Forest Ecology and Management 348 (2015) 124–141

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Review

Quantifying consequences of removing harvesting residues on forest soils and tree growth – A meta-analysis

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A R T I C L E I N F O

Article history:
Received 12 January 2015
Received in revised form 25 March 2015
Accepted 27 March 2015

Keywords:
Forest
Harvesting residues
Modern fuelwood
Nutrient outputs
Soil fertility
Tree growth

A B S T R A C T

Increasing attention is being paid to using modern fuelwood as a substitute for fossil energies to reduce CO_2 emissions. In this context, forest biomass, particularly harvesting residues (branches), and stumps and associated coarse roots, can be used to supply fuelwood chains. However, collecting harvesting residues can affect soil properties and trees, and these effects are still not fully understood. The main objective of the present study was to compile published data worldwide and to quantify the overall effects of removing harvesting residues on nutrient outputs, chemical and biological soil fertility and tree growth, through a meta-analysis. Our study showed that, compared with conventional stem-only harvest, removing the stem plus the harvesting residues generally increases nutrient outputs thereby leading to reduced amounts of total and available nutrients in soils and soil acidification, particularly when foliage is harvested along with the branches. Losses of available nutrients in soils could also be explained by reduced microbial activity and mineralization fluxes, which in turn, may be affected by changes in organic matter quality and environmental conditions (soil compaction, temperature and moisture). Soil fertility losses were shown to have consequences for the subsequent forest ecosystem: tree growth was reduced by 3–7% in the short or medium term (up to 33 years after harvest) in the most intensive harvests (e.g. when branches are exported with foliage). Combining all the results showed that, overall, whole-tree harvesting has negative impacts on soil properties and trees that may have an impact on the functioning of forest ecosystems. Practical measures that could be taken to mitigate the environmental consequences of removing harvesting residues are discussed.

Contents

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http://dx.doi.org/10.1016/j.foreco.2015.03.042
0378-1127/

1. Introduction

In Western countries, the use of traditional fuelwood was low - or decreasing- until the end of the 1970s (Fig. 1). Then, there was an interest in using modern fuelwood, mainly due to oil crises in 1973 and 1979 (fuelwood demand increased in parallel with oil price); locally other reasons contributed to this increased demand (e.g. decision to phase out nuclear energy in 1980 in Sweden). To supply fuelwood chains, foresters developed alternative cropping systems (such as short rotation coppices, Ranger and Nys, 1986) and adapted harvest practices (Nicholls et al., 2009; Diaz-Yanez et al., 2013). One of the adaptations proposed was to remove those tree components that were conventionally left in the forest: the so-called “harvesting residues” such as branches, foliages, tree tops, small diameter trees and technically damaged trees (e.g. Nunez-Regueira et al., 2005; Diaz-Yanez et al., 2013). In Europe, the new harvest practices included the integration of a second passage for removing harvesting residues (through better planning and logistics for extraction). In North America, harvesting systems in which residues are left at roadside (“full-tree-to-roadside” systems; Morris et al., 2014) have been developed in the late 1980s for economic and safety purposes. There was therefore no new harvesting system as fuelwood is a by-product of residue piles and not a primary objective.

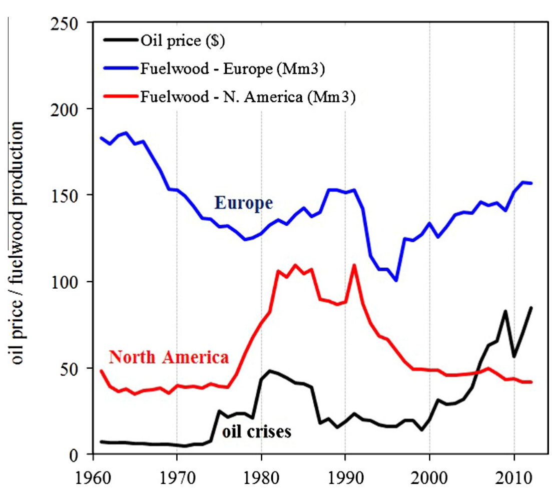

Fig. 1. Historical trends in oil price and fuelwood use in Europe and North America. Sources: oil price = World Bank Commodity Price Data (http://knoema.com); fuelwood = FAOSTAT (http://faostat.fao.org). Oil price in real 2005 US $ for crude oil. Fuelwood includes both traditional and modern fuelwoods. In Europe, the use of traditional fuelwood have decreased until the end of the 1970s. Then, there was a development of modern fuelwood and new interest in traditional fuelwood.

Early studies were carried out to assess possible environmental impacts of exporting harvesting residues (e.g. Tamm, 1969; Mann, 1984; Thompson et al., 1986; Mann et al., 1988; see also early studies in Scandinavia cited by Tveite and Hanssen (2013)). Experiment networks were also established, such as the North American long-term soil productivity study (LTSP) network (launched in 1989; Powers et al., 2005), the experiment network in Scandinavia (established in the 1970s and 1980s; Helmisaari et al., 2011; Tveite and Hanssen, 2013) or the Site Management and Productivity in Tropical Plantation Forests network (managed by the Center for International Forestry Research (CIFOR) since 1995; Nambiar et al., 2004; Nambiar, 2008). However, the demand for fuelwood decreased in the early 1990s following the collapse of the price of oil in the middle of the 1980s (Fig. 1). Interest in harvesting residues and related scientific research and funding consequently decreased. Since 2000, the emergence of developing economies (BRICS countries: Brazil, Russia, India, China and South Africa) triggered a long-term increase in the demand for energy causing a major trend toward an increase in the price of oil (Fig. 1). In the context of expensive oil and of climate change (IPCC, 2007), European countries introduced policies to promote the substitution of fossil fuel by renewable energies like fuelwood (European Commission, 2000) to enable national energy security (reduced oil dependence) and to decrease the emission of greenhouse gases (Stupak et al., 2007). One consequence of these policies was to revive interest in forest harvesting residues as a possible source of energy (Nicholls et al., 2009). Displacing fossil fuels is also the result of international competition for forest products, which led to diversification into new markets such as energy. It also should be noted that whole-tree harvesting in North America was mainly driven by the evolution of equipment for economic and safety purposes as explained before.

Already in the 1980–1990s in North America and even earlier in Scandinavia, some authors reported that collecting harvesting residues may negatively impact forest ecosystems (Tamm, 1969; Mann, 1984; Thompson et al., 1986; Mann et al., 1988; Johnson et al., 1991) because this kind of biomass (branches, foliage and tops) contains large amount of nutrients (Fahey et al., 1991; Yanai, 1991, 1998; Son and Gower, 1992) that are useful for the sustainability of ecosystem functioning and functions (Ranger and Turpault, 1999). Recently, the possible impacts of exporting harvesting residues were reviewed (Lattimore et al., 2009; Thiffault et al., 2011; Wall, 2012). Reviews and meta-analyses have also been carried out for LTSP installations in North America

(Powers et al., 2005; Fleming et al., 2006; Ponder et al., 2012). These useful studies confirmed that these practices can have negative effects on forest soils and tree growth. In the present study, we aimed to go one step further as our first objective was to quantify the overall impacts of removing harvesting residues by comparing whole tree harvesting with conventional stem-only harvesting using data published world-wide. We assessed the impacts on a large number of soil properties and tree growth variables. To this end, we compiled published data and analyzed two datasets using a meta-analysis approach. A first dataset on nutrient stocks in the different tree components and soil profiles was used to quantify the increases in nutrient outputs (exportations with harvested biomass) due to removing harvesting residues, and to compare nutrient outputs with nutrient stocks in soils (hereafter referred to as "nutrient stocks" dataset). Another dataset (referred to as "environmental impacts" dataset) was used to identify and quantify the impacts on soil fertility (e.g. soil nutrient stocks, organic matter quality, biological activity) and the growth of subsequent forest stands. Our second objective was to evaluate the effect of the intensity of residue harvest (e.g. harvest of branches vs. branches + foliage) and the potential causes of heterogeneity in the response of the soils and of the trees (e.g. soil type, inherent soil fertility, time elapsed since harvesting) with the aim of identifying practical measures that could be used to mitigate the environmental consequences of removing harvesting residues.

2. Materials and methods

2.1. Data acquisition

We used the ISI Web of Science database and holistic non-specific queries (Pullin and Stewart, 2006; Augusto et al., 2013). Then we used inclusion and exclusion criteria to select publications that reported relevant data. First, we selected publications with data on trees and related soil nutrient stocks so that we could determine nutrient removals with different intensities of biomass harvesting and compare this with soil nutrient capital. We therefore identified publications using keywords related to the amounts of nutrient in the tree components (e.g. "nutrient" or "nitrogen" or "phosphorus"; "content" or "concentration" or "stock" or "amount"; "forest" or "woodland" or "tree") and compiled a "nutrient stocks" dataset. To be included in the dataset, the studies had to satisfy the following criteria: (1) nutrient amounts in the tree components had to be quantified by destructive sampling (estimations based on published allometric relationships were excluded); (2) nutrient stocks (in kg ha^{-1}) in the tree components had to be included in the studies or calculated using nutrient concentrations (e.g. in mg g^{-1}) and biomass values (in Mg ha^{-1}; i.e. studies that reported only nutrient concentrations could not be used), (3) stem data had to be given separately from the other tree components to enable comparison among harvests (see types of harvest treatments in Fig. 2 and details in Section 2.2.1; studies that only reported nutrient stocks in total tree biomass could not be used), (4) soil nutrient data were included only when they corresponded to stocks. This selection stage led to a list of 230 primary articles representing 749 case studies (a case study was defined as the unique combination of one site and one tree species; see references list in Supplementary Information).

Secondly, we identified publications with data on the impacts of different intensities of biomass harvesting by using keywords related to the collection of harvesting residues (e.g. "whole-tree" or "slash" or "residues" or "debris"; "harvesting" or "management") and compiled an "environmental impacts" dataset. Because we wanted to assess the impacts of removing harvesting residues on a large number of physical and chemical soil properties

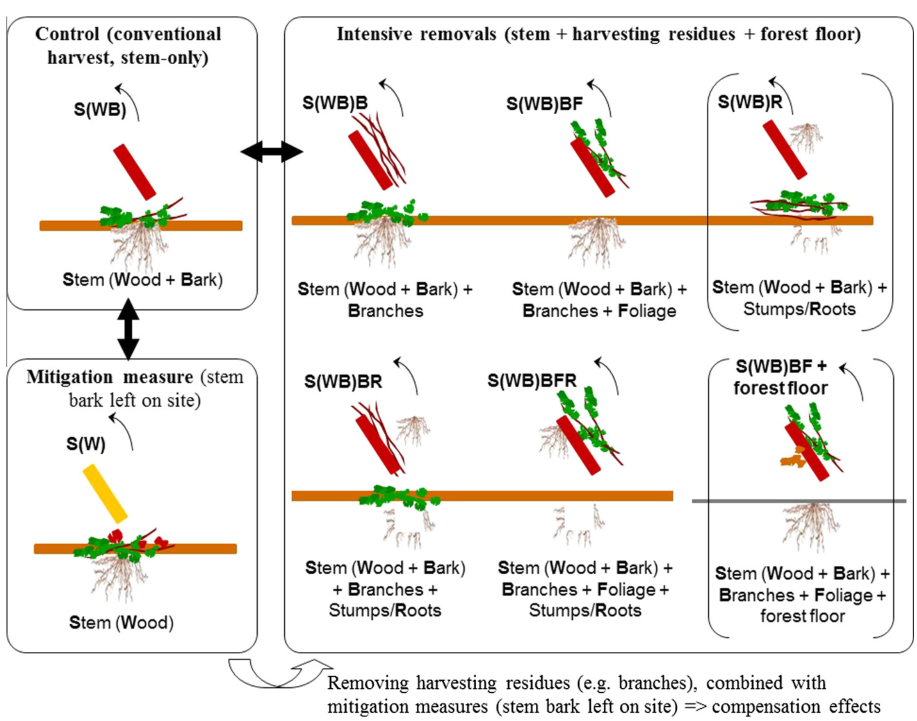

Fig. 2. Main harvest treatments considered in this study. Conventional stem-only harvest (S(WB), control) compared to different types of intensive removals or to stem wood harvest (S(W), stem bark left on site; mitigation measure). Treatments in brackets (removing stumps and associated coarse roots, with branches left on site: treatment S(WB)R; removing harvesting residues and forest floor: S(WB)BF + forest floor) are only included in the "environmental impacts" dataset. The "environmental impacts" dataset also includes case studies in which intensive removals are compared to *double slash* treatment (i.e. stem-only harvest with harvesting residues left on site and inputs of residues from an intensive removal treatment). The removal of forest floor and the *double slash* treatment were included in some experiments mainly to create large variations in treatment impacts and for theoretical reasons.

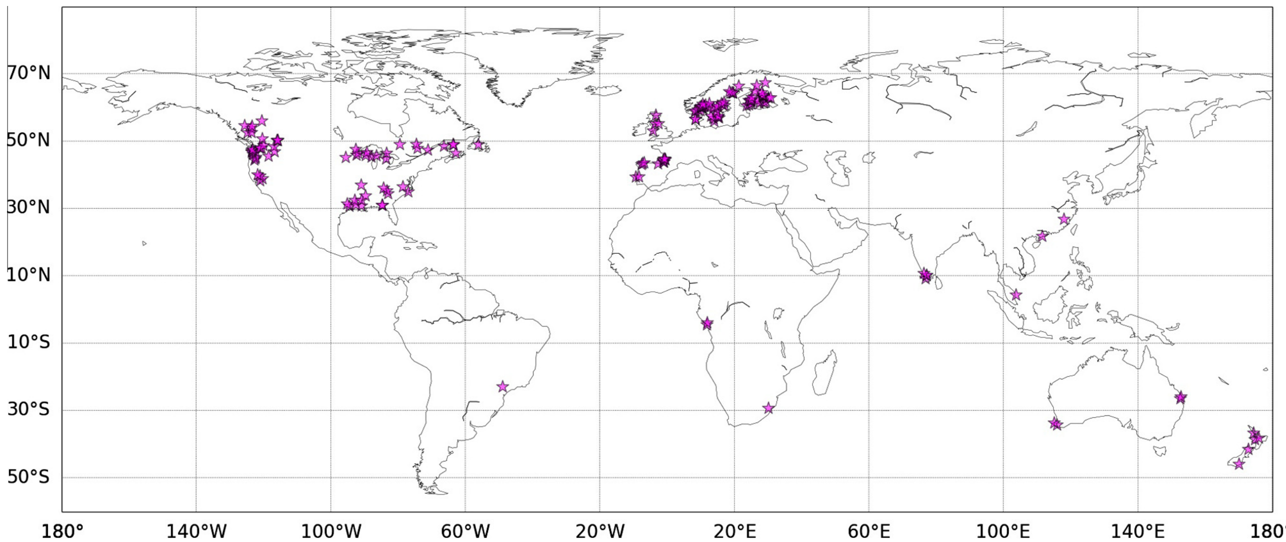

Fig. 3. Spatial distribution of the study sites ("environmental impacts" dataset). The dataset includes 168 experimental sites distributed as follow: 43% in North America (29% in USA, 14% in Canada, mainly from the "North American long-term soil productivity" study (LTSP network)), 1% in South America, 45% in Europe (35% from experiment network in Scandinavia), 4% in Asia, 2% in Africa and 5% in Oceania. Several sites in the tropics are from the "Site Management and Productivity in Tropical Plantation Forests" network (CIFOR project). Sites were mostly under temperate climate (40%) and cold climate (51%) based on the Koeppen climate classes.

(e.g. carbon (or organic matter) and nutrient concentrations (or stocks) in soils, soil pH), environmental conditions (e.g. soil temperature and moisture), biological soil properties (e.g. fauna, microbiological and enzymatic activities, decomposition processes) and tree variables (nutrient status, survival and growth), we focused our selection criteria on harvest treatments rather than on data themselves. Removing harvesting residues can also have consequences on water quality and biodiversity (e.g. Lattimore et al., 2009). These effects were however not assessed in the present study.

We selected studies that compared the conventional stem-only harvest with the removing of the stem plus harvesting residues (i.e. branches, foliage), stumps and associated coarse roots and sometimes the forest floor (Powers et al., 2005; Mariani et al., 2006; Thiffault et al., 2011; Wall, 2012). Although the forest floor can be used as fuelwood (e.g. in South Europe; Nunez-Regueira et al., 2005), its removal was generally included in experiments to create large variation in treatment impacts for theoretical reasons (e.g. in North America, LTSP network). It should also be mentioned that, contrarily to other treatments, stump removal includes soil disturbance that could also affect soil properties and tree growth (Egnell et al., 2015). To be included into the database, treatments had to be compared in experimental designs or in adjacent stands (paired sites with similar soil conditions and vegetation). This selection led to a list of 140 articles and a total of 168 experimental forest sites for the "environmental impacts" dataset. Because these studies were not all based on the same response variables, the number of case studies depended on the soil or tree variable studied and ranged from three to 57 (see lists of references in Supplementary Information).

While collecting the data from the publications, we used the DataThief III (version 1.5) software to extract the values from figures (when these were not given in tables).

The studies used for the compilation of both datasets were conducted worldwide (see Fig. 3 for the "environmental impacts" dataset and Fig. S1 in Supplementary Information for the "nutrient stocks" dataset). But, most of the sites were located in the northern hemisphere (USA, Canada and Europe) under temperate or cold climates. The "environmental impacts" dataset included soil and tree response data up to 33 years after harvesting (see as an example the complete dataset for the effects of removing harvesting residues on tree growth; Fig. S2 in Supplementary Information).

2.2. Data handling and statistics

2.2.1. Estimation of nutrient outputs ("nutrient stocks" dataset)

Nutrient outputs were estimated for the conventional harvest treatment (stem-only harvest, including wood and bark (S(WB)); i.e. control treatment) and each of the intensive harvest treatments (stem (wood + bark) + different harvesting residues; Fig. 2). The harvesting residues we considered in this study included branches and stumps (with attached coarse roots), because both can be used to produce fuelwood (e.g. Diaz-Yanez et al., 2013). We assessed the effect of exporting branches with or without foliage (nutrient rich component; Santa Regina, 2000; Ponette et al., 2001; Augusto et al., 2008a), depending on harvest conditions (e.g. with or without a delay of 1–3 months between delimbing and harvesting the branches, or more efficiently a delay between tree cutting and delimbing, which would allow the foliage to dry out and fall off the branches; Nord-Larsen, 2002; Stupak et al., 2008). Finally, the intensive harvest treatments we studied correspond to different combinations of harvested residues (Fig. 2). Some harvest treatments were not included in the "nutrient stocks" dataset. This was the case of the treatments S(WB)R (the stumps and coarse roots were harvested, while the branches were left on site) and S(WB)BF + forest floor (removal of harvesting residues and of the forest floor) which were assessed in the "environmental impacts" dataset only.

We also estimated nutrient outputs when only stem wood was harvested (stems debarked and the bark left on site); we tested this harvest treatment as a possible measure to reduce nutrient outputs because bark is known to concentrate large amounts of nutrients, particularly Ca (André et al., 2010; André and Ponette, 2003). This treatment corresponds to a real harvesting method, which is used, for instance, in Congolese commercial plantations (Laclau et al., 2010).

Nutrient outputs were estimated in two steps. In the first step, potential outputs were estimated assuming that tree components were totally removed; these estimates are defined here as *theoretical values calculated using 100% harvest rates*. However, our preliminary analysis revealed differences between these potential values and observed nutrient output data (potential values could be significantly higher than the observed values; based on data from Johnson et al. (1982), Johnson and Todd (1987), Tritton et al. (1987), Fraysse and Cotten (2008)). Indeed, several studies have shown that in practice, not all harvesting residues can be collected (see harvest rates in Eriksson (1993), Bergquist et al. (1999), Egnell and Leijon (1999), Nurmi and Hillebrand (2001), Cacot et al. (2007), Fraysse and Cotten (2008), Wall (2008), Wall and Hytönen (2011), Augusto et al. (2015); see also the recent review written by Thiffault et al. (2014)). Therefore, in the second step, we used harvest rate values that simulated incomplete harvests. Because harvest rates differed among studies (e.g. Thiffault et al., 2014), we used mean values based on all references cited above: 100% of stem wood, 20–80% of stem bark depending on the harvest method used (80% when a chainsaw was used; down to 20% as potential value when logging machines were used, as these could cause large quantities of bark to detach from the stems), 60% of stumps and associated roots, 50% of branches of coniferous tree species and 60% of branches of broadleaf tree species, and 0–40% of foliage depending on the harvest conditions (down to 0% of leaves and 10% of needles as potential values, after a delay between cutting the stem and harvesting the branches, which allowed the foliage to dry and fall off the branches; 0% of leaves when branches were harvested in fall or winter; 40% when these conditions were not met). Theoretical changes using 100% harvest rates were estimated for several macronutrients (N, P, K, Ca, Mg and S) and micronutrients (Na, Fe, Mn, Zn, Cu, Ni), while theoretical changes based on realistic rates were estimated only for macronutrients.

Finally, for each harvest treatment, theoretical N, P, K, Ca and Mg outputs were compared to the nutrient stocks in soils (stocks of total N and P, available P and exchangeable K, Ca and Mg) to assess potential impacts on chemical soil fertility (Tamminen et al., 2012). It should be noted that available/exchangeable soil nutrient data is more relevant than total soil nutrient data to assess potential impacts; there is however no data on available N in the dataset. The mean thickness of the soil profiles we analyzed was 84 ± 21 cm.

2.2.2. Data classification

For both datasets, data were primarily classified as a function of the type of harvest treatment, as shown in Fig. 2. In addition to the general effects of the harvest of each type of residues, we also assessed possible causes of heterogeneity. To this end, we collected variables as possible predictors and classified our data accordingly.

For the "nutrient stocks" dataset, data were classified based on vegetation (mainly the two classes studied: coniferous and broadleaf trees). We also assessed the effect of removing harvesting residues on nutrient outputs in relation with stand characteristics (tree age, stem biomass, tree height and diameter (DBH)).

For the "environmental impacts" dataset, because impacts on soil properties generally depend on soil depth, we split our data into four soil layers: wood debris ("WD"), forest floor ("FF") and two mineral soil layers. The mineral soil layers were classified with respect to the sampling depth: top soil ("Top" refers to soil depth <20 cm) and deep soil ("Deep" refers to a soil depth >20 cm). Data were also classified according to the methods of soil analysis used (e.g. quantification of total or only plant-available nutrients in soils, concentration or stocks of nutrients). Variations also exist among methods used to assess exchangeable/available nutrients and data are generally not directly comparable among studies. However, the metric used in the present study (response ratio) enabled avoiding any effect of methodological differences (see next section). Data were also classified based on possible predictors: time elapsed after harvesting (two classes: 0–10 years and >10 years), tree species in the subsequent forest stands (coniferous vs. broadleaf tree species), location (there were enough data only to compare Europe and North America), Koeppen climate classes (determined based on geographical coordinates; http://koeppen-geiger.vu-wien.ac.at/present.htm) and soil types (based on the FAO classification). When not specified in the publications, we determined the FAO soil type based on soil description and properties, or on correspondences among soil classification systems (e.g. Esu, 2010).

2.2.3. Calculation of the magnitude of change

To make it possible to compare publications across a wide range of experimental conditions, we calculated the magnitude of change (i.e. percent change (higher or lower); Elser et al., 2007; Nave et al., 2010; Wei et al., 2014) in nutrient outputs ("nutrient stocks" dataset) and soil and tree variables ("environmental impacts" dataset) in response to the removal of harvesting residues:

$$\text{e.g. Percent change} = \left(\frac{\mathrm{S(WB)BF} - \mathrm{S(WB)}}{\mathrm{S(WB)}}\right) \times 100 \tag{1}$$

Although comparisons between treatments are presented as the arithmetic difference (see Eq. (1)), statistics were carried out using the relative response metric (Nave et al., 2010; Augusto et al., 2013), as it is generally the case in meta-analyses:

$$\text{e.g. Relative response} = \log\left(\frac{\mathrm{S(WB)BF}}{\mathrm{S(WB)}}\right) \tag{2}$$

Values of the relative response close to 0 are associated with a negligible effect of the intensive harvest treatments tested. Negative and positive values indicate negative and positive effects, respectively. To test the significance of the effect of each intensive harvest treatment, the relative response was compared to 0 using one sample *t*-test. Comparisons among classes of explanatory variables were also assessed using a generalized linear model and the Bonferroni *t*-test. Statistics were performed using SYSTAT (version 10, Software Inc., Chicago, IL, USA) software.

In meta-analyses, the relative response metric can be weighted by the precision of the study (i.e. using variances and sampling sizes; Gurevitch and Hedges, 1999). Because variance estimates were not available in many studies, we used an unweighted metric. According to Gurevitch and Hedges (1999), an unweighted metric can be used in meta-analysis without severely hampering test validity. Contrary to many previous meta-analyses, we avoided pseudo-replicates. Indeed, the number of values in a given publication depends on the quantity of repeated measurements (e.g. several sampling dates). Because the number of values varied greatly among the publications, assuming that each value was an independent case study would lead to different statistical weights and consequently would bias the meta-analysis (Gurevitch and Hedges, 1999; Ioannidis, 2010). When several relative responses corresponded to one case study, to avoid pseudo-replications, we calculated a single mean value. When assessing the effect of elapsed time after harvesting, sequential data of a given case study were split into different classes (0–10 and >10 year) and a mean value per class was calculated. Here, we define a case study as being based on one geographical location, the type of removal of harvesting residues, and the tree species in the forest concerned.

Another difficulty encountered in meta-analyses is publication bias (Gurevitch and Hedges, 1999; Ioannidis, 2010). Publication bias occurs when the probability of publication depends on the statistical significance, magnitude or direction of the effect and causes a bimodal distribution of the number of studies (e.g. low frequency associated with low values of relative response and high frequencies with high values of relative response). Here, we generally found unimodal distributions of the case studies in relation to the values of relative response (see examples in Fig. S3 in

Supplementary data). We consequently concluded that there was no publication bias.

3. Results

3.1. Effects of removing harvesting residues on nutrient outputs ("nutrient stocks" dataset)

3.1.1. Theoretical changes in nutrient outputs

Compared with conventional S(WB) harvest with chainsaw logging (with 80% of bark removed), S(WB) harvest with machine logging (with only 20% of bark removed) enabled reductions in nutrient outputs of up to −38% for Ca (Table 1; theoretical reductions calculating using 100% harvest rates were up to −56%; see also Tables S1 and S2).

Changes in nutrient outputs caused by removing the stem plus harvesting residues and calculated using realistic harvest rates reached +128% and were significantly lower than the theoretical values calculated using 100% harvest rates (up to 4 times lower; see comparisons in Table 1 and S2). In general, the magnitude of change increases with an increase in the number of tree components harvested (% change in S(WB)B < % change in S(WB)BF ⩽ % change in S(WB)BR < % change in S(WB)BFR). Collecting branches (e.g. treatment S(WB)B in Table 1) led to increases in nutrient outputs of +26% to 31%. Adding the removal of foliage or stumps/roots (S(WB)BF or S(WB)BR in Table 1) resulted in bigger changes in nutrient exports (+40% to 68% and +48% to 63%, respectively), but mitigation measures such as harvesting in winter or after a delay which allows the foliage to dry and fall off the branches strongly reduce these effects (increase in nutrient outputs of +28% to 38% under S(WB)BF). Adding other mitigation measures to the S(WB)BF harvest treatment to reduce the export of bark (i.e. using machines for logging), led to an increase in nutrient outputs of only +8% to 13% (no change in the case of Ca, Table 1).

Theoretical changes in macronutrient outputs due to the removal of harvesting residues are generally higher than the gain in biomass (Table S1). In particular, exporting the foliage induces a small gain in biomass harvest but huge nutrient exports/losses, because foliage mass is generally low and its nutrient concentrations are high (Fig. S4). The changes in theoretical nutrient outputs displayed high inter-site heterogeneity (e.g. Fig. S4), which appears to be correlated with the stage of development of the forest stand. Indeed, the magnitude of changes in nutrient outputs due to the collection of branches and foliage increases with decreasing tree diameter (Fig. S5A), and also tree height, tree age and stem biomass (Fig. S6). This result can be explained by the fact that the contribution to total tree biomass of foliage and thin branches, i.e. tree components with high nutrient concentrations, is larger in young stands than in old stands (Fig. S5B). The variability of nutrient outputs can also be explained by an effect of tree species. Indeed, changes were greater in coniferous tree species than in broadleaf trees as shown in Fig. S5 and other results (significant differences ($P < 0.05$) were generally found between the two classes in each harvest treatment (data not shown)).

3.1.2. Comparison between theoretical nutrient outputs and nutrient stocks in soils

Theoretical N outputs were low compared to total N stocks in the soil profiles under all types of harvest (N outputs <10% of total soil N). This was also the case when P outputs were compared with total P in soils (P outputs <2% of total soil P; data not shown). However, theoretical nutrient outputs were high compared with the stocks of available/exchangeable nutrients in soils, particularly when harvesting residues were removed. Indeed, P, K, Ca and Mg outputs generally corresponded to 20–30% of available/exchangeable soil nutrients in conventional (S(WB)) harvest, and up to 100% or more in intensive harvests (Fig. 4). Thus, in addition to results concerning percent changes in nutrient outputs, comparisons with nutrient stocks in soils also strongly suggest that intensive harvests can negatively affect chemical soil fertility.

Comparing theoretical nutrient outputs to nutrient stocks in soils also showed that harvesting wood stems without the bark (S(W) treatment) can mitigate the impacts of biomass harvest on chemical soil fertility (particularly on soil Ca, Fig. 4). This result is coherent with those on nutrient outputs (potential reduction of 56% in Ca outputs; Table 1).

3.2. Impacts of removing harvesting residues on soils and trees ("environmental impacts" dataset)

3.2.1. Soil organic matter and nutrients

In general, removing harvesting residues led to significant losses of soil organic matter (or C), particularly in the wood debris (−40%, as a median value), forest floor (−10% to −45%) and deep soil layer (−10%). Significant decreases were found for soil organic matter stocks and concentrations; Table 2). When we focused on stocks of organic matter in the forest floor, results suggest that losses increase with increasing harvest intensity (losses in S(WB)B < S(WB)BF < S(WB)BFR < S(WB)BF + forest floor).

Removing harvesting residues significantly decreased the amount of nutrients in soils (Table 2). Results for total N were similar to those for soil organic matter, with increased N losses with increasing harvest intensity (e.g. see comparisons of the effect of different harvest treatments on N stocks in the forest floor). There were also significant losses of other nutrients such as total P or Ca (−6% to −9%; no effect for total K and Mg). The consequences of removing harvesting residues for available soil N (KCl extractable NH_4 and NO_3) were generally not significant, except when the forest floor is harvested (−24% in topsoil). However, our results showed overall negative and significant effects on available soil P, cation exchange capacity and base saturation (examples for S(WB)BF treatment: changes of −8% to −12% in the forest floor, and of −10% to −17% in top soils). Concomitant with the decreases in exchangeable cations and base saturation, soil acidification can also be inferred from slight decreases in soil pH and increases in exchange acidity and exchangeable H and Al (data mainly from Northern boreal forests).

Although overall there were significant negative effects, soil responses to removing harvesting residues displayed strong heterogeneity that may be related to several explanatory variables. Classifying data based on Koeppen climate classes showed that the decrease in organic matter and total N was higher under temperate climate than cold climate (Fig. S7; there were not enough data to compare climate classes for other soil variables). Classifying data based on the elapsed time after harvesting (0–10 yrs. and >10 yrs.) showed that the decreases in total N (stock in the forest floor), and exchangeable K and Mg tended to be stronger during the first years after harvesting than later (Figs. S8 and S9). However, there were generally no significant differences among the two classes. In contrast, there was a significant effect of elapsed time after harvesting on topsoil pH, with reduced values only during the first years (Fig. S10). We did not find any significant relationship between percent changes in soil organic matter or nutrients and concentrations in control treatment (i.e. indicators of inherent soil fertility). Finally, we assessed data distribution based on geographical locations and soil types. In several cases, data distribution was unbalanced: USA and/or Sweden/Finland were generally the most frequently represented countries, and podzol the most represented soil type (acrisols, gleysols and andosols were also present). Where comparisons were possible, results showed no effects of location or of soil types.

Table 1
Percent changes in nutrient outputs due to removing harvesting residues. Theoretical values calculated using harvest rates[a] ("nutrient stocks" dataset).

	Harvest treatments compared to conventional stem-only harvest (wood + bark, S(WB); logging with chainsaw[b])							
	S(WB) Stem (wood + bark)	S(WB)B Stem (wood + bark) + branches	S(WB)BF Stem (wood + bark) + branches + foliage			S(WB)BR Stem (wood + bark) + branches + stumps/roots	S(WB)BFR Stem (wood + bark) + branches + foliage + stumps/roots	
	Machine[b]	Chainsaw[b]	Chainsaw	Chainsaw, in winter or after drying step[c]	Machine, in winter or after drying step	Chainsaw	Chainsaw	Chainsaw, in winter or after drying step
N								
(Number of case studies)	(117)	(112)	(109)	(109)	(109)	(35)	(35)	(35)
Mean, Median (Q1, Q3)	−24, −25 (−30, −18)	37, 30 (18, 50)	87, 68 (49, 102)	46, 37 (24, 57)	21, 13 (1, 30)	79, 59 (43, 100)	113, 100 (76, 112)	85, 65 (50, 103)
Min, Max	−62, −2	5, 216	10, 425	5, 259	−54, 222	19, 400	43, 422	26, 400
Potential Mean, Median[d]	−37, −37	77, 56	177, 150	177, 150	177, 150	140, 126	222, 192	222, 192
P								
(Number of case studies)	(109)	(105)	(102)	(102)	(102)	(34)	(34)	(34)
Mean, Median (Q1, Q3)	−24, −23 (−33, −15)	43, 31 (18, 47)	84, 62 (41, 100)	50, 38 (22, 54)	25, 11 (2, 29)	81, 52 (44, 101)	109, 96 (57, 128)	87, 59 (47, 101)
Min, Max	−56, −2	5, 541	11, 704	5, 541	−20, 525	15, 446	23, 464	15, 446
Potential Mean, Median	−36, −36	90, 62	183, 152	183, 152	183, 152	172, 122	240, 200	240, 200
K								
(Number of case studies)	(110)	(107)	(104)	(104)	(104)	(36)	(36)	(36)
Mean, Median (Q1, Q3)	−22, −21 (−28, −15)	32, 27 (18, 40)	62, 55 (34, 83)	37, 31 (19, 47)	14, 11 (0, 23)	76, 63 (45, 99)	103, 85 (69, 123)	82, 67 (52, 102)
Min, Max	−51, −2	3, 127	9, 166	5, 137	−20, 106	16, 276	28, 294	16, 276
Potential Mean, Median	−33, −32	69, 48	146, 119	146, 119	146, 119	125, 105	185, 159	185, 159
Ca								
(Number of case studies)	(102)	(101)	(98)	(98)	(98)	(36)	(36)	(36)
Mean, Median (Q1, Q3)	−37, −38 (−47, −25)	32, 26 (16, 44)	54, 40 (26, 65)	37, 28 (19, 51)	0, −3 (−18, 10)	61, 48 (38, 65)	76, 58 (41, 102)	64, 49 (38, 74)
Min, Max	−69, −10	4, 192	6, 215	5, 192	−52, 154	14, 288	38, 296	23, 288
Potential Mean, Median	−56, −56	64, 47	122, 83	122, 83	122, 83	113, 93	147, 120	147, 120
Mg								
(Number of case studies)	(101)	(100)	(97)	(97)	(97)	(36)	(36)	(36)
Mean, Median (Q1, Q3)	−25, −25 (−33, −16)	40, 27 (19, 47)	66, 53 (32, 84)	45, 34 (21, 56)	20, 8 (0, 29)	76, 59 (39, 98)	96, 80 (59, 124)	80, 59 (43, 105)
Min, Max	−57, −3	4, 273	9, 331	5, 273	−30, 261	15, 185	20, 187	15, 185
Potential Mean, Median	−38, −39	74, 51	135, 99	135, 99	135, 99	129, 109	171, 143	171, 143

[a] Harvest rates: 100% of stem wood, 20–80% of stem bark depending on harvest conditions (see below), 50–60% of branches depending on tree species, 0–40% of foliage depending on harvest conditions (see below), 60% of roots.
[b] Logging with a chainsaw causes low bark losses, 80% of the bark remains on the stem and is exported, while machine logging significantly increases bark losses, only 20% of the bark remains on the stem and is exported.
[c] Foliage exports are strongly reduced with mitigation measures (100% of foliage is left on site when broadleaf trees are removed in winter or when residues are removed after a delay that allows the foliage to dry and fall off the branches, 90% of foliage is left on site when residues of coniferous trees are removed after a delay that allows the foliage to dry and fall off the branches).
[d] Comparison with the theoretical values calculated using harvest rates of 100%.

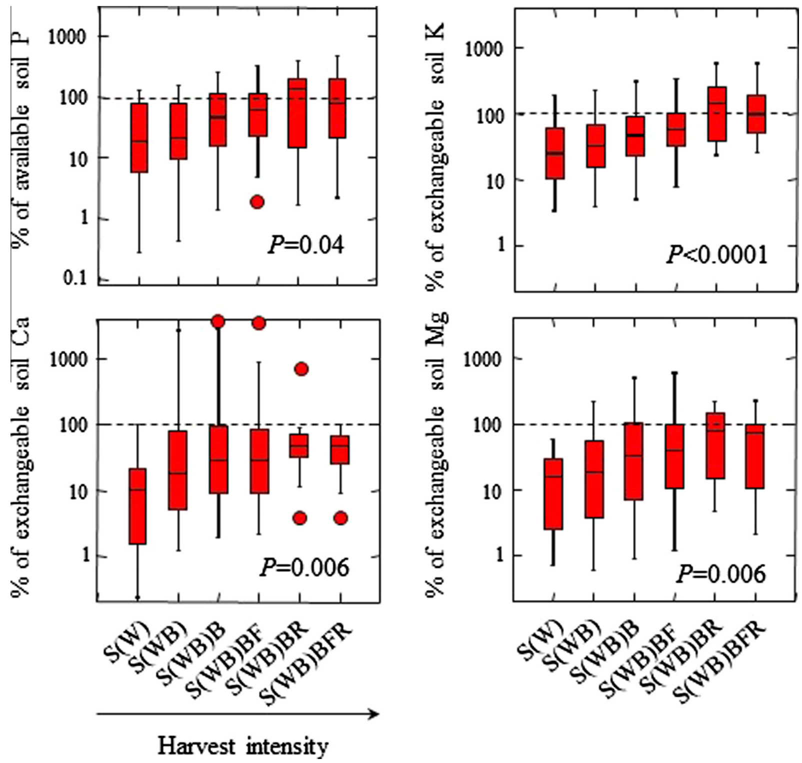

Fig. 4. Nutrient outputs at a theoretical harvesting rate of 100% as a percentage of soil nutrient stocks under different types of biomass removals ("nutrient stocks" dataset). The mean soil profile thickness is 80 cm. Number of case studies = 11–42. *P* values represent the general effects of the harvest.

3.2.2. Factors affecting soil biological activity

Effects on organic matter quality and environmental factors that may affect biological activity (compaction, soil temperature and soil moisture) are presented in Table 3.

Results suggested that removing harvesting residues may have an impact on the quality of soil organic matter, as shown by increased C:N ratios in the forest floor (+2% when all treatments are taken together; Table 3), as well as some significant changes in chemical composition of the soil organic matter. Indeed, there were reductions in the concentrations of diterpenes under S(WB)BF harvests (−15%; P = 0.063; n = 7), as well as reductions in the light fraction organic matter, lignin-derived phenols, cutin-derived compounds and alkyl C concentration when all treatments are taken together (−9% to −30%; P = 0.023–0.085; n = 3–7). However, there was generally no effect on other compounds, such as sesquiterpenes, triterpenes and phenolic compounds (including tannins; data not shown).

Soil compaction increased in the case of intensive harvests, as revealed by significant increases in topsoil bulk density (+4% increase under the S(WB)BF harvest treatment; Table 3).

Removing harvesting residues led to significant increases in topsoil temperature in spring and summer, while soil temperature was not affected in fall, and tended to decrease in winter (+5% to 10% increase in mean soil temperature; Table 3 and Fig. S11). In contrast, we found no significant change in topsoil moisture (Table 3) and no clear difference were observed among seasons.

3.2.3. Biological activity and decomposition processes

We found no significant effect of removing harvesting residues on soil fauna inferred from the number of individuals (mites, springtails, millipedes, nematodes, annelids, beetles, etc.) or species richness (Table 3). Microbiological activity in mineral soil layers, inferred with microbial biomass, soil respiration in incubated soils or other indicators, significantly decreased under S(WB)BF and S(WB)BF + forest floor treatments (−8% to −28% changes; no significant effect in the forest floor). Microbial C:N was however not significantly changed. An impact of removing harvesting residues on soil microbiological activity can also be suggested through reduced soil CO_2 efflux (10% decrease). In addition, there were significant decreases in enzymatic activities (particularly those involved in N mineralization (37–50% decreases), but also those involved in C decomposition and phosphate hydrolyze; Table 3).

Decomposition processes inferred from wood decomposition (*mass losses*) were not significantly affected, but net N mineralization fluxes in the forest floor and topsoil were significantly reduced. Data on other N processes (nitrification, microbial N immobilization) were also available. Their responses to the removal of harvesting residues remained unclear, although results showed an increase in nitrification when harvesting residues and forest floor are removed (Table 3).

Data on microbiological activity and decomposition processes are generally scarce and the response to removing harvesting residues was highly variable. In addition, data distribution based on explanatory factors was unbalanced (e.g. soils were mainly podzols or acrisols). Consequently, we were unable to assess the causes of heterogeneity of the effects of residue harvesting on biological soil fertility.

3.2.4. Tree growth

Our results showed that all residue harvest treatments generally had no effect on tree nutrient status, except for foliar Ca concentration, which was significantly and negatively reduced under the S(WB)BF harvest treatment (−4%; Table 4). Foliar K concentration was also reduced in some cases, i.e. when we compared residue harvest with double slash treatments (per cent change = −8%). Removing harvesting residues had generally no effect on tree survival. In contrast, our results clearly showed that tree growth was

Table 2
Percent changes in physical–chemical soil properties due to removing harvesting residues ("environmental impacts" dataset).

	Harvest treatments compared to conventional stem-only harvest (wood + bark, S(WB))					Compared to *double slash*
	All treatments	S(WB)B Stem (wood + bark) + branches	S(WB)BF Stem (wood + bark) + branches + foliage	S(WB)R or S(WB)BFR Stem (wood + bark) + branches + foliage + stumps/roots	S(WB)BF + forest floor Stem (wood + bark) + branches + foliage + forest floor	S(WB)BF Stem (wood + bark) + branches + foliage
Soil organic matter (or C) stock						
WD[a]	**−40.6 [−57.5, −33.2](20)*****	–[b]	**−40.0 [−47.8, −31.2](19)*****	–	–	–
FF	**−15.4 [−31.2, −2.9](39)*****	+1.7 [−6.3, 8.2](5)^{ns}	**−10.3 [−24.9, −2.3](36)****	**−24.4 [−30.0, −21.1](4)***	**−44.9 [−68.2, −34.3](8)***	–
Top	−2.1 [−6.8, 3.1](34)^{ns}	−1.1 [−3.1, 6.0](5)^{ns}	−1.1 [−5.2, 4.2](29)^{ns}	+2.8 [−0.2, 5](4)^{ns}	**−11.1 [−22.7, −7.5](10)***	**−5.5 [−6.1, −3.3](5)**(*)
Deep	**−8.0 [−14.3, 0.7](10)***	–	**−9.6 [−14.5, 1.9](9)***	–	−2.2 [−5.6, −1.5](5)^{ns}	–
Soil organic matter (or C) concentration						
FF	**−1.8 [−6.5, −0.1](27)***	–	**−3.0 [−8.2, −0.1](27)****	–	+6.6 [−7.0, 12.4](5)^{ns}	−3.7 [−3.8, −0.6](5)^{ns}
Top	**−7.3 [−19.3, 1.5](24)**(*)	–	−6.9 [−12.7, 2.4](16)^{ns}	–	**−23.5 [−38.3, −14.3](8)***	−6.8 [−25.8, −2.6](3)^{ns}
Deep	+3.0 [−2.1, 6.9](11)^{ns}	–	+2.1 [−0.9, 5.4](9)^{ns}	–	–	–
Total N stock						
FF	**−11.3 [−31.1, −1.3](24)****	+5.4 [−7.3, 17.2](6)^{ns}	**−12.1 [−31.5, −3.4](23)****	–	−51.2 [−52.4, −32.6](5)^{ns}	–
Top	−0.8 [−6.6, 1.8](27)^{ns}	−2.0 [−2.8, 6.0](5)^{ns}	−0.3 [−8.7, 2.1](25)^{ns}	–	−6.5 [−11.9, 1.7](9)^{ns}	**−8.6 [−10.2, −6.9](4)****
Deep	−5.6 [−9.1, −2.7](7)^{ns}	–	−9.0 [−11.9, −5.4](6)^{ns}	–	0.0 [−7.4, 3.5](5)^{ns}	–
Total N concentration						
FF	−2.4 [−8.1, 0.6](21)^{ns}	–	−2.4 [−7.1, 1.7](21)^{ns}	–	+9.9 [−16.3, 10.2](5)^{ns}	+0.5 [−2.2, 2.3](4)^{ns}
Top	**−10 [−18.8, −4.0](24)****	–	−7.4 [−9.7, 6.0](14)^{ns}	**−16.2 [−19.7, −15.4](5)****	**−18.8 [−27.4, −10.1](7)***	–
Deep	−1.5 [−10.7, 1.5](8)^{ns}	–	−3.0 [−12.8, 0.0](7)^{ns}	–	–	–
Total P						
FF	−4.3 [−6.8, −1.7](7)^{ns}	–	**−6.2 [−8.3, −3.6](6)**(*)	–	–	–
Top	−11.6 [−20.4, −0.4](8)^{ns}	–	0.0 [−6.0, 2.8](5)^{ns}	–	–	−6.2 [−14.2, −2.9](4)^{ns}
Total K						
FF (+ Top)	0.0 [−7.7, 5.3](9)^{ns}	–	0.0 [−5.6, 3.7](7)^{ns}	–	–	–
Total Ca						
FF	**−6.6 [−11.9, −4.6](7)***	–	**−9.1 [−15.4, −4.5](6)***	–	–	–
Total Mg						
FF	0.0 [−8.2, 7.6](7)^{ns}	–	−4.0 [−8.3, 4.2](6)^{ns}	–	–	–
Available N						
FF	+3.2 [−8.3, 9.7](13)^{ns}	–	−0.9 [−8.3, 5.8](13)^{ns}	–	–	–
Top	−15.7 [−22.2, 9.8](12)^{ns}	–	+5.7 [−11.8, 16.6](8)^{ns}	–	**−23.9 [−41.6, −11.3](6)**(*)	+2.2 [−9.6, 14.4](3)^{ns}
Available P						
FF	**−9.6 [−19.3, −5.7](13)***	–	**−12.0 [−19.3, −8.2](13)***	–	–	–
Top	**−21.4 [−39.5, −7.8](13)***	–	−12.5 [−30.8, −3.2](10)^{ns}	–	**−25.6 [−28.1, −21.4](5)***	–
Cation exchange capacity						
FF	**−12.5 [−17.0, −3.9](11)***	+0.3 [−10.1, 6.8](4)^{ns}	**−12.5 [−17.0, −3.9](11)***	–	–	–
Top	**−10.1 [−17.8, −4.5](11)****	+1.0 [−6.7, 1.2](5)^{ns}	**−9.9 [−16.7, −3.4](8)**(*)	–	–	−21.0 [−27.7, −13.5](3)^{ns}
Deep	**−23.9 [−27.1, −20.6](4)***	–	**−22.8 [−28.1, −18.4](3)**(*)	–	–	–
Base saturation						
FF	**−5.8 [−11.3, −3.7](11)****	−4.0 [−5.8, −1.7](4)^{ns}	**−8.4 [−13.1, −4.1](11)****	–	–	–
Top	**−13.2 [−23.1, −6.7](9)***	−4.8 [−8.0, −0.8](5)^{ns}	**−17.4 [−19.8, −12.2](7)***	–	–	–
Deep	+8.3 [−1.6, 17.7](4)^{ns}	–	+2.2 [−5.5, 15.0](3)^{ns}	–	–	–
Soil pH						
FF	−0.4 [−1.9, 2.0](29)^{ns}	0.0 [−0.5, 0.4](4)^{ns}	−0.5 [−1.6, 2.0](29)^{ns}	–	–	0.0 [−0.7, 1.3](3)^{ns}
Top	−0.2 [−1.3, 0.4](22)^{ns}	−0.5 [−1.1, −0.3](4)^{ns}	**−0.2 [−2.2, 0.1](19)**(*)	–	+2.4 [0.9, 3.2](5)^{ns}	–
Deep	−0.3 [−0.7, 1.2](7)^{ns}	–	−0.3 [−0.6, 1.2](7)^{ns}	–	–	–

Table 2 (*continued*)

	Harvest treatments compared to conventional stem-only harvest (wood + bark, S(WB))					Compared to *double slash*
	All treatments	S(WB)B Stem (wood + bark) + branches	S(WB)BF Stem (wood + bark) + branches + foliage	S(WB)R or S(WB)BFR Stem (wood + bark) + branches + foliage + stumps/roots	S(WB)BF + forest floor Stem (wood + bark) + branches + foliage + forest floor	S(WB)BF Stem (wood + bark) + branches + foliage
Exchange acidity						
FF	+46.6 [6.4, 57.0](5)^{ns}	−2.1 [−4.3, 7.8](4)^{ns}	**+78.3 [15.4, 102.5](5)**(*)	–	–	–
Top	+2.6 [−2.5, 6.2](4)^{ns}	+4.8 [−0.3, 7.5](4)^{ns}	+0.4 [−4.8, 5.0](4)^{ns}	–	–	–
Exchangeable H						
FF	+11.9 [−2.4, 31.3](7)^{ns}	**+15.3 [8.5, 24.6](4)**(*)	+20.7 [−2.4, 33.7](7)^{ns}	–	–	–
Top	+6.2 [−2.5, 18.1](4)^{ns}	+1.1 [−8.1, 17.3](4)^{ns}	+11.3 [3.2, 19.0](4)^{ns}	–	–	–
Exchangeable Al						
FF	**+13.0 [3.7, 32.1](11)***	+10.7 [2.3, 19.7](3)^{ns}	**+13.0 [6.1, 37.5](11)***	–	–	–
Top	−1.4 [−4.5, 4.8](9)^{ns}	+7.6 [1.3, 13.7](5)^{ns}	−3.0 [−10.3, 0.2](7)^{ns}	–	–	–
Deep	**−22.6 [−29.1, −10.3](5)**(*)	–	−16.4 [−24.2, −4.9](4)^{ns}	–	–	–

Median value [Quartile 1, Quartile 3] (number of case studies).
Bold values indicate statistically significant effects. Statistical significance: not significant ($P > 0.1$), ns; $P < 0.1$, (*);
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
[a] WD, woody debris; FF, forest floor; Top, top mineral soil layer; Deep, deep mineral soil layer.
[b] Not determined (number of case studies < 3).

significantly decreased by removing harvesting residues. Under S(WB)BF and S(WB)BF + forest floor harvest treatments, reductions were observed on tree height (−3%), tree diameter (−4% to −7%) and tree volume, basal area and biomass (−3% to −7%; Table 4). There were also decreases in tree growth under residues harvest treatments compared to double slash treatments (per cent change = −10% to −14%), and results suggested that the effects increased with increasing harvest intensity. An exception was an increase in tree growth in some cases (up to +20% increase), when stumps and associated coarse roots are removed (S(WB)R or S(WB)BF treatment; Fig. S2).

Like for soil response, results revealed high inter-site differences in the effect on tree growth response and the data enabled an assessment of the effect of elapsed time and some comparisons among locations, soil types, and vegetation types. Differences were found among locations in tree survival, with significant increase in Scandinavia but not North America (Fig. S12). In addition, tree growth was overall negatively and significantly impacted by removing harvesting residues in European countries while only trends could be observed in North America (Fig. S12). Although there was no significant effect of elapsed time (two classes studied: 0–10 year and >10 year, Fig. S13) the data suggested stronger positive or negative impacts during the first years after harvesting (see Fig. S2). Using data from Scandinavia, no significant relationship was found between tree response to the removal of harvesting residues and the site index (Fig. S14); because there was no common method for determining inherent soil fertility, no relationship could be assessed using the whole dataset. Finally, trees growing on gleysols and podzols tended to be more impacted than trees growing on acrisols and cambisols, and growth of coniferous tree species tended to be more affected than that of broadleaf tree species. For instance, there were significant decreases in total height, diameter, volume, basal area and biomass for coniferous ($P = 0.007–0.022$; $n = 19–41$; −2.8% to −4.4% decreases in treatment S(WB)BF), but not for broadleaf trees ($P > 0.492$; $n = 6–7$).

4. Discussion

4.1. Theoretical nutrient outputs

Based on nutrient stock data, we found that removing harvesting residues can lead to theoretical increases in nutrient outputs, which are considerable especially when the foliage is removed. Under the most intensive harvests, theoretical nutrient outputs could represent up to 100% of available/exchangeable P, K, Ca and Mg stocks in soils. This suggests potential negative impacts on chemical soil fertility if processes, such as mineral weathering, are too low to compensate those large nutrient exports. Based on realistic harvest rates, we found that nutrient exports were notably lower, demonstrating the importance of using realistic harvest rates to evaluate nutrient outputs caused by harvesting tree biomass. The harvest treatments that left most foliage and/or bark on site considerably reduced the nutrient costs of removing harvesting residues (e.g. treatments with a delay between cutting the stem and harvesting the branches, thus allowing the foliage to dry and fall off the branches). The increase in nutrient exports were highest in young stands probably because the relative contribution of foliage and thin branches (i.e. tree components that are rich in nutrients; André and Ponette, 2003; Augusto et al., 2008a; André et al., 2010) to above stump biomass decreases with increasing age.

4.2. Overall consequences of removing harvesting residues on soils and trees

To meet our first objective, we combined all the results of the present study and provide an overview of the impacts of intensive

Table 3
Percent changes in soil organic matter quality, environmental conditions, soil fauna and microbiological soil properties due to removing harvesting residues (“environmental impacts” dataset).

	Harvest treatments compared to conventional stem-only harvest (wood + bark, S(WB))					Compared to *double slash*
	All treatments	S(WB)B Stem (wood + bark) + branches	S(WB)BF Stem (wood + bark) + branches + foliage	S(WB)R or S(WB)BFR Stem (wood + bark) + branches + foliage + stumps/roots	S(WB)BF + forest floor Stem (wood + bark) + branches + foliage + forest floor	S(WB)BF Stem (wood + bark) + branches + foliage
Organic matter quality: C/N ratio						
FF[a]	**+2.3 [0.0, 5.7](30)**([*])	+0.5 [−0.6, 2.6](5)[ns]	+1.6 [−0.7, 5.6](30)[ns]	–	−3.6 [−4.5, 22.7](5)[ns]	+1.3 [−1.9, 2.9](6)[ns]
Top	+1.1 [−4.8, 5.2](27)[ns]	+2.7 [0.4, 5.4](5)[ns]	+1.2 [−3.2, 5.0](22)[ns]	–	−7.7 [−12.2, −1.7](6)[ns]	+4.2 [−0.7, 4.9](3)[ns]
Deep	−4.4 [−16, 6.8](5)[ns]	–[b]	−4.2 [−20.7, 7.8](4)[ns]	–	–	–
Bulk density						
Top	**+4.5 [1.1, 6.5](21)**[*]	–	**+3.7 [0.8, 8.3](12)**([*])	+5.2 [3.4, 5.7](5)[ns]	+3.6 [−3.7, 10.2](6)[ns]	–
Mean soil temperature						
Top	**+4.9 [−1.8, 14.0](22)**[**]	–	**+5.4 [−2.1, 10.8](17)**[*]	–	**+9.9 [1.6, 18.7](12)**[*]	–
Mean soil moisture						
Top	−3.3 [−8.1, 8.7](11)[ns]	–	+5.4 [−1.2, 11.7](6)[ns]	–	−8.5 [−12.4, −3.4](7)[ns]	–
Fauna: number of individuals (mites, springtails, millipedes, nematodes, annelids, beetles, etc.)						
Top	+25.1 [−3.7, 53.7](9)[ns]	–	+50.4 [14.4, 101.9](6)[ns]	–	+25.1 [6.7, 42.2](3)[ns]	−3.7 [−15.4, −0.8](3)[ns]
Fauna: species richness						
Top	−4.8 [−22.5, 50.8](5)[ns]	–	−4.8 [−16.8, 50.8](5)[ns]	–	–	–
Microbial C						
FF	−1.8 [−6.5, 8.5](12)[ns]	–	−3.0 [−7.5, 8.5](12)[ns]	–	–	0.0 [−1.1, 3.4](5)[ns]
Top	**−14.3 [−20.4, −11.6](8)**[***]	–	−19.1 [−22.3, −10.7](4)[ns]	–	**−13.9 [−14.7, −12.9](5)**[**]	–
Microbial N						
FF	−0.4 [−7.6, 5.6](15)[ns]	–	0.0 [−7.6, 8.2](15)[ns]	–	+0.2 [−6.2, 5.8](4)[ns]	−6.0 [−6.3, 0.0](5)[ns]
Top	**−19.6 [−23.2, −13.4](11)**[*]	–	−10.3 [−17.0, −4.3](8)[ns]	–	**−28.3 [−39.2, −15.0](7)**[**]	–
Microbial activity (soil respiration, mainly in incubated soils)						
FF + Top	−8.8 [−12.8, 0.1](14)[ns]	–	**−8.3 [−13.0, −0.8](13)**([*])	–	–	−6.2 [−8.3, −3.1](5)[ns]
Other indicators of microbial activity (fungi ergosterol, fungi and bacterial PLFA, etc.)						
FF + Top	−4.9 [−13.9, −1.1](5)[ns]	–	–	–	–	–
All indicators of microbial activity combined						
FF	−2.1 [−7.9, 8.8](16)[ns]	–	−0.4 [−7.2, 10.1](15)[ns]	–	+2.2 [−6.2, 16.2](4)[ns]	−4.4 [−5.6, −2.3](6)[ns]
Top	**−13.9 [−20.6, −8.4](15)**[**]	–	−9.4 [−15.2, −2.7](11)[ns]	–	**−22.6 [−32.8, −12.2](9)**[**]	–
Microbial C/N						
FF	+0.8 [−1.0, 8.5](12)[ns]	–	+0.9 [−0.7, 6.8](12)[ns]	–	–	−0.4 [−1.1, 10.0](5)[ns]
Top	+3.6 [0.6, 5.3](6)[ns]	–	+0.8 [−2.5, 4.8](4)[ns]	–	+5.5 [0.0, 24.0](3)ns	–
Soil CO_2 efflux						
FF + Top	−7.0 [−21.6, 1.0](8)[ns]	–	**−9.7 [−21.5, −4.3](5)**([*])	–	–	–
Enzymatic activity (enzymes grouped into three functional groups based on their abilities to decompose C substrates and to release N and P)[c]						
FF + Top/C	**−25.2 [−28.6, −10.2](7)**[*]	–	−12.5 [−28.4, −3.7](6)[ns]	–	–	**−41.5 [−50.6, −30.9](4)**[*]
FF + Top/N	**−43.3 [−46.7, −23.5](7)**[**]	–	**−36.6 [−44.5, −24.5](6)**[**]	–	–	**−50.5 [−51.4, −44.6](4)**[*]
FF + Top/P	**−18.9 [−30.7, −6.5](7)**([*])	–	−10.1 [−17.6, 3.7](6)[ns]	–	–	**−30.3 [−36.6, −22.6](4)**[*]
FF + Top/all	**−31.8 [−36.7, −21.1](7)**[**]	–	**−22.6 [−31.0, −19.0](6)**[**]	–	–	**−41.5 [−44.5, −37.0](4)**[**]
Debris decomposition (mass losses)						
WD	−5.3 [−35.6, −1.3](3)[ns]	–	−5.3 [−46.4, 5.1](3)[ns]	–	–	–
Net N mineralization						
FF	−19.8 [−41.3, −12.0](12)[ns]	–	**−27.4 [−41.8, −13.5](12)**([*])	–	–	−14.8 [−19.6, 0.0](5)[ns]
Top	−16.2 [−23.3, −1.6](16)[ns]	–	−5.4 [−14.8, 14.5](12)[ns]	–	**−23.1 [−47.8, −5.9](11)**[*]	**−25.5 [−25.6, −21.1](3)**[*]
FF + Top	−18.2 [−24.4, −1.2](27)[ns]	–	−14.5 [−29.1, 5.2](23)[ns]	–	−22.8 [−42.2, 2.4](12)[ns]	−18.2 [−25.6, −11.1](8)[ns]

Table 3 (*continued*)

	Harvest treatments compared to conventional stem-only harvest (wood + bark, S(WB))					Compared to *double slash*
	All treatments	S(WB)B Stem (wood + bark) + branches	S(WB)BF Stem (wood + bark) + branches + foliage	S(WB)R or S(WB)BFR Stem (wood + bark) + branches + foliage + stumps/roots	S(WB)BF + forest floor Stem (wood + bark) + branches + foliage + forest floor	S(WB)BF Stem (wood + bark) + branches + foliage
Nitrification						
FF + Top	+14.5 [−1.7, 52.9](6)[ns]	–	−12.9 [−25.9, −1.7](4)[ns]	–	**+103.0 [66.0, 142.3](3)(*)**	–
N Immobilization						
Top	−4.7 [−52.2, 14.0](3)[ns]	–	–	–	–	–

Median value [Quartile 1, Quartile 3] (number of case studies).
Bold values indicate statistically significant effects. Statistical significance: not significant ($P > 0.1$), ns; $P < 0.1$, (*);
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
[a] WD, woody debris; FF, forest floor; Top, top mineral soil layer; Deep, deep mineral soil layer.
[b] Not determined (number of case studies < 3).
[c] Ability to decompose labile or recalcitrant C substrates (hydrolysis of cellulose, starch, glucose, lignin): cellobiohydrolase, α-1,4-glucosidase, β-1,4-glucosidase, peroxidase, phenol oxidase, dehydrogenase. Ability to hydrolyze organic N (glucosamine or amino acids): β-1,4-N-acetylglucosaminidase, protease. Ability to hydrolyze phosphate: acid and alkaline phosphatases.

harvests on forest ecosystem processes, compared with conventional stem-only harvest (Fig. 5). However, soil and tree responses varied greatly among case studies, depending on site conditions and/or on the intensity of residue harvest; the overall effects summarized in Fig. 5 rather correspond to the most intensive harvests, such as S(WB)BF. It should therefore be noted that significant impacts were not always found when harvesting residues (i.e. branches) were exported without foliage (i.e. under the S(WB)B treatment).

4.2.1. Consequences for chemical soil fertility

The results we obtained with the "nutrient stocks" dataset (changes in nutrient outputs and comparison with nutrient stocks in soils) may suggest that intensive harvests have a negative impact on chemical soil fertility. However, previous studies have shown that increased nutrient output or immobilization in trees does not systematically cause depletion of total or available soil nutrients, owing to several processes including the soil buffer capacity (e.g. ability of soils to provide base cations through mineral weathering; Kimmins, 1974; Ranger and Turpault, 1999; Bélanger et al., 2004) or the dynamic response of trees to different levels of nutrient availability (e.g. ability to promote mineral weathering). Nevertheless, the "environmental impacts" dataset enabled us to show overall reductions in total N and P stocks, as well as reductions in available soil P and 'base cation' saturation. The decrease in base saturation was the result of a concomitant decrease in non-acidic cations (Ca^{2+}, Mg^{2+}, K^{+}) and an increase in exchangeable H and Al (Olsson et al., 1996; Iwald et al., 2013). There was also a decrease in the cation exchange capacity, probably due to a reduction in the amount of soil organic matter, changes in its chemical composition (Thiffault et al., 2008), and maybe because of Al polymerization inside clay minerals caused by acidification (Augusto et al., 2001).

Soil nutrient leaching is expected to be low in the case of intensive harvests in which inputs of organic matter available for mineralization are reduced, compared with conventional stem-only harvest (Adams, 1999; Arocena, 2000). Yet, comparing the results of several experiments revealed no clear evidence for this effect because of several interactions with soil fertility and vegetation (Blumfield and Xu, 2003; Devine et al., 2012). Therefore, leaching could also exacerbate losses of several soil nutrients (with the exception of phosphorus) when forest residues are harvested. In addition to increased nutrient outputs through harvesting of tree biomass, and in some cases through leaching, the decrease in soil microbiological activity could also explain the reduced amounts of available nutrients in the soil in intensively harvested sites.

4.2.2. Decrease in biological soil activity and decomposition processes

Soil biological activity and decomposition/mineralization of soil organic matter play a crucial role in forest functioning as they make nutrients more available to the trees (Ranger et al., 2011). Relatively to stem-only harvest, microbial activity, enzymatic activities and N mineralization fluxes were reduced in intensive harvests. Because soil CO_2 efflux has two components (heterotrophic and autotrophic), the significant and negative impacts on this variable may be related to reductions not only in microbial activity but also in root respiration (decreases in both processes were found in one case study; Versini et al., 2013). The overall effects on microbial activity and mineralization fluxes may be explained by other effects on organic matter amounts and composition (Smolander et al., 2013) and environmental factors such as compaction, soil temperature, moisture and pH (see below).

In sites where harvesting residues are removed, the quantity of organic matter in soils is significantly reduced and its quality may be affected through an increase in the C:N ratio and changes in

Table 4
Percent changes in nutrient status, survival and growth of trees due to removing harvesting residues ("environmental impacts" dataset).

	Harvest treatments compared to conventional stem-only harvest (wood + bark, S(WB))					Compared to *double slash*
	All treatments	S(WB)B Stem (wood + bark) + branches	S(WB)BF Stem (wood + bark) + branches + foliage	S(WB)R or S(WB)BFR Stem (wood + bark) + branches + foliage + stumps/roots	S(WB)BF + forest floor Stem (wood + bark) + branches + foliage + forest floor	S(WB)BF Stem (wood + bark) + branches + foliage
Nutrient status of trees						
Foliar mass	−3.1 [−5.3, 3.0](19)^{ns}	–[a]	−1.1 [−3.0, 2.6](18)^{ns}	–	–	−7.3 [−7.6, 0.1](6)^{ns}
Foliar N Concentration	0.0 [−2.5, 2.0](37)^{ns}	0.0 [−1.7, 2.2](6)^{ns}	+0.8 [−2.0, 2.6](29)^{ns}	–	−0.1 [−0.7, 1.5](6)^{ns}	−1.9 [−3.5, −1.2](7)^{ns}
Foliar P Concentration	−0.2 [−3.6, 2.3](32)^{ns}	−2.6 [−4.7, 0.6](6)^{ns}	0.0 [−1.7, 3.1](28)^{ns}	–	0.0 [−2.5, 0.7](3)^{ns}	0.0 [−3.6, 3.8](7)^{ns}
Foliar K Concentration	−0.1 [−4.6, 4.1](32)^{ns}	+2.8 [−0.4, 13.6](7)^{ns}	+1.1 [−4.5, 4.6](28)^{ns}	–	−3.4 [−3.7, 0.6](3)^{ns}	**−8.1 [−14.6, −5.1](7)***
Foliar Ca Concentration	**−3.6 [−10.9, 2.9](32)***	−2.0 [−8.1, −0.3](7)^{ns}	**−3.6 [−7.0, 2.5](28)***	–	−22.5 [−36.9, −7.1](3)^{ns}	−2.7 [−10.6, 2.9](7)^{ns}
Foliar Mg Concentration	0.0 [−4.5, 4.6](32)^{ns}	−1.9 [−2.5, 2.9](7)^{ns}	0.0 [−4.6, 4.5](28)^{ns}	–	+0.8 [−6.7, 1.4](3)^{ns}	0.0 [0.0, 7.8](7)^{ns}
Foliar Mn Concentration	−3.3 [−7.9, 1.0](10)^{ns}	+1.7 [−0.3, 3.4](4)^{ns}	**−5.1 [−11.2, −2.3](9)**(*)	–	–	–
Foliar Zn Concentration	−3.3 [−4.4, 1.5](9)^{ns}	−2.2 [−4.2, 1.0](4)^{ns}	−3.3 [−4.4, 2.1](9)^{ns}	–	–	–
Foliar Cu Concentration	+0.9 [−7.6, 3.3](5)^{ns}	–	+0.9 [−7.6, 3.3](5)^{ns}	–	–	–
Foliar B Concentration	−1.2 [−6.4, 5.8](16)^{ns}	–	+0.2 [−5.8, 5.8](16)^{ns}	–	–	−6.2 [−6.4, −1.2](5)^{ns}
Tree Survival	+1.0 [−3.6, 2.3](21)^{ns}	+2.6 [0.7, 5.9](4)^{ns}	+0.3 [−6.8, 2.9](20)^{ns}	–	+5.3 [−0.2, 10.2](8)^{ns}	–
Tree growth						
Height	**−2.6 [−7.6, 0.5](49)****	−1.7 [−6.9, −0.1](6)^{ns}	**−2.8 [−6.9, 0.5](45)****	–	−3.2 [−12.2, 2.3](15)^{ns}	**−10.6 [−10.6, −9.7](3)****
Height increment	−10.9 [−18.8, 0.0](9)^{ns}	–	−1.5 [−11.9, 1.2](7)^{ns}	–	−16.3 [−45.1, −2.1](5)^{ns}	–
Diameter	**−3.5 [−9.6, 0.0](30)****	–	**−4.4 [−8.9, 0.0](25)***	–	**−7.5 [−12.8, −1.6](9)**(*)	**−10 [−13.1, −9.0](3)***
Diameter increment	−0.6 [−17.4, 1.8](8)^{ns}	–	+0.2 [−10.4, 11.2](6)^{ns}	–	−9.9 [−24.9, 1.7](5)^{ns}	–
Volume, basal area or biomass	**−5.2 [−16.1, 0.3](57)***	−6.2 [−12.1, 0.9](6)^{ns}	**−3.1 [−15.1, 2.8](48)**(*)	–	−15.0 [−30.1, −5.2](13)^{ns}	**−14.1 [−29.4, −3.8](10)***
Volume, basal area or biomass increment	**−7.0 [−12.4, −3.3](34)*****	–	**−7.5 [−12.6, −3.3](33)*****	–	–	−12.5 [−22.3, −11.9](3)^{ns}
Root biomass	−10.1 [−20.2, 0.3](6)^{ns}	–	−0.6 [−6.3, 4.4](4)^{ns}	–	–	–

Median value [Quartile 1, Quartile 3] (number of case studies).
Bold values indicate statistically significant effects. Statistical significance: not significant ($P > 0.1$), ns; $P < 0.1$, ($*$);
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$;
[a] Not determined (number of case studies < 3).

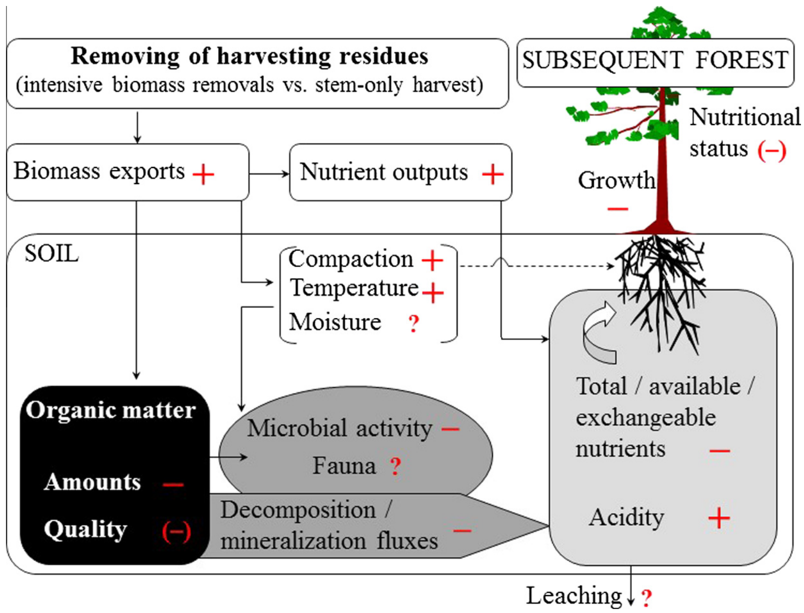

Fig. 5. Overview of the main impacts of removing harvesting residues on forest ecosystem functioning, based on the results of the meta-analysis. Negative effects are denoted by a minus sign. Positive effects are denoted by a plus sign. Signs in brackets denote trends (non-significant results or low number of sites/studies). Question marks denote unclear results. The figure mainly focuses on the effects of the most intensive removals, such as S(WB)BF or S(WB)BF + forest floor. There were far fewer impacts when the branches were exported without foliage (i.e. in S(WB)B).

chemical composition. There were reductions in the amounts of labile compounds characterized by rapid mineralization due to their biochemical nature and to the lack of protection by soil colloids (such as the light soil organic matter fraction; Huang et al., 2011a,b), but also reductions in stable compounds (alkyl C, lignin- and cutin-derived C). These changes in organic matter composition can be explained by the fact that removing harvesting residues deprives the soil of inputs of recent organic matter and certain compounds derived from plant litter (see more details on the effects of residues removal on chemical composition of light and heavy soil organic matter and other compounds and plant biomarkers in Mathers et al. (2003), Mathers and Xu (2003), Thiffault et al. (2008), Huang et al. (2011a,b) and Smolander et al. (2013)). On the other hand, effects of removing residues at harvest on soil organic matter quality may be limited because of the large amount of high quality biomass that is delivered to the soil during a rotation period. Finally, one could expect that reduced amounts of organic matter and changes in its quality could decrease mineralization fluxes and hence the supply of plant-available nutrients (O'Connell et al., 2003, 2004).

Soil micro-organisms may also be affected by the environmental changes documented in this study. Removing harvesting residues had an effect on soil pH, which is known to affect microbial activity (Fuentes et al., 2006). Decreases of soil pH were however small and micro-organisms were probably more affected by the changes in organic matter quality and the lack of fresh plant material supporting C sources. Removing harvesting residues also increases soil compaction, which was inferred from an increase in soil bulk density in the present meta-analysis or from an increase in soil strength (Carter et al., 2006; Han et al., 2009). Indeed, removing harvesting residues prevents the creation of slash mats, which distribute the weight of the harvesters, skidders and forwarders over a larger area and hence reduce direct contact between the machines and the soil surface (Han et al., 2009). Effect on soil compaction can also be explained by differences among harvest treatments in machine characteristics (e.g. machine mass and how it is distributed over the wheels, and hence pressure on the soil) as well as harvesting operations (number of machine passes; Ampoorter et al., 2012; Han et al., 2009) and may vary among countries owing to differences in harvest practices (e.g. two passes in the European system vs. one pass in the full-tree-to-roadside system in North America). Soil compaction could in turn reduce soil porosity and fluid transfer (water and gas) (Wilpert and Schäffer, 2006; Startsev and McNabb, 2009) thereby reducing microbial activity (Jordan et al., 2003) and soil CO_2 efflux (Goutal et al., 2012). Soil microbial activity may also be affected by microclimate changes. In particular, soil temperature increased significantly when residues were removed probably because soils were more exposed to solar radiation (Proe et al., 2001; O'Connell et al., 2004). Moreover, positive effects of removing harvesting residues on spring and summer temperatures and no -or negative- effects on fall and winter temperatures suggest that residues play a role in regulating seasonal variations; a role in diurnal variations has also been demonstrated (O'Connell et al., 2004). The increase in mean annual soil temperature could lead to an increase in mineralization rates (in % of soil organic matter) under intensive harvests (Dessureault-Rompré et al., 2010), thus contributing to organic matter losses. But, as shown in a previous study (O'Connell et al., 2004), mineralization fluxes in the forest floor and top mineral soil could remain at a lower level under these treatments mainly because of reduced inputs of organic matter and hence in substrates available for mineralization. In addition, an increase in soil temperature in summer and a decrease in winter could hamper mineralization processes by creating suboptimal conditions. Through the *mulching effect*, residues could also play a role in maintaining soil moisture, which in turn affects microbial activity (O'Connell et al., 2004; Roberts et al., 2005). However, in the present study, no generally and significant effect of removing harvesting residues was found on topsoil moisture, perhaps because of antagonistic effects of soil compaction (increase in soil water saturation, Goutal et al., 2012) and decreased *mulching effect*.

In addition to soil micro-organisms, soil fauna also plays a role in decomposition processes and the density and diversity of soil fauna were recently reported to be potentially affected by slash removal and the associated chemical and physical soil disturbances (Bouget et al., 2012). However, in the present study, we did not find any significant effect of removing harvesting residues on those faunal characteristics.

4.2.3. Consequences for tree growth

Results revealed negative impacts of removing harvesting residues on tree growth, which is probably due to a combination of several effects on soil, such as reduced chemical soil fertility (and hence tree nutrition). The increased soil compaction could also have negatively impacted tree growth, owing to an effect on root penetration and hence nutrient uptake; Kozlowski, 1999; Kabzems and Haeussler, 2005; Wilpert and Schäffer, 2006), but the opposite (positive effects of compaction on tree growth) has also been shown in compaction experiments (in coarse textured-soils in North America LTSP studies; Ponder et al., 2012). In addition to the vital role of residues and their decomposition for tree nutrition (particularly in soils with low fertility; Laclau et al., 2010; Ranger et al., 2011), residues could have an indirect effect on tree survival and growth through a negative effect on the density of competitive vegetation (Harrington and Schoenholtz, 2010). Although the general impacts on trees are negative (reduced growth), positive effects of residues removal were reported in some case studies (Fig. S2); these positive effects may be due to more favorable soil conditions (higher soil temperature; Roberts et al., 2005) or reduced root disease (when stumps and associated coarse roots are removed; Cleary et al., 2013). Positive effects on tree biomass have also been reported after stump harvesting and deep soil cultivation because soil disturbance stimulated N mineralization leading to increased tree nutrition (Egnell et al., 2015). The largest effects on growth are observable in the few years following residues harvesting, which corresponds to the seedling stage. Indeed, despite low nutrient requirements in absolute values, seedlings rely relatively more on topsoil supply because of lower nutrient reserves and soil exploration by their roots than older individuals, such as saplings and mature trees. Consequently, seedlings are probably more exposed to changes of growth rate. In addition, soil changes induced by intensive harvests, in comparison to stem-only harvest, tend to become insignificant with time. This trend may contribute to the convergence of treatments in terms of tree growth after one decade.

The absence of significant tree growth response in North America is in agreement with previous findings based on the LTSP installations; it was explained by the facts that most sites were established on productive sites and harvesting operations in less productive sites enabled substantial amounts of residues to be left on-site (Fleming et al., 2006; Ponder et al., 2012).

4.2.4. Recovery of forest ecosystems or long-term effects?

Although removing harvesting residues had significant and negative impacts on soil fertility and tree growth, the magnitude of changes was generally low (e.g. decrease of only 3–7% in tree growth). In addition, results suggest that chemical soil fertility may recover because stronger negative impacts on total N and exchangeable cations tend to occur during the first decade after harvesting. Some tree responses tend to display a similar pattern as the biggest changes in tree diameter and height occurred during the first years after harvesting. Soil recovery may occur through for instance tree litterfall and/or mineral weathering processes, which compensate for organic matter and nutrient losses (Ranger et al., 2011). However, in addition to the comparison with other harvest treatments, the comparison to pre-harvest conditions (e.g. such as in Nave et al., 2010) is also needed to determine if a recovery occurs.

In the "environmental impacts" dataset, the time elapsed after harvesting ranged between 0.2 and 33 years, and the slight impacts we found rather correspond to short or medium term effects and are generally the result of a single harvest (two harvests at thinning in Scandinavian studies), which may allow the forest ecosystem to recover. For the future, trials where harvesting residues have been collected once should be monitored on the long term (e.g. one complete rotation). Cumulative impacts of repeated residue removals should also be studied. Effects of repeated removal of harvesting residues in thinning and final felling have started to be studied in Finnish experiments (Tamminen and Saarsalmi, 2013; Kaarakka et al., 2014). Alternatively to long term experiments, effects due to cumulated intensive harvests have been assessed through modeling approaches, and showed a 20–40% decrease in forest productivity after 3–5 rotations (Peng et al., 2002), as well as long term effects on soil organic matter and nutrients (Peng et al., 2002; Aherne et al., 2008; Ranatunga et al., 2008; Scheller et al., 2011).

4.3. Limits of the study: causes of heterogeneity and predictors

Concerning the "nutrient stocks" dataset, it should be noted that even though soil fertility may influence tree nutrient concentrations and hence nutrient outputs, no site-specific relationship was calibrated based on available data.

Concerning the "environmental impacts" dataset, data were not equally distributed among geographic locations. As a consequence, most effects we found are representative of North America and/or Europe. Moreover, the European sub-dataset is mainly representative for Scandinavia. Data are also not equally distributed among soil types, podzol being the most represented in several cases. Data distribution and, for some soil variables, data scarcity hampered our assessment of the reasons for the heterogeneity of soil and tree responses. Only an effect of the time that elapsed after harvesting and some differences among climate classes and tree species were found. However, these effects are tricky to disentangle because they are region-dependent. For instance, for the effects on total tree height, diameter, volume, basal area and biomass, the >10 year class is largely represented by Scandinavian sites, while both North America and Scandinavia are well represented in the 0–10 year class. The effect of the climatic class is also difficult to assess because most cold sites are in Scandinavia where treatments are applied mostly at thinning and not at clear-cutting as done in other regions of the World. Finally, differences among tree species may partly reflect an effect of soil fertility, since coniferous trees are generally planted on infertile soils. Tree response to the harvesting of residues depends on several factors, among which certain were not systematically mentioned (e.g. nutrient outputs at harvest) or not quantified using the same methods among studies (e.g. initial amounts of available nutrients in the soils, or site index). As a consequence, it was not possible to assess relationships between tree growth response to intensive harvests and soil fertility indices (e.g. Scott and Dean, 2006; Fig. S14) using the whole "environmental impacts" dataset.

4.4. Prevention and mitigation measures to reduce impacts on soil fertility and tree growth

To prevent the negative effects of removing harvesting residues on site fertility (also on water quality and biodiversity) from occurring, general and/or site-specific guidelines have been developed in many countries. For instance, it is generally recommended to avoid (or limit) removing harvesting residues on *sensitive* soils such as shallow, highly acidic, highly weathered or coarse textured soils (e.g. Pinchot institute, 2010; Dickinson et al., 2012).

Besides site-specific considerations, and when harvest practices are not sustainable, measures should be taken to reduce the environmental consequences. The most impacting harvests tested in our study were clearly those including a removal of foliage [i.e. S(WB)BF]. Removing foliage strongly increases nutrient outputs, while the gain in harvested biomass is low. The strong imprint of foliage export is clearly visible in estimates of nutrient exports, reductions in soil nutrient stocks, and growth of subsequent forest stand. In comparison, harvests which avoid collecting foliage [i.e. S(WB)B] have little or no impact. Our results are in good agreement with modeling studies in Finland, which showed that S(WB)B, but not S(WB)BF harvests, had only slight effects on chemical soil fertility (Aherne et al., 2012). Besides the small effects on soil nutrients, treatment S(WB)B had also no significant effects on tree growth. In addition to the high nutrient cost of harvesting foliage, bark also contains high nutrient concentrations (Ponette et al., 2001; André et al., 2010). As a consequence, the nutrient cost of harvesting branches (or roots) could be compensated for by leaving most of the foliage and bark on site. More generally, nutrient costs and impacts on chemical soil fertility were found to increase with increasing harvest intensity. In agreement with previous conclusions (Stupak et al., 2008; Aherne et al., 2012; Augusto et al., 2015), our study thus shows that practical measures that reduce biomass exports (particularly foliage, through a removal after a drying step or the leaf-fall in winter for hardwoods, and bark) could be used to reduce nutrient costs due to removing harvesting residues.

Nutrient costs at harvest and tree growth response were both higher for coniferous tree species than for broadleaf tree species (but maybe in relation with soil fertility), and nutrient costs were higher in young stands than in old stands. Therefore, other measures of prevention may consist in removing harvesting residues preferentially in broadleaf forests and/or mature stands (e.g. at the clear-cut stage). Besides those recommendations, more studies are needed to assess the relationships between tree growth response to the removing of harvesting residues (i.e. site sensitivity) and physical and chemical soil properties (e.g. inherent soil fertility; Scott and Dean, 2006) to define prevention measures adapted to local site fertility.

If, despite the use of general and site-specific guidelines of good practices of biomass harvest, some serious consequences on forest functioning occur, some practices may help the recovery of the ecosystem. A first and easy to apply approach is based on the concept of *ecological length of rotation* (Kimmins, 1974; Ranger and Turpault, 1999). This concept states that the ecological length of a forest rotation is defined as the number of years necessary to processes, such as atmospheric deposition or weathering of soil minerals, to compensate the loss of nutrients induced by biomass export. In practice, extending the rotation could be an easy method to enable a forest to recovering from slight to moderate impacts of former intensive harvests. However, in case of severe disturbances, some forests might be not resilient enough to grow as healthy as before, even with an extended rotation length. In those cases, some mitigation measures, such as applications of fertilizers or wood ash (e.g. Augusto et al., 2008b; Helmisaari et al., 2011), may be used to compensate nutrient losses; the dose of nutrient to apply being possibly estimated using simple allometric relationships (Augusto et al., 2000; see Table S3 which is a by-product of our study). It should however be noted that fertilization, and all over wood ash application, is becoming an option also for preventing negative impacts from occurring in European countries where the development of power stations supplied with biomass consequently produces large amounts of wood ash. Conversely, this mitigation approach is currently prohibited, or discouraged, in other countries such as in North America.

5. Conclusion

We found that removing harvesting residues induces increases in nutrient outputs which can be theoretically considerable, especially when foliage is harvested. We also showed that realistic harvest rates should be taken into account as their use resulted in much lower nutrient costs. In response to our first objective, the concomitant use of our two datasets demonstrated that the most intensive harvests (e.g. of branches + foliage) often has negative impacts on chemical and biological soil fertility and tree growth, but with large disparities among harvest treatments, vegetation types, and stand development stages. Some practical measures can be taken to reduce the environmental consequences of removing harvesting residues. In particular, our results revealed low and/or non-significant negative impacts when branches are exported but the foliage is left on site. Additional mitigation measures need to be developed by establishing the link between site fertility and the intensity of the impact of removing harvesting residues.

Acknowledgments

This research was supported by the French agency for energy and environment (ADEME) and the French ministry of agriculture, food and forestry through the project RESOBIO. We thank Bruno Ringeval for assistance with preparing the map figures and determining Koeppen climate classes, Mark Bakker for checking the English language and Laurent Saint André for helpful discussion. We also thank three anonymous reviewers for improving the study.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.03.042.

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Quantifying consequences of removing harvesting residues on forest soils and tree growth – A meta-analysis

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Supplementary Information (14 figures, 3 tables, references used in the meta-analyses)

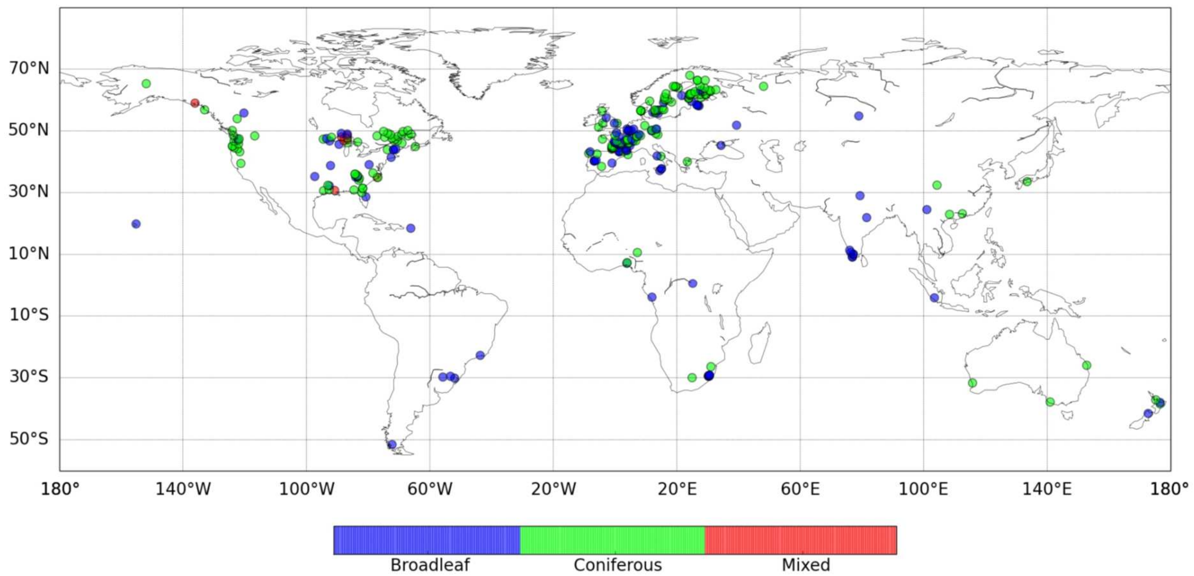

Figure S1 Spatial distribution of the study sites ("nutrient stocks" dataset). Broadleaf in blue, coniferous in green, mixed stands in red.

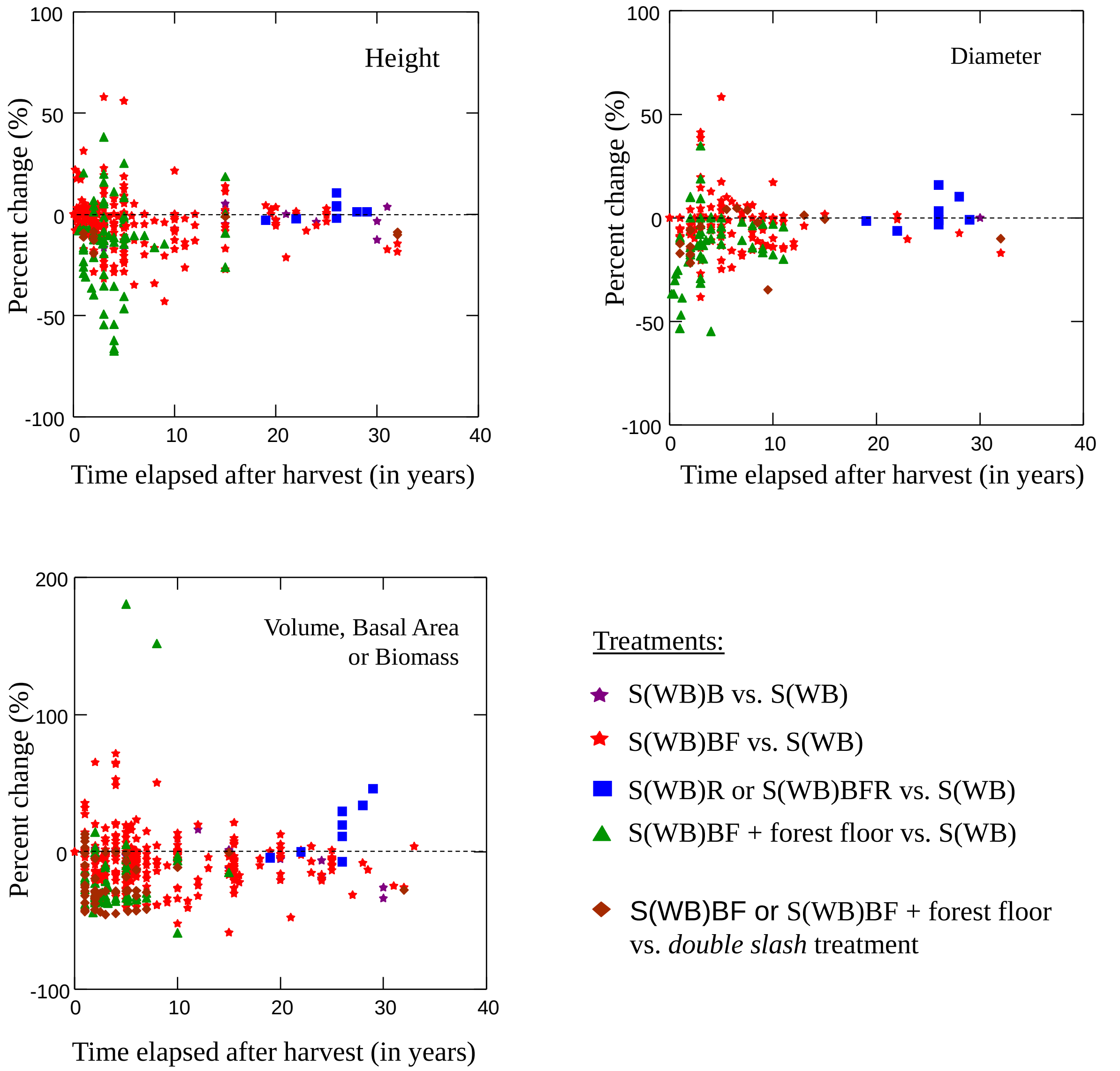

Figure S2 Effects of removing harvesting residues on tree growth as a function of the time elapsed since the removal: complete "environmental impacts" dataset. See explanation for the type of harvest in Figure 2.

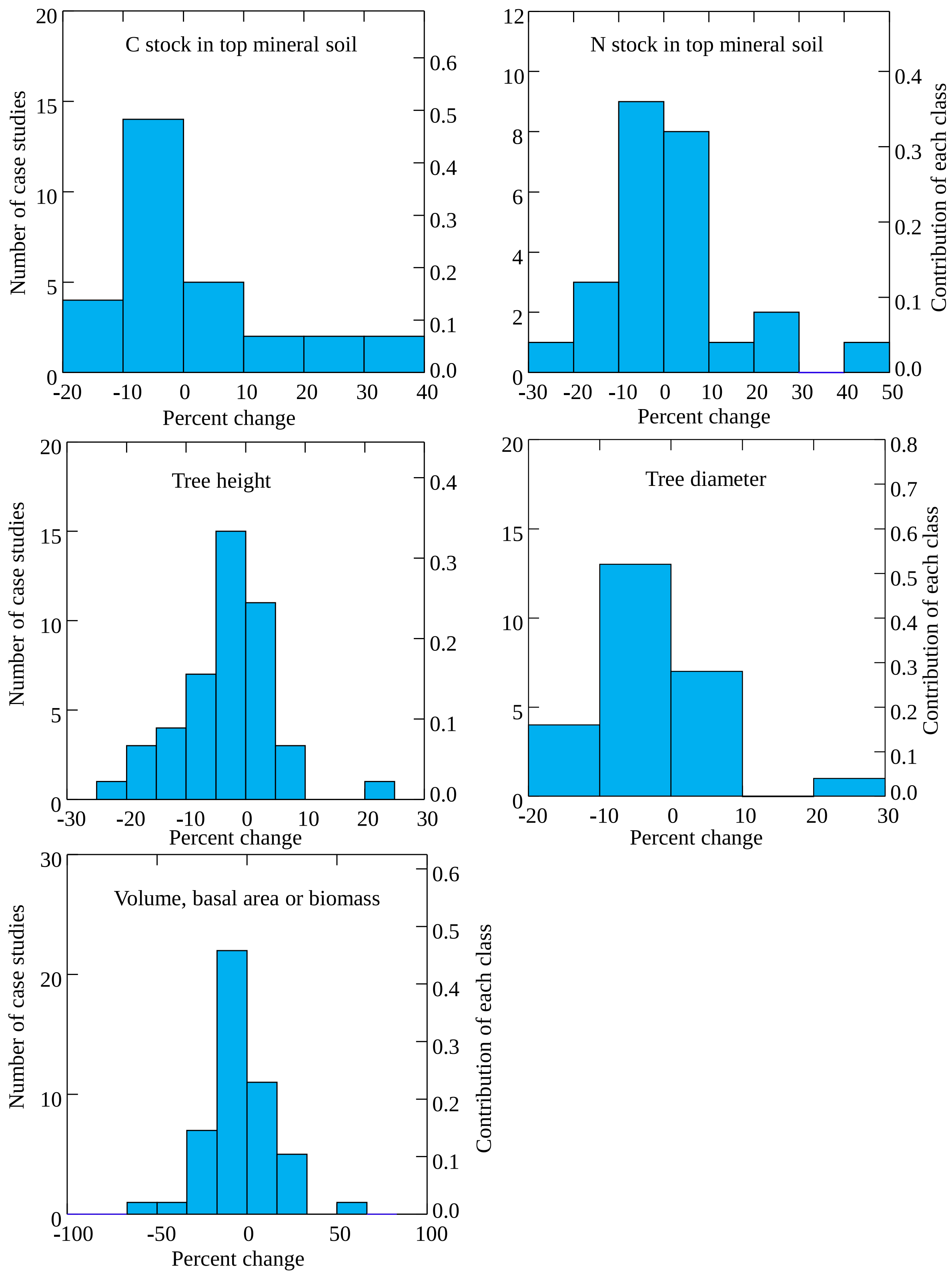

Figure S3 Statistical distribution of the case studies as a function of the percent change. "Environmental impacts" dataset, examples of C and N stocks in top mineral soils and of tree growth under treatment S(WB)BF vs. S(WB).

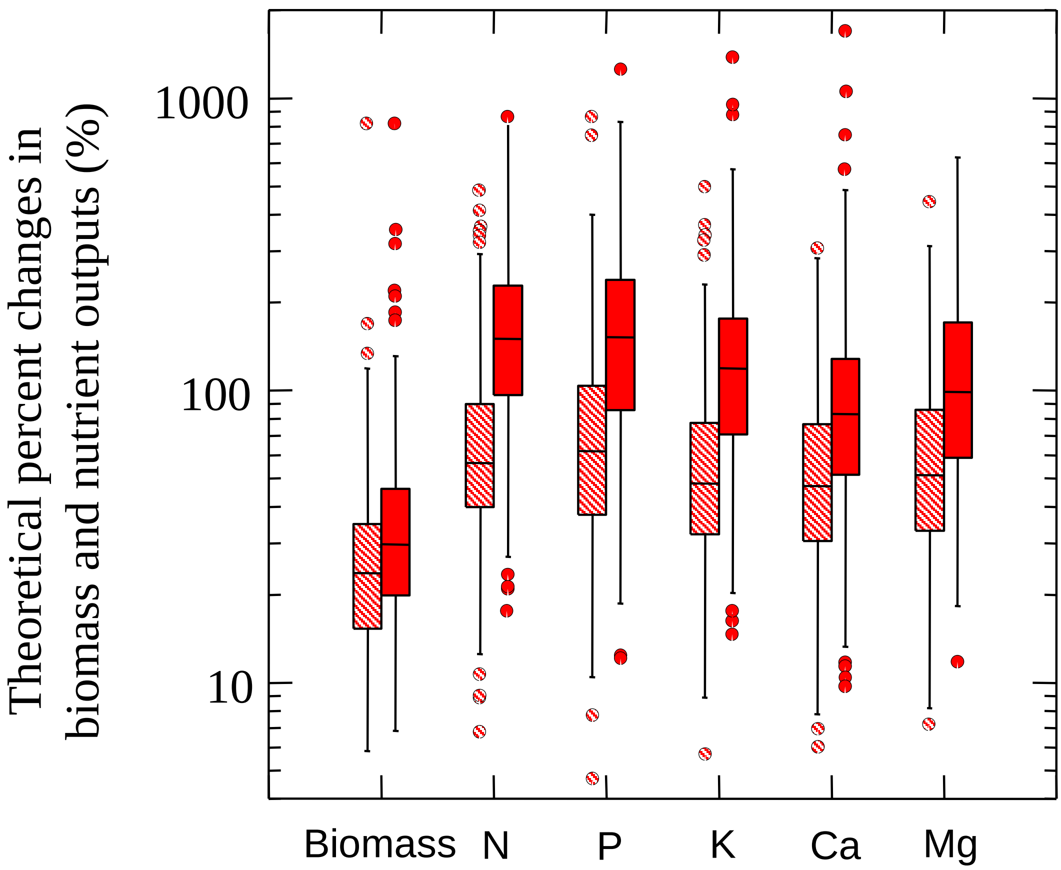

Figure S4 Theoretical percent changes in biomass and nutrient outputs as a result of removing stem + branches (treatment S(WB)B, hatched boxplots) or stem + branches + foliage (treatment S(WB)BF, solid boxplots) compared to conventional stem-only harvest (S(WB)). Theoretical values calculated using harvest rates of 100% (“nutrient stocks” dataset). Number of case studies = 214-323.

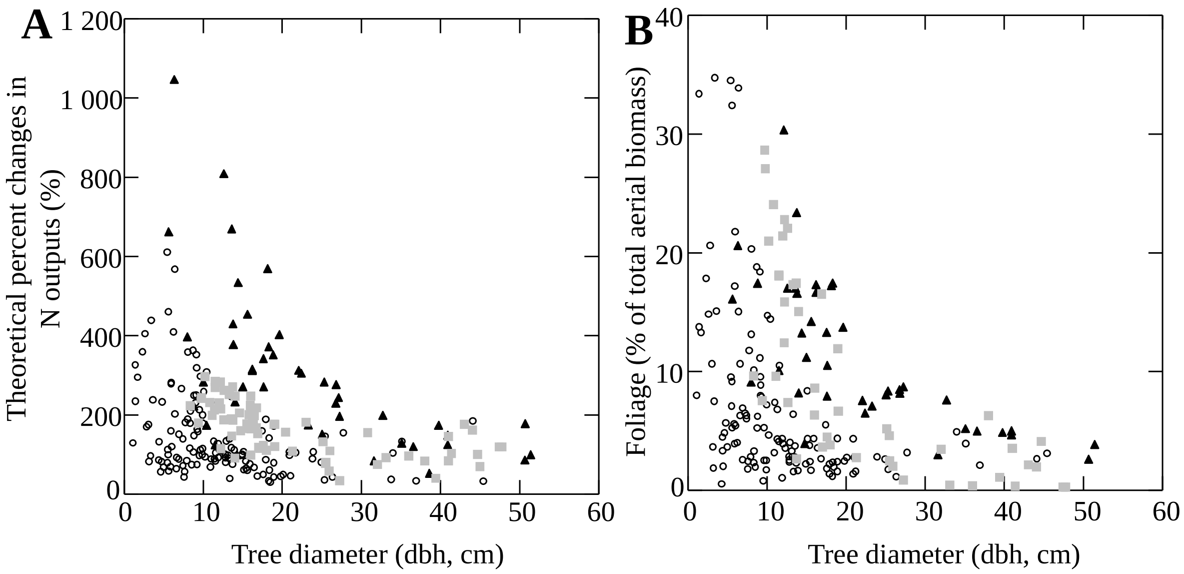

Figure S5 Theoretical percent changes in nutrient outputs as a result of removing stem + branches + foliage (treatment S(WB)BF) compared to conventional stem-only harvest (S(WB)); example for N, panel A) and contribution of foliage biomass to total aerial biomass (panel B): relationships with tree diameter. Theoretical values calculated using harvest rates of 100% ("nutrient stocks" dataset). Open circle, broadleaf trees; grey square, sparse canopy coniferous (mainly *Pinus*, also *Larix* or *Agathis*); black triangle, dense canopy coniferous (*Picea*, *Abies* and *Pseudotsuga*). For more details (relationships with tree age, tree height and stem biomass of all species) see Supplementary Figure S6.

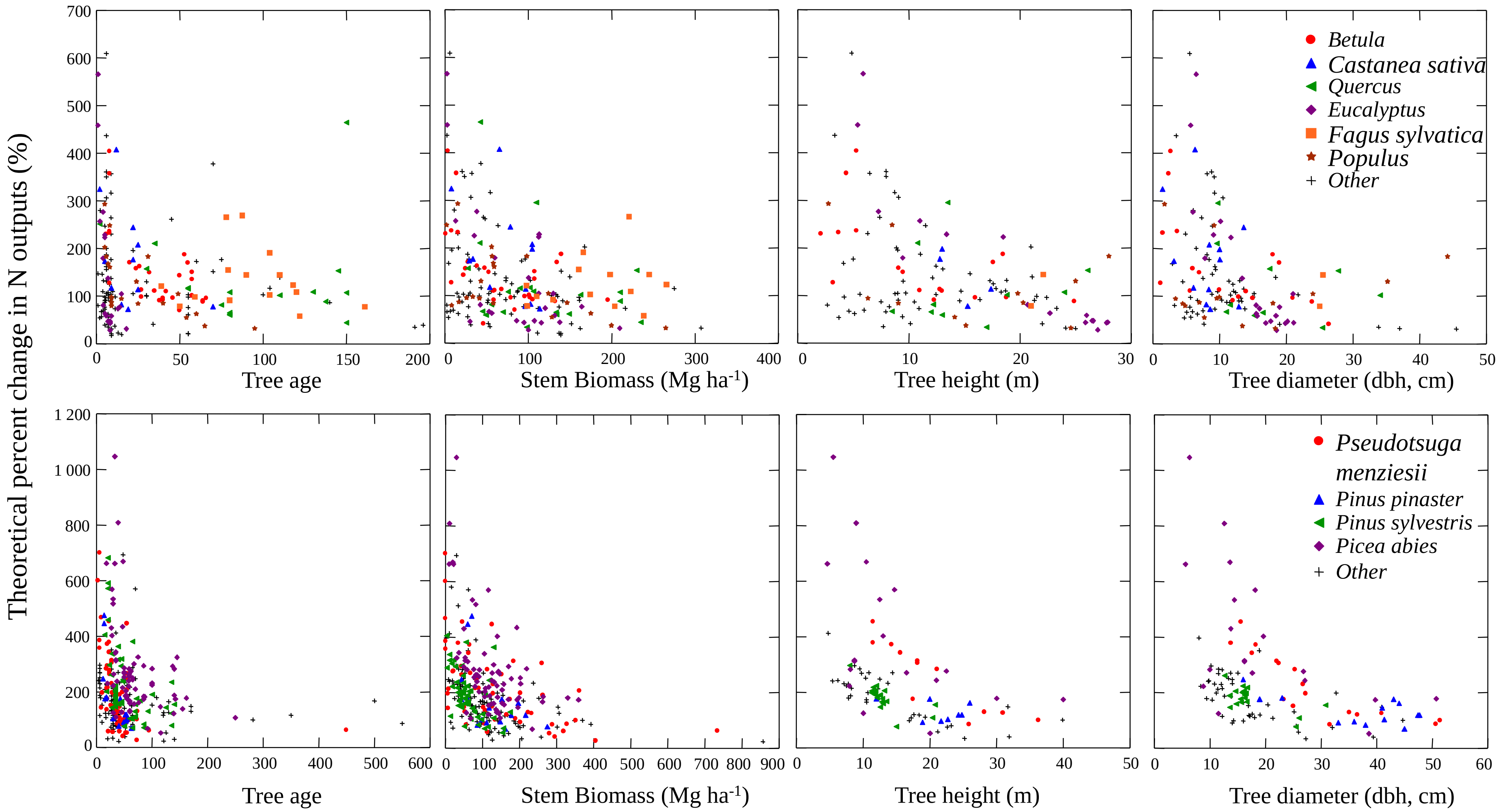

Figure S6 Theoretical percent change in nutrient outputs as a result of removing stem + branches + foliage (treatment S(WB)BF), compared to conventional stem-only harvesting (S(WB)) (example for N): relationships with tree age, stem biomass, tree height and tree diameter. Theoretical values calculated using harvest rates of 100% (“nutrient stocks” dataset). *Top*, broadleaf tree species; *Bottom*, coniferous tree species.

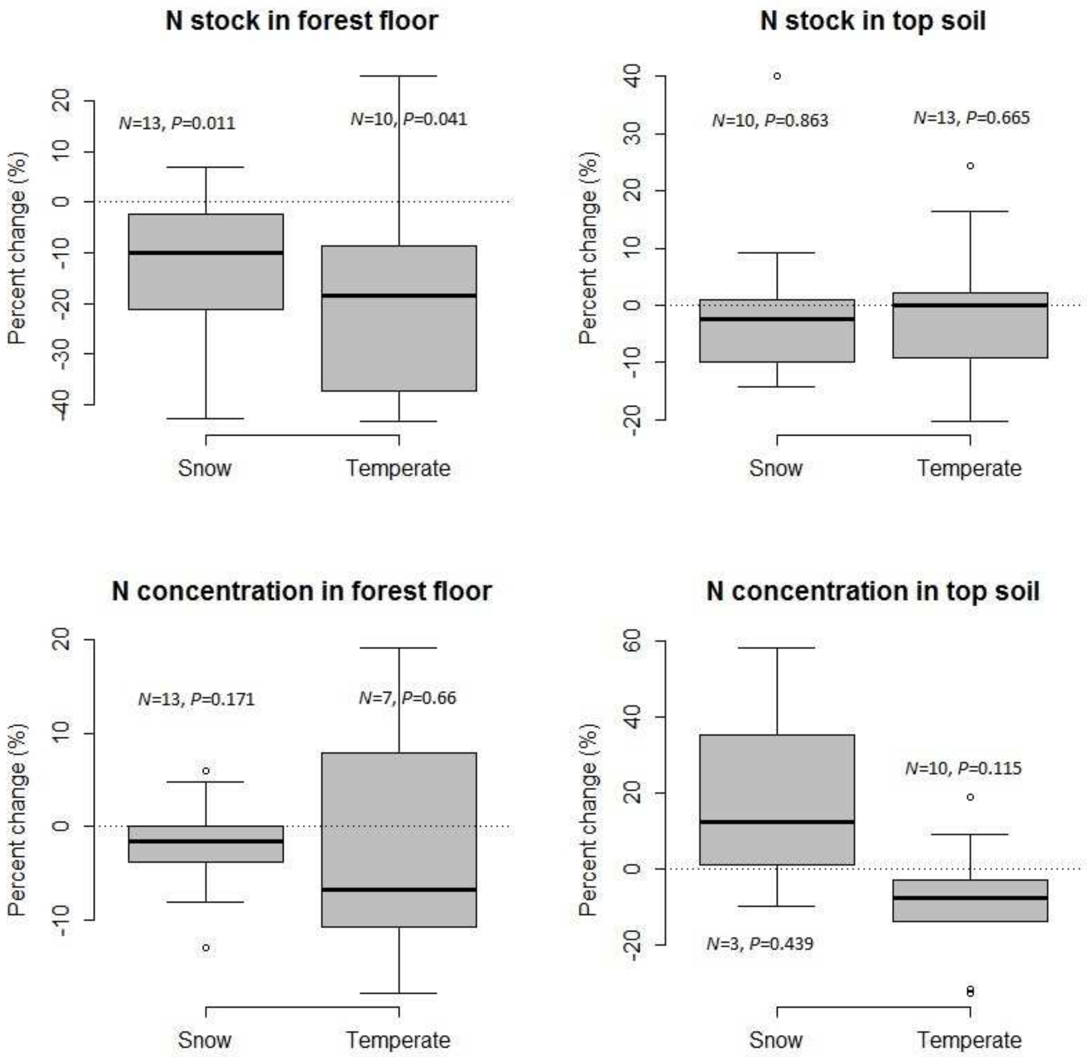

Figure S7 Effects of removing harvesting residues on total N in forest floor and top mineral soil as a function of the Koeppen climate classes ("environmental impacts" dataset, treatment S(WB)BF compared to conventional stem-only harvest S(WB)). Number of case studies and *P* value (difference between the log ratio and value 0, one sample *t* test) are shown for each class (cold climate (snow Koeppen climate class) or temperate climate). There was generally no significant difference among classes (*P*=0.081 for N concentration in top soil, *P*=0.538-0.955 for other variables). Similar patterns were also observed for organic C.

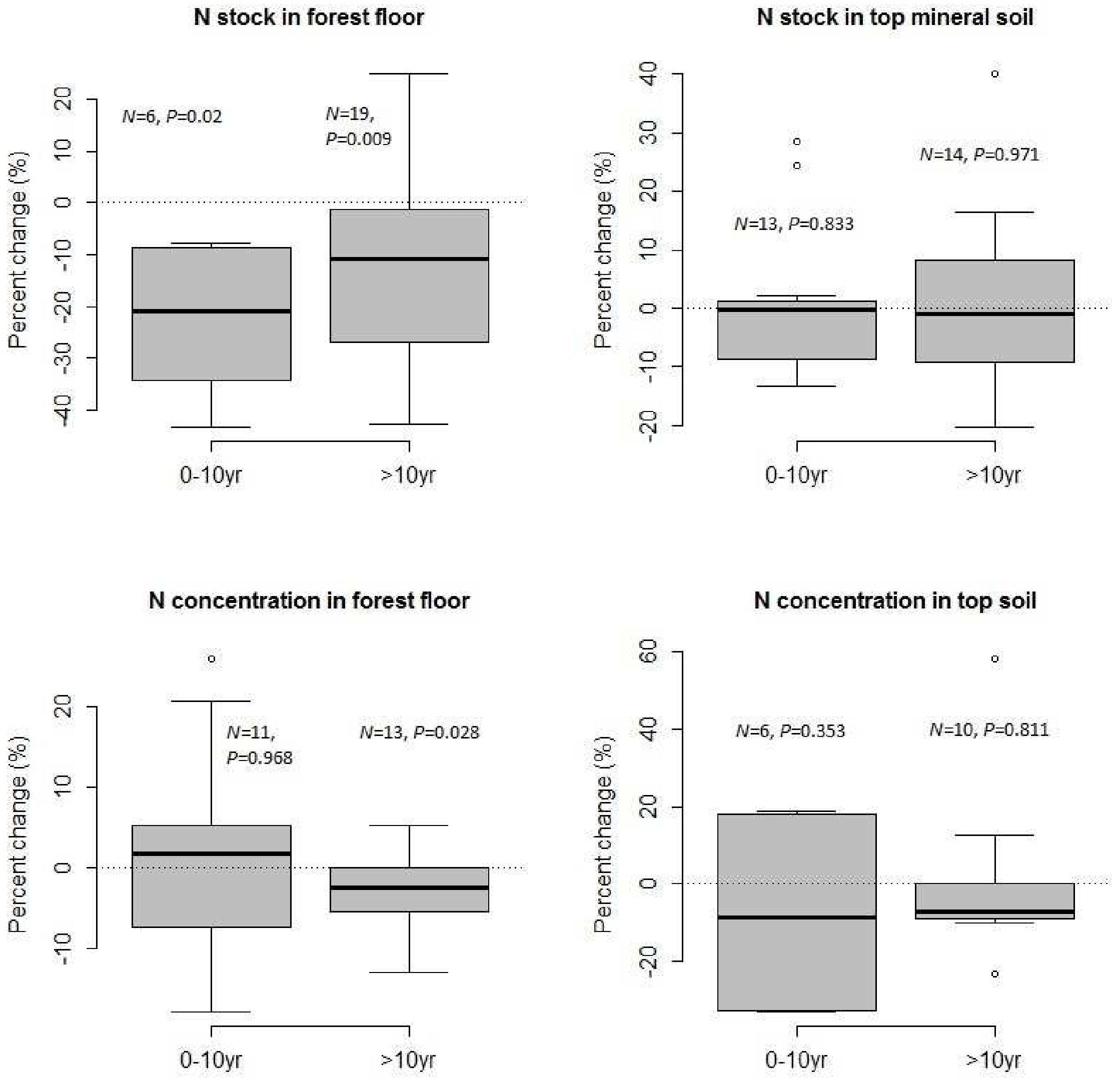

Figure S8 Effects of removing harvesting residues on total N in forest floor and top mineral soil as a function of the time elapsed since the removal ("environmental impacts" dataset, treatment S(WB)BF compared to conventional stem-only harvest S(WB)). Number of case studies and *P* value (difference between the log ratio and value 0, one sample *t* test) are shown for each class. There was no significant difference among classes (*P*=0.290-0.909).

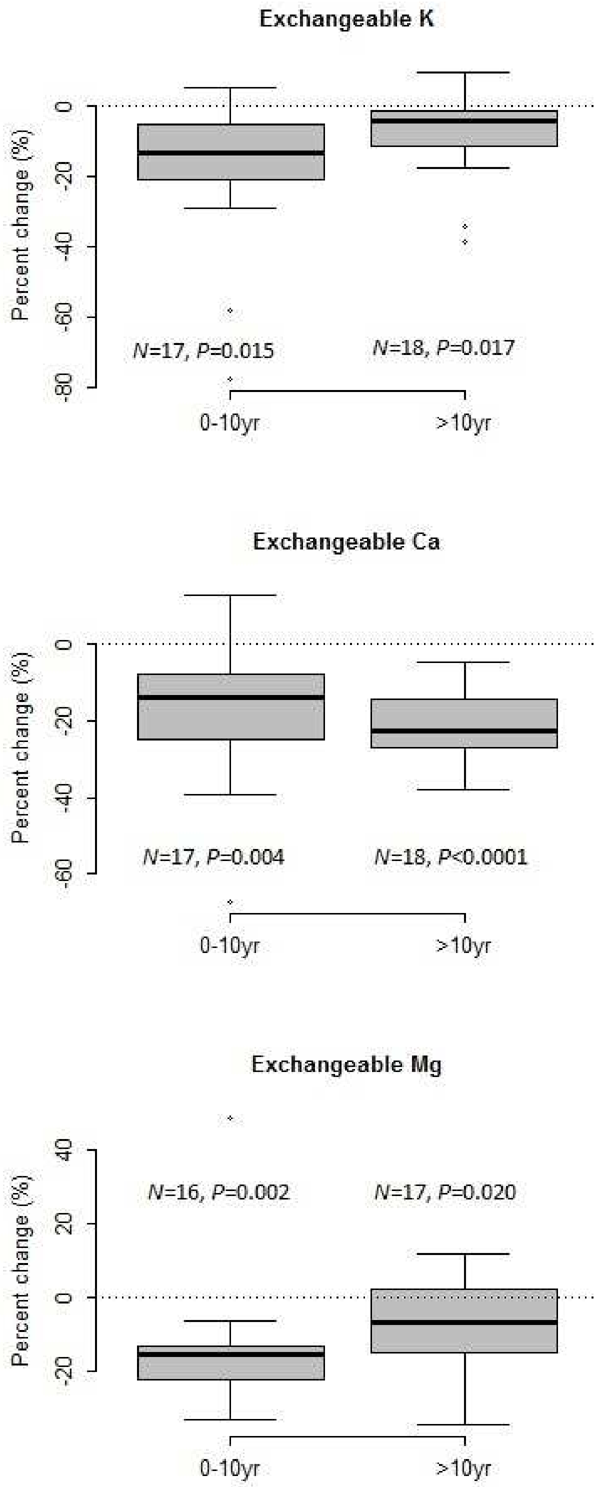

Figure S9 Effects of removing harvesting residues on exchangeable K, Ca and Mg in forest floor + top mineral soil as a function of the time elapsed since the removal ("environmental impacts" dataset, treatment S(WB)BF compared to conventional stem-only harvest S(WB)). Number of case studies and *P* value (difference between the log ratio and value 0, one sample *t* test) are shown for each class. There was no significant difference among classes (*P*=0.115-0.648).

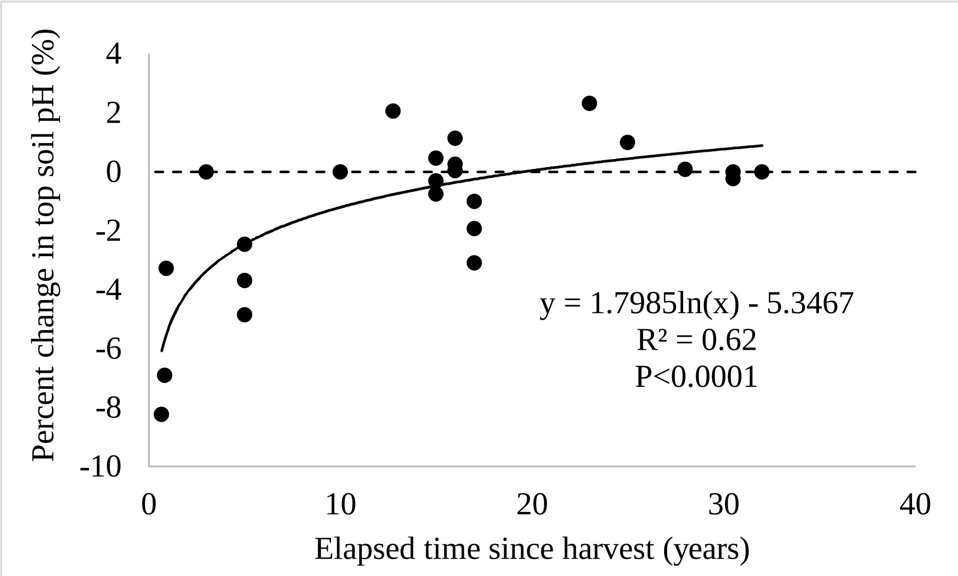

Figure S10 Effects of removing harvesting residues on pH in top mineral soil as a function of the time elapsed since the removal ("environmental impacts" dataset, treatment S(WB)BF compared to conventional stem-only harvest S(WB)). There was significant relationships between percent change in soil pH and elapsed time (P<0.0001, non-linear regression).

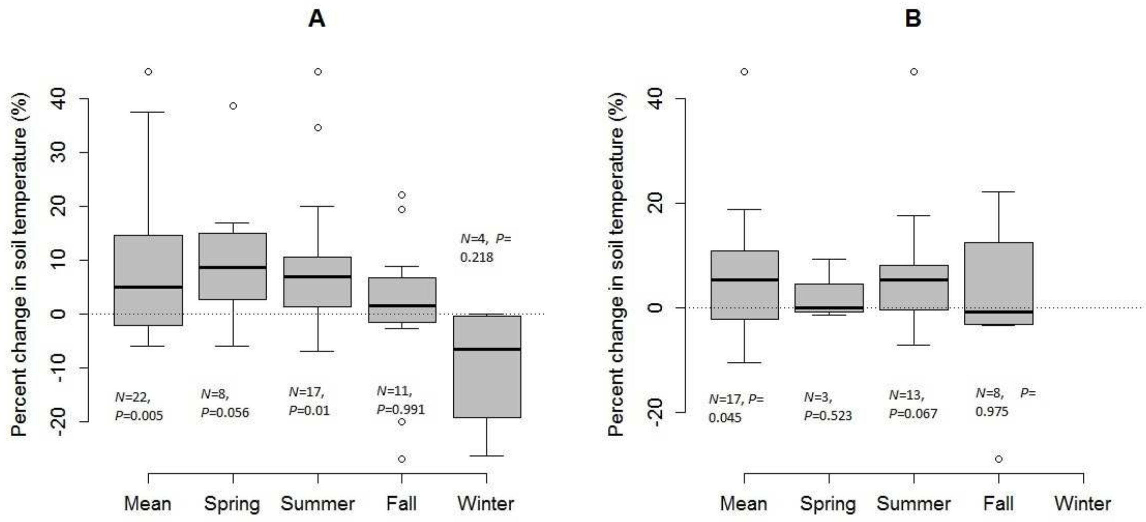

Figure S11 Effect of removing stem + harvesting residues on the temperature of the top mineral soil compared to stem-only harvest ("environmental impacts" dataset). Panel A includes all types of intensive harvests taken together. Panel B only includes removing of stem + branches + foliage (S(WB)BF)). There were significant effects on mean soil temperature and soil temperature in spring and summer (log ratio significantly higher than 0).

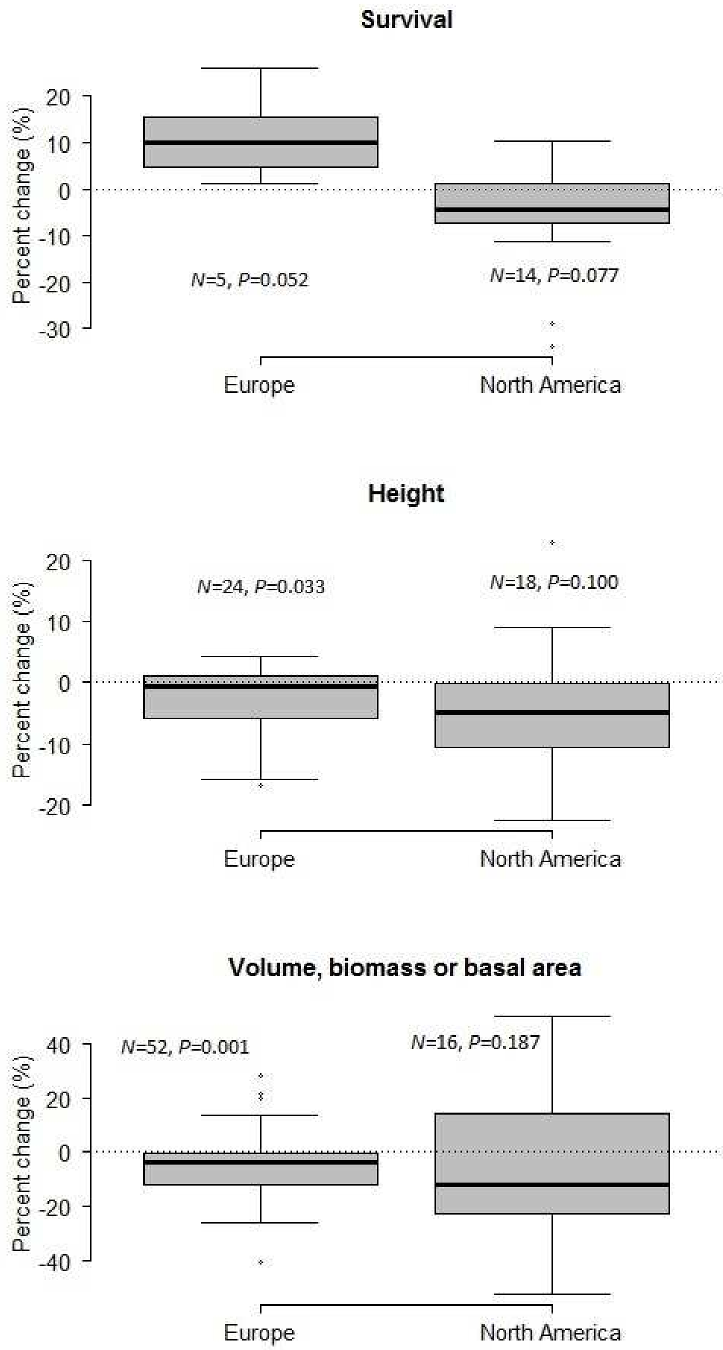

Figure S12 Effects of removing harvesting residues on tree growth: comparison between Europe and North America ("environmental impacts" dataset, treatment S(WB)BF compared to conventional stem-only harvest S(WB)). Number of case studies and *P* value (difference between the log ratio and value 0, one sample *t* test) are shown for each class. There was significant difference among classes in tree survival (*P*=0.018) but not in tree growth (tree height, tree volume, biomass or basal area; *P*=0.466-0.605).

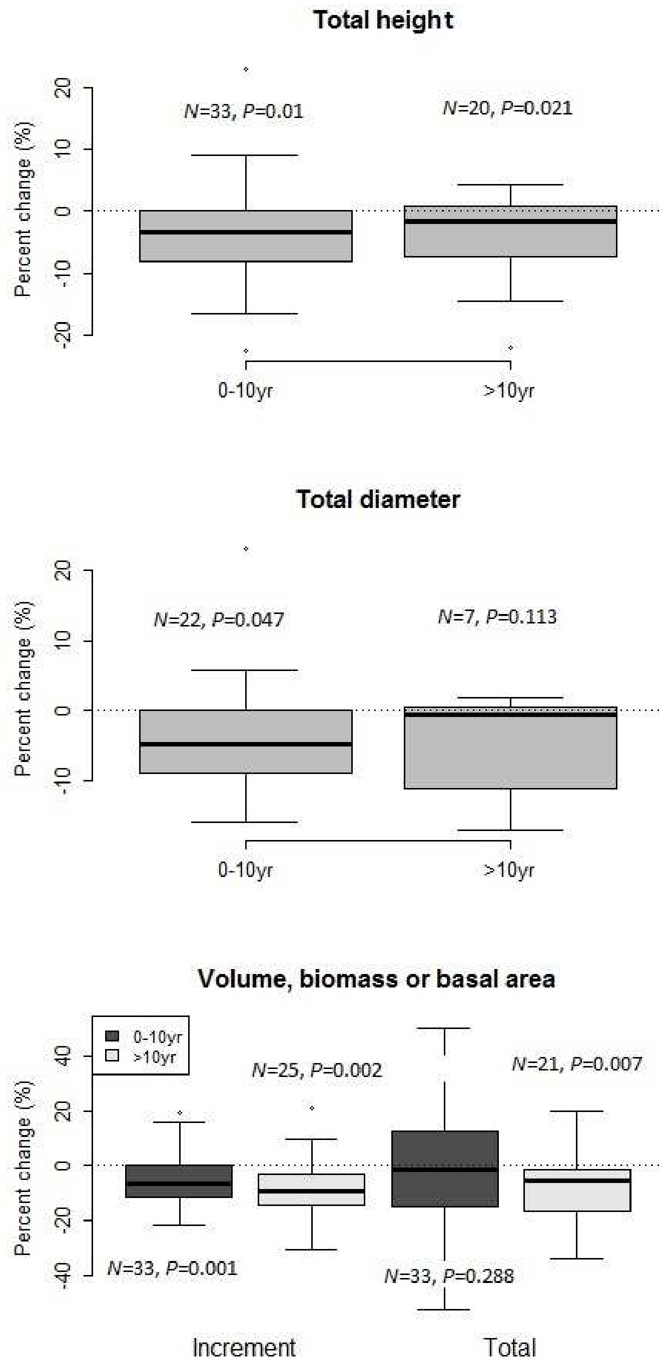

Figure S13 Effects of removing harvesting residues on tree growth as a function of the time elapsed since the removal ("environmental impacts" dataset, treatment S(WB)BF compared to conventional stem-only harvest S(WB)). Number of case studies and *P* value (difference between the log ratio and value 0, one sample *t* test) are shown for each class. There was no significant difference among classes (*P*=0.242-0.961).

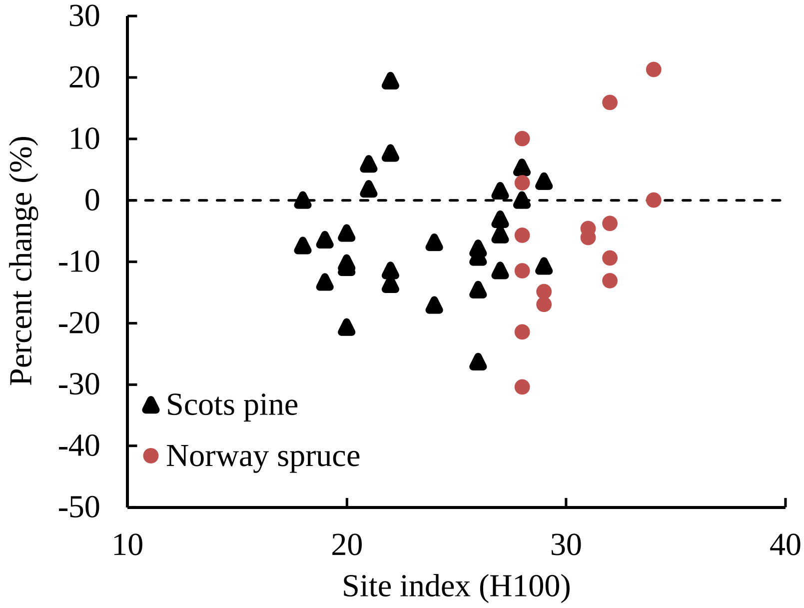

Figure S14 Effects of removing harvesting residues on tree growth (volume increment) in relation with the site index ("environmental impacts" dataset, treatment S(WB)BF compared to conventional stem-only harvest S(WB)). These data are from Helmisaari et al. 2011 (22 sites in Finland, Norway and Sweden). There are no relationship between percent change in tree growth and the site index (this figure or with data from other studies in Scandinavia (Tveite & Hanssen, 2013; Egnell & Ulvcrona, 2015)).

Table S1: Potential percent changes in biomass and nutrient outputs due to removing harvesting residues. Theoretical values calculated using harvest rates of 100% ("nutrient stocks" dataset).

	Harvest treatments compared to conventional stem-only harvest (wood + bark; S(WB))				
	S(W)	S(WB)B	S(WB)BF	S(WB)BR	S(WB)BFR
	Stem wood‡	Stem (wood + bark) + branches	Stem (wood + bark) + branches + foliage	Stem (wood + bark) + branches + stumps/roots	Stem (wood + bark) + branches + foliage + stumps/roots
Biomass					
(Number of case studies)	(113)	(240)	(314)	(98)	(101)
Mean, Median (Q1, Q3)	-14, -12 (-16, -10)	32, 24 (15, 35)	42, 30 (20, 46)	61, 54 (38, 67)	70, 62 (44, 76)
Min, Max	-73, -3	6, 813	7, 813	11, 363	23, 368
N					
(Number of case studies)	(122)	(254)	(323)	(98)	(104)
Mean, Median (Q1, Q3)	-37, -37 (-45, -28)	77, 56 (40, 90)	177, 150 (96, 228)	140, 126 (74, 168)	222, 192 (135, 281)
Min, Max	-85, -4	7, 482	18, 854	33, 692	54, 792
P					
(Number of case studies)	(113)	(231)	(290)	(88)	(92)
Mean, Median (Q1, Q3)	-36, -36 (-49, -23)	90, 62 (38, 104)	183, 152 (86, 238)	172, 122 (79, 211)	240, 200 (122, 309)
Min, Max	-78, -3	5, 856	12, 1244	23, 995	42, 1058
K					
(Number of case studies)	(116)	(235)	(293)	(93)	(96)
Mean, Median (Q1, Q3)	-33, -32 (-42, -23)	69, 48 (32, 77)	146, 119 (71, 176)	125, 105 (71, 158)	185, 159 (120, 216)
Min, Max	-72, -3	6, 495	15, 1378	24, 510	44, 566
Ca					
(Number of case studies)	(108)	(218)	(271)	(82)	(85)
Median (Q1, Q3)	-56, -56 (-69, -40)	64, 47 (31, 76)	122, 83 (51, 128)	113, 93 (62, 126)	147, 120 (73, 180)
Min, Max	-94, -16	6, 306	10, 1687	25, 770	38, 824
Mg					
(Number of case studies)	(107)	(214)	(222)	(79)	(82)
Mean, Median (Q1, Q3)	-38, -39 (-49, -26)	74, 51 (33, 86)	135, 99 (59, 169)	129, 109 (75, 150)	171, 143 (101, 227)
Min, Max	-80, -5	7, 438	12, 627	23, 456	33, 568
S					
(Number of case studies)	(17)	(42)	(35)	(15)	(16)
Mean, Median (Q1, Q3)	-37, -39 (-47, -28)	56, 44 (29, 61)	136, 75 (64, 131)	141, 99 (74, 108)	213, 124 (112, 161)
Min, Max	-58, -11	2, 230	12, 788	27, 758	33, 1317
Na					
(Number of case studies)	(7)	(17)	(17)	(9)	(9)
Mean, Median (Q1, Q3)	-24, -25 (-28, -21)	126, 37 (20, 109)	174, 87 (30, 141)	266, 248 (57, 351)	345, 258 (133, 424)
Min, Max	-33, -11	10, 811	10, 1091	25, 829	46, 1108
Fe					
(Number of case studies)	(12)	(19)	(19)	(4)	(4)
Mean, Median (Q1, Q3)	-28, -25 (-36, -20)	88, 39 (24, 75)	123, 55 (38, 140)	297, 185 (126, 355)	325, 234 (161, 399)
Min, Max	-64, -6	7, 672	10, 810	66, 752	78, 754
Mn					
(Number of case studies)	(21)	(28)	(27)	(8)	(8)
Mean, Median (Q1, Q3)	-32, -33 (-50, -19)	66, 38 (23, 55)	113, 73 (46, 114)	137, 73 (56, 171)	183, 119 (97, 210)
Min, Max	-58, -8	7, 433	19, 519	46, 431	73, 461
Zn					
(Number of case studies)	(11)	(11)	(11)	_	_
Mean, Median (Q1, Q3)	-36, -41 (-45, -29)	69, 42 (19, 119)	108, 63 (32, 190)	_	_
Min, Max	-58, -5	10, 164	12, 231	_	_
Cu					
(Number of case studies)	(10)	(10)	(10)	_	_
Mean, Median (Q1, Q3)	-18, -19 (-22, -14)	56, 45 (32, 74)	85, 72 (46, 118)	_	_
Min, Max	-27, -11	17, 137	22, 173	_	_
Ni					
(Number of case studies)	(4)	(4)	(4)	_	_
Mean, Median (Q1, Q3)	-10, -7 (-11, -6)	22, 25 (15, 32)	28, 32 (21, 40)	_	_
Min, Max	-20, -5	6, 33	8, 40	_	_
B					
(Number of case studies)	_#	(5)	(5)	(4)	(4)
Mean, Median (Q1, Q3)	_	94, 109 (78, 123)	153, 178 (105, 180)	152, 146 (139, 158)	206, 220 (190, 237)
Min, Max	_	24, 135	102, 201	121, 193	148, 237
Al					
(Number of case studies)	(3)	(6)	(6)	(3)	(3)
Mean, Median (Q1, Q3)	-44, -42 (-48, -40)	64, 66 (30, 97)	128, 147 (68, 189)	240, 290 (178, 327)	296, 360 (258, 365)
Min, Max	-54, -37	22, 101	27, 203	65, 365	156, 370

‡ Stem bark left on site (mitigation measures).

Not determined (number of case studies < 3).

Table S2: Percent changes in nutrient outputs due to removing harvesting residues. Theoretical values calculated using harvest rates# ("nutrient stocks" dataset).

	Harvest treatments compared to stem-only harvest (wood + bark, S(WB); logging with machine†)					
	S(WB)B	S(WB)BF		S(WB)BR	S(WB)BFR	
	Stem (wood + bark) + branches	Stem (wood + bark) + branches+foliage		Stem (wood + bark) + branches + stumps/roots	Stem (wood + bark) + branches + foliage + stumps/roots	
	Machine†	Machine	Machine, in winter or after drying step‡	Machine	Machine	Machine, in winter or after drying step
N						
(Number of case studies)	(112)	(109)	(109)	(35)	(35)	(35)
Mean, Median (Q1, Q3)	51, 41 (22, 69)	122, 95 (63, 139)	63, 52 (29, 74)	107, 73 (57, 126)	153, 127 (106, 142)	116, 93 (67, 127)
Min, Max	6, 325	11, 680	6, 414	22, 649	48, 684	29, 649
Potential Mean, Median¶	77, 56	177, 150	177, 150	140, 126	222, 192	222, 192
P						
(Number of case studies)	(105)	(102)	(102)	(34)	(34)	(34)
Mean, Median (Q1, Q3)	59, 43 (22, 70)	120, 90 (51, 158)	70, 52 (27, 87)	109, 72 (49, 152)	149, 128 (64, 191)	118, 86 (50, 156)
Min, Max	6, 642	12, 836	7, 642	19, 604	31, 627	20, 604
Potential Mean, Median	90, 62	183, 152	183, 152	172, 122	240, 200	240, 200
K						
(Number of case studies)	(107)	(104)	(104)	(36)	(36)	(36)
Mean, Median (Q1, Q3)	43, 35 (20, 54)	84, 70 (45, 107)	50, 40 (24, 62)	95, 79 (53, 120)	128, 104 (83, 144)	101, 85 (59, 121)
Min, Max	3, 183	11, 338	5, 206	19, 343	34, 365	20, 343
Potential Mean, Median	69, 48	146, 119	146, 119	125, 105	185, 159	185, 159
Ca						
(Number of case studies)	(101)	(98)	(98)	(36)	(36)	(36)
Median (Q1, Q3)	55, 42 (23, 73)	91, 70 (37, 121)	62, 50 (28, 87)	108, 75 (52, 129)	132, 97 (66, 158)	112, 78 (53, 140)
Min, Max	8, 310	10, 327	9, 310	18, 675	48, 693	30, 675
Potential Mean, Median	64, 47	122, 83	122, 83	113, 93	147, 120	147, 120
Mg						
(Number of case studies)	(100)	(97)	(97)	(36)	(36)	(36)
Mean, Median (Q1, Q3)	53, 37 (24, 67)	89, 74 (42, 118)	60, 44 (26, 77)	97, 84 (49, 137)	124, 112 (74, 177)	103, 87 (50, 145)
Min, Max	5, 310	11, 375	6, 310	22, 206	28, 249	22, 207
Potential Mean, Median	74, 51	135, 99	135, 99	129, 109	171, 143	171, 143

Harvest rates: 100% of stem wood, 20-80% of stem bark depending on harvest conditions (see below), 50-60% of branches depending on tree species, 0-40% of foliage depending on harvest conditions (see below), 60% of roots.

† Logging with a chainsaw causes low bark losses, 80% of the bark remains on the stem and is exported, while machine logging significantly increases bark losses, only 20% of the bark remains on the stem and is exported.

‡ Foliage exports are strongly reduced with mitigation measures (100% of foliage is left on site when broadleaf trees are removed in winter or when residues are removed after a delay that allows the foliage to dry and fall off the branches, 90% of foliage is left on site when residues of coniferous trees are removed after a delay that allows the foliage to dry and fall off the branches).

¶ Comparison with the theoretical values calculated using harvest rates of 100%.

<u>Allometric relationships (“nutrient stocks" dataset)</u>

In our meta-analysis, the effects of removing harvesting residues on nutrient outputs are expressed as percent changes relative to the conventional stem-only harvest (see results in the main text (**Table 1**) and Supplementary **Tables S1** and **S2** and **Figures S4** to **S6**).

We also used the “nutrient stocks" dataset to build allometric relationships that enable estimating theoretical nutrient outputs in kg ha^{-1} (considering 100% harvest rates) as a function of stem biomass. We built allometric relationships for macronutrients (N, P, K, Ca and Mg). These allometric relationships were fitted for several broadleaf (*Betula, Castanea sativa, Quercus, Eucalyptus, Fagus sylvatica,* and *Populus*) and needleleaf tree species (*Pseudotsuga menziesii, Picea abies, Pinus pinaster*, and *Pinus sylvestris*). These relationships make possible to quantify nutrient stocks in kg ha^{-1} in trees and hence theoretical nutrient outputs depending on stem biomass and harvest intensity. Relationships were generally robust with a high or moderate confidence index in most cases (based on R^2 values; see details in **Table S3**).

Allometric relationships are by-products of case study data compilation and were not used in the meta-analysis. We determined allometric relationships because they are useful tools to estimate for instance the amounts of fertilizers or wood ash to apply (i.e. in case of compensatory strategies).

Table S3 Relationships between nutrient stocks in trees (*y*, in kg ha^{-1}) and stem biomass (wood + bark; *x*, in Mg ha^{-1}) (theoretical values, 100% harvest rates; "nutrient stocks" dataset).

Nutrient	Components	Model	Parameter a	Parameter b	N_{obs}	R^2	P	Biomass range†	Confidence index‡
Betula sp.									
N	S(W)	y=ax^b	3.8722	0.6376	9	0.86	<0.0001	10–110	High
N	S(WB)	y=ax^b	4.2674	0.7453	29	0.92	<0.0001	10–150	High
N	S(WB)B	y=ax^b	8.2710	0.6973	23	0.86	<0.0001	10–150	High
N	S(WB)BF	y=ax^b	17.1810	0.6134	30	0.78	<0.0001	10–150	High
N	S(WB)BFR	y=ax^b	10.5250	0.8228	7	0.98	<0.0001	50–140	High
P	S(W)	y=ax^b	0.8814	0.4476	9	0.47	0.041	10–110	Moderate
P	S(WB)	y=ax^b	0.6590	0.6217	28	0.72	<0.0001	10–150	High
P	S(WB)B	y=ax^b	1.2662	0.5686	22	0.71	<0.0001	10–150	High
P	S(WB)BF	y=ax^b	2.3967	0.5102	29	0.57	<0.0001	10–150	High
P	S(WB)BFR	y=ax^b	1.1651	0.7689	7	0.91	0.001	50–140	High
K	S(W)	y=ax^b	2.0339	0.6404	9	0.74	0.003	10–110	High
K	S(WB)	y=ax^b	2.2351	0.7061	28	0.85	<0.0001	10–150	High
K	S(WB)B	y=ax^b	4.2162	0.6391	22	0.85	<0.0001	10–150	High
K	S(WB)BF	y=ax^b	7.2588	0.6126	29	0.78	<0.0001	10–150	High
K	S(WB)BFR	y=ax^b	4.9815	0.7600	7	0.98	<0.0001	50–140	High
Ca	S(W)	nd	*mean = 49 kg ha^{-1}*		4	nd	nd	60–110	nd
Ca	S(WB)	y=ax^b	2.9600	0.8545	23	0.87	<0.0001	20–150	High
Ca	S(WB)B	y=ax^b	6.3915	0.7800	17	0.87	<0.0001	20–150	High
Ca	S(WB)BF	y=ax^b	6.6964	0.7860	24	0.88	<0.0001	20–150	High
Ca	S(WB)BFR	y=ax^b	10.0840	0.8093	7	0.98	<0.0001	50–140	High
Mg	S(W)	nd	*mean = 16 kg ha^{-1}*		4	nd	nd	60–110	nd
Mg	S(WB)	y=ax^b	0.3196	0.9152	16	0.97	<0.0001	30–140	High
Mg	S(WB)B	y=ax^b	0.4873	0.8996	17	0.96	<0.0001	30–140	High
Mg	S(WB)BF	y=ax^b	0.7957	0.8468	17	0.92	<0.0001	30–140	High
Mg	S(WB)BFR	y=ax^b	1.0256	0.9008	7	0.95	<0.0001	50–140	High
Castanea sativa									
N	S(W)	y=ax^b	4.6356	0.6232	5	1.00	<0.0001	10–120	High
N	S(WB)	y=ax^b	5.2603	0.6345	17	0.44	0.004	10–140	Moderate
N	S(WB)B	y=ax^b	9.7291	0.6441	17	0.66	<0.0001	10–140	High
N	S(WB)BF	y=ax^b	52.4600	0.3397	11	0.47	0.019	10–120	Moderate
N	S(WB)BFR	nd	nd	nd	0	nd	nd	nd	nd
P	S(W)	y=ax^b	*similar to S(WB)*		5	0.99	<0.0001	10–120	High
P	S(WB)	y=ax^b	0.6838	0.4729	15	0.37	0.016	10–140	Moderate
P	S(WB)B	y=ax^b	1.3065	0.5010	15	0.69	<0.0001	10–140	High
P	S(WB)BF	y=ax^b	3.4282	0.4178	9	0.87	<0.0001	10–120	High
P	S(WB)BFR	nd	nd	nd	0	nd	nd	nd	nd
K	S(W)	y=ax^b	*similar to S(WB)*		5	0.99	<0.0001	10–120	High
K	S(WB)	y=ax^b	3.3794	0.5050	17	0.29	0.025	10–140	Moderate
K	S(WB)B	y=ax^b	6.4518	0.5614	17	0.70	<0.0001	10–140	High
K	S(WB)BF	y=ax^b	20.9460	0.3746	11	0.67	0.002	10–120	High
K	S(WB)BFR	nd	nd	nd	0	nd	nd	nd	nd
Ca	S(W)	y=ax^b	1.7350	0.6186	5	0.99	<0.0001	10–120	High
Ca	S(WB)	y=ax^b	8.4702	0.6423	17	0.49	0.002	10–140	Moderate
Ca	S(WB)B	y=ax^b	12.5500	0.6684	17	0.68	<0.0001	10–140	High
Ca	S(WB)BF	y=ax^b	28.3490	0.5202	11	0.59	0.006	10–120	High
Ca	S(WB)BFR	nd	nd	nd	0	nd	nd	nd	nd
Mg	S(W)	y=ax^b	0.8231	0.6206	5	0.99	<0.0001	10–120	High
Mg	S(WB)	y=ax^b	1.3925	0.6583	17	0.71	<0.0001	10–140	High
Mg	S(WB)B	y=ax^b	1.9152	0.7229	17	0.73	<0.0001	10–140	High
Mg	S(WB)BF	y=ax^b	9.0851	0.4084	11	0.56	0.008	10–120	High
Mg	S(WB)BFR	nd	nd	nd	0	nd	nd	nd	nd

nd, not determined due to the small number of case studies.

† Range of stem biomass in which models can be used to estimate nutrient stocks.

‡ Confidence index based on R^2 values (*low* : R^2=0.00-0.25; *moderate* : R^2=0.25-0.50; *high* : R^2=0.50-1.00).

Table S3 Continued.

Nutrient	Components	Model	Parameter a	Parameter b	N_{obs}	R^2	P	Biomass range†	Confidence index‡
Quercus sp.									
N	S(W)	$y=ax^b$	1.4867	1.0000	6	0.91	<0.0001	30–210	High
N	S(WB)	$y=ax^b$	6.7645	0.7573	27	0.85	<0.0001	10–240	High
N	S(WB)B	$y=ax^b$	4.1451	0.9689	40	0.94	<0.0001	10–300	High
N	S(WB)BF¶	$y=ax^b$	14.5020	0.7346	35	0.92	<0.0001	10–150	High
N	S(WB)BFR	$y=ax^b$	33.5290	0.6202	13	0.30	0.052	70–300	Moderate
P	S(W)	$y=ax^b$	0.4419	0.6242	7	0.35	0.162	30–470	Moderate
P	S(WB)	$y=ax^b$	0.5721	0.6974	26	0.63	<0.0001	10–470	High
P	S(WB)B	$y=ax^b$	0.9695	0.7470	30	0.78	<0.0001	10–470	High
P	S(WB)BF#	$y=ax^b$	2.4499	0.5849	30	0.86	<0.0001	10–200	High
P	S(WB)BFR	$y=ax^b$	0.5419	0.9450	11	0.35	0.054	70–300	Moderate
K	S(W)	$y=ax^b$	1.1612	0.9458	7	0.96	<0.0001	30–470	High
K	S(WB)	$y=ax^b$	3.8190	0.7659	27	0.88	<0.0001	10–470	High
K	S(WB)B	$y=ax^b$	5.6453	0.7668	30	0.89	<0.0001	10–470	High
K	S(WB)BF	$y=ax^b$	8.2330	0.7214	30	0.95	<0.0001	10–240	High
K	S(WB)BFR	$y=ax^b$	32.6460	0.4921	11	0.14	0.259	70–240	Low
Ca	S(W)	$y=ax^b$	6.8519	0.4535	7	0.23	0.275	30–470	Low
Ca	S(WB)	$y=ax^b$	12.4870	0.7606	22	0.30	0.009	10–470	Moderate
Ca	S(WB)B	$y=ax^b$	18.3890	0.7872	30	0.68	<0.0001	10–470	High
Ca	S(WB)BF	$y=ax^b$	16.4410	0.8489	30	0.88	<0.0001	10–300	High
Ca	S(WB)BFR	$y=ax^b$	38.7160	0.6977	11	0.46	0.022	70–240	Moderate
Mg	S(W)	$y=ax^b$	0.1470	0.8821	7	0.56	0.053	30–470	High
Mg	S(WB)	$y=ax^b$	0.4068	0.8785	21	0.45	0.001	30–470	Moderate
Mg	S(WB)B	$y=ax^b$	1.0088	0.8108	28	0.84	<0.0001	10–470	High
Mg	S(WB)BF	$y=ax^b$	2.2021	0.6919	28	0.92	<0.0001	10–240	High
Mg	S(WB)BFR	$y=ax^b$	1.7033	0.8106	9	0.46	0.044	70–240	Moderate

¶ Other model: $y= -0.0039x^2+4.6999x+25.538$ (R^2=0.79; range of stem biomass = 10-300 Mg ha^{-1})

Other model: $y=0.2493x+10.358$ (R^2 = 0.62; range of stem biomass = 50-300 Mg ha^{-1})

Nutrient	Components	Model	Parameter a	Parameter b	N_{obs}	R^2	P	Biomass range†	Confidence index‡
Eucalyptus									
N	S(W)	$y=ax^b$	1.8298	0.9121	24 (22)	0.90 (0.77)§	<0.0001 (<0.0001)§	5–170	High
N	S(WB)	$y=ax^b$	3.7891	0.7834	27 (25)	0.84 (0.65)	<0.0001 (<0.0001)	5–170	High
N	S(WB)B	$y=ax^b$	6.1370	0.7536	23 (21)	0.92 (0.83)	<0.0001 (<0.0001)	5–170	High
N	S(WB)BF	$y=ax^b$	27.8850	0.5003	28 (26)	0.77 (0.66)	<0.0001 (<0.0001)	5–170	High
N	S(WB)BFR	nd	nd	nd	2	nd	nd	nd	nd
P	S(W)	$y=ax^b$	0.5431	0.7331	24 (22)	0.63 (0.30)	<0.0001 (0.009)	5–140	Moderate
P	S(WB)	$y=ax^b$	1.3348	0.6014	26 (24)	0.56 (0.22)	<0.0001 (0.02)	5–140	Low
P	S(WB)B	$y=ax^b$	2.2210	0.5675	23 (21)	0.66 (0.37)	<0.0001 (0.003)	5–140	Moderate
P	S(WB)BF	$y=ax^b$	3.3855	0.5076	28 (26)	0.65 (0.54)	<0.0001 (<0.0001)	5–140	High
P	S(WB)BFR	nd	nd	nd	2	nd	nd	nd	nd
K	S(W)	$y=ax^b$	3.2245	0.6591	19 (18)	0.48 (0.08)	0.001 (0.271)	5–210	Low
K	S(WB)	$y=ax^b$	7.4630	0.5364	22 (21)	0.35 (0.04)	0.004 (0.292)	5–210	Low
K	S(WB)B	$y=ax^b$	10.2720	0.5566	18 (17)	0.43 (0.07)	0.003 (0.317)	5–210	Low
K	S(WB)BF	$y=ax^b$	17.8990	0.4847	23 (22)	0.42 (0.19)	0.001 (0.043)	5–210	Low
K	S(WB)BFR	nd	nd	nd	2	nd	nd	nd	nd
Ca	S(W)	$y=ax^b$	0.3725	1.0220	15 (14)	0.68 (0.21)	<0.0001 (0.096)	5–210	Low
Ca	S(WB)	$y=ax^b$	3.8803	0.7489	18 (17)	0.39 (0.11)	0.006 (0.192)	5–210	Low
Ca	S(WB)B	$y=ax^b$	6.6855	0.7293	14 (13)	0.38 (0.05)	0.018 (0.481)	5–210	Low
Ca	S(WB)BF	$y=ax^b$	55.7860	0.3635	19 (18)	0.12 (0.01)	0.150 (0.724)	5–210	Low
Ca	S(WB)BFR	nd	nd	nd	2	nd	nd	nd	nd
Mg	S(W)	$y=ax^b$	0.8946	0.6483	20 (18)	0.88 (0.72)	<0.0001 (<0.0001)	5–210	High
Mg	S(WB)	$y=ax^b$	4.0630	0.4553	23 (21)	0.51 (0.21)	<0.0001 (0.038)	5–210	Low
Mg	S(WB)B	$y=ax^b$	5.2454	0.5086	19 (17)	0.83 (0.58)	<0.0001 (<0.0001)	5–210	High
Mg	S(WB)BF	$y=ax^b$	14.8410	0.3374	24 (22)	0.62 (0.28)	<0.0001 (0.011)	5–210	Moderate
Mg	S(WB)BFR		nd	nd	2	nd	nd	nd	nd

§ In some cases (particularly for K and Ca), relationships were not significant when a case study with low stem biomass values was deleted (range of stem biomass = 2.4-2.8 Mg ha^{-1}). Results (R^2 and P) without this case study are shown in brackets.

nd, not determined due to the small number of case studies.

† Range of stem biomass in which models can be used to estimate nutrient stocks.

‡ Confidence index based on R^2 values (*low* : R^2=0.00-0.25; *moderate* : R^2=0.25-0.50; *high* : R^2=0.50-1.00).

Table S3 Continued.

Nutrient	Components	Model	Parameter a	Parameter b	N_{obs}	R^2	P	Biomass range†	Confidence index‡
Fagus sylvatica									
N	S(W)	nd	nd	nd	1	nd	nd	nd	nd
N	S(WB)	$y=ax^b$	2.5034	0.8845	18	0.69	<0.0001	100–360	High
N	S(WB)B	$y=ax^b$	7.7513	0.7764	12	0.36	0.039	100–260	Moderate
N	S(WB)BF	$y=ax^b$	5.1332	0.9045	15	0.48	0.004	100–260	Moderate
N	S(WB)BFR	$y=ax^b$	8.8325	0.8219	9	0.34	0.097	110–260	Moderate
P	S(W)	nd	nd	nd	2	nd	nd	nd	nd
P	S(WB)	$y=ax^b$	0.5453	0.7145	17	0.49	0.002	100–650	Moderate
P	S(WB)B	$y=ax^b$	0.8057	0.7611	11	0.67	0.002	110–650	High
P	S(WB)BF	$y=ax^b$	4.5732	0.4654	13	0.23	0.096	100–260	Low
P	S(WB)BFR	$y=ax^b$	3.5641	0.5675	8	0.29	0.172	110–260	Moderate
K	S(W)	nd	nd	nd	2	nd	nd	nd	nd
K	S(WB)	$y=ax^b$	0.6568	1.0887	18	0.86	<0.0001	100–650	High
K	S(WB)B	$y=ax^b$	0.4877	1.2105	12	0.87	<0.0001	110–650	High
K	S(WB)BF	$y=ax^b$	1.0530	1.0935	14	0.77	<0.0001	100–260	High
K	S(WB)BFR	$y=ax^b$	0.5770	1.2475	9	0.71	0.005	110–260	High
Ca	S(W)	nd	nd	nd	2	nd	nd	nd	nd
Ca	S(WB)	$y=ax^b$	0.7019	1.1351	18	0.70	<0.0001	100–650	High
Ca	S(WB)B	$y=ax^b$	1.8013	1.0550	12	0.68	0.001	110–650	High
Ca	S(WB)BF	$y=ax^b$	0.6456	1.2734	14	0.61	0.001	100–260	High
Ca	S(WB)BFR	$y=ax^b$	2.3965	1.0738	9	0.38	0.077	110–260	Moderate
Mg	S(W)	nd	nd	nd	2	nd	nd	nd	nd
Mg	S(WB)	$y=ax^b$	0.2421	0.9792	18	0.75	<0.0001	100–650	High
Mg	S(WB)B	$y=ax^b$	0.0900	1.2178	12	0.83	<0.0001	110–650	High
Mg	S(WB)BF	$y=ax^b$	0.1546	1.1489	14	0.55	0.002	100–260	High
Mg	S(WB)BFR	$y=ax^b$	0.0196	1.5935	9	0.69	0.006	110–260	High
Populus sp.									
N	S(W)	$y=ax^b$	0.8383	1.0585	15	0.90	<0.0001	5–260	High
N	S(WB)	$y=ax^b$	1.8012	1.0000	33	0.86	<0.0001	5–260	High
N	S(WB)B	$y=ax^b$	5.8306	0.8019	34	0.73	<0.0001	5–260	High
N	S(WB)BF	$y=ax^b$	5.7802	0.8323	22	0.80	<0.0001	5–260	High
N	S(WB)BFR	nd	nd	nd	5	nd	nd	nd	nd
P	S(W)	$y=ax^b$	0.1681	0.9516	15	0.79	<0.0001	5–260	High
P	S(WB)	$y=ax^b$	0.3127	0.9945	28	0.79	<0.0001	5–260	High
P	S(WB)B	$y=ax^b$	0.6342	0.9359	30	0.74	<0.0001	40–260	High
P	S(WB)BF	$y=ax^b$	1.1822	0.8292	21	0.71	<0.0001	40–260	High
P	S(WB)BFR	nd	nd	nd	5	nd	nd	nd	nd
K	S(W)	$y=ax^b$	0.6219	1.1115	15	0.93	<0.0001	5–260	High
K	S(WB)	$y=ax^b$	1.2996	1.0130	28	0.85	<0.0001	5–260	High
K	S(WB)B	$y=ax^b$	2.5824	0.9215	30	0.83	<0.0001	5–260	High
K	S(WB)BF	$y=ax^b$	3.4357	0.8685	21	0.89	<0.0001	5–260	High
K	S(WB)BFR	nd	nd	nd	5	nd	nd	nd	nd
Ca	S(W)	$y=ax^b$	0.6182	1.2921	15	0.87	<0.0001	5–260	High
Ca	S(WB)	$y=ax^b$	2.1540	1.1643	24	0.90	<0.0001	5–260	High
Ca	S(WB)B	$y=ax^b$	3.8769	1.1089	26	0.86	<0.0001	5–260	High
Ca	S(WB)BF	$y=ax^b$	3.9373	1.0937	17	0.91	<0.0001	5–260	High
Ca	S(WB)BFR	nd	nd	nd	5	nd	nd	nd	nd
Mg	S(W)	$y=ax^b$	0.2114	1.1068	15	0.87	<0.0001	5–260	High
Mg	S(WB)	$y=ax^b$	0.5467	0.9445	24	0.79	<0.0001	5–260	High
Mg	S(WB)B	$y=ax^b$	1.0309	0.8857	26	0.85	<0.0001	5–260	High
Mg	S(WB)BF	$y=ax^b$	1.4646	0.8606	17	0.90	<0.0001	5–260	High
Mg	S(WB)BFR	nd	nd	nd	5	nd	nd	nd	nd

nd, not determined due to the small number of case studies.

† Range of stem biomass in which models can be used to estimate nutrient stocks.

‡ Confidence index based on R^2 values (*low* : R^2=0.00-0.25; *moderate* : R^2=0.25-0.50; *high* : R^2=0.50-1.00).

Table S3 Continued.

Nutrient	Components	Model	Parameter a	Parameter b	N_{obs}	R^2	P	Biomass range†	Confidence index‡
Pseudotsuga menziesii									
N	S(W)	$y=ax^b$	1.4397	0.7888	28	0.66	<0.0001	10–360	High
N	S(WB)	$y=ax^b$	2.2392	0.8170	54	0.84	<0.0001	10–360	High
N	S(WB)B	$y=ax^b$	4.4195	0.7496	42	0.83	<0.0001	10–360	High
N	S(WB)BF	$y=ax^b$	10.8690	0.6906	53	0.86	<0.0001	10–360	High
N	S(WB)BFR	$y=ax^b$	11.2680	0.7008	5	1.00	<0.0001	10–260	High
P	S(W)	$y=ax^b$	0.3570	0.5664	26	0.47	<0.0001	10–360	Moderate
P	S(WB)	$y=ax^b$	0.4128	0.7577	51	0.84	<0.0001	10–360	High
P	S(WB)B	$y=ax^b$	0.8010	0.6858	39	0.90	<0.0001	10–360	High
P	S(WB)BF	$y=ax^b$	2.5802	0.5932	52	0.75	<0.0001	10–360	High
P	S(WB)BFR	nd	nd	nd	4	nd	nd	nd	nd
K	S(W)	$y=ax^b$	2.0696	0.6028	28	0.45	<0.0001	10–360	Moderate
K	S(WB)	$y=ax^b$	2.1536	0.7027	55	0.57	<0.0001	10–360	High
K	S(WB)B	$y=ax^b$	4.0643	0.6623	41	0.66	<0.0001	10–360	High
K	S(WB)BF	$y=ax^b$	8.3087	0.6229	54	0.81	<0.0001	10–360	High
K	S(WB)BFR	nd	nd	nd	5	nd	nd	nd	nd
Ca	S(W)	$y=ax^b$	0.9292	0.7656	28	0.69	<0.0001	10–360	High
Ca	S(WB)	$y=ax^b$	1.5043	0.8102	54	0.75	<0.0001	10–360	High
Ca	S(WB)B	$y=ax^b$	3.4356	0.7773	41	0.81	<0.0001	10–360	High
Ca	S(WB)BF	$y=ax^b$	6.8160	0.7315	53	0.85	<0.0001	10–360	High
Ca	S(WB)BFR	nd	nd	nd	5	nd	nd	nd	nd
Mg	S(W)	$y=ax^b$	0.2854	0.6313	28	0.43	<0.0001	10–360	Moderate
Mg	S(WB)	$y=ax^b$	0.2991	0.7601	52	0.72	<0.0001	10–360	High
Mg	S(WB)B	$y=ax^b$	0.6224	0.7096	41	0.77	<0.0001	10–360	High
Mg	S(WB)BF	$y=ax^b$	1.4035	0.6696	51	0.82	<0.0001	10–360	High
Mg	S(WB)BFR	nd	nd	nd	5	nd	nd	nd	nd
Picea abies									
N	S(W)	$y=ax^b$	1.2060	0.8717	13	0.46	0.011	20–360	Moderate
N	S(WB)	$y=ax^b$	1.7360	0.9086	70	0.76	<0.0001	10–360	High
N	S(WB)B	$y=ax^b$	9.3033	0.7139	39	0.73	<0.0001	10–360	High
N	S(WB)BF	$y=ax^b$	28.1650	0.5772	70	0.62	<0.0001	10–360	High
N	S(WB)BFR	$y=ax^b$	134.1900	0.3023	18	0.25	0.035	50–200	Low
P	S(W)	$y=ax^b$	0.1732	0.8067	13	0.37	0.027	20–360	Moderate
P	S(WB)	$y=ax^b$	0.2860	0.7971	63	0.54	<0.0001	10–360	High
P	S(WB)B	$y=ax^b$	0.7614	0.7634	35	0.68	<0.0001	10–360	High
P	S(WB)BF	$y=ax^b$	3.1991	0.5609	63	0.51	<0.0001	10–360	High
P	S(WB)BFR	$y=ax^b$	12.5660	0.3388	13	0.18	0.145	50–360	Low
K	S(W)	$y=ax^b$	0.4279	1.0000	13	0.75	<0.0001	20–360	High
K	S(WB)	$y=ax^b$	0.6849	0.9959	63	0.72	<0.0001	10–360	High
K	S(WB)B	$y=ax^b$	1.3383	0.9834	37	0.85	<0.0001	10–360	High
K	S(WB)BF	$y=ax^b$	7.8444	0.6854	63	0.67	<0.0001	10–360	High
K	S(WB)BFR	$y=ax^b$	27.2920	0.4917	13	0.52	0.006	50–360	High
Ca	S(W)	$y=ax^b$	1.2558	0.8688	13	0.86	<0.0001	20–360	High
Ca	S(WB)	$y=ax^b$	2.7402	0.8520	62	0.83	<0.0001	10–360	High
Ca	S(WB)B	$y=ax^b$	9.2711	0.6798	37	0.84	<0.0001	10–360	High
Ca	S(WB)BF	$y=ax^b$	28.1520	0.5172	62	0.62	<0.0001	10–360	High
Ca	S(WB)BFR	$y=ax^b$	43.9320	0.4775	13	0.58	0.003	50–360	High
Mg	S(W)	$y=ax^b$	0.1164	1.0000	13	0.96	<0.0001	20–360	High
Mg	S(WB)	$y=ax^b$	0.2381	0.9226	44	0.90	<0.0001	10–360	High
Mg	S(WB)B	$y=ax^b$	1.1894	0.6877	37	0.83	<0.0001	10–260	High
Mg	S(WB)BF	$y=ax^b$	3.0129	0.5675	44	0.66	<0.0001	10–260	High
Mg	S(WB)BFR	$y=ax^b$	3.3890	0.5806	13	0.60	0.002	50–260	High

nd, not determined due to the small number of case studies.

† Range of stem biomass in which models can be used to estimate nutrient stocks.

‡ Confidence index based on R^2 values (*low*: R^2=0.00-0.25; *moderate*: R^2=0.25-0.50; *high*: R^2=0.50-1.00).

Table S3 Continued.

Nutrient	Components	Model	Parameter a	Parameter b	N_{obs}	R^2	P	Biomass range†	Confidence index‡
Pinus pinaster									
N	S(W)	y=ax+b	0.5419	-5.5503	12	0.87	<0.0001	40–220	High
N	S(WB)	y=ax+b	0.6162	26.9980	16	0.69	<0.0001	40–220	High
N	S(WB)B	y=ax+b	1.5237	-2.9646	11	0.96	<0.0001	40–220	High
N	S(WB)BF	y=ax+b	0.8728	137.4000	15	0.62	0.001	90–160	High
N	S(WB)BFR	y=ax+b	1.5418	113.9400	11	0.89	<0.0001	40–220	High
P	S(W)	y=ax+b	0.0841	-1.0829	11	0.73	0.001	40–220	High
P	S(WB)	y=ax+b	0.0900	0.3606	15	0.86	<0.0001	40–220	High
P	S(WB)B	y=ax+b	0.1302	0.6000	11	0.95	<0.0001	40–220	High
P	S(WB)BF	y=ax+b	0.0813	10.9030	15	0.72	<0.0001	90–160	High
P	S(WB)BFR	y=ax+b	0.1260	9.9355	11	0.88	<0.0001	40–220	High
K	S(W)	y=ax+b	0.5069	-4.2406	11	0.90	<0.0001	40–220	High
K	S(WB)	y=ax+b	0.5503	11.7300	15	0.79	<0.0001	40–220	High
K	S(WB)B	y=ax+b	0.7436	10.7420	11	0.80	<0.0001	40–220	High
K	S(WB)BF	y=ax+b	0.4401	77.2670	15	0.34	0.022	90–160	Moderate
K	S(WB)BFR	y=ax+b	1.1011	58.7790	11	0.95	<0.0001	40–220	High
Ca	S(W)	y=ax+b	0.5074	-3.8934	11	0.94	<0.0001	40–220	High
Ca	S(WB)	y=ax+b	0.6020	18.3670	15	0.94	<0.0001	40–220	High
Ca	S(WB)B	y=ax+b	0.3835	82.6030	11	0.30	0.084	40–220	Moderate
Ca	S(WB)BF	y=ax+b	0.4793	78.2380	13	0.40	0.02	90–220	Moderate
Ca	S(WB)BFR	y=ax+b	0.7715	79.1760	11	0.57	0.007	40–220	High
Mg	S(W)	y=ax+b	0.2298	-0.8903	11	0.85	<0.0001	40–220	High
Mg	S(WB)	y=ax+b	0.2547	4.7620	15	0.83	<0.0001	40–220	High
Mg	S(WB)B	y=ax+b	0.8482	-9.8245	11	0.74	0.001	40–220	High
Mg	S(WB)BF	y=ax+b	*similar to S(WB)B*		15	0.48	0.004	40–220	Moderate
Mg	S(WB)BFR	y=ax+b	1.0608	-14.2080	11	0.87	<0.0001	40–220	High
Pinus sylvestris									
N	S(W)	$y=ax^b$	0.4498	1.1743	16	0.49	0.002	40–70	Moderate
N	S(WB)	$y=ax^b$	1.9726	0.8729	57	0.81	<0.0001	10–190	High
N	S(WB)B	$y=ax^b$	6.3295	0.7618	21	0.61	<0.0001	40–150	High
N	S(WB)BF	$y=ax^b$	12.8890	0.6529	55	0.70	<0.0001	10–150	High
N	S(WB)BFR	nd	nd	nd	3	nd	nd	nd	nd
P	S(W)	$y=ax^b$	0.2004	0.7569	16	0.74	<0.0001	40–70	High
P	S(WB)	$y=ax^b$	0.4737	0.6055	52	0.36	<0.0001	10–190	Moderate
P	S(WB)B	$y=ax^b$	1.9850	0.4652	19	0.29	0.017	40–150	Moderate
P	S(WB)BF	$y=ax^b$	1.7423	0.5641	53	0.50	<0.0001	10–150	High
P	S(WB)BFR	nd	nd	nd	1	nd	nd	nd	nd
K	S(W)	$y=ax^b$	3.3876	0.4704	16	0.28	0.034	40–70	Moderate
K	S(WB)	$y=ax^b$	0.7360	0.9240	54	0.82	<0.0001	10–190	High
K	S(WB)B	$y=ax^b$	7.4907	0.5067	21	0.37	0.003	40–150	Moderate
K	S(WB)BF	$y=ax^b$	4.9738	0.6723	54	0.72	<0.0001	10–150	High
K	S(WB)BFR	nd	nd	nd	1	nd	nd	nd	nd
Ca	S(W)	$y=ax^b$	1.1869	0.8259	16	0.69	<0.0001	40–70	High
Ca	S(WB)	$y=ax^b$	1.2434	0.9316	52	0.87	<0.0001	10–190	High
Ca	S(WB)B	$y=ax^b$	1.1151	1.0488	21	0.77	<0.0001	40–80	High
Ca	S(WB)BF	$y=ax^b$	5.9176	0.6874	52	0.78	<0.0001	10–150	High
Ca	S(WB)BFR	nd	nd	nd	1	nd	nd	nd	nd
Mg	S(W)	$y=ax^b$	0.3257	0.8056	16	0.76	<0.0001	40–70	High
Mg	S(WB)	$y=ax^b$	0.1738	1.0466	29	0.88	<0.0001	30–190	High
Mg	S(WB)B	$y=ax^b$	0.3942	0.9270	21	0.69	<0.0001	30–150	High
Mg	S(WB)BF	$y=ax^b$	0.6632	0.8755	27	0.71	<0.0001	30–150	High
Mg	S(WB)BFR	nd	nd	nd	1	nd	nd	nd	nd

nd, not determined due to the small number of case studies.

† Range of stem biomass in which models can be used to estimate nutrient stocks.

‡ Confidence index based on R^2 values (*low* : R^2=0.00-0.25; *moderate* : R^2=0.25-0.50; *high* : R^2=0.50-1.00).

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