to a sustainable level need to be developed. At the same time, additional measures, such as wood ash recycling, may help to improve the nutrient balance of the base cations and P, without burdening the ecosystems with ever more N.

Acknowledgments: We acknowledge support by the Federal Ministry of Education and Research and the Open Access Publication Funds of the TU Dresden. The authors would like to thank Clemens Kurth for advice concerning the forest treatment and Henning Andreae, Frank Jacob, and Hendrik Horn for help with the biomass inventories and functions. We are very grateful for the valuable improvements of the manuscript provided by two anonymous reviewers.

Author Contributions: Christine Knust and Karl-Heinz Feger conceived and designed the experiments; Christine Knust and Karoline Schua performed the experiments; Christine Knust analyzed the data; Christine Knust wrote the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Fachagentur Nachwachsende Rohstoffe e.V. (FNR). *Basisdaten Bioenergie Deutschland 2014: Festbrennstoffe, Biokraftstoffe, Biogas*; FNR: Gülzow, Germany, 2014.
2. BMU; BMELV. *Nationaler Biomasseaktionsplan für Deutschland: Beitrag der Biomasse für Eine Nachhaltige Energieversorgung*; BMU, BMELV: Berlin, Germany, 2010.
3. Kizha, A.R.; Han, H.-S. Processing and sorting forest residues: Cost, productivity and managerial impacts. *Biomass Bioenergy* **2016**, *93*, 97–106. [CrossRef]
4. Wolfsmayr, U.J.; Rauch, P. The primary forest fuel supply chain: A literature review. *Biomass Bioenergy* **2014**, *60*, 203–221. [CrossRef]
5. Cremer, T. Bereitstellung von Holzhackschnitzeln Durch Die Forstwirtschaft: Produktivitätsmodelle als Entscheidungsgrundlage über Verfahren und Aushaltungsvarianten, Entwickelt auf der Basis Einer Metaanalyse. Ph.D. Thesis, University of Freiburg i.Br., Freiburg, Germany, 2008.
6. Vangansbeke, P.; de Schrijver, A.; de Frenne, P.; Verstraeten, A.; Gorissen, L.; Verheyen, K. Strong negative impacts of whole tree harvesting in pine stands on poor, sandy soils: A long-term nutrient budget modelling approach. *For. Ecol. Manag.* **2015**, *356*, 101–111. [CrossRef]

7. Egnell, G. Is the productivity decline in Norway spruce following whole-tree harvesting in the final felling in boreal Sweden permanent or temporary? *For. Ecol. Manag.* **2011**, *261*, 148–153. [CrossRef]
8. Walmsley, J.; Jones, D.; Reynolds, B.; Price, M.; Healey, J. Whole tree harvesting can reduce second rotation forest productivity. *For. Ecol. Manag.* **2009**, *257*, 1104–1111. [CrossRef]
9. Weis, W.; Göttlein, A. Nährstoffnachhaltige Biomassenutzung: Bei der Nutzung von Biomasse ist Vorsicht geboten: Nicht jeder Waldstandort verträgt den erhöhten Nährstoffentzug. *LWF Aktuell* **2012**, *90*, 44–47.
10. Helmisaari, H.-S.; Hanssen, K.H.; Jacobson, S.; Kukkola, M.; Luiro, J.; Saarsalmi, A.; Tamminen, P.; Tveite, B. Logging residue removal after thinning in Nordic boreal forests: Long-term impact on tree growth. *For. Ecol. Manag.* **2011**, *261*, 1919–1927. [CrossRef]
11. Clarke, N.; Gundersen, P.; Jönsson-Belyazid, U.; Kjønaas, O.J.; Persson, T.; Sigurdsson, B.D.; STUPAK, I.; Vesterdal, L. Influence of different tree-harvesting intensities on forest soil carbon stocks in boreal and northern temperate forest ecosystems. *For. Ecol. Manag.* **2015**, *351*, 9–19. [CrossRef]
12. Lassauce, A.; Lieutier, F.; Bouget, C. Woodfuel harvesting and biodiversity conservation in temperate forests: Effects of logging residue characteristics on saproxylic beetle assemblages. *Biol. Conserv.* **2012**, *147*, 204–212. [CrossRef]
13. Pitman, R.M. Wood ash use in forestry—A review of the environmental impacts. *Forestry* **2006**, *79*, 563–588. [CrossRef]
14. Knust, C.; Schua, K.; Göttlein, A.; Ettl, R.; Wolferstetter, T.; Feger, K.-H. Compensation of nutrient losses resulting from the intensified use of woody biomass using bark-ash-pellets. In *Bioenergy from Dendromass for the Sustainable Development of Rural Areas*; Butler Manning, D., Bemmann, A., Bredemeier, M., Lamersdorf, N., Ammer, C., Eds.; Wiley (Imprint), Inc.: Weinheim, Germany, 2015; pp. 269–286.
15. Demeyer, A.; Voundi Nkana, J.C.; Verloo, M. Characteristics of wood ash and influence on soil properties and nutrient uptake: An overview. *Bioresour. Technol.* **2001**, *77*, 287–295. [CrossRef]
16. Ingerslev, M.; Hansen, M.; Pedersen, L.B.; Skov, S. Effects of wood chip ash fertilization on soil chemistry in a Norway spruce plantation on a nutrient-poor soil. *For. Ecol. Manag.* **2014**, *334*, 10–17. [CrossRef]
17. Rademacher, P.; Schönfelde, E.; Meiwes, K.J. Elementgehalte in Baumkompartimenten von Fichte (*Picea abies* [L.] Karst), Kiefer (*Pinus sylvestris* [L.] Karst), Buche (*Fagus sylvatica* [L.] Karst), Eiche (*Quercus petraea und robur* [L.] Karst) und Douglasie (*Pseudotsuga menziesii* [L.] Karst). In *Möglichkeiten und Grenzen der Vollbaumnutzung: Ergebnisbericht (FKZ: 22015407)*; Nordwestdeutsche Forstliche Versuchsanstalt, Universität Göttingen: Göttingen, Germany, 2011; pp. 125–154.
18. Merino, A.; Balboa, M.A.; Rodríguez Soalleiro, R.; González, J.Á. Nutrient exports under different harvesting regimes in fast-growing forest plantations in southern Europe. *For. Ecol. Manag.* **2005**, *207*, 325–339. [CrossRef]
19. Tveite, B.; Hanssen, K.H. Whole-tree thinnings in stands of Scots pine (Pinus sylvestris) and Norway spruce (Picea abies): Short- and long-term growth results. *For. Ecol. Manag.* **2013**, *298*, 52–61. [CrossRef]
20. Zetterberg, T.; Olsson, B.A.; Löfgren, S.; Hyvönen, R.; Brandtberg, P.-O. Long-term soil calcium depletion after conventional and whole-tree harvest. *For. Ecol. Manag.* **2016**, *369*, 102–115. [CrossRef]
21. Jacobson, S.; Kukkola, M.; Mälkönen, E.; Tveite, B. Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. *For. Ecol. Manag.* **2000**, *129*, 41–51. [CrossRef]
22. Jacobson, S.; Kukkola, M.; Mälkönen, E.; Tveite, B.; Möller, G. Growth response of coniferous stands to whole-tree harvesting in early thinnings. *Scand. J. For. Res.* **1996**, *11*, 50–59. [CrossRef]
23. Döbbeler, H.; Alber, M.; Schmidt, M.; Nagel, J.; Schröder, J. *BWINPro—Programm zur Bestandesanalyse und Prognose: Handbuch zur Gemeinsamen Version von BWINPro und BWINPro-S*; Version 6.3; Nordwestetsche Forstliche Versuchsanstalt, Göttingen, Germany and TU Dresden, Lehrstuhl für Holzmeßkunde und Waldwachstum: Tharandt, Germany, 2011.
24. Andreae, H. (Staatsbetrieb Sachsenforst, Kompetenzzentrum Wald und Forstwirtschaft, Saxony, Germany). Personal communication, 2014.
25. Von Wilpert, K.; Bösch, B.; Bastian, P.; Zirlewagen, D.; Hepperle, F.; Holzmann, S.; Puhlmann, H.; Schäffer, J.; Kändler, G.; Sauter, U.H. Biomasse-Aufkommensprognose und Kreislaufkonzept für den Einsatz von Holzaschen in der Bodenschutzkalkung in Oberschwaben. *Ber. Freibg. Forstl. Forsch.* **2011**, *87*, 155.
26. Hildebrand, E.E.; Wilpert, K. von; Kohler, M. *Ionenspeicher- und Mobilisierungspotentiale im Skelett und Feinboden des Standortes Conventwald bei Unterschiedlichen Depositionsszenarien: Abschlussbericht, FKZ PEF196009 und PEF 196010, BWC 99 009 und BWC 99010*; Universität Freiburg und Forstliche Versuchs- und Forschungsanstalt: Freiburg, Germany, 2000.

27. Rademacher, P. Contents of nutrient elements in tree components of economical important species in relation to their residual utilisation. *Holz Werkst.* **2005**, *63*, 285–296. [CrossRef]
28. Eisenhauer, D.-R.; Sonnemann, S. Waldbaustrategien unter sich ändernden Umweltbedingungen: Leitbilder, Zielsysteme und Waldentwicklungstypen. *Waldökol. Landsch. Nat.* **2009**, *8*, 71–88.
29. Fischer, H.; Wagner, S. Silvicultural responses to predicted climate change scenarios. *J. For. Ecol. For. Manag.* **2009**, *2*, 12–23.
30. Rumpf, S.; Nagel, J.; Schmidt, M. Biomasseschätzfunktionen von Fichte (*Picea abies* [L.] Karst), Kiefer (*Pinus sylvestris* [L.] Karst), Buche (*Fagus sylvatica* [L.] Karst), Eiche (*Quercus robur und petraea* [L.] Karst) und Douglasie (*Pseudotsuga menziesii* [L.] Karst) für Nordwestdeutschland. In *Möglichkeiten und Grenzen der Vollbaumnutzung: Ergebnisbericht (FKZ: 22015407)*; Nordwestdeutsche Forstliche Versuchsanstalt, Universität Göttingen: Göttingen, Germany, 2011; pp. 25–123.
31. Jacobsen, C.; Rademacher, P.; Meesenburg, H.; Meiwes, K.J. Gehalte chemischer Elemente in Baumkompartimenten: Literaturstudie und Datensammlung. In *Berichte des Forschungszentrums Waldökosysteme, Reihe B*; Universität Göttingen: Göttingen, Germay, 2003.
32. Oulehle, F.; Hofmeister, J.; Cudlín, P.; Hruška, J. The effect of reduced atmospheric deposition on soil and soil solution chemistry at a site subjected to long-term acidification, Načetín, Czech Republik. *Sci. Total Environ.* **2006**, *370*, 532–544. [CrossRef] [PubMed]
33. Wunderlich, S.; Raben, G.; Andreae, H.; Feger, K.-H. Schwefel-Vorräte und Sulfat-Remobilisierungspotential in Böden der Level-II-Standorte Sachsens. *AFZ-Der. Wald* **2006**, *60*, 762–765.
34. Kaarakka, L.; Tamminen, P.; Saarsalmi, A.; Kukkola, M.; Helmisaari, H.-S.; Burton, A.J. Effects of repeated whole-tree harvesting on soil properties and tree growth in a Norway spruce (*Picea abies* (L.) Karst.) stand. *For. Ecol. Manag.* **2014**, *313*, 180–187. [CrossRef]
35. Roxby, G.E.; Howard, T.E. Whole-tree harvesting and site productivity: Twenty-nine northern hardwood sites in central New Hampshire and western Maine. *For. Ecol. Manag.* **2013**, *293*, 114–121. [CrossRef]
36. Achat, D.L.; Deleuze, C.; Landmann, G.; Pousse, N.; Ranger, J.; Augusto, L. Quantifying consequences of removing harvesting residues on forest soils and tree growth—A meta-analysis. *For. Ecol. Manag.* **2015**, *348*, 124–141. [CrossRef]
37. Klaminder, J.; Lucas, R.W.; Futter, M.N.; Bishop, K.H.; Köhler, S.J.; Egnell, G.; Laudon, H. Silicate mineral weathering rate estimates: Are they precise enough to be useful when predicting the recovery of nutrient pools after harvesting? *For. Ecol. Manag.* **2011**, *261*, 1–9. [CrossRef]
38. Vadeboncoeur, M.A.; Hamburg, S.P.; Yanai, R.D.; Blum, J.D. Rates of sustainable forest harvest depend on rotation length and weathering of soil minerals. *For. Ecol. Manag.* **2014**, *318*, 194–205. [CrossRef]
39. Kreutzer, K. Ecological problems of full tree utilization. *Forstwiss. Cent.* **1979**, *98*, 298–308. [CrossRef]
40. Glatzel, G. The impact of historic land use and modern forestry on nutrient relations of Central European forest ecosystems. *Fertil. Res.* **1991**, *27*, 1–8. [CrossRef]
41. Feger, K.H. Bedeutung von ökosysteminternen Umsätzen und Nutzungseingriffen für den Stoffhaushalt von Waldlandschaften (Habilitationsschrift)—*Freiburger Bodenkundliche. Abhandlungen* **1993**, *31*, 237.
42. Ingerslev, M.; Skov, S.; Sevel, L.; Pedersen, L.B. Element budgets of forest biomass combustion and ash fertilisation—A Danish case-study. *Biomass Bioenergy* **2011**, *35*, 2697–2704. [CrossRef]
43. Kikamägi, K.; Ots, K.; Kuznetsova, T. Effect of wood ash on the biomass production and nutrient status of young silver birch (Betula pendula Roth) trees on cutaway peatlands in Estonia. *Ecol. Eng.* **2013**, *58*, 17–25. [CrossRef]
44. Saarsalmi, A.; Smolander, A.; Kukkola, M.; Moilanen, M.; Saramäki, J. 30-year effects of wood ash and nitrogen fertilization on soil chemical properties, soil microbial processes and stand growth in a Scots pine stand. *For. Ecol. Manag.* **2012**, *278*, 63–70. [CrossRef]
45. Solla-Gullón, F.; Santalla, M.; Rodríguez-Soalleiro, R.J.; Merino, A. Nutritional status and growth of a young Pseudotsuga menziesii plantation in a temperate region after application of wood-bark ash. *For. Ecol. Manag.* **2006**, *237*, 312–321. [CrossRef]