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Nutrient Exports Under Different Harvesting Regimes in Two Types of Larch Plantation with Different Age in Northeastern China

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Abstract: It has been confirmed in studies conducted in different regions and forest types that the harvesting regime has a significant impact on the export of nutrients from a plantation. Through establishing allometric growth equations and studying nutrient distribution patterns, the amounts of nutrients exported from larch (Larix spp.) plantations with different stand ages under different harvesting regimes (removal of stem wood, branches and bark (Rsbb), removal of stem wood and bark (Rsb), and removal of stem wood (Rs)) were determined in the present study. The results showed the following: 1) the organs of 20-year-old and 40-year-old larch trees exhibited basically the same nutrient distribution pattern. However, due to the difference in biomass partitioning in trees of these ages, they showed a significant difference in the cumulative amounts of nutrients in their organs. Specifically, the cumulative amounts of nutrient elements in the leaves and old branches of 20-year-old larch trees were significantly higher than in 40-year-old larch trees. However, the cumulative amounts of various nutrients in the xylem of the trunks of 20-year-old larch trees were significantly lower than in 40-year-old larch trees. 2) Compared with the Rsbb20, Rsbb40 or Rsb20 could result in significant decreases in the annual mean amounts of nutrients exported, the ratio of the annual mean total amount of nutrients exported to the annual net cumulative total amount of nutrients and the proportion of soil nutrients in the 0-30 cm soil layer. Changing the Rsbb20 to an Rsb40 or an Rs40 could further reduce the annual mean amounts of nutrients exported, the ratio of the annual mean total amount of nutrients exported to the annual net cumulative total amount of nutrients and the proportion of soil nutrients in the 0-30 cm soil layer. 3) Among the examined harvesting regimes, the Rs20 resulted in the lowest annual mean amounts of nutrients being exported. However, there was no significant difference in the annual mean amounts of nutrients exported between the Rs20 and the Rs40. The amounts of N, Ca and Mg exported under the Rs20 were slightly higher than under the Rs40, whereas the amounts of P and K exported under the Rs20 were slightly lower than under the Rs40. Hence, the harvesting regime is an important factor that results in the export of system nutrients and a decline in soil fertility. Therefore, prolonging the harvesting cycle and adopting Rs are two options for reducing the nutrients export.

Keywords: Allometric Growth Equation, Different Stand Ages, Larch Plantation, Biomass, Nutrient Distribution Pattern

1. Introduction

Much attention has long been paid to the decline in soil fertility in plantations [1], [2]. Maintaining a balance between the import and export of nutrient elements to ensure the stability of the nutrient capital of the soil is the basis for a forest ecosystem to achieve sustainable productivity [3]. We often observe this type of balance in natural ecosystems [4]. However, the periodic harvesting of timber may result in disruption of the balance between the import and export of nutrient elements in plantations, which account for 7% of the total forest area worldwide [5]. Researchers have indeed observed a decline in soil nutrients caused by harvesting in different types of plantations [6], [7], [8], [9]. Therefore, how to maintain the capacity of a soil to provide a long-term nutrient supply under continued harvesting has been attracting increasing attention [10].

Through numerous studies involving allometric growth equations and nutrient distribution patterns, it has been found that different harvesting regimes have a significant impact on the maintenance of the capacity of a soil to provide a long-term nutrient supply [6], [9]. On this basis, government agencies have formulated regulations and various rules to ensure the sustainable utilization of nutrients in plantations. For example, current guidelines by Wisconsin Department of Natural Resources (WDNRs) for the harvesting of forested areas recommend that detritus with a diameter less than 10cm be left on-site along with roots, stumps, the litter layer, and any woody detritus that was already on the forest floor [11]. States from Maine to Missouri, Canada, and some European countries also made the similar rules [12].

While the importance of harvesting in the cycling of nutrients in plantation ecosystems has been acknowledged [10], [13] and researchers have carried out many studies on the nutrient utilization rates of different tree species [14], [15], [16], [17], [18], there are significant differences between different regions and different tree species [19]. One study showed that a decline in soil fertility can easily occur in fast-growing, high-yield plantations in tropical regions [20], whereas declines in soil fertility do not readily occur in temperate forests with abundant nutrients, such as the forest areas in northeastern China [21]. However, a recent study revealed an increasingly prominent declining trend in soil fertility in the larch plantations in northeastern China [22], [23], [24], [25], [26], [27]. The forest areas in northeastern China account for 31.4% of the total forest area in China. The area of natural forest in the forest areas of northeastern China is gradually decreasing, whereas the plantation area in these forest areas is continuously increasing. Larch (*Larix spp.*) is one of the main timber species in the forest areas in northeastern China. Large areas of pure larch forests have been created since the 1950s. The larch plantation area currently covers 2.0×10^6 hm^2, accounting for approximately 55% of the total plantation area in northeastern China [28]. If the declining trend in soil fertility continues, a serious threat will be posed to the plantations in northeastern China, or even the entire country. Studies in other regions and forest types have shown that different harvesting regimes (e.g., different harvesting cycles or harvesting regimes involving the removal of stem wood, branches and bark (Rsbb) or only stem wood and bark (Rsb)) have a significant impact on the export of nutrients from plantations [6], [29], [30], [31]. However, we still do not understand the impact of different harvesting regimes on the export of nutrients from the larch plantations in northeastern China and whether the harvesting regime has already become the chief cause of declining soil fertility in this type of plantation.

Studying nutrient distribution patterns can provide accurate information for estimation of the loss of nutrients caused by harvesting [6], [9]. Through establishing allometric growth equations and investigating nutrient distribution patterns, the impact of different harvesting regimes (Rsbb, Rsb, removal of stem wood (Rs)) on the export of nutrients from larch plantations with two different stand ages was evaluated in the present study, and whether the difference in the export of nutrients would impact the soil nutrient contents and result in a decline in soil fertility in the plantations was assessed. Finally, the impacts of different harvesting regimes on plantation site conditions were determined, providing a basis for scientifically selecting a harvesting regime in northeastern China.

2. Materials and Methods

2.1. Site Characteristics

The study was conducted at the Maoershan Experimental Station (45°21′–45°25′N, 127°30′–127°34′E) of the Northeast Forestry University in northeastern China. The site has a continental temperate monsoon climate with the mean January, July, and annual air temperatures of –19.6°C, 20.9°C, and 2.8 °C, respectively. The mean annual precipitation is 723mm with 477 mm falling from June to August. The soils are Hap-Boric Luvisols, well drained with high organic matter and frozen to a depth of 1m during the winter (from December to April).

2.2. Biomass Determination

In March 2012, three experimental plantation plots (20 m×20 m) with a stand age of 20 years and three experimental plantation plots (20 m×20 m) with a stand age of 40 years were selected at the Maoershan Experimental Station of the Northeast Forestry University. In each plot, five standard trees were selected and cut down. The biomass of the trunk, branches and leaves of each standard tree was determined using the vertical stratifying method, while the biomass of the roots of each standard tree was determined using the whole digging method [32]. The samples collected from different parts of each standard tree were dried, after which the biomass of each organ was calculated. Then, a correlation model between the biomass of each organ and the diameter at breast height (DBH) was established.

2.3. Nutrient Contents in Different Parts of the Trees and Soil

Samples were collected from the trunks, bark, leaves, branches and roots of standard larch trees in stands with different ages. After the samples were ground and sieved, nutrient contents were determined. C and N contents were determined using an element analyzer after digesting the samples with concentrated H_2SO_4–H_2O_2 (Elementary Vario EL III, Germany). The P content was determined using the Mo-Sb colorimetric method [33]. The digestion solution was also employed for the determination of K, Ca and Mg contents (Atomic Absorption Spectroscopy, PE Aanlyst 800, USA) using the atomic absorption method [34], [35], [36].

Soil samples collected from the field were dried in air, after which the soil nutrient contents were determined. The total N content was determined using the Kjeldahl method. The total P content was determined using the $HClO_4$–H_2SO_4 method. The total K content was determined using the HF–$HClO_4$ digestion method, and Ca^{2+} and Mg^{2+} contents were determined using the atomic absorption method. The cumulative amount of each soil nutrient was the product of the soil nutrient content and the soil volume [37].

2.4. Statistical Analyses

The cumulative amount of each nutrient in each organ of a single tree was the product of the concentration of the nutrient and the biomass of the organ [38]. The cumulative total amount of nutrients in each organ was the sum of the cumulative amounts of nutrients in the sections at different heights. The biomass, cumulative amounts of nutrients and C storage at the stand level were obtained by multiplying the relevant data for a standard tree by the stand density. Statistical data analysis was performed with SPSS 13.0. The prediction results of the biomass optimization model for each organ were examined using the mean accuracy (average accuracy, AA):

$$AA = 1 - \sum \left(\left| a - e \right| / a \right) / N \times 100\% \qquad (1)$$

where a represents the true value, and e represents the estimated value. The closer the value of AA is to 1, the better the prediction results of the model are. Generally, AA was >80%, indicating that the model was relatively consistent with the actual conditions [39], [40]. The significance of the difference was compared using the least significant difference method (α=0.05).

The amounts of nutrients exported under different harvesting regimes were estimated based on the biomass model and the cumulative amounts of nutrient elements in the organs. The examined harvesting regimes were as follows:

Harvesting regime 1: removal of stem wood, branch and bark (Rsbb), which includes two types, one is $Rsbb_{20}$ that Rsbb harvesting regime with a 20-year harvesting cycle, another is $Rsbb_{40}$ that Rsbb harvesting regime with a 40-year harvesting cycle.

Harvesting regime 2: removal of stem wood, and bark (Rsb), which includes two types, one is Rsb_{20} that Rsb harvesting regime with a 20-year harvesting cycle, another is Rsb_{40} that Rsb harvesting regime with a 40-year harvesting cycle.

Harvesting regime 3: removal of stem wood (Rs), which includes two types, one is Rs_{20} that Rs harvesting regime with a 20-year harvesting cycle, another is Rs_{40} that Rs harvesting regime with a 40-year harvesting cycle.

3. Results

3.1. Soil Properties

Similar to previous research findings [21], the soil in the study area contained relatively high nutrient contents (Table 1). The N, P and K contents of the soil all gradually decreased with increasing soil layer depths, but to different degrees. The N and K contents decreased to a relatively large degree, whereas the P content decreased to a relatively small degree with an increasing soil layer depth. The N content in the 0–10 cm soil layer was 0.963% and decreased to 0.412% in the 21–30 cm soil layer (an over 50% decrease). The K content in the 0–10 cm soil layer was 0.35% and decreased to 0.1% in the 21–30 cm soil layer (an over 70% decrease). There were no significant differences in the Ca and Mg contents between different soil layers. In addition, the Ca and Mg contents did not exhibit a clear increasing or decreasing trend. The soil density gradually increased with increasing soil layer depth. The soil density was 0.62 g/cm^3 in the 0–10 cm soil layer and increased to 1.5 g/cm^3 in the 21–30 cm soil layer (an over 50% increase).

Table 1. *Basic physical and chemical properties of the soil in the larch plantation.*

Nutrients element	Soil layers	Soil nutrients (%)
N	0-10cm	0.963
	11-20cm	0.692
	21-30cm	0.412
P	0-10cm	0.159
	11-20cm	0.137
	21-30cm	0.111
K	0-10cm	0.350
	11-20cm	0.250
	21-30cm	0.100
Ca	0-10cm	0.760
	11-20cm	0.630
	21-30cm	0.730
Mg	0-10cm	0.007
	11-20cm	0.017
	21-30cm	0.026
Soil density g/cm^3	0-10cm	0.620
	11-20cm	0.930
	21-30cm	1.500

3.2. Biomass Production and Nutrient Concentrations in Tree Components

A regression equation for DBH and the biomass of each organ was established using 10 standard trees:

$$W = aD^b \qquad (2)$$

Where W represents the biomass, and D represents DBH (diameter at breast height).

The coefficient of determination (R^2) and the residual sum of squares (RSS) were used as the evaluation indexes to evaluate the fitting results of each model. The results show that among the 22 biomass models for the 11 indexes (total biomass; aboveground biomass; biomass of the xylem of the trunk; biomass of the bark; biomass of the stalks; biomass of the branches; biomass of the new branches; biomass of the old branches; biomass of the leaves; belowground biomass; and biomass of the root system) of the larch trees with two different stand ages, 11 exhibited an R^2 between 0.814 and 0.991, an *RSS* between 0.007 and 0.081 and an evaluation accuracy between 81.7% and 95.1% (Table 2), indicating that the models established with the DBH as an independent variable could satisfactorily predict the biomass of each organ of a larch tree. However, the model for the biomass of the new branches of the 20-year-old larch trees showed an R^2 of only 0.659, an *RSS* of 0.754 and a mean accuracy of only 40.4% (Table 2), indicating that this model displayed a low prediction accuracy. The biomass of the new branches of the 20-year-old larch trees was reestablished using the regression equation for DBH and tree height:

$$W = a(D^2H)^b \tag{3}$$

Where W represents the biomass, and D represents DBH (diameter at breast height), and H represents height of tree.

Table 2. *Single-tree biomass estimation model for the larch plantation and examination of the accuracy of the model.*

Organ	Regression equation	Coefficient		R^2	Sum of squared residuals	Average accuracy (%)
	$M = aD^b$	a	b			
Total	40 years	1.785	2.676	0.925	0.025	91.3
	20 years	1.117	2.607	0.947	0.067	84.3
Above ground	40 years	1.555	2.826	0.908	0.034	88.7
	20 years	1.051	2.593	0.945	0.069	84.1
Woody tissues of Stem	40 years	1.704	2.685	0.931	0.023	91.2
	20 years	1.700	2.416	0.982	0.019	92.9
Bark	40 years	0.889	2.528	0.814	0.061	84.7
	20 years	0.886	2.512	0.935	0.077	81.7
Stem	40 years	1.711	2.701	0.929	0.024	90.0
	20 years	1.756	2.434	0.98	0.021	92.1
Total branch	40 years	-1.938	4.645	0.978	0.020	90.9
	20 years	1.104	2.566	0.949	0.062	84.5
New branch	40 years	-2.569	3.936	0.964	0.024	91.3
	20 years	-0.682	2.884	0.659	0.754	40.4
Older branch	40 years	-1.961	4.655	0.980	0.018	92.7
	20 years	1.105	2.562	0.957	0.051	85.9
Total foliage	40 years	-2.801	4.147	0.965	0.026	90.1
	20 years	1.437	1.714	0.867	0.079	82.5
Below ground	40 years	0.480	3.116	0.918	0.032	89.1
	20 years	0.272	2.674	0.948	0.069	82.8
Root	40 years	-3.008	4.335	0.991	0.007	95.1
	20 years	-1.641	2.322	0.981	0.081	91.9

R^2, *RSS*, AA are respectively 0.88, 0.007, 84.1%. The Rsbb, Rsb and Rs harvesting regimes are widely used (Merino, 2005). Some organs (e.g., stalks, xylem of the trunk, leaves and bark) are directly related to the export of nutrients caused by harvesting, while other organs (e.g., roots) are unrelated to the export of nutrients caused by harvesting. Regardless of how old the larch trees were, among the organs that are directly related to the export of nutrients caused by harvesting, those organs (e.g., leaves, bark, new branches) [41] that exhibited a relatively high proportion of living tissue (e.g., parenchyma cells) showed relatively high nutrient contents (Fig. 1), whereas those (e.g., xylem) [41] that displayed a relatively low proportion of living tissue exhibited relatively low nutrient element contents. These results are similar to those of previous studies on other tree species [42], [43], [27].

The organs of the 20-year-old larch trees basically showed the same nutrient distribution patterns as in the 40-year-old larch trees, except for some individual indexes (e.g., N content, underground P content). There was no significant difference in the nutrient contents of the organs between the larch trees with two different stand ages (Fig. 1). However, due to the difference in biomass partitioning, there was a significant difference in the cumulative amounts of nutrients in the organs between the larch trees with two different stand ages (Fig. 1).

As the growth time extends, the cumulative amount of xylem biomass in the trunk of a tree will gradually increase [42], [43], and the proportion of the biomass partitioned to the xylem of the trunk of the tree will also gradually increase. As a result of the increase in the proportion of the biomass partitioned to the xylem of the trunks of the 40-year-old larch trees, the cumulative amounts of nutrients in the 40-year-old larch trees were significantly higher than in the 20-year-old larch trees. Similar to the xylem of the trunk, there was also a difference in the cumulative amounts of nutrients between the leaves and old branches due to the difference in biomass partitioning. However, in contrast to the xylem, the cumulative amounts of nutrient elements in the leaves and old branches of the 20-year-old larch trees were significantly higher than in the 40-year-old larch trees (Fig. 1). While there was no significant difference in the cumulative amounts of nutrient elements in the new branches and bark between the larch trees with two different stand ages, the difference in the cumulative amounts of nutrient elements in other organs resulted in a significant difference between the 20-year-old larch trees and the 40-year-old larch trees in terms of the aboveground cumulative total amount of nutrients (corresponding to the Rsbb harvesting regime), the cumulative amounts of nutrient elements in the trunk (corresponding to the Rsb harvesting regime) and the cumulative amounts of nutrient elements in the xylem of the trunk (corresponding to the Rs harvesting regime) (Fig. 1).

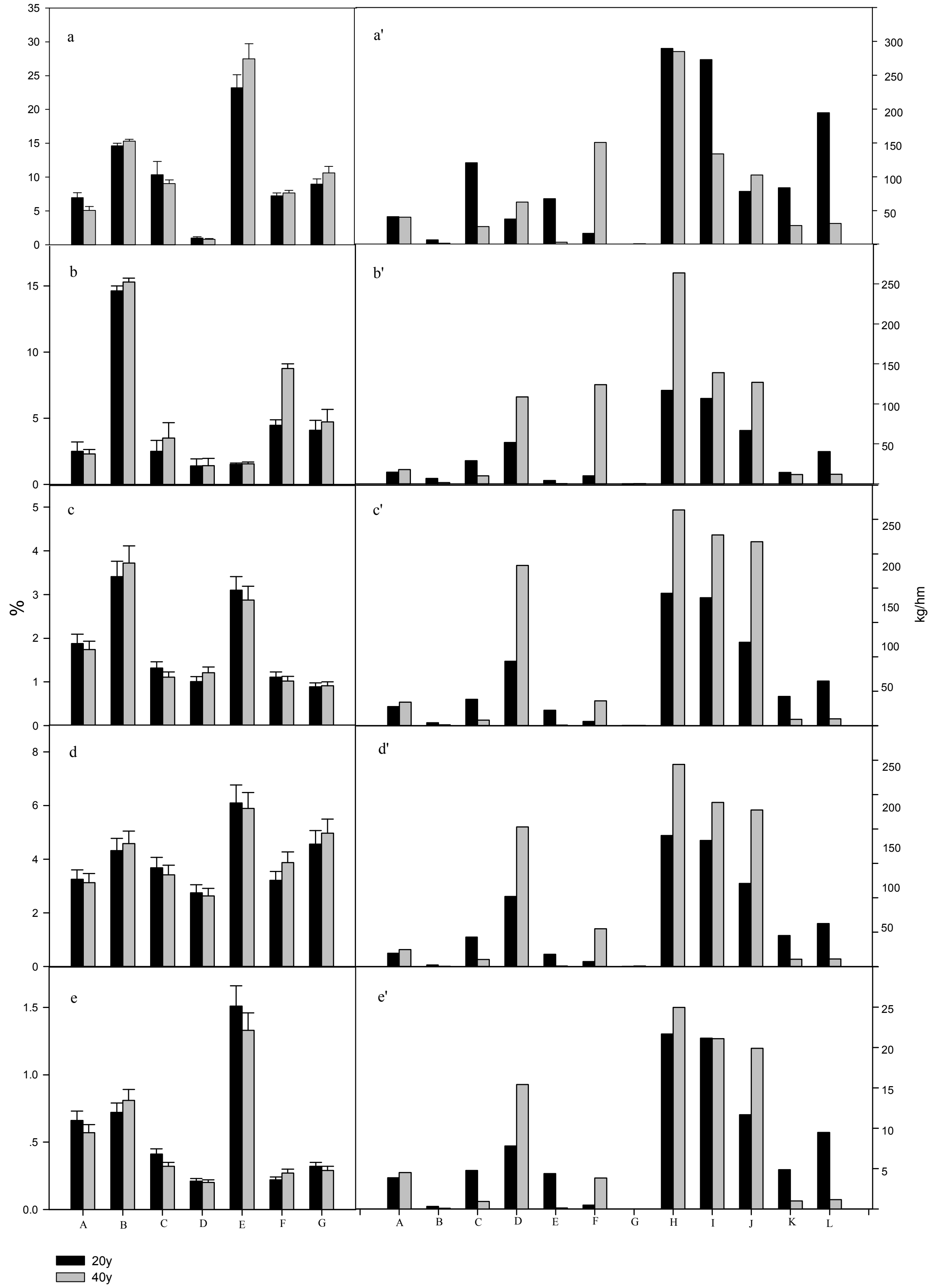

Fig. 1. *Contents and cumulative amounts of nutrients in each organ of the larch trees.*

A: Bark; B: New branch; C: Older branch; D: Woody tissues of Stem; E: Total foliage; F: Below ground; G: Root; H: Total; I: Above ground; J: Stem; K: Total branch; L: Total branch +Total foliage

a: N concentration; b: P concentration; c: K concentration; d: Ca concentration; e: Mg concentration

a': N accumulation; b': P accumulation; c': K accumulation; d': Ca accumulation; e': Mg accumulation

3.3. Nutrient Contents in Tree Biomass Components and Soil

Compared with the $Rsbb_{20}$, prolonging the harvesting cycle ($Rsbb_{40}$) or switching to an Rsb_{20} dramatically reduced the annual mean amounts of nutrients exported. Compared with the $Rsbb_{20}$, these two measures reduced the total amount of nutrients exported by 50.53–51.21% (reducing the annual mean amount of N exported by 71.30–75.54%, the annual mean amount of P exported by 35.07–37.69%, the annual mean amount of K exported by 25.49–34.85%, the annual mean amount of Ca exported by 34.13–34.95% and the annual mean amount of Mg exported by 44.86–50.19%) (Table 3). These measures also resulted in a decrease in the ratio of the annual mean total amount of nutrients exported to the annual net cumulative total amount of nutrients from 2.72 to 1.35–1.33. Furthermore, these measures caused significant decreases in the proportions of the annual mean amount of each nutrient exported within the corresponding soil nutrient contents of the 0–30 cm soil layer (the proportion of the annual mean total amount of nutrients exported within the total soil nutrient content of the 0–30 cm soil layer decreased from 0.07% to 0.03%; that of N exported within the N content of this layer decreased from 0.07% to 0.02%; that of P exported within the P content of this layer decreased from 0.14% to 0.08–0.09%; that of K exported within the K content of this layer decreased from 0.06% to 0.04–0.05%; that of Ca exported within the Ca content of this layer decreased from 0.04% to 0.03%; and that of Mg exported within the Mg content of this layer decreased from 0.40% to 0.22–0.19%) (Table 3).

Table 3. *Annual export of different nutrient elements in approximately 20- and 40-year-old larch plantation forests under different harvesting regimes.*

		Rsbb20 years (Base type)	Rsb 20 years	Rs 20 years	Rsbb 40 years	Rsb 40 years	Rs 40 years
N	Annual nutrient exports (kg/hm^2)	13.65	3.92	1.87	3.34	2.57	1.56
	Annual nutrient exports/Annual nutrient exports of Base type	100.00%	28.70%	13.73%	24.46%	18.79%	11.44%
	Annual nutrient exports/Soil nutrients concentration (0-10cm)	0.23%	0.07%	0.03%	0.06%	0.04%	0.03%
	Annual nutrient exports/Soil nutrients concentration (0-20cm)	0.11%	0.03%	0.02%	0.03%	0.02%	0.01%
	Annual nutrient exports/Soil nutrients concentration (0-30cm)	0.07%	0.02%	0.01%	0.02%	0.01%	0.01%
P	Annual nutrient exports (kg/hm^2)	5.35	3.33	2.60	3.47	3.17	2.72
	Annual nutrient exports/Annual nutrient exports of Base type	100.00%	62.31%	48.58%	64.93%	59.32%	50.84%
	Annual nutrient exports/Soil nutrients concentration (0-10cm)	0.54%	0.34%	0.26%	0.35%	0.32%	0.28%
	Annual nutrient exports/Soil nutrients concentration (0-20cm)	0.24%	0.15%	0.11%	0.15%	0.14%	0.12%
	Annual nutrient exports/Soil nutrients concentration (0-30cm)	0.14%	0.08%	0.07%	0.09%	0.08%	0.07%
K	Annual nutrient exports (kg/hm^2)	3.72	2.43	1.87	2.77	2.68	2.33
	Annual nutrient exports/Annual nutrient exports of Base type	100.00%	65.15%	50.32%	74.51%	71.86%	62.64%
	Annual nutrient exports/Soil nutrients concentration (0-10cm)	0.17%	0.11%	0.09%	0.13%	0.12%	0.11%
	Annual nutrient exports/Soil nutrients concentration (0-20cm)	0.08%	0.05%	0.04%	0.06%	0.06%	0.05%
	Annual nutrient exports/Soil nutrients concentration (0-30cm)	0.06%	0.04%	0.03%	0.05%	0.04%	0.04%
Ca	Annual nutrient exports (kg/hm^2)	9.17	6.04	5.08	5.96	5.69	5.07
	Annual nutrient exports/Annual nutrient exports of Base type	100.00%	65.87%	55.46%	65.05%	62.03%	55.32%
	Annual nutrient exports/Soil nutrients concentration (0-10cm)	0.19%	0.13%	0.11%	0.13%	0.12%	0.11%
	Annual nutrient exports/Soil nutrients concentration (0-20cm)	0.09%	0.06%	0.05%	0.06%	0.05%	0.05%
	Annual nutrient exports/Soil nutrients concentration (0-30cm)	0.04%	0.03%	0.02%	0.03%	0.03%	0.02%
Mg	Annual nutrient exports (kg/hm^2)	1.06	0.58	0.39	0.53	0.50	0.39
	Annual nutrient exports/Annual nutrient exports of Base type	100.00%	55.14%	36.82%	49.81%	47.06%	36.44%
	Annual nutrient exports/Soil nutrients concentration (0-10cm)	2.43%	1.34%	0.90%	1.21%	1.14%	0.89%
	Annual nutrient exports/Soil nutrients concentration (0-20cm)	0.76%	0.42%	0.28%	0.38%	0.36%	0.28%
	Annual nutrient exports/Soil nutrients concentration (0-30cm)	0.40%	0.22%	0.15%	0.20%	0.19%	0.15%
Total nutrient	Annual nutrient exports (kg/hm^2)	32.95	16.30	11.82	16.08	14.60	12.07
	Annual nutrient exports/Annual nutrient exports of Base type	100.00%	49.47%	35.87%	48.79%	44.30%	36.63%
	Annual nutrient exports/Soil nutrients concentration (0-10cm)	0.24%	0.12%	0.09%	0.12%	0.11%	0.09%
	Annual nutrient exports/Soil nutrients concentration (0-20cm)	0.11%	0.05%	0.04%	0.05%	0.05%	0.04%
	Annual nutrient exports/Soil nutrients concentration (0-30cm)	0.07%	0.03%	0.02%	0.03%	0.03%	0.02%
	Annual nutrient exports/Annual nutrient accumulation of whole system*	2.72	1.35	0.98	1.33	1.21	1.00
	Annual production of Woody tissues (kg/hm^2)	1041.01			1285.31		

* Net cumulative total amount of nutrients of Larch plantation ecosystem equals to the difference value of nutrient content of the Runoff input and output (12.1 kg/hm^2, from Ding et al (Ding et al., 1989))

Compared with the $Rsbb_{20}$, the Rsb_{40} or the Rs_{40} further reduced the total amount of nutrients exported by 55.70–63.37% (reducing the annual mean amount of N exported by 81.21-88.56%, the annual mean amount of P exported by 40.68-49.16%, the annual mean amount of K exported by 28.14-37.36%, the annual mean amount of Ca exported by 37.97-44.68 and the annual mean amount of Mg exported by 52.94-63.56%) and the ratio of the annual mean total amount of nutrients exported to the annual net cumulative total amount of nutrients to 1.21–1.00 (Table 3). In addition, the proportions of the annual mean amounts of nutrients exported in the corresponding soil nutrient contents in the 0–30 cm soil layer also continued to decrease.

Compared with the $Rsbb_{20}$, among the other harvesting regimes, the Rs_{20} resulted in the lowest annual mean amounts of nutrients exported. Under the Rs_{20}, the annual mean total amount of nutrients exported was only 35.87% of that under the $Rsbb_{20}$ (with the annual mean amount of N exported decreasing by 86.27%; that of P exported decreasing by 51.42%; that of K exported decreasing by 49.68%; that of Ca exported decreasing by 44.54%; and that of Mg exported decreasing by 63.18%) (Table 3). In addition, the ratio of the annual mean total amount of nutrients exported to the annual net cumulative total amount of nutrients also decreased to 0.98. The proportions of the annual mean amounts of nutrients exported within the corresponding soil nutrient contents in the 0–30 cm soil layer also decreased to the lowest level (the proportion of the annual mean total amount of nutrients exported within the total soil nutrient content of the 0–30 cm soil layer decreased from 0.07% to 0.02%; that of N exported within the N content of this layer decreased from 0.07% to 0.01%; that of P exported within the P content of this layer decreased from 0.14% to 0.07%; that of K exported within the K content of this layer decreased from 0.06% to 0.03%; that of Ca exported within the Ca content of this layer decreased from 0.04% to 0.02%; and that of Mg exported within the Mg content of this layer decreased from 0.40% to 0.15%) (Table 3).

Compared with the harvesting regime with a 20-year harvesting cycle, the annual mean growth of the xylem increased from 1,041.01 kg/hm^2 to 1,285.31 kg/hm^2 under the harvesting regime with a 40-year harvesting cycle (Table 3).

4. Discussion

4.1. Construction of an Allometric Growth Equation

Allometric growth equations are a widely used, reliable method for estimating the biomass, net primary productivity and carbon budgets of trees [44]. However, there is currently no uniform model for allometric growth equations for trees. The majority of researchers accept a power function of $M=aD^b$ [45], [46], [47]. The allometric growth equations established in the present study were similar to those established in previous studies [46], [48]. The power function of $M=aD^b$ could be used to establish relatively satisfactory allometric growth equations, except for the new branches of the 20-year-old trees, similar to the results of previous studies on the growth of plants of the genus *Larix* [43], [27]. New branches are relatively more significantly affected by environmental factors. Therefore, relatively high variability of new branches has been observed in various tree species [49], [50], [43]. The new branches of larch trees in stands with relatively young ages exhibit particularly high variability. Some parameters of the new branches of larch trees in stands with relatively young ages, such as the total number of branches, branch diameter and branch angle, are not significantly correlated with DBH [34], which might be the main reason that more factors were required to fit the new branches of the 20-year-old larch trees.

4.2. Proportion of Belowground Biomass of Plants

Previous studies have shown that the belowground biomass of a plant accounts for approximately 21% of its total biomass, while the aboveground living biomass of a plant accounts for approximately 70% of its total biomass [51], [52]. King et al. studied the aboveground and belowground biomass of red pine trees in stands with different ages using the whole harvesting method and found that the belowground biomass accounted for approximately 22.64% of the biomass of the whole tree [53]. Our research results indicated that the proportion of belowground biomass in the larch plantations in northeastern China was relatively low (the belowground biomass of the 40-year-old and 20-year-old larch trees accounted for 15.6% and 16.8% of the total biomass, respectively) (Fig. 1), which might be due to the following reasons:

(1) Trees can adapt to environmental changes through adjusting their aboveground and belowground biomass structure. The type, age and size of a plant as well as the external environment can alter the partitioning pattern of the biomass of each organ in a forest tree [54]; i.e., plants adapt to changes in the nutrient environment through adjusting the aboveground and belowground partitioning patterns and maintain and balance the aboveground–belowground relationship through their feedback mechanism [55], [56]. When there is a lack of soil nutrients and water, a plant partitions more C to its belowground parts, resulting in an increase in the ratio of the belowground biomass to the aboveground biomass [57]. Previous researchers have observed this adaptive response in a number of plants [58], [59], [60]. For example, a hybrid poplar tree was found to partition more C to its aboveground parts due to a relatively high N supply [61], while P deficiency and low P conditions resulted in an increase in the proportion of carbohydrates partitioned to the roots by seedlings [62], [63]. In the present study, the soil contained abundant nutrients, which might be one of the main causes of the relatively low belowground biomass.

(2) The proportion of fine roots in the biomass of a larch tree can reach approximately 10% [64]. However, it is relatively difficult to collect samples from the belowground root system when employing the harvesting method, and a considerable amount of fine roots will inevitably be lost during the sampling process [65], which might be another cause of the relatively low belowground biomass indicated by the results of the present study.

(3) Stand age is an important factor that affects biomass partitioning [64], [65], [66], [67]. The proportion of branches and leaves in the biomass of a tree decreases with increasing stand age, while the proportion of the trunk increases, as observed in the larch trees in the present study. There are multiple reasons why stand age affects the allometric growth equation. First, the development of the height and leaves of a tree is relatively important in the early stage of tree growth, but the growth of the stalks and coarse roots is more important in the late stage. As a result, trees in stands with different ages

exhibit different biomass partitioning strategies [68]. In addition, relatively large trees display a relatively small leaf area, resulting in a decrease in the proportion of the branches and leaves [69]. The results of the present study show that the biomass of the trunk continued to increase with increasing stand age, but there was no significant difference in the total biomass of branches and leaves between trees in stands with different ages. Under the impact of these factors, the increase in the proportion of the trunk with increasing stand age will become a general phenomenon [70], [71], [72], [73].

4.3. Nutrient Element Distribution Patterns

There is relatively high similarity between the nutrient distribution patterns in different tree species in different regions. Generally speaking, leaves, small branches, bark and fine roots exhibit relatively high nutrient contents, whereas stalks, old branches and root systems show relatively low nutrient contents [74], [75], [76]. However, the nutrient distribution pattern also varies to a certain extent between species. For example, the leaves of larch trees display relatively low nutrient contents.

The environmental temperature is an important factor that affects the nutrient contents of leaves. Relatively low temperatures have an inhibitory effect on the degradation and mineralization rate of litter, thereby reducing the contents of N and P that soils can absorb [77]. In addition, relatively low temperatures reduce the capacity of a plant to absorb nutrients through altering the physiological characteristics of the plant (e.g., the permeability and liquid-state viscosity of the plasma membrane) [78], [79], and N and P contents exhibit a decreasing trend with decreasing temperatures. Northeastern China, a region suitable for the growth of larch trees, is characterized by relatively low temperatures, and plants in this region adapt to relatively low temperatures through relatively low N contents at the leaf level [80], resulting in relatively low nutrient contents of the leaves of larch trees.

4.4. Effect of Harvesting on Soil Nutrients

The nutrients lost by a forest ecosystem can be replenished through internal and external processes (e.g., precipitation, biological fixation) [81], [4], [82]. However, in a plantation ecosystem, the export of nutrients caused by harvesting may exceed the natural import of nutrients, resulting in a decrease in soil nutrients [7], [8]. The mechanism by which harvesting results in the loss of soil nutrients in a plantation is very complicated [16], as are the specific ways in which soil nutrients are lost [83], [2], [84]. Changes in the material cycle and hydrothermal conditions are some of the possible mechanisms by which harvesting results in a loss of soil nutrients [85], [86], [87] [88]. However, the important role of harvesting in the loss of soil nutrients in a plantation has gradually been recognized [7], [8]. The export of nutrients and a high proportion of soil nutrients will affect the long-term accumulation of soil nutrients [13]. The results of the present study showed that in the temperate larch plantations of northeastern China, the proportions of the total amount of nutrients exported due to harvesting within the cumulative total amount of soil nutrients and the net cumulative total amount of nutrients in the system were both high and that the export of nutrients caused by harvesting would result in a significant decline in soil fertility (Table 3). Similar to findings in other plantations, it was shown in the present study that prolonging the harvesting cycle and changing the harvesting regime are both important methods for reducing the annual mean amounts of nutrients exported and the loss of soil nutrients [89]. The difference in the annual mean amount of nutrients exported between different harvesting ages was mainly due to the difference in the annual mean amount of nutrients exported from the branches, leaves and bark. However, the impact of the annual mean amount of nutrients exported from the xylem was relatively insignificant. Compared with the trunk, the branches, leaves and bark display a relatively short growth time [41]. Therefore, there is a relatively small difference in the biomass of the branches, leaves and bark between trees in stands with different ages. As a result, there is no significant difference in the annual mean amounts of nutrients exported from the branches, leaves and bark between different harvesting ages. Other tree species in northeastern China also have this characteristic [43]. Among the examined harvesting regimes, the annual mean amount of nutrients exported was significantly higher than the net cumulative amount of nutrients in the system under both the Rsbb and Rsb harvesting regimes, regardless of whether the 20-year or 40-year harvesting cycle was selected. The annual mean amount of nutrients exported was the same as the net cumulative amount of nutrients in the system under the Rs_{40} and was slightly lower than the net cumulative amount of nutrients in the system under the Rs_{20}. While the Rs harvesting regime has been widely used internationally [3], this harvesting regime is not stipulated in the operational rules for forest harvesting of China. The Rs harvesting regime is not used in the harvesting in the forest areas in northeastern China. However, the Rs harvesting regime can effectively reduce the amounts of nutrients exported from plantations.

5. Conclusions

In the larch plantation ecosystems of northeastern China, the harvesting regime is an important factor resulting in the export of nutrients, which in turn causes declining soil fertility. Prolonging the harvesting cycle and adopting an Rs harvesting regime are both important methods for reducing the export of nutrients. The Rs_{20} resulted in the lowest amount of nutrients being exported. However, there was no significant difference in the amount of nutrients exported between the Rs_{20} and the Rs_{40}, mainly because the annual mean amounts of P and K exported under the Rs_{20} were lower than those under the Rs_{40}, and the annual mean amounts of N, Ca and Mg exported under the Rs_{20} were higher than those under the Rs_{40}. The Rs_{40} resulted in a higher yield of timber. A harvesting regime should be selected based on the consideration of multiple factors, such as the results of the present study, the goal of harvesting (e.g., final harvesting, thinning or sanitation harvesting) and the purpose of harvesting (e.g., for timber, firewood or craft material).

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