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How much does leaf leaching matter during the pre-drying period in a whole-tree harvesting system?

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ABSTRACT

In European temperate forests, whole-tree harvesting increases nutrient exports and could compromise soil fertility in long term, especially when leaves, nutrient-rich compartments (leaves, fine and small wood) are exported. Pre-drying felled trees may allow leaves, twigs and branches to fall down or break during skidding, thereby remaining in the stand. However, the recommended pre-drying time is often based on expert estimates, and currently ranges from two to three months.

In this study, we developed an experimental device to quantify nutrient leaching *via* rainfall (pH: 6.8 ± 0.4) from fully developed leaves (collected in summer period) of four broadleaf species. We first set up an outdoor experiment under natural rainfall conditions to monitor the kinetics of nutrient leaching over around two and a half months. Second, we set up two controlled experiments under simulated rainfall conditions to investigate the effect of rainfall intensity and frequency on nutrient leaching.

Foliar K was highly leached 60–79%, followed by Mg: 19–50%, P: 22–30% and only small proportions for Ca and N, < 16%. Nutrient leaching was positively correlated with rainfall amounts of < 30 mm but small rainfall amounts < 4 mm were more effective in leaching per unit (mm) than heavier rainfalls. More nutrients were leached out when the same rainfall amount was fractioned into small rainy events over several days.

However, leaf leaching remains unsatisfactory because a large part of nutrients is still exported by foliage. Total nutrient exports by whole-tree harvest including foliage increased nutrient exports by 1.2–1.6 times compared to conventional harvesting. The exports by foliage are of equal importance as fine and small wood exports and thus leaving the foliage on the forest would increase significantly nutrient saving. We therefore recommend harvesting during the leafless period when possible and otherwise, letting all the leaves fall to the ground before skidding not only for nutrient returns but also because easily degradable organic matter is very important for soil biological activity.

1. Introduction

The European Union has set high targets to promote the use of energy from renewable sources. The revised directives establish a new binding renewable energy target for the EU for 2030 of at least 32%, with a clause for a possible upwards revision by 2023 (EU, 2018). These targets are mostly driven by climate change concerns and an increased interest in the utilization of forest biomass for energy to mitigate greenhouse gas emissions and reduce energy dependence on fossil fuels. The use of forest biomass for energy has grown substantially over the last two decades because of the emergence of new biomass mobilization techniques such as mechanized harvesting systems. The mechanization degree varies greatly among European countries: the percentage is close to 100% in the Nordic countries, United Kingdom and Ireland, and notably smaller in Eastern Europe (Asikainen et al., 2011). However, this new practice, in which all the parts of the tree above the stump are harvested, may adversely affect soil properties and tree growth because of the large quantities of nutrients exported in the foliage and fine wood. (Thiffault et al., 2011; Aherne et al., 2012; Achat et al., 2015; Augusto et al., 2015; Johnson et al., 2016). This practice is called whole-tree harvesting, in contrast to stem-only harvesting where only the trunk and the largest branches [$d > 7$ cm] are harvested. The stem-only harvesting is considered to have less impact on site productivity because the nutrient content of the stem wood removed is rather low and the most nutrient-rich components (leaves, twigs and small branches) are left on site (Wall, 2012). Since forest soils are a slowly renewable resource and are on average poorer than agricultural soils (Bonneau, 1995), it is crucial to maintain soil fertility by adopting

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sustainable management practices.

In European countries, national and international groups have elaborated different recommendations for whole-tree harvesting that cover a wide range of topics including economic, ecological, environmental, social, technical and practical aspects. One of these recommendations concerns pre-drying operations in whole-tree harvesting systems.

It is highly recommended to harvest during the leafless period to avoid exporting leaves from forests. However, when harvesting takes place within the leafed period on evergreen species, extracting crown biomass is recommended only after pre-drying operation (Cacot et al., 2005; Stupak et al., 2008; Landmann et al., 2018). Pre-drying felled trees is carried out on the forest before skidding operations. This operation has two major roles: first, it may allow the weakened leaves, twigs and fine wood to fall off during the skidding. Second, it allows maintaining a certain amount of nutrients by leaching *via* rainfall, depending on weather conditions.

European guidelines for sustainable harvesting of forest biomass generally recommend to leave felled trees to dry between two to three months when harvesting in spring and summer (Cacot et al., 2005, Egnell et al., 2006, Landmann et al., 2018). The suggested reference period in France is three months, and may be adjusted on a case-by-case basis depending on species, harvesting period and weather conditions (Landmann et al., 2018). Nevertheless, the suggested three-month duration was based on expert opinion and not on field data or experiments.

Nutrient returns to the soil through leaf-fall from felled trees and nutrient leaching are still unknown. Leaching is defined as the removal of substances from plants by the action of aqueous solutions such as rain (Tukey, 1970; Bonneau, 1995). Nutrient returns by leaching are dependent on precipitation quantity and quality, leaf surface properties such as water repellency, the extent of foliar washing, nutrient content and seasonality of the leaf component (Rolfe et al., 1978; Bonneau, 1995; Carnol and Bazgir, 2013; Legout et al., 2014; Styger et al., 2016). These studies showed that leached nutrient amount is correlated with rainfall amount and that, simultaneously, the foliage can absorb nutrients loaded in the precipitation (Attiwill, 1966; Kelly and Strickland, 1986). Wind speed has no correlation with the leaching process (Styger et al., 2016). The net impact on short-term nutrient requirements was confirmed by several studies, which demonstrated that nutrient inputs through leaching are immediately available contrary to litterfall inputs which depend on a slow delayed decomposition process (Rolfe et al., 1978; Zimmermann et al., 2008; Carnol and Bazgir, 2013).

For common beech (*Fagus sylvatica* L.), birch (*Betula pendula* Roth) and oak (*Quercus petraea* (Matt.) Liebl.), the optimal order of foliar nutrient concentrations is N > K ≈ Ca > Mg > P (Oksanen et al., 2005; Mellert and Göttlein, 2012). At around 2%, nitrogen is more present in leaf tissues, compared to other nutrients (i.e. N is three times higher than average K and Ca, fifteen times higher than Mg and P). Nevertheless, N appears to be difficult to leach, P and Mg have slightly better leachability and K is easily leachable (Edwards, 1982).

This study aimed to quantify foliar nutrient leaching of four broadleaf species, hornbeam, oak, birch and beech, under conditions simulating a pre-drying operation, in both outdoor and controlled experiments. The four species were chosen because of their abundance in European deciduous forests managed as coppice-with-standards. We also investigated the rainfall factors affecting the leaching process according to different rain scenarios. We established four hypotheses: (i) Leaching increases with increasing rainfall intensity; (ii) Rain frequency has a positive effect on the leaching process, (iii) Small fractionated rainfalls leach out more nutrients than heavy rainfalls (iv) Nutrient leaching rate is increasing then slows over time.

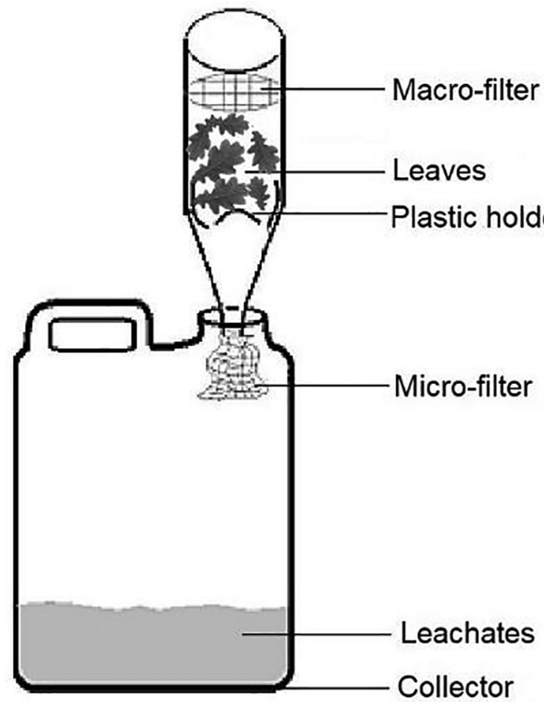

Fig. 1. Schematic drawing of the experimental device for collecting leachates: a macro-filter was used to protect the leaves, a perforated plastic support to hold leaf material and a nylon particle filter (0.5 mm) to prevent the passage of small leaf particles, which could contaminate the leachates.

2. Materials and methods

2.1. Leaf material and experimental device

We set up one outdoor experiment and two controlled experiments on four species: common hornbeam (*Carpinus betulus* L.), European white birch (*Betula pendula* Roth), common beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Matt) Liebl.). We collected leaves on the same fuelwood logging site in the Orleans Forest (September 2017), stored indoors until the launch of the experiments. An experimental device (Fig. 1) was prepared for each experiment with 4 g of plant material for each species. There was also a control with no leaf material in order to subtract the nutrients contained in or carried by the rain. The surface area of the leaves in contact with rainfall was 8.5 cm in diameter ($S = 56.75\ cm^2$).

2.2. Outdoor experiment

The outdoor experiment was conducted from March 14 to May 24, 2018 (71 days) on an experimental platform in Nogent-sur-Vernisson, Centre-Val de Loire region, France. The study area has a temperate continental climate and daily rainfall of between (0.3 and 6.7 mm) regularly distributed throughout the year. The mean monthly rainfall is around 60 mm (Fig. A1).

The experiment aimed to study the natural kinetics of nutrients leached by rainfall. The experimental device was replicated five times, for each species and the control with no leaf material, and the devices were distributed randomly at the site. We also used five rain gauges to check the homogeneity of the rainfall over the experimental setup. The leachates were collected after every rain event, for a total of ten times. The total volume of each leachate sample was measured and a subsample of 20 ml from each device was stored at −20 °C to avoid any contamination or changes in chemical characteristics.

Table 1
Foliar nutrient concentrations ($mg \cdot g^{-1}$, mean ± SD; n = 5) for each species before (T_0) and after 71 days of the experiment (T_{71}), and percentage of leached elements. Different letters in rows indicate significant differences between species under ANOVA and Tukey's HSD tests.

		Birch	Hornbeam	Oak	Beech	P-Value	F-statistic
Before rainfall (T_0) ($mg \cdot g^{-1}$)	N	23.48 ± 0.61 b	19.71 ± 0.79 a	23.06 ± 0.59 b	22.73 ± 0.13 b	< 0.0001	28.04
	K	8.03 ± 0.14 a	7.55 ± 0.20 a	8.20 ± 0.59 a	9.28 ± 0.45 b	0.004	10.55
	Ca	6.60 ± 0.22 a	9.54 ± 0.24 b	8.85 ± 0.40 b	6.69 ± 0.28 a	< 0.0001	78.86
	Mg	1.25 ± 0.06 ab	1.16 ± 0.02 ab	1.33 ± 0.13 b	1.08 ± 0.04 a	0.016	6.44
	P	0.88 ± 0.02 b	0.77 ± 0.01 a	0.88 ± 0.05 b	0.77 ± 0.01 a	0.001	16.59
After rainfall (T_{71}) ($mg \cdot g^{-1}$)	N	22.12 ± 1.53 b	18.04 ± 0.24 a	22.27 ± 0.31 b	20.78 ± 1.11 b	< 0.0001	20.66
	K	1.98 ± 0.51 a	1.60 ± 0.35 a	1.76 ± 0.25 a	3.71 ± 0.17 b	< 0.0001	40.32
	Ca	6.50 ± 0.51 a	8.06 ± 0.44 b	8.88 ± 0.75 b	6.39 ± 0.51 a	< 0.0001	23.21
	Mg	1.01 ± 0.04 c	0.58 ± 0.05 a	0.88 ± 0.09 b	0.87 ± 0.02 b	< 0.0001	48.87
	P	0.08 ± 0.01 a	0.19 ± 0.01 b	0.09 ± 0.02 a	0.10 ± 0.01 a	< 0.0001	43.7
Leached elements (%)	N	2.6 ± 2.7 a	7.8 ± 0.9 b	2.6 ± 0.6 a	4.8 ± 1.7 ab	0.001	9.7
	K	75.3 ± 6.3 b	78.8 ± 4.7 b	78.5 ± 3.1 b	60.0 ± 1.8 a	< 0.0001	20.64
	Ca	1.5 ± 7.7 a	15.5 ± 4.6 b	−0.4 ± 8.5 a	4.4 ± 7.7 ab	0.014	4.82
	Mg	18.6 ± 3.6 a	49.7 ± 4.5 c	34.2 ± 6.9 b	19.0 ± 1.5 a	< 0.0001	54.58
	P	29.7 ± 3.4 a	22.5 ± 2.4 a	23.9 ± 9.1 a	21.7 ± 1.7 a	0.084	2.64

2.3. Controlled experiments: artificial rain

The controlled experiments aimed to investigate the effect of rainfall factors (both amount and frequency) on nutrient leaching. We used locally collected rain (pH: 6.8 ± 0.4) and a spray gun with a constant automatic airflow to simulate rainfall (2 ml was used each time to moisten the leaves before beginning the simulation phase). Our experimental simulation method was based on the analysis of climate data from 1992 to 2017 (Table A1) for the summer periods only (June to September), corresponding to the pre-drying period for leafy trees typical in whole-tree biomass harvesting. From these data, daily rainfall of less than or equal to 2 mm represented half (50%) of all rainfall events, while 95% of all rainfall events were less than or equal to 20 mm (n = 1279).

First, we investigated the effect of rainfall amount on nutrient leaching through the simulation of nine scenarios, corresponding to extreme values (min = 0.2 and max = 66 mm), quartiles (0.4 and 8 mm), median (2 mm), mean (4 mm) and intermediate intensities (1, 15 and 30 mm).

Next, we set up a second controlled experiment in order to compare nutrient leaching with the same amount of simulated rain but at different frequencies of occurrence. A total of twenty millimeters of rainfall per device and per day was sprayed on the leaf samples in four modalities (20 mm × 1; 10 mm × 2; 6.67 mm × 3; 4 mm × 5), so the experiment lasted over a period of five consecutive days.

Both controlled experiments were replicated three times for each of the four species and the controls with no plant material. For small rain amounts of < 2 mm, it was necessary to combine the leachates from all the replicates for a given species in order to have enough volume for laboratory measurements. After each simulated rainfall, the plant material was left to drain. Then the leachates were collected and stored at −20 °C before carrying out laboratory measurements.

2.4. Laboratory measurements and chemical analyses

First, for each leachate sample, we used a COND6$^+$ EUTECH instrument to measure its electrical conductivity ($\mu S \cdot cm^{-1}$). According to these results, we then selected samples to be analyzed for chemical concentrations of K, Ca, Mg, P, NH_4^+ and NO_3^-. Chemical analyses were performed at the ECODIV laboratory, PRESEN platform, Rouen, France. The samples were filtered through a 0.45-μm nylon membrane filter, acidified to pH < 2 by adding sulfuric acid, then analyzed through inductively coupled plasma optical emission spectrometry (ICP-OES Thermo-scientific model ICAP 7200 D). Based on the results of this analysis, we used the correlation between conductivity and the major nutrients (K, Ca, Mg and P) to estimate the total concentrations for the non-analyzed samples: total nutrients ($mg \cdot g^{-1}$) = 0.3739 × conductivity, n = 97, $R^2 = 0.93$ (Fig. A2). Relative proportion of each element in the analyzed samples was calculated for each sampling date. We were then able to estimate the concentrations of each element for the non-analyzed samples taken at the same sampling dates.

On the plant material, samples from the same lot of leaves used for the experiment were chemically analyzed before rainfall (T_0). We also analyzed the plant material used in the experiments at the end of the procedure (T_{71}). Leaves were dried to a constant weight (65 °C, 48 h), weighed and finely crushed in a laboratory mill (0.25 mm). The samples were prepared for microwave acid digestion, then analyzed through elemental analysis ICP as for the leachates.

2.5. Statistics

To illustrate the kinetics of nutrient leaching, we used non-linear regression model, which is called first order equation used often for kinetics with decreasing rate over time. The equation defined for each element by the following asymptotic function:

Cumulative amount ($mg \cdot g^{-1}$) = $a\,(1 - e^{(-b * t)})$, where a and b are mathematical constants and t is time. Parameter a has a biological implication and represents for each species the maximum cumulative leached K, Ca, Mg and P in $mg \cdot g^{-1}$. The correlation coefficients of the models were fitted using STATGRAPHICS Centurion XVI. To compare nutrient leaching among species and between different modalities, we performed an ANOVA test, and when this was significant ($p < 0.05$), followed up with a Tukey HSD test. Small letters indicate significant differences. Values presented in bars and lines charts using Microsoft Excel software are means ± SD.

3. Results

3.1. Foliar nutrient concentrations before and after 71 days of rainfall

Before rainfall, the foliar nutrient concentrations (T_0) were in descending order: N, K, Ca and smaller proportions of Mg and P (Table 1). Indeed, nitrogen concentrations were generally three times higher than K and Ca, which showed similar levels. For all species, N concentrations were around 23 $mg \cdot g^{-1}$, except for hornbeam, which had lower concentrations (19.71 ± 0.79 $mg \cdot g^{-1}$). Potassium was significantly higher in beech (9.28 ± 0.45 $mg \cdot g^{-1}$), while for other species K was around 8 $mg \cdot g^{-1}$. Calcium concentrations were much higher in hornbeam and oak (9 $mg \cdot g^{-1}$), compared to both birch and beech, at around 6.5 $mg \cdot g^{-1}$. Mg and P were present in very low concentrations, from 1 to 1.25 $mg \cdot g^{-1}$ for Mg and < 1 $mg \cdot g^{-1}$ for P.

After 71 days (T_{71}), K was the most leached element for all four investigated species (Table 1). The mean leached K for birch, oak and hornbeam was similar, from 75 to 78%, higher than for beech at 60%. Mg and P were more leachable than N and Ca for all species. Nevertheless, Mg leached more in hornbeam 50% and oak 34% than in birch and beech, both at around 19%. Furthermore, we found no significant differences between species for leached P, which ranged from 21.7 to 29.7%. The percentages of leached N and Ca were extremely low, < 16%, except for hornbeam (N: 7.8 ± 0.9%; Ca: 15.4 ± 4.6%).

3.2. Kinetics of nutrient leaching over time in the outdoor experiment

The kinetics of leached K, Ca, Mg and P over 71 days (cumulated rainfall = 166 mm) are illustrated by non-linear regression models for each species (Fig. 2). In all cases, the cumulative amount of K, Ca, Mg and P measured in leachates increased with time, while mineral nitrogen accumulation (NH_4^+, NO_3^-) was not statistically different from zero; in other words, no significant mineral nitrogen was leached during the experiment period (data not shown).

Leaching seemed to occur faster at the beginning than at the end of the period (Fig. A3). The leaching rate gradually decreased with time. During the first 33 days and for all species, the cumulative rainfall of 72 mm had leached more than three quarters of the final amounts of leached elements at the end of the experiment (K: 72–79%, Mg: 78–85%, Ca: 76–96% and P: 88–95%). From days 33 to 71, only 5 to 28% of the final leached amounts of elements were collected, despite the fact that the cumulative rainfall occurring during this second period was greater than during the first one (93 mm).

It should be noted that time was a confounding factor with accumulated rainfall as there is a high correlation between time (days) and cumulative rainfall (R^2 = 98.98%).

A summary of the statistical analyses (ANOVA) for the mean values of parameter a are given in (Table 2). For all four species, the maximum cumulative leaching for K (4.6–7.5 $mg \cdot g^{-1}$) was much higher than for the other elements (< 1 $mg \cdot g^{-1}$). Differences among species were significant (p-value < 0.05) for all the elements. Indeed, hornbeam leached the highest amounts of K, Mg and Ca compared to other species. The highest amounts of phosphorus were detected in oak and birch, 0.19 and 0.17 $mg \cdot g^{-1}$ respectively. Beech consistently had the lowest amounts for all four elements.

Generally, the mean ratio between the observed cumulative leaching over 71 days and the maximum cumulative leaching for K, Mg, Ca and P ranged from 90% to 100% for all species; this means that maximum leaf leaching had almost been reached at 71 days (Table 2). After this period, only minimal amounts of nutrients would continue to leach from the leaves.

3.3. Effect of rainfall amount and frequency on leaching

For the controlled experiments, we first found that an increase in rainfall amount up to 30 mm had an influence on nutrient leaching. The heavier the rain, the more the elements were leached out. The maximum nutrient amount leached was reached at 30 mm; beyond that, extreme rainfall events (66 mm) did not leach more nutrients (Fig. 3a). Only oak showed a significant difference between 30 mm and 66 mm rainfall (p-value > 0.05); leaching was slightly less with 66 mm than with 30 mm of rainfall (p-value = 0.04), probably due to substantial dilution. Hornbeam globally exhibited greater nutrient leaching compared to the other species. Birch was less sensitive to single rainfall events because it leached the lowest nutrient amounts regardless of the quantity of rain.

Per unit of rainfall, leaching was greater with lighter rainfall than with heavier rainfall. For all four species, maximum leaching was reached for 4 mm of rainfall, from 0.04 to 0.12 $mg \cdot g^{-1}$ per mm (Fig. 3b). Therefore, rainfall events of < 4 mm proved to leach more efficiently than much higher rainfall amounts. Beyond 4 mm, the leached amount of nutrients per unit of rainfall decreased as the amount of rainfall increased. Sixty-six mm of rainfall leached almost the same nutrient amounts per unit as did 2 mm of rainfall.

The second controlled experiment aimed to investigate the effect of rainfall frequency on nutrient leaching. Our results show a gradual increase in leaching for all four elements when rainfall frequency increases from one to five (Fig. 4). Nutrient leaching was maximal when the same amount of rainfall (20 mm) was delivered five times. For all four elements, except for Ca in hornbeam, there were no significant species differences between the first two modalities (20 mm × 1 and 10 mm × 2).

The amount of leached K, Mg and P was significantly higher when rainfall was distributed over at least three times, though oak required even more frequent rainfall (20 mm × 5) to leach more nutrients. For Ca, very small amounts were detected in birch, beech and oak compared to hornbeam, which released much more than the other three species. In general, for the same rainfall amount, the sum of the leaching during cumulated small rain events contributed more nutrients compared to heavy rains for all species.

4. Discussion

4.1. Nutrient leaching and species effect

Leaf nutrient concentrations of the studied species were in the following order N > K ≈ Ca > Mg > P (Table 1). Previous studies on the same species have also shown that the major mineral components of the leaves are N followed by K ≈ Ca and Mg ≈ P (Mellert and Göttlein, 2012; Carnol and Bazgir, 2013; Nickmans et al., 2015). In general, our foliar nutrient concentrations compared satisfactorily to reference values. For oak and beech, the foliar nutrient concentrations we found were within the normal range according to the critical foliar concentrations in van den Burg (1985) and the compiled literature (Mellert and Göttlein, 2012), except for P and Mg, which could compromise biological functioning. Foliar P concentrations were deficient for both species (< 1 $mg \cdot g^{-1}$) while Mg was deficient in beech (< 1.1 $mg \cdot g^{-1}$) and in the lower normal range for oak (1.2–1.6 $mg \cdot g^{-1}$).

Leached K was distinctly higher for all species compared to the other nutrients. Indeed, more than 75% of foliar K was leached for birch, hornbeam and oak, and 60% for beech. Similarly, several studies

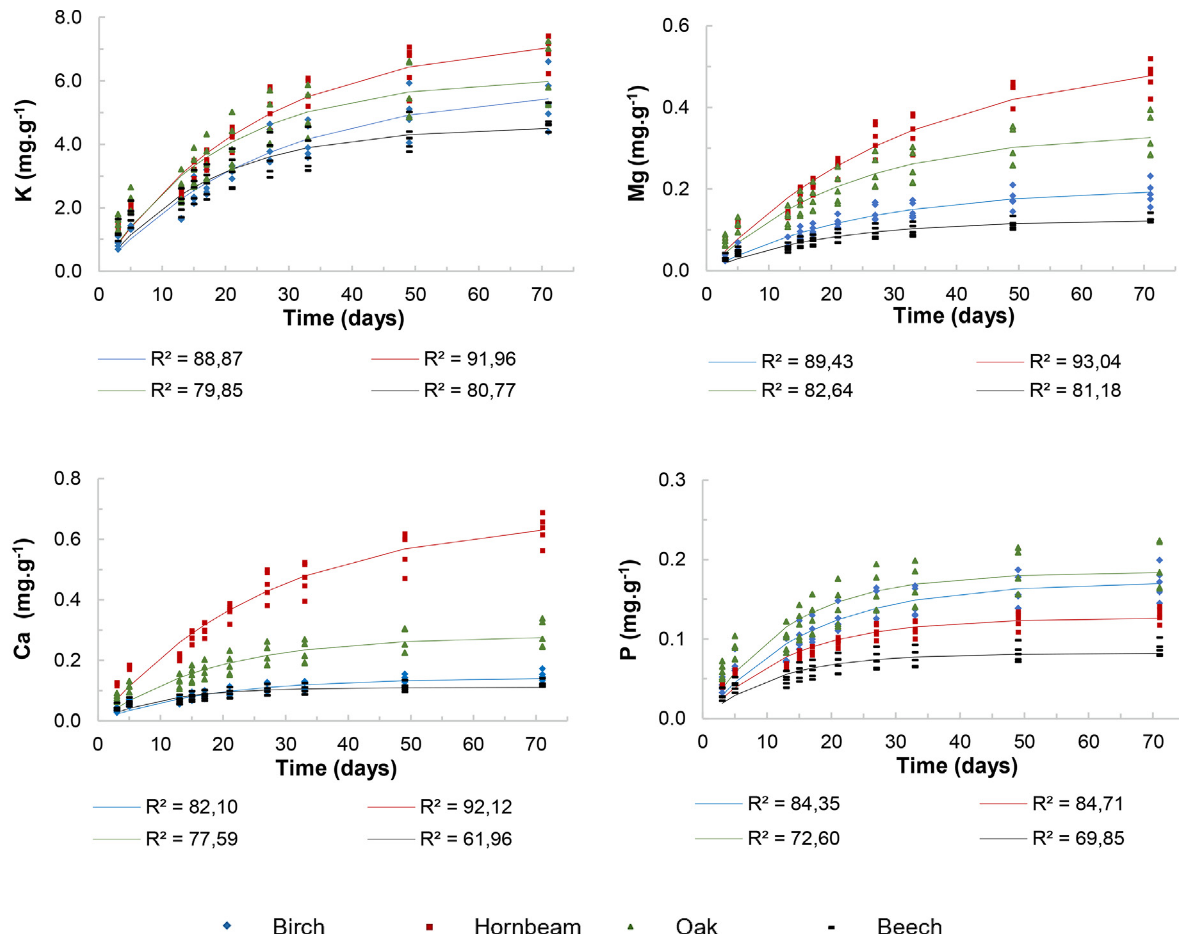

Fig. 2. Cumulative nutrient leaching over time for K, Mg, Ca and P in hornbeam (red), oak (green), birch (blue) and beech (black), illustrated by mean fitted models (n = 5). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

have pointed out the high leachability of foliar K (Edwards, 1982; Schroth et al., 2001; Carnol and Bazgir, 2013). This is primarily because K is the most abundant cation in cells and is exclusively present in its ionic form (K^+), or in weak complexes from which it is easily exchangeable (Marschner, 2012). The second most leached element was Mg: average Mg returns for beech and birch were 19%; they were much higher for oak (34%) and reach as much as 50% for hornbeam. Mg is less leachable than K because it is located in the chlorophyll, where it is the central ion (Willows, 2007). Foliage is the major source of both K and Mg, which plants require in large quantities since they critically contribute to a number of crucial physiological processes (Rolfe et al., 1978; Tränkner et al., 2018).

Leached phosphorus came third, between 22 and 30%. It is present in small amounts in the foliage and is associated with multiple organic

Table 2
Maximum cumulative values ($mg \cdot g^{-1}$, mean value ± SD, n = 5) corresponding to parameter a in the model $y = a\,(1 - e^{(-b*t)})$, for hornbeam, oak, birch and beech. Different letters in rows indicate significant differences among species (ANOVA, Tukey's HSD tests). The mean ratio between the observed amount over 71 days and the modeled maximum cumulative leaching is given in the second section of the table.

		Birch	Hornbeam	Oak	Beech	P-value	F-statistic
Modeled maximum cumulative leaching ($mg \cdot g^{-1}$)	K	6.03 ± 1.35 ab	7.46 ± 0.79 b	6.16 ± 1.00 ab	4.63 ± 0.34 a	0.002	7.55
	Mg	0.21 ± 0.04 b	0.54 ± 0.06 d	0.34 ± 0.06 c	0.13 ± 0.01 a	< 0.0001	79.71
	Ca	0.15 ± 0.02 a	0.68 ± 0.07 c	0.28 ± 0.05 b	0.11 ± 0.01 a	< 0.0001	165.43
	P	0.17 ± 0.02 c	0.13 ± 0.01 b	0.19 ± 0.03 c	0.08 ± 0.01 a	< 0.0001	28.02
$\frac{\text{Observed}}{\text{Modeled}} \times 100$	K	91 ± 7	95 ± 4	99 ± 2	102 ± 2		
	Mg	92 ± 4	89 ± 3	97 ± 2	101 ± 6		
	Ca	100 ± 3	93 ± 4	101 ± 2	103 ± 6		
	P	99 ± 3	103 ± 3	101 ± 1	102 ± 4		

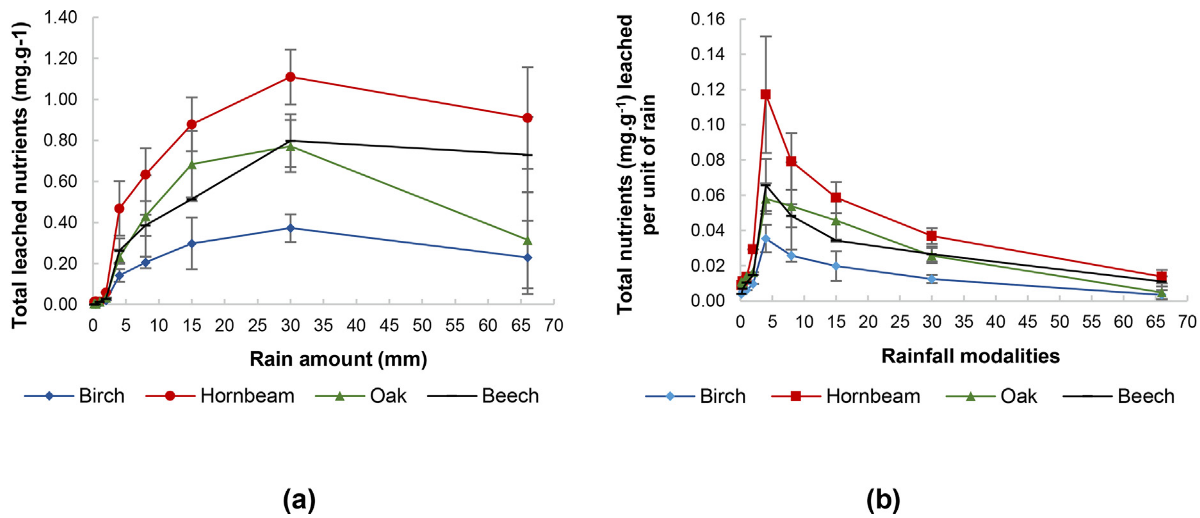

Fig. 3. (a) Effect of rain amount (mm) in individual rain events on nutrient leaching ($mg \cdot g^{-1}$) for hornbeam, oak, birch and beech. We estimated total nutrients (SD, n = 3) by correlating total nutrients ($mg \cdot g^{-1}$) and conductivity, (R^2 = 0.93). (b) Total nutrients ($mg \cdot g^{-1}$) leached by each millimeter of rainfall under the nine rainfall modalities.

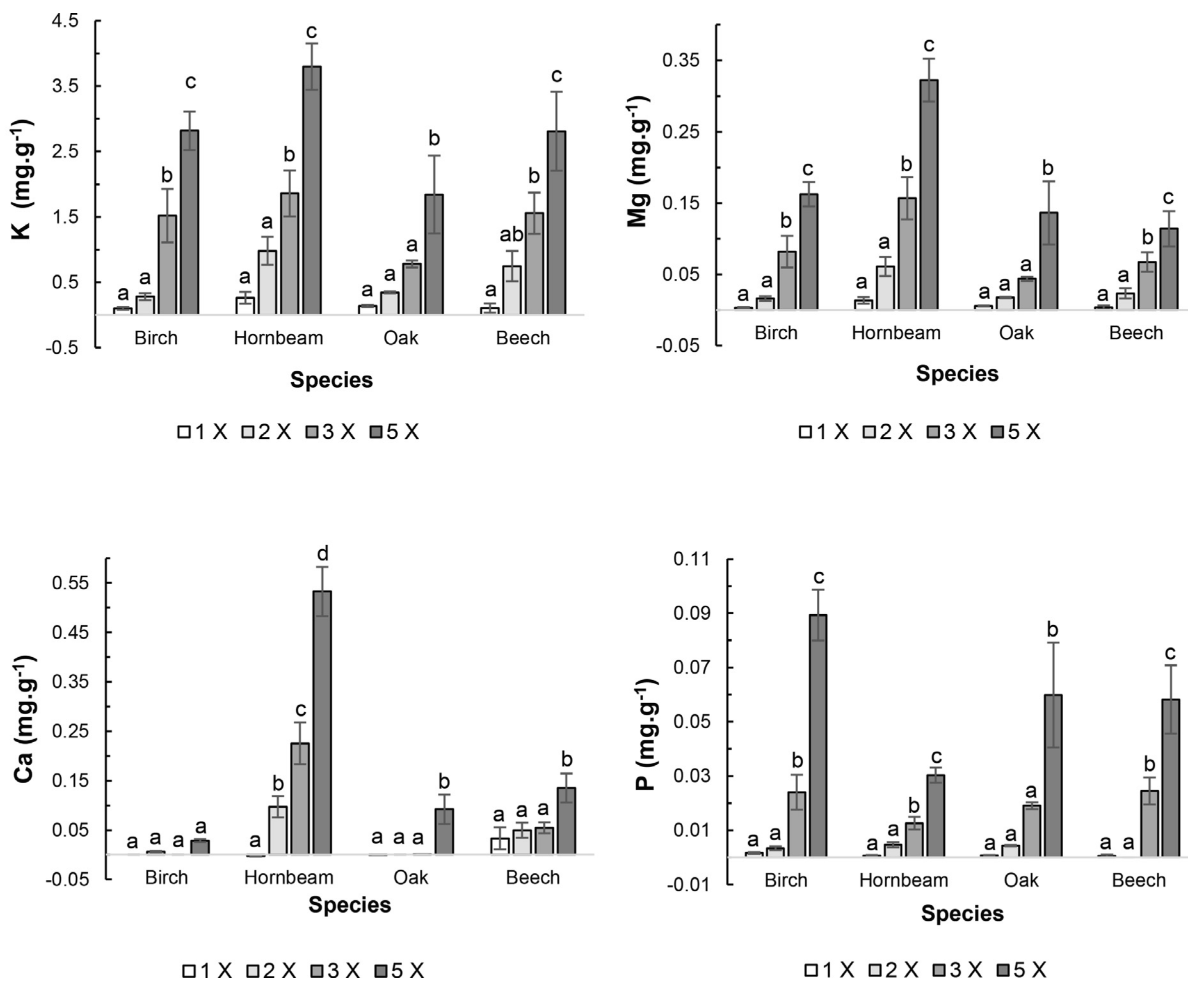

Fig. 4. Effect of rain frequency on the leaching of K, Mg, Ca and P for hornbeam, oak, birch and beech. According to four modalities (1X, 2X, 3X and 5X), the same rainfall amount (20 mm) was partitioned into small equivalent amounts and simulated over 1, 2, 3 and 5 days. Error bars represent SD and different letters above the bars indicate significant differences among the four modalities (ANOVA, Tukey's HSD tests).

combinations. Phosphorus plays a major role in promoting seedlings and stimulating root systems and tree growth (Braun et al., 2010). According to Stefan et al. (2000), minimum phosphorus concentrations in the foliage must be at least 1 $mg \cdot g^{-1}$ for sufficient nutrition. The leaf phosphorus levels in our target species were critically low, which led to very low return percentages and a risk of further impoverishing the soil. Lastly, Ca and N returns were extremely low, except for hornbeam. Previous studies have already shown that N is not readily leached from

Table A1
Summary of the daily rainfall amounts (mm) occurring during the summer periods (June to September) from 1992 to 2017. Climatic data were collected from the INRAE automated weather station (Nogent-sur-Vernisson, 47°50′ N, 2°44′ E), France. Days without rain (0 mm) have been excluded (n = 1279).

Mean	SD	Median	Min	Max	Range	1st Quartile (Q1)	3rd Quartile (Q3)	Interquartile range
4.1	7.0	2.2	0.2	65.8	65.6	0.4	8.2	5.8

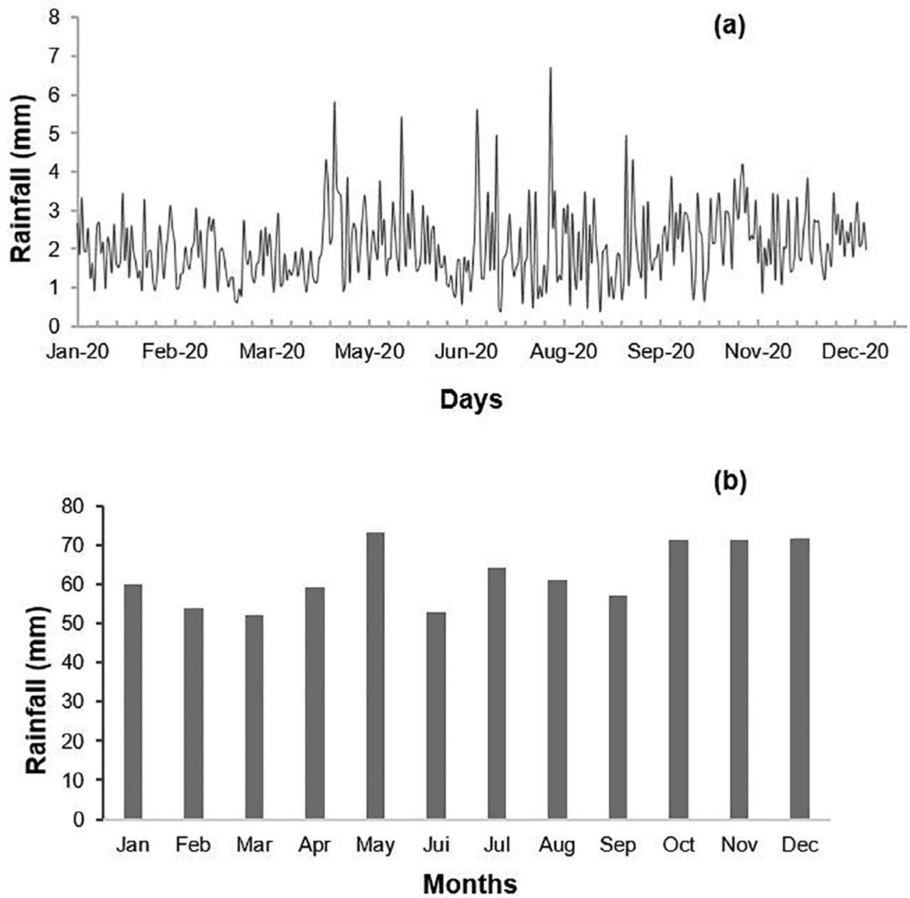

Fig. A1. (a) Mean daily rainfall (mm) (b) Mean monthly rainfall (mm). Climatic data were collected over 26 years (1992–2017) from the INRAE automated weather station (Nogent-sur-Vernisson, 47°50′ N, 2°44′ E), France.

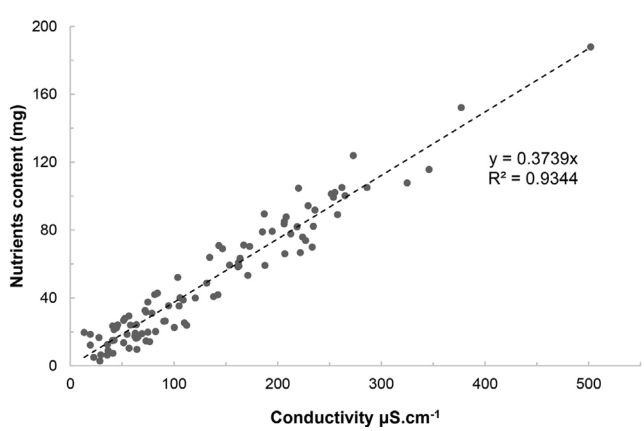

Fig. A2. Relationship between nutrient content K, Ca, Mg and P (mg) and conductivity (µS·cm^{-1}) in the leachates analyzed with ICP (n = 97). The analyzed samples correspond to all sampling dates for all species.

leaves despite its abundance in leaf tissues because it is one of the main constituents of proteins and is therefore more stable (Marschner, 2012). According to Berg and Staaf (1981), nitrogen release starts only at the beginning of the leaf decomposition process (Berg and Staaf, 1981). For calcium, < 5% was leached, except for hornbeam (15.5 ± 4.6%), because Ca^{2+} ions are less mobile due to the fact that calcium is an important constituent of the plant cell walls (Demarty et al., 1984). Therefore, our experiment showed major differences in leached

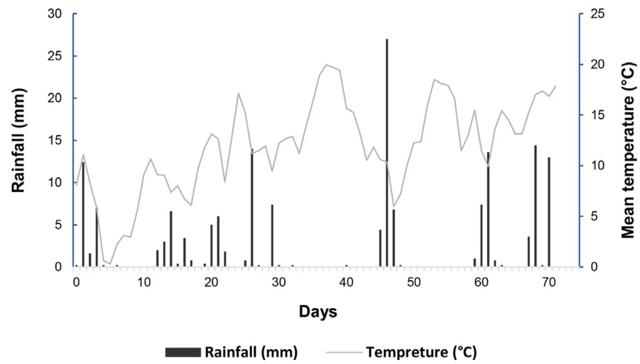

Fig. A3. Variations in daily rainfall (mm) and mean temperatures (°C) for the outdoor experiment from March 14, 2018 to May 24, 2018. Climatic data were collected from the INRAE automated weather station (Nogent-sur-Vernisson, 47°50′ N, 2°44′ E), France.

nutrient returns depending firstly on the element, and secondly, on the species. Regardless of species, the nutrient returns were very high for K and non-negligible for Mg and P, especially for soils with a deficiency of these elements.

On the other hand, the temporal variations of the leaching process are related to a range of factors including time, species, frequency and amount of precipitation (Zimmermann et al., 2008; Kowalska et al., 2016). In this study, we showed that nutrient leaching was controlled by time but that, underlying this factor, cumulative rainfall was implicated. Indeed, leaching is impossible without rain. We had a strong correlation between time and cumulative rain (R^2 = 98.98%) since it rained regularly throughout the experiment. Our results show that the cumulative amounts of leached K, Mg, Ca and P clearly increased with time during the early rainfall events, but then exhibited less significant increase after 33 days (Fig. 2).

Our findings highlight the role of the leaf leaching process for trees felled during the pre-drying period. According to our results, no more leaching will be significantly occurred after one and a half month as long as it rains regularly (around 15 mm per week) (Fig. A3). However, rainfall frequency can be significantly less in certain years in summer, so in this case, it would be necessary to wait until autumn to ensure more regular rainfall.

4.2. Rainfall factors controlling nutrient leaching

Our controlled experiments showed that total nutrient leaching increased with rainfall amounts less than or equal to 30 mm, and was slightly lower for extreme rain events (66 mm). Several studies have demonstrated that leaf leaching is strongly related to rainfall amount and intensity. Generally, the longer the water remains on the leaf surface, the greater the amount leached per unit quantity of precipitation (Rolfe et al., 1978; Teale et al., 2014; Styger et al., 2016). Indeed, Wei et al. (2017) have found that leaf nutrient leaching occurred when rainfall was < 20 mm, while no further nutrients were leached when rainfall exceeded 25 mm because most of the water saturated the leaf surface. Our results are in agreement with these findings; we therefore conclude that rainfall amount affects leaching magnitude, with maximum leaching probably occurring at around 30 mm of rainfall. In addition, small rainfall amounts, around 4 mm, were the most efficient at leaching due to the time of residence in the leaf (Rolfe et al., 1978).

Secondly, rainfall frequency had a positive effect on nutrient leaching; multiple small rains recurring over time enhanced nutrient leaching. These results are consistent with Tukey (1970), who argued that lower, regular rainfall intensities cause greater leaching from leaves. Moreover, in Crockford et al. (1996), the leaching process was greatly influenced by rain frequency; this indicates that a much slower nutrient detachment process yields higher leached nutrient amounts. More frequent and less intense events are more effective at reducing the hydrophobicity of a leaf and thus increase the quantity of nutrients leached from a leaf (Tukey, 1970; Runyan et al., 2013).

To sum up, both rainfall amount and frequency had significant effects on the leaching process. Nutrient returns seem optimal when rain falls in small amounts, around 4 mm per day or every two days over at least one month in our study. However, the regularity of rainfall events seems to be the most important factor to obtain the fast nutrient leaching desired during the pre-drying period. Additional parameters, such as rainfall duration, quality, pH and leaf phenology and seasonal variations (Bonneau, 1995) are also of importance and should be investigated in further studies.

4.3. How much does leaf leaching matter?

In whole-tree harvesting systems, full trees are cut to length directly at the stump and completely removed. This harvest method constrasts with conventional harvesting, which exports the stem and only larger wood than 7 cm, while the fine wood, small wood and leaves are left on the site.

Biomass and nutrient concentrations of the different tree compartments are necessary to estimate nutrient exports by harvest. In the case of whole-tree harvesting, they are crucial for understanding the importance of leaves, fine and small wood in nutrient cycles as well as the assessment of the sustainability of forest management (Blanco et al., 2005; Achat et al., 2015; Augusto et al., 2015). Whatever the species, the part of each compartment in the total tree biomass is proportional to the diameter of the compartment: stem and large branches [d > 7 cm] represent most of biomass, followed by small wood [d = 4–7 cm], fine wood [d < 4 cm] and leaves (Augusto et al., 2008; Wernsdörfer et al., 2014). It is the inverse order for nutrient concentrations: leaf compartment has by far the highest concentrations, followed in decreasing order by fine wood and small wood, larger branches and the stem (Kimmins, 1976; Hagen-Thorn et al., 2004; Landmann et al., 2018). Our results are in accordance with this order as we found that foliar nutrient concentrations (Table 1, at T_0) are higher than in fine and small wood. These decreases in nutrient concentrations with increasing diameter of wood pieces can be explained by translocation of nutrients from older to younger plant tissue and by the increasing bark-wood ratio with decreasing branch diameter (André and Ponette, 2003; Balboa-Murias et al., 2006; Andre et al., 2010).

Foliar nutrient concentrations, compared with fine wood [d < 4 cm] (André and Ponette, 2003; Pyttel et al., 2015; and our results not shown), are three to four times higher for N and K, twice as high for Mg, while Ca and P are almost equal. Besides, foliar nutrient concentrations are even higher than in small wood [d = 4–7 cm]: N is 6–8 times higher, K is 4–7 times higher, Ca is 2–4 times higher, Mg and P are almost three times higher. Larger wood diameter implies lower concentrations, from 4 to 20 times depending on the element. Indeed, in wood pieces of diameter larger than 7 cm N concentrations were around 2 mg·g^{-1} for N and K, 4 mg·g^{-1} for Ca, 0.25 mg·g^{-1} for Mg and

P (André and Ponette, 2003; Pyttel et al., 2015).

Though foliage represents a small part of total biomass removal in whole-tree harvesting system, from 1 to 3%, harvesting during leafy period can lead to significant extra exportation of nutrients due to its high concentrations. Foliar production of our investigated species is estimated to be around 2000–3000 $kg{\cdot}ha^{-1}{\cdot}y^{-1}$ for basal area *G* from 20 to 40 $m^2{\cdot}ha^{-1}$ (Pardé, 1977; Landmann et al., 2018). Based on these figures and foliar concentrations (Table 1, at T_0), whole-tree harvesting during leafy period would export by foliage between 39 and 70 $kg{\cdot}ha^{-1}$ for N, 13–29 $kg{\cdot}ha^{-1}$ for Ca, 15–28 $kg{\cdot}ha^{-1}$ for K, 2.2–4 $kg{\cdot}ha^{-1}$ for Mg and 1.5–2.6 $kg{\cdot}ha^{-1}$ for P. If felled trees are pre-dried for two months on the stand before skidding, more than 60% of K can return to the soil through leaching, 20–50% for Mg and P, and < 16% for N and Ca.

Whole-tree harvesting in mixed oak-birch coppice stands (Pyttel et al., 2015), including foliage, would export from 1.2 to 1.6 times more nutrients than in conventionnal harvesting. Potential nutrient exports by foliage represent 33% for N, 28% for P, 22% for Mg, 15% for K and 5% for Ca. The part of exported nutrients by harvesting fine and small wood is in the same range as for the foliage.

In brief, though foliage, fine and small wood represented around 30% of the total harvested biomass, nutrient exports of N, Mg and P due to harvesting these compartments represent approximately 60% in whole-tree harvesting system, 30% for K and 20% for Ca.

Leaving the foliage would increase significantly nutrient saving and will maximize nutrient returns to soil in case of whole-tree harvesting. We therefore recommend (1) to harvest during leafless period, otherwise, (2) to wait for the leaves to wilt and fall before skidding because nutrient leaching during pre-drying is low, (3) to let on site a sufficient percentage of small and fine wood.

5. Conclusion

Loss of soil fertility and productivity as a result of whole-tree harvesting has attracted more attention recently, especially when foliage is exported inducing more increases in nutrient outputs. In our experiments, we found that pre-drying felled trees on the stand before skidding for two and a half months allows to maintain, as long as it rains around 15 mm per week, more than three quarters of foliar K, 19–50% for Mg 22–30% for P and < 16% for calcium and nitrogen. However, these amounts are not satisfactory compared to nutrient exports due to harvesting foliage and nutrient-rich wood with diameter of < 7 cm. We therefore highly recommend harvesting during the leafless period. Otherwise, additional measures, especially on technical aspects, need to be developed to mitigate the impact of removing foliage and fine wood for sustainable biomass harvesting.

CRediT authorship contribution statement

Abdelwahab Bessaad: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Nathalie Korboulewsky:** Methodology, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Table A1 and Figs. A1–A3.

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