forests

MDPI

Article

Regular Fertilization Effects on the Nutrient Distribution of Bamboo Components in a Moso Bamboo (*Phyllostachys pubescens* (Mazel) Ohwi) Stand in South Korea

Choonsig Kim [1,*], Gyeongwon Baek [1], Byung Oh Yoo [2], Su-Young Jung [2] and Kwang Soo Lee [2]

[1] Department of Forest Resources, Gyeongnam National University of Science and Technology, Jinju 52725, Korea; kwb1926@naver.com

[2] Forest Biomaterials Research Center, National Institute of Forest Science, Jinju 52817, Korea; boyoofri@korea.kr (B.O.Y.); suyoung.jung@korea.kr (S.-Y.J.); beldel660@korea.kr (K.S.L.)

* Correspondence: ckim@gntech.ac.kr; Tel.: +82-55-751-3247

Received: 23 August 2018; Accepted: 24 October 2018; Published: 26 October 2018

check for updates

Abstract: Fertilizers are commonly applied to improve the productivity and quality of bamboo. However, the nutrient responses of bamboo components after regular fertilization are not fully understood. This study was carried out to determine the effects of regular fertilization on the nutrient distribution of biomass components (i.e., culms, branches, leaves, roots, rhizomes) in a Moso bamboo stand in southern Korea. The study site was fertilized regularly for approximately 30 years to produce edible bamboo shoots. A total of 20 bamboo plants (10 fertilized and 10 unfertilized) were cut to measure the nutrient (C, N, P, K, Ca, Mg) concentrations of each bamboo component. Belowground roots and rhizomes were sampled at a 30-cm soil depth. The N, P, and K concentrations and stocks of aboveground biomass components were increased by regular fertilization, whereas the C, Ca, and Mg stocks were attributed to culm densities. The nutrient stocks of belowground roots were significantly lower in the fertilized plots than those in the unfertilized plots, except for the P stocks. The results indicate that regular fertilization could be a key factor to maintaining bamboo shoot productivity because of the increased responses of the nutrient concentration and stocks of bamboo components.

Keywords: bamboo; biometric equation; carbon; fertilization; nutrient; rhizome; roots

1. Introduction

In addition to being a traditional source of energy, bamboo provides a number of potential ecosystem services including carbon (C) sequestration [1], soil and water conservation, biofuel production, and food sources, among multiple other uses [2,3]. Thus, bamboo forest cover is increasing around the world for the production and utilization of bamboo [1,4,5].

Fertilizers are commonly applied to improve the productivity and quality of bamboo, as soil nutrient availability often limits bamboo growth and production [2,6]. Several studies have found that bamboo shoot and culm production can be significantly increased with additions of nitrogen (N) or compound (NPK) fertilizers [7–9]. The nutritional properties of bamboo shoots, such as sugar and amino acid contents, were also improved with the application of fertilizers [2]. Bamboo plants have, in fact, a dense root system that is efficient in taking up plant available-nutrients, which explains the fast response of bamboo to fertilization that has been reported in previous studies [2,3,8]. Thus, the use of fertilizers in bamboo stands has long been a management practice to increase the productivity of bamboo shoots and culms. While fertilization increases bamboo productivity, it also has significant impacts on the nutrient distribution of bamboo stands because of different regulatory mechanism of nutrient allocation induced by fertilization [2,3].

The evaluation of nutrient distribution by bamboo following fertilization is a useful approach to evaluate the nutrient status of bamboo stands, since the variation of nutrient concentration and content could generally be interpreted by the supply of nutrients. Leaf analyses were widely used as indicators for bamboo nutrient status [2], while neglecting the responses of other bamboo components such as culms, branches, and roots. However, bamboo may have different nutrient requirement among bamboo components (leaves, branches, culms, roots) that live for several years. Thus, it is necessary to investigate the nutrient status of bamboo components regarding altered soil nutrient availability due to fertilization.

Regular fertilization is important for maintaining the productivity of bamboo because considerable amounts of nutrients can be removed annually by harvestings edible shoots and culms. It is necessary to maintain high fertility in bamboo stands over long-term cultivation periods from a sustainability point of view. Although there have been many field trials on fertilizer responses in bamboo stands, most of these studies focused on a short period of time [2,3,5], which is expected to differ considerably from those in the long term. In addition, little is known about the impacts of regular fertilization on the nutrient distribution of bamboo stands.

Bamboo forests occupy more than 22 thousand hectares in South Korea [10]. Eleven dominant bamboo species (*Phyllostachys bambusoides* Sieb. et Zucc, *P. nigra* var. *henonis* Stapf ex. Rendle, *P. pubescens* (Mazel) Ohwi, *Sasa gracilis* (Nakai) T. Lee, *Arundinaria simonii* A et C Riviere, *Sasa borealis* (Hack.) Makino, and *Pseudosasa japonica* (Sieb. et Zucc.) Makino, etc.) occur either naturally or are planted in subtropical forest zones of the country [6]. Moso bamboo (*P. pubescens* (Mazel) Ohwi) is one of the most widely distributed species for the cultivation of edible bamboo shoots [6]. About 980,000 kg of bamboo shoots are produced annually throughout South Korea [6]. In addition, bamboo consumption has been confined mostly to bamboo shoots since the 1990s due to rapid declines in bamboo manufacturing industries in South Korea.

Although many studies have recommended fertilization for improved productivity and quality of bamboo and for increased economic and ecological benefits from bamboo [2,5,9], little information is available on nutrient distribution following regular fertilizer supplements in bamboo forests. In addition, a better understanding of the distribution of nutrients is strongly required for maintaining and improving the productivity of Moso bamboo stands. The objective of this study was to determine the effects of regular compound fertilizer applications on the nutrient status of bamboo components in a Moso bamboo stand fertilized over the last 30 years. Changes in nutrient concentration and stocks of bamboo components were examined to evaluate the effect of regular fertilization. In this study, we hypothesized that regular fertilization would increase the nutrient uptake of bamboo components in response to the improvement of soil fertility.

2. Materials and Methods

2.1. Study Site and Experimental Design

This study was conducted in a Moso bamboo stand in the Gajwa National Experimental Forest administered by the Forest Biomaterials Research Center, Jinju, southern Korea (Figure 1). The study site was located within an area where bamboo shoot production typically occurs [6]. The 7.2 ha of Moso bamboo stands were established to produce edible bamboo shoots between 1970 and 1972. The annual average precipitation and temperature in this area are 1512 mm year^{-1} and 13.1 °C, respectively. The soil is a slightly dry, reddish-brown forest soil (mostly Inceptisols, United States Soil Taxonomy) originating from sandstone or shale with a silt loam texture [11]. Bamboo forests are widely distributed in a slightly dry brown forest soil (mostly Inceptisols) or a slightly dry reddish-brown forest soil of the South Korean subtropical forest zone [6].

The experimental design consisted of a completely randomized design involving six plots of 10 × 10 m (2 treatments (fertilized: 35°09′ N 128°06′ E, elevation of 50 m a.s.l., unfertilized: 35°09′ N; 128°06′ E, elevation of 67 m a.s.l.) × 3 replicated plots) in the stand (Figure 1). The data for this study were collected from three replicated plots by using a sampling scheme with identical designs for adjacent sites in order to minimize spatial variations. Fertilizer was applied manually on the forest floor in mid-June of each year for approximately 30 years based on the fertilization guidelines of bamboo forests (N:P:K: 21:17:17; 244 kg N ha^{-1} $year^{-1}$, 196 kg P ha^{-1} $year^{-1}$, 196 kg K ha^{-1} $year^{-1}$) in South Korea [6], whereas the unfertilized stands were not managed for the same period.

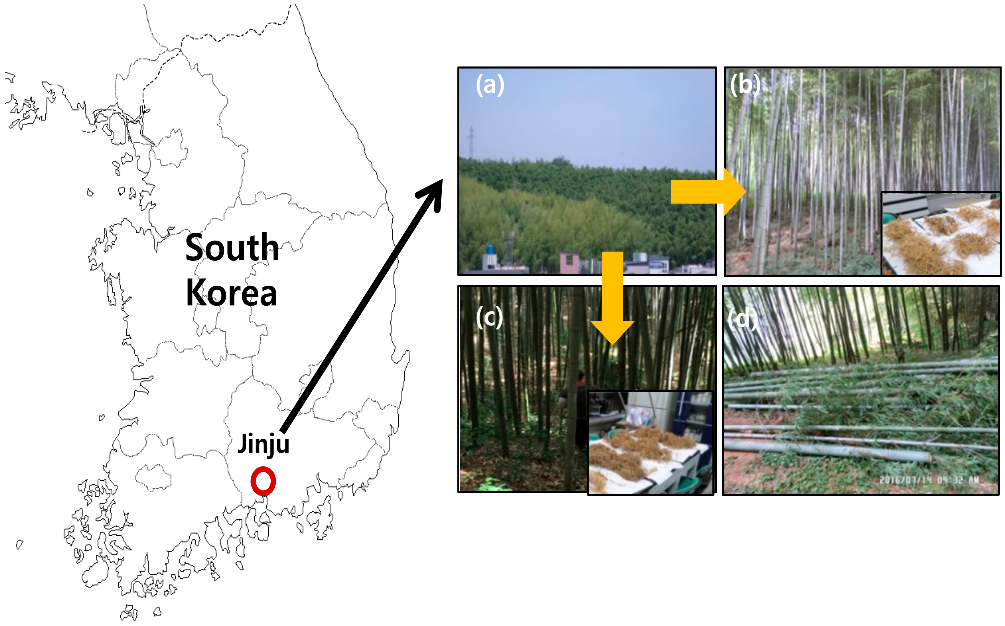

Figure 1. Dark green color of leaves in fertilized sites and light green color of leaves in unfertilized sites (**a**) of a Moso bamboo (*Phllostachys pubescens*) stand in the Gajwa National Experimental Forest, Jinju, Korea. Bamboo roots and rhizomes of fertilized (**b**) and unfertilized (**c**) plots. Sampled bamboo from fertilized plots (**d**).

2.2. Analysis of Bamboo Components

The diameter at the height of 1.2 m (DBH) of each bamboo in each plot was measured, and two bamboo age classes (current-year and >1-year-old bamboo) were recorded based on the status of the culm sheaths. All bamboo were grouped into five DBH classes covering the full range of DBHs, according to the bamboo age classes. Twenty bamboo samples were obtained from the fertilized (five bamboo in current-year, five bamboo in >1-year-old) and unfertilized (five bamboo in current-year, five bamboo in >1-year-old) plots based on five DBH classes and two age classes of each treatment plot because the nutrient concentration of bamboo components was sensitive to ages of bamboo [12].

The bamboo samples were destructively sampled and separated into component parts (i.e., leaves, branches, and culms) in July of 2016. The fresh biomass for all the bamboo components was determined in the field using portable electronic balances. Subsamples to determine the fresh-to-oven-dried biomass ratio were taken from each bamboo component and oven-dried at 85 °C for one week.

Roots and rhizome samples regardless of diameter size were collected up to a soil depth of 30 cm (30 cm in length, 30 cm in width) from three random places in each treatment plot because the belowground biomass of Moso bamboo stands were mostly distributed in the upper 30 cm of soil [2]. This technique is the most widespread approach to quantify root and rhizome biomass in bamboo forests [11,13]. All roots and rhizomes were transported to a laboratory and separated carefully with washing by tap water to remove mineral soils. The separated roots and rhizomes were dried to a constant mass at 85 °C for one week.

The dried samples of each bamboo component were ground in a Wiley mill and passed through a 40-mesh stainless-steel sieve. C and N concentrations from the ground materials were determined using an elemental analyzer (Thermo Fisher Scientific Flash 2000, Milan, Italy). Phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentrations were determined through dry ashing 0.5 g of the ground material at 470 °C for 4 h, digesting the ash with 3 mL of concentrated 5 M HCl, diluting the digest with 0.25 mL of concentrated HNO_3 and 3 mL of concentrated 5 *M* HCl [13], and measuring the concentrations via ICP-OES (Perkin Elmer Optima 5300DV, Shelton, CT, USA). The nutrient content of each bamboo component (g $bamboo^{-1}$) was determined by multiplying the dry weight and nutrient concentration of each bamboo component.

The allometric equations [14] developed to estimate the nutrient content of each bamboo component (i.e., culms, branches, leaves) were as follows (Equation (1)):

$$\log_{10}Y = a + b \times \log_{10}(DBH) \quad (1)$$

where Y is the nutrient content (g) of the respective bamboo component, DBH is the diameter at breast height (cm), and a and b are regression coefficients. The accuracy of the allometric equations was evaluated by the coefficient of determination (r^2). The nutrient stocks (kg ha^{-1}) based on an area were calculated from the DBH of each treatment plot using the allometric equations developed to estimate the nutrient content of each bamboo component. However, the allometric equations were not significant at $p < 0.05$, and the nutrient content was estimated by the ratio of dry weight and the nutrient content of the sampled bamboo components.

2.3. Analysis of Soil Properties

Soil samples per each treatment plot were collected at three locations of two different depths (0–10 cm, 10–20 cm) using 405 cm^3 soil sampling cores (7.04 cm inner diameter, 10.4 cm height). Three samplings at each location were done randomly between the bamboo canopy and beneath the bamboo canopy. Soil samples were transported to a laboratory and sieved with a 2-mm mesh sieve. The soil pH (1:5 soil water suspension) and electrical conductivity (EC) were measured using an ion-selective glass electrode (ISTEC Model pH-220L, Seoul, Korea) and an EC meter (Thermo Fisher Scientific Orion 3-Star, Singapore), respectively. Soil C and N concentrations were determined using an elemental analyzer (Vario Macro cube, Langenselbold, Germany). The available soil P concentration extracted by NH_4F and HCl solutions [15] was determined by a UV spectrophotometer (Jenway 6505, Staffordshire, UK). Exchangeable K, Ca, and Mg concentrations extracted by NH_4Cl solution [15] with a mechanical vacuum extractor (Model 24VE, SampleTeck, Science Hill, KY, USA) were determined through ICP-OES (Perkin Elmer Optima 5300DV, Shelton, CT, USA).

2.4. Data Analysis

The nutrient concentrations of aboveground bamboo components were analyzed by a two-way analysis of variance (ANOVA) to determine the significance of main effects (fertilizer treatment (T), bamboo age class (A)) and their interactions (T × A) at a significance level of $p < 0.05$ using the General Linear Models procedure in SAS (SAS Institute, Cary, NC, USA) [16]. Student's *t* tests were used to determine the effects of regular fertilization on the soil properties, nutrient concentration of the roots and rhizomes, and nutrient stocks of bamboo components.

3. Results and Discussion

3.1. Stand and Soil Attributes

Culm densities were higher in the unfertilized plots than those in the fertilized plots, whereas the densities of current-year bamboo were slightly lower in the fertilized plots than those in the unfertilized plots (Table 1). The low density of current-year culms in the fertilized plot could be due to the annual edible shoot harvest. In this study, the culm density in the fertilized plot was similar to the optimal culm density (4283 culm ha^{-1}) in Moso bamboo stands in China [17]. The mean DBH was similar between the fertilized (10.8 cm) and the unfertilized (10.7 cm) plots. Although a decrease in culm density implies an increase in the diameter of culms [18], the growth of DBH in current-year or >1-year-old bamboo was similar between the fertilized and unfertilized plots despite the different culm density. DBH growth in fertilized plots could be affected by the increased number of new shoots following fertilizer application [19]. The values of DBH in this study were slightly higher than the range (mean: 8.37–10.12 cm) of Moso bamboo stands (culm density: 3400–4732 culm ha^{-1}) in the subtropical region of China [20].

Table 1. General characteristics of the study site in a Moso bamboo stand (n = 3).

Treatment	Aspect	Slope (°)	Culm Density (culm ha^{-1})			DBH (cm)		
			Current-Year	>1-Year-Old	Mean	Current-Year	>1-Year-Old	Mean
Fertilized	E	<15	1200 (0)	3433 (384)	4633 (384)	11.4 (0.4)	10.1 (0.3)	10.8 (0.4)
Unfertilized	N	15–20	1333 (133)	5500 (208)	6833 (317)	11.2 (0.3)	10.1 (0.3)	10.7 (0.3)

Values in parenthesis are standard error. DBH: diameter at the height of 1.2 m.

Soil texture of the surface soil (0–10 cm), soil pH, organic C, and total N concentrations were not significantly different between the fertilized and the unfertilized plots, whereas the available P concentration and EC of the soil were significantly improved in the fertilized plots compared with the unfertilized plots (Table 2). An increase in available soil P concentration was generally observed following the compound fertilizer application because the retentive capacity of P in the soil can be enhanced by P fertilizer addition [21,22].

Table 2. Soil physiochemical properties between fertilized and unfertilized plots in a Moso bamboo stand (n = 3).

Depth (cm)	Treatment	Sand (%)	Silt (%)	Clay (%)	pH	EC (µS cm^{-1})	Carbon (%)	TotalN (%)	Avail. P (mg kg^{-1})	Exchangeable (cmolc kg^{-1})		
										K^+	Ca^{2+}	Mg^{2+}
0–10	Fertilized	53 (2)	37 (2)	10 (2)	4.59 (0.3)	290 (31)	2.48 (0.46)	0.23 (0.03)	174.5 (11.4)	3.84 (0.51)	3.49 (1.15)	0.07 (0.017)
	Unfertilized	63 (4)	29 (2)	8 (2)	4.69 (0.1)	138 (26)	2.46 (0.37)	0.21 (0.02)	6.22 (1.4)	3.18 (1.25)	1.32 (0.30)	0.03 (0.002)
	p-Value	0.08	0.05	0.46	0.75	**0.02**	0.97	0.65	**<0.01**	0.65	0.14	0.05
10–20	Fertilized	47 (2)	40 (2)	13 (0)	4.45 (0.1)	263 (72)	2.03 (0.19)	0.20 (0.01)	132.3 (21.4)	3.74 (1.65)	2.49 (0.50)	0.06 (0.007)
	Unfertilized	56 (3)	31 (1)	12 (3)	4.56 (0.1)	116 (17)	2.31 (0.45)	0.19 (0.03)	5.2 (0.3)	2.27 (0.86)	1.31 (0.50)	0.03 (0.009)
	p-Value	0.07	**0.01**	0.56	0.54	0.11	0.59	0.85	**0.03**	0.47	0.16	**0.02**

Values in parenthesis are standard error. Bold values denote significance at $p < 0.05$. EC: electrical conductivity.

3.2. Nutrient Concentrations of Bamboo Components

There was no significant interaction effect between the fertilizer application and the bamboo age classes, except for the Mg concentrations in the culms and branches (Figure 2). The C concentration in the culms and leaves was not significantly different between the fertilized (culm: 456 mg kg^{-1}; leaf: 439 mg kg^{-1}) and unfertilized plots (culm: 461 mg kg^{-1}; leaf: 444 mg kg^{-1}). Similar results were reported for the C concentrations of the foliage of Japanese cypress trees in Korea, which were not affected by the different nutrient availability following fertilizer application [21]. However, the significant high C concentration (469 mg kg^{-1}) of the branches in the unfertilized plots could be due to the lower P and K concentrations compared with the C concentrations (461 mg kg^{-1}) of the branches in the fertilized plot (Figure 2). This result was consistent with a previous study in which the C concentration of tree components was generally greater in nutrient-poor site conditions due to the low nutrient concentration of tree components compared with trees grown in better site conditions [22,23]. In this study, the C concentration in the culm was slightly lower than the C concentration (466 mg kg^{-1}) of *P. bambusoides* in Japan [24] and the global mean value of 475 mg kg^{-1} for wood C concentration [25].

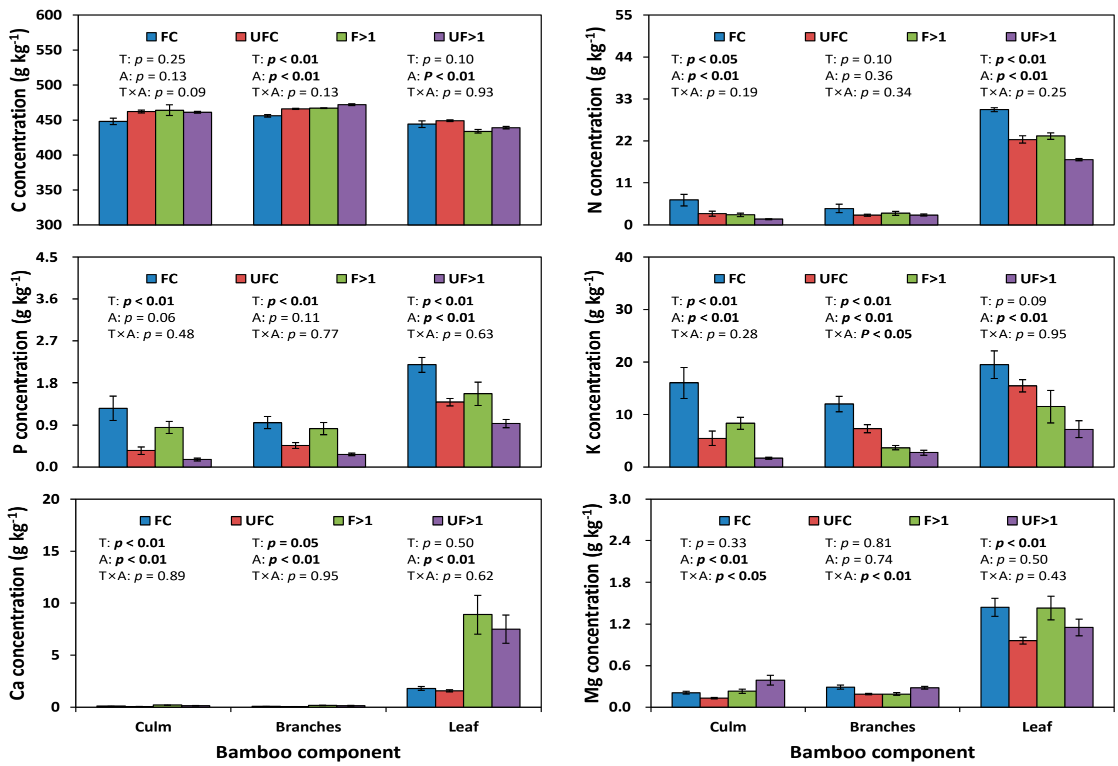

Figure 2. Nutrient concentration (n = 5) of aboveground bamboo components in a Moso bamboo stand (T: fertilizer treatment; A: bamboo age classes; T × A: interactions; FC: current-year bamboo in fertilized plot; UFC: current-year bamboo in unfertilized plot; F > 1: 1-year-old bamboo in fertilized plot; UF > 1: 1-year-old bamboo in unfertilized plot). Vertical bars represent standard error. Bold values denote significance at $p < 0.05$.

The N, P, and K concentrations of aboveground bamboo components were significantly higher in the fertilized plots than those in the unfertilized plots. A significant increase in N, P, K, and Ca in culms, P and K in branches, as well as N, P, and Mg in leaves was observed in the regular fertilized plots, indicating the increased uptakes of these nutrients. There is no question that fertilizer application increases nutrient concentration in bamboo components because nutrient responses in the components are commonly sensitive to soil nutrient conditions [2,26,27]. Mean leaf N and P concentrations in this study were 26.8 g kg^{-1} and 1.88 g kg^{-1}, respectively, in the fertilized plots, whereas they were 19.8 g kg^{-1} and 1.16 g kg^{-1}, respectively, in unfertilized plots. The changes in N and P concentrations in response to the fertilization were similar in leaves of Moso bamboo in fertilized (N: 26.4 g kg^{-1}, P: 1.48 g kg^{-1}) and unfertilized (N: 21.4 g kg^{-1}, P: 1.16 g kg^{-1}) stands in China [26]. These results confirmed the findings of previous studies in which nutrient concentrations of bamboo components are strongly controlled by the available nutrient status of the soils following fertilizer application [2,3,26,27]. Contrary to this finding, the leaf N concentration of Sasa bamboo in Japan did not change because of the dilution effect by increased leaf production after N addition [28]. Regular fertilization did not affect the K concentration in leaves ($p > 0.05$). Similar results were observed in seven bamboo species in Reunion Island, with no significant increase in K concentration in leaves with increasing fertilization [18]. A previous study reported that K nutrients may be rapidly translocated from leaves for the growth of new tissues such as culm [18], since K nutrients in bamboo species are the most important element stored by bamboo components such as culm. However, in this study, the K nutrients may not be limited due to the high concentration of available soil K in both treatments (Table 2).

Fertilization enhanced the ability for bamboo to store nutrients with increased concentrations of P and K in culms and branches. This result could be associated with the characteristics of culm and branches living for several years. Similarly, other studies observed the increased N or P concentrations in the culm and branches of bamboo [18] and pine seedlings [29] following fertilization. Contrary to these findings, the nutrient concentration of stem wood in matured tree was independent of fertilization [30].

The N, P, and K concentrations in leaves were significantly increased in current-year bamboo compared with >1-year-old bamboo, whereas the Ca concentrations of aboveground bamboo components were significantly higher in >1-year-old bamboo than in current-year bamboo (Figure 2). Since N, P, and K nutrients in leaves are generally mobile, these nutrients can be transported to the current-year bamboo from >1-year-old bamboo, indicating a higher demand for N, P, and K nutrients in current-year bamboo, while Ca acts as an immobile nutrient in the leaves.

Although there was no significant difference in the C, N, Ca, and Mg concentrations in belowground bamboo components between the fertilized and the unfertilized plots (Table 3), the nutrient concentrations in belowground bamboo components followed a pattern similar to aboveground biomass components. For example, the N, P, and K concentrations in roots and rhizomes were generally increased with fertilizer application because the bamboo in the fertilized plots absorbs and transports more nutrients compared with the unfertilized plots. In contrast to the fertilized plots, low nutrient concentrations in unfertilized plots could be associated with a dilution effect by high culm density with less soil nutrient available for bamboo growth. However, low root K concentrations in the unfertilized plot could be associated with the competition between K^+ and Mg^{2+} at the cellular level [31] by high root Mg concentrations in unfertilized plots. There is a strong antagonism between K^+ and Mg^{2+} uptake in *Populus trichocarpa* Brayshaw [31].

Table 3. Nutrient concentration of roots and rhizome in a Moso bamboo stand ($n = 3$).

Component	Treatment	Nutrient Concentration (g kg^{-1})					
		C	N	P	K	Ca	Mg
Roots	Fertilized	429 (14.4)	5.20 (0.5)	0.69 (0.2)	6.40 (0.77)	0.44 (0.07)	0.85 (0.13)
	Unfertilized	364 (41.9)	4.06 (0.81)	0.11 (0.04)	3.50 (0.25)	0.54 (0.05)	1.31 (0.11)
	p-Value	0.21	0.31	0.05	**0.02**	0.29	0.06
Rhizome	Fertilized	450 (3.49)	3.95 (0.46)	1.26 (0.24)	5.00 (1.05)	0.23 (0.04)	0.29 (0.05)
	Unfertilized	456 (1.85)	3.09 (0.38)	0.25 (0.03)	3.53 (0.83)	0.22 (0.06)	0.64 (0.17)
	p-Value	0.22	0.22	**0.01**	0.33	0.93	0.11

Values in parenthesis are standard error. Bold values denote significance at $p < 0.05$.

3.3. Nutrient Content and Stocks of Biomass Components

The C, N, and P content of aboveground bamboo components can be estimated accurately by allometric equations, with DBH accounting for 46%–81% of the variation in the C, N, and P content of the fertilized plots and with DBH accounting for 45%–85% in the C, N, and P content of the unfertilized plots (Table A1). This result is consistent with a previous study that demonstrated that allometric equations developed by DBH parameters provided reliable estimates of C contents of Moso bamboo [18]. However, the allometric equations in branches and leaves were not appropriate for the K, Ca, and Mg contents, having low coefficient of determination (r^2) values in allometric equations. The K, Ca, and Mg content in the branches and leaves of both treatments exhibited considerable variations because of the heterogeneity of branches and leaf nutrients in similar DBH classes (Figure 3). Based on r^2, the best fits for nutrient content were obtained generally for culm and total measurements, whereas the nutrient content of branches and leaves had the worst fit among all the bamboo components.

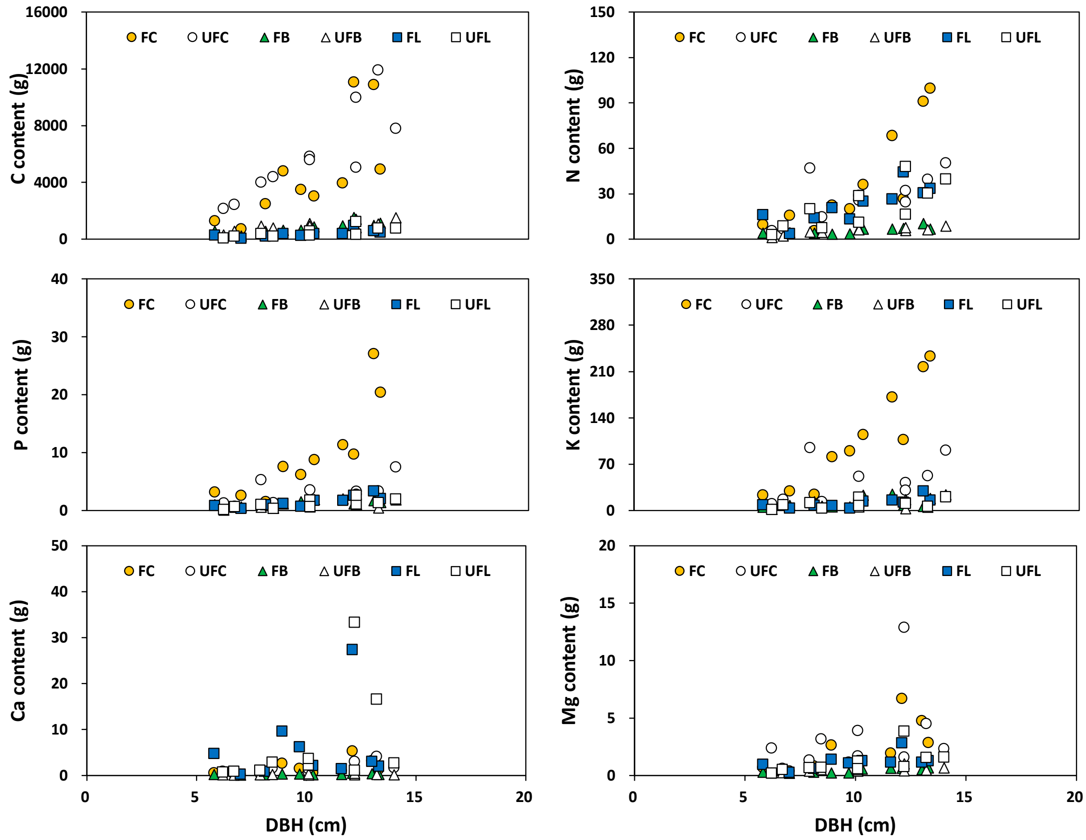

Figure 3. Relationships between nutrient content of bamboo components (n = 20) and DBH of fertilized and unfertilized plots in Moso bamboo (FC: culms in fertilized plots; UFC: culms in unfertilized plots; FB: branches in fertilized plots; UFB: branches in unfertilized plots; FL: leaves in fertilized plots; UFL: leaves in unfertilized plots).

Nutrient stocks of aboveground and belowground biomass components vary with fertilizer application. The N, Ca, and Mg stocks, as well as the P and K stocks, of aboveground biomass components were determined by the increased nutrient concentration following the fertilization, regardless of the culm density or C stocks in bamboo components (Table 4). For example, total aboveground N stocks were not affected by the difference in culm density between the fertilized (4633 culms ha^{-1}) and the unfertilized (6833 culms ha^{-1}) plots because of increased N concentration following fertilizer application. However, the difference in Ca and Mg stocks of aboveground biomass components could be attributed to the difference of C stocks by high culm density in the unfertilized plot. Nutrient stocks of the aboveground biomass in unfertilized plots in this study were 344 kg ha^{-1} for N, 31 kg ha^{-1} for P, and 362 kg ha^{-1} for K. The values were slightly higher than in Moso bamboo forests (N: 274 kg ha^{-1}, P: 17 kg ha^{-1}, K: 289 kg ha^{-1}) in China [19]. In addition, the C stocks of 48,900 kg ha^{-1} in this study were within the range (48,310 kg ha^{-1}–60,580 kg ha^{-1}) observed in Moso bamboo stands of the subtropical region in China [20].

Table 4. Nutrient stocks of bamboo components in a Moso bamboo stand (n = 3).

Part	Bamboo Component	Treatment	Nutrient Stock (kg ha^{-1})					
			C	N	P	K	Ca	Mg
Aboveground	Culms	Fertilized	20,810.5 (2406.7)	167.7 (20.0)	43.3 (5.1)	510.4 (61.7)	6.4 (0.7)	9.8 (1.2)
		Unfertilized	39,851.3 (2936.1)	176.1 (14.3)	18.7 (1.4)	243.5 (17.5)	7.8 (0.6)	18.3 (1.3)
		p-Value	**<0.01**	0.75	**<0.01**	**0.01**	0.22	**<0.01**
	Branches	Fertilized	3783.1 (380.0)	26.4 (2.5)	6.4 (0.6)	29.0 (2.7)	0.9 (0.1)	1.9 (0.2)
		Unfertilized	6371.6 (429.0)	36.0 (2.8)	4.8 (0.4)	55.6 (3.3)	1.0 (0.1)	3.1 (0.2)
		p-Value	**0.01**	0.06	0.09	**<0.01**	0.56	**0.01**
	Leaves	Fertilized	1738.0 (185.3)	103.7 (10.9)	7.2 (0.8)	52.4 (5.3)	13.8 (1.4)	5.2 (0.5)
		Unfertilized	2947.6 (253.1)	131.6 (11.6)	7.4 (0.6)	62.7 (4.5)	26.3 (2.6)	6.8 (0.6)
		p-Value	**0.02**	0.16	0.88	0.22	**0.01**	0.10
	Total	Fertilized	26,331.6 (2971.7)	297.9 (33.4)	56.8 (6.5)	591.8 (69.7)	21.2 (2.2)	16.9 (1.8)
		Unfertilized	48,900.4 (3616.6)	343.6 (28.7)	30.8 (2.3)	361.8 (25.3)	35.1 (3.1)	28.3 (2.0)
		p-Value	**<0.01**	0.36	0.02	**0.04**	**0.02**	**0.01**
Belowground	Roots	Fertilized	1010.7 (207.1)	12.2 (3.0)	1.7 (0.8)	14.7 (2.7)	1.0 (0.3)	1.9 (0.4)
		Unfertilized	4140.4 (444.4)	46.6 (10.0)	1.3 (0.5)	39.8 (2.8)	6.1 (0.5)	14.9 (0.9)
		p-Value	**<0.01**	**0.03**	0.63	**<0.01**	**<0.01**	**<0.01**
	Rhizomes	Fertilized	1418.9 (294.9)	13.0 (4.1)	4.3 (1.6)	16.8 (6.8)	0.8 (0.3)	1.0 (0.3)
		Unfertilized	3258.3 (2160.7)	25.5 (18.2)	2.1 (1.5)	27.9 (18.0)	2.2 (1.8)	5.6 (4.6)
		p-Value	0.45	0.54	0.37	0.60	0.48	0.37

Values in parenthesis are standard error. Bold values denote significance at $p < 0.05$.

Nutrient stocks in roots were significantly higher in the unfertilized plots than those in the fertilized plots, except for the P stocks of roots, whereas the nutrient stocks in rhizomes were not affected by regular fertilization (Table 4). Although the mean N, P, and K concentrations of belowground roots and rhizomes in fertilized plots were much higher than those of unfertilized plots, the nutrient stocks of roots were significantly higher in the unfertilized plots than those in the fertilized plots. This result could be attributed to the greater root production (i.e., C stocks in roots) in the higher culm density of the unfertilized plot compared to the lower culm density of the fertilized plot. Additionally, bamboo in unfertilized plots are able to invest relatively more C allocation in roots to take up more nutrients under poor nutrient conditions and less in branches or leaves [32], suggesting that C partitioning to bamboo components is regulated by the nutrient availability. For example, in this study, the proportion of crown C stocks to total aboveground C stocks was slightly higher in the fertilized (branches: 14.4%, leaves: 6.6%) plots than that in the unfertilized (branches: 13.0%, leaves: 6.0%) plots.

4. Conclusions

This study examined the nutrient distribution patterns of Moso bamboo components (aboveground: leaves, branches, culms; belowground: roots, rhizomes) in response to regular fertilization. The N, P, and K concentrations of aboveground bamboo components were increased by regular fertilization, whereas the nutrient stocks of belowground roots except for P stocks were significantly greater in nutrient-deficient conditions compared with those of bamboo grown in better nutrient conditions via fertilization. It can be inferred that the nutrient concentrations and stocks of those bamboo components were mainly governed by nutrient availability, which can be managed easily through fertilization. Thus, the measurement of nutrient concentrations following fertilization is strongly recommended for the evaluation of nutrient stocks in order to maintain the productivity of bamboo stands. These results suggest that regular fertilization is a valuable nutrient management practice to sustain the productivity of bamboo shoots and culms because fertilizer practices alter the nutrient allocation patterns in aboveground and belowground bamboo components in a Moso bamboo stand.

Author Contributions: C.K. and G.B. designed and conducted the field trial, analyzed data, and wrote the manuscript. B.O.Y., S.-Y.J. and K.S.L. helped with funding acquisition and data analysis.

Funding: This work was partially supported by a grant of the National Institute of Forest Science (2016) and by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2017R1D1A3B03029826).

Acknowledgments: We gratefully thank two anonymous reviewers for providing valuable comments on the manuscript.

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

Appendix A.

Table A1. Allometric equations ($\log_{10}Y = a + b \times \log_{10}DBH$) to estimate nutrient content of a Moso bamboo. DBH (cm). Bold values denote significance at $p < 0.05$.

Treatment	Nutrient (Y, g)	Bamboo Component	Regression Coefficient		r^2	p-Value
			a	b		
Fertilized ($n = 10$)	Carbon	Culm	0.9625	2.6188	0.71	**0.0021**
		Branch	1.3693	1.5106	0.61	**0.0074**
		Leaf	0.5548	1.9725	0.49	**0.0242**
		Total	1.3294	2.3679	0.70	**0.0026**
	Nitrogen	Culm	−1.4140	2.8903	0.70	**0.0027**
		Branch	−0.2927	1.0293	0.55	**0.0145**
		Leaf	−0.5651	1.8717	0.52	**0.0193**
		Total	−0.4568	2.2326	0.81	**0.0004**
	Phosphorus	Culm	−1.9100	2.8015	0.73	**0.0016**
		Branch	−0.7133	0.8399	0.46	**0.0323**
		Leaf	−1.8775	2.0203	0.66	**0.0042**
		Total	−1.3794	2.4172	0.78	**0.0007**
	Potassium	Culm	−1.0276	2.9832	0.88	**<0.0001**
		Branch	0.1173	0.8972	0.16	0.2461
		Leaf	−0.5822	1.6010	0.45	**0.0346**
		Total	−0.5008	2.5651	0.90	**<0.0001**
	Calcium	Culm	−2.4260	2.5019	0.48	**0.0270**
		Branch	−1.8901	1.1857	0.25	0.1397
		Leaf	−1.0544	1.4982	0.09	0.4106
		Total	−1.0032	1.6494	0.14	0.2811
	Magnesium	Culm	−2.4380	2.6881	0.67	**0.0037**
		Branch	−1.9000	1.4823	0.61	**0.0077**
		Leaf	−1.3545	1.3770	0.35	0.0733
		Total	−1.5660	2.0895	0.62	**0.0067**

Table A1. *Cont.*

Treatment	Nutrient (Y, g)	Bamboo Component	Regression Coefficient		r^2	*p*-Value
			a	b		
Unfertilized (n = 10)	Carbon	Culm	1.9574	1.7762	0.85	**0.0002**
		Branch	1.5492	1.3988	0.71	**0.0022**
		Leaf	0.1814	2.4027	0.69	**0.0031**
		Total	2.0680	1.7604	0.85	**0.0002**
	Nitrogen	Culm	−0.7733	2.1422	0.63	**0.0063**
		Branch	−1.3282	2.0120	0.76	**0.0010**
		Leaf	−1.3116	2.5406	0.68	**0.0034**
		Total	−0.6070	2.2745	0.72	**0.0019**
	Phosphorus	Culm	−1.3110	1.7178	0.45	**0.0348**
		Branch	−2.0073	1.8216	0.54	**0.0152**
		Leaf	−2.2409	2.2278	0.60	**0.0084**
		Total	−1.1065	1.7459	0.58	**0.0105**
	Potassium	Culm	−0.1370	1.6607	0.35	0.0701
		Branch	−0.0608	0.9591	0.13	0.3016
		Leaf	−0.7150	1.6399	0.34	0.0744
		Total	0.1877	1.5243	0.35	0.0702
	Calcium	Culm	−1.6439	1.6714	0.29	0.1048
		Branch	−1.6183	0.7783	0.09	0.3959
		Leaf	−2.4853	2.9499	0.43	**0.0381**
		Total	−1.8777	2.5137	0.40	0.0515
	Magnesium	Culm	−1.0697	1.4745	0.26	0.1339
		Branch	−1.6570	1.2979	0.63	**0.0063**
		Leaf	−2.3823	2.3328	0.65	**0.0050**
		Total	−0.9404	1.5479	0.40	0.0502

References

1. Nath, A.J.; Lal, R.; Das, A.K. Managing woody bamboos for carbon farming and carbon trading. *Glob. Ecol. Conserv.* **2015**, *3*, 654–663. [CrossRef]
2. Kleinhenz, V.; Midmore, D.J. Aspects of bamboo agronomy. *Adv. Agron.* **2001**, *74*, 99–145. [CrossRef]
3. Kleinenz, V.; Milne, J.; Walsh, K.B.; Midmore, D.J. A case study on the effects of irrigation and fertilization on soil water and soil nutrient status, and on growth and yield of bamboo (*Phyllostachys pubescens*) shoots. *J. Bamboo Rattan* **2003**, *2*, 281–294. [CrossRef]
4. Lee, K.S.; Jung, S.Y.; Yoo, B.O.; Park, J.H.; Kim, C.; Ju, N.G. Biomass estimation for Moso bamboo (*Phyllostachys pubescens*) stands and Henon bamboo (*Phyllostachys nigra*) stands in southern Korea. *J. Agric. Life Sci.* **2014**, *48*, 109–118. [CrossRef]
5. Zhang, Q.; Wang, J.; Wang, G.; Shamsi, I.H.; Wang, X. Site-specific nutrient management in a bamboo forest in Southeast China. *Agric. Ecosyst. Environ.* **2014**, *197*, 264–270. [CrossRef]
6. Korea Forest Research Institute. *Encyclopedia of Bamboos in Korea*; New Research Report 7; Ukgo Publishing: Seoul, Korea, 2005; p. 203.
7. Jeong, J.S.; Kwon, Y.H.; Lee, W.K. Effect of organic fertilizer in *Phyllostarchys pubecens*. *FRI. J. For. Sci.* **1995**, *51*, 59–63.
8. Gao, P.; Zuo, Z.; Zhang, R.; Qiu, Y.; He, R.; Gao, R.; Gui, R. Optimum nitrogen fertilization for *Phyllostachys edulis* productivity and photosynthetic response. *Agron. J.* **2016**, *108*, 448–458. [CrossRef]
9. Yoo, B.O.; Park, J.H.; Park, Y.B.; Jung, S.Y.; Lee, K.S.; Kim, C. Assessment of expansion characteristics and classification of distribution types for bamboo forests using GIS. *J. Korean Assoc. Geogr. Inf. Stud.* **2017**, *20*, 55–64. [CrossRef]
10. Tang, X.; Xia, M.; Guen, F.; Fan, S. Spatial distribution of soil nitrogen, phosphorus and potassium stocks in Moso bamboo forests in subtropical China. *Forests* **2016**, *7*, 267. [CrossRef]
11. Korea Forest Research Institute. *The Forest Soil Profiles in Korea*; Ukgo Publishing: Seoul, Korea, 2005; p. 143.

12. Wu, J.; Xu, Q.; Jiang, P.; Cao, Z. Dynamics and distribution of nutrition elements in bamboo. *J. Plant Nutr.* **2009**, *32*, 489–501. [CrossRef]
13. Hwang, J.H.; Chung, Y.G.; Lee, S.T.; Kim, B.B.; Shin, H.C.; Lee, K.J.; Park, K.J. Estimation of aboveground biomass and belowground nutrient contents for a *Phyllostachys pubescens* stand. *J. Korean For. Soc.* **2005**, *94*, 161–167.
14. Fukushima, K.; Usus, N.; Ogawa, R.; Tokuchi, N. Impacts of Moso bamboo (*Phyllostachys pubescens*) invasion on dry matter and carbon and nitrogen stocks in a broad-leaved secondary forest located in Kyoto, western Japan. *Plant Spec. Biol.* **2015**, *30*, 8–95. [CrossRef]
15. Kalra, Y.P.; Maynard, D.G. *Methods Manual for Forest Soil and Plant Analysis. Northwest Region, Information Report. NOR-X-319*; Northern Forestry Centre: Edmonton, AB, Canada, 1991; p. 115.
16. SAS Institute Inc. *SAS/STAT Statistical Software*; Version 9.1; SAS Publishing: Cary, NC, USA, 2003.
17. Xu, L.; Shi, Y.; Zhou, G.; Xu, X.; Liu, E.; Zhou, Y.; Zhang, F.; Li, C.; Fang, H.; Chen, L. Structural development and carbon dynamics of Moso bamboo forests in Zhejing province, China. *For. Ecol. Manag.* **2018**, *409*, 479–488. [CrossRef]
18. Piouceau, J.; Bois, G.; Panfili, F.; Anastase, M.; Dufossé, L.; Arfi, V. Effects of high nutrient supply on the growth of seven bamboo species. *Int. J. Phytoremediat.* **2014**, *16*, 1042–1057. [CrossRef] [PubMed]
19. Li, R.; Werger, M.J.A.; During, H.J.; Zhong, Z.C. Carbon and nutrient dynamics in relation to growth rhythm in the giant bamboo *Phyllostachys pubescens*. *Plant Soil* **1998**, *201*, 113–123. [CrossRef]
20. Xu, M.; Ji, H.; Zhuang, S. Carbon stock of Moso bamboo (*Phyllostachys pubescens*) forests along a latitude gradient in the subtropical region of China. *PLoS ONE* **2018**, *13*, e0193024. [CrossRef] [PubMed]
21. Jeong, J.; Jo, C.G.; Baek, G.W.; Park, J.H.; Ma, H.S.; Yoo, B.O.; Kim, C. Soil and the foliage nutrient status following soil amendment applications in a Japanese cypress (*Camaecyparis obtusa* Endlicher) plantation. *J. Sustain. For.* **2017**, *36*, 289–303. [CrossRef]
22. Kim, C.; Jeong, J.; Park, J.H.; Ma, H.S. Growth and nutrient status of foliage as affected by tree species and fertilization in a fire-disturbed urban forest. *Forests* **2015**, *6*, 2199–2233. [CrossRef]
23. Peri, P.L.; Grgalione, V.; Pastur, G.M.; Lencinas, M.V. Carbon accumulation along a stand development sequence of Northofagus Antarctica forests across a gradient in site quality in Southern Patagonia. *For. Ecol. Manag.* **2010**, *260*, 229–237. [CrossRef]
24. Isagi, Y. Carbon stock and cycling in a bamboo *Phyllostachys bambusoides* stand. *Ecol. Res.* **1994**, *9*, 47–55. [CrossRef]
25. Thomas, S.C.; Malczewski, G. Wood carbon content of tree species in Eastern China: Interspecific variability and the importance of the volatile fraction. *J. Environ. Manag.* **2007**, *85*, 659–662. [CrossRef] [PubMed]
26. Li, R.; Werger, M.J.A.; de Kroon, H.; During, H.J.; Zhong, Z.C. Interactions between shoot age structure, nutrient availability and physiological integration in the giant bamboo *Phyllostachys pubescens*. *Plant Biol.* **2000**, *2*, 437–446. [CrossRef]
27. Tu, L.H.; Hu, T.X.; Zhang, J.; Li, R.H.; Dai, H.Z.; Luo, S.H. Short-term stimulated nitrogen deposition increases carbon sequestration in *Pleioblastus amarus* plantation. *Plant Soil* **2011**, *340*, 383–396. [CrossRef]
28. Watanabe, T.; Fukuzawa, K.; Shibata, H. Short-term response of Sasa dwarf bamboo to a change of soil nitrogen fertility in a forest ecosystem in northern Hokkaido, Japan. *Plants* **2016**, *5*, 19. [CrossRef] [PubMed]
29. Jeong, J.; Kim, C. Growth response of container-grown red pine and black pine seedlings at different types of fertilization. *For. Sci. Tech.* **2011**, *7*, 126–133. [CrossRef]
30. Augusto, L.; Bakker, M.R.; De LavaIssière, C.; Jordan-Meille, L.; Saur, E. Estimation of nutrient content of woody plants using allometric relationships: Quantifying the difference between concentration values from the literature and actuals. *Forestry* **2009**, *82*, 463–477. [CrossRef]
31. Diem, B.; Godbold, D.L. Potassium, calcium and magnesium antagonism in clones of *Populus trichocarpa*. *Plant Soil* **1993**, *155/156*, 411–414. [CrossRef]
32. Poorter, H.; Niklas, K.J.; Reich, P.B.; Oleksyn, J.; Poot, P.; Mommer, L. Biomass allocation to leaves, stems and roots: Meta-analyses of interspecific variation and environmental control. *New Phytol.* **2012**, *193*, 30–50. [CrossRef] [PubMed]