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Growth and Tissue Nutrient Responses of *Fraxinus rhynchophylla*, *Fraxinus mandshurica*, *Pinus koraiensis*, and *Abies holophylla* Seedlings Fertilized with Nitrogen, Phosphorus, and Potassium

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Abstract : Fertilization increases the crop productivity and produces high quality seedlings for plantation. We quantitatively measured both physical performances and nutrient responses of *Fraxinus rhynchophylla*, *Fraxinus mandshurica*, *Pinus koraiensis*, and *Abies holophylla* seedlings, which are commercially planted species in Korea, to nitrogen, phosphorus, and potassium fertilization. We analyzed the growth performances by using Dickson's quality index (QI) and the nutrient status by using vector diagnosis. Nitrogen or phosphorus treatment increased height and root collar diameter growth of *F. rhynchophylla* and *F. mandshurica*, however, did not increase those of *P. koraiensis* and *A. holophylla*. The order of QI was N > P > K > control for *F. rhynchophylla*, P ≥ N > Control ≥ P for *F. mandshurica*, P > Control ≥ K > N for *P. koraiensis* and *A. holophylla*. In *F. rhynchophylla*, fertilization diluted N concentration in tissues by 5-25% because growth responses were higher than fertilization uptake. *P. koraiensis* and *A. holophylla* showed N excess showing "toxic accumulation". *F. rhynchophylla* and *F. mandshurica* showed P deficiency with P fertilization, however, *P. koraiensis* and *A. holophylla* showed "luxury accumulation". Vector diagnosis indicated that more fertilization was applicable for *F. rhynchophylla* and *F. mandshurica*, and high fertilization rates were inefficient for *P. koraiensis* and *A. holophylla*. Both QI and vector diagnosis can be applied to verify seedling quality in the light of growth responses and nutrient status in fertilization trials.

Key words **:** *Dickson's quality index, fertilization, nursery culture, vector diagnosis*

Introduction

Commercial fertilizer has been applied on tree seedling production in nursery culture (Timmer, 1996; Son *et al.*, 1998; Shin *et al.,* 1999; Jacobs and Timmer, 2005). Fertilization is the tool to increase the crop productivity and to improve seedling quality for forest plantation. The benefits of fertilization during nursery culture are 1) to increase nutrient storage, 2) to enhance seedling growth, 3) to increase resistance to drought stress, freezing temperature, and disease, 4) to reduce seedling transplant shock, and 5) to improve initial survival rate and seedling outplanting performance (Carlson, 1981; Imo and Timmer, 1999; Quoreshi and Timmer, 2000).

Morphological and physiological characteristics of seedlings are related with high survival rate and growth performance and are important for successful plantation establishment. Seedling quality depends on several factors such as seedling dimensions (height, diameter), seedling weights (shoot, root, and whole seedling), indices (height to diameter ratio, root to shoot ratio, and Dickson's quality index), and seedlings physiological characteristics (vigor, nutrient balance, and photosynthetic capacity) (Timmer, 1996; Davis and Jacobs, 2005; Bayala *et al.,* 2009).

Although we know the improvement in the growth and nutrient status is evident after fertilization, we have only limited quantitative and statistical understood in both physical performances and nutrient responses. We used vector diagnosis, which is traditionally used to assess the relationship between plant growth and nutrient status to investigate the seedling responses to nutrient supply (Timmer and Stone, 1978; Imo and Timmer, 1999; Quoreshi and Timmer, 2000). This approach offers

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a simplified interpretation of complex interactions between plant nutrient concentration, content, and mass. Dickson's quality index, which is one of the most appropriate indicators to predict early field performance, was also used to verify seedling quality (Bayala *et al.,* 2009). The index is a combination of seedling dry weight, shoot to root dry weight ratio, and sturdiness quotient.

The objective of this study was to measure the responses of *Fraxinus rhynchophylla*, *F. mandshurica*, *Pinus koraiensis*, and *Abies holophylla* seedlings, which are commercially planted species in Korea, to nitrogen, phosphorus, and potassium fertilization. We analyzed growth performances and nutrient status of tree seedlings after fertilization by using Dickson's quality index and vector diagnosis.

Materials and Methods

1. Study sites and species

This study was conducted in the Forest Practice Research Center (37° 45' E and 127° 09' W) located in Pochoen, Gyeonggi Province. The average temperature is 11.3°C, and annual precipitation is 1,365 mm (Kang *et al*., 2007).

F. rhynchophylla and *A. holophylla* seedlings were raised in the Yongmoon National Nursery Station located in Yangpyeong county, Gyeonggi Province. *F. mandshurica* seedlings were raised in the Pyeongchang National Nursery Station located in Pyeongchang county and *P. koraiensis* seedlings were raised in a commercial nursery located in Yanggu county, Gangwon Province. *F. rhynchophylla* and *F. mandshurica* were sown in spring 2006. *P. koraiensis* were sown in spring 2005 and *A. holophylla* were sown in spring 2004 and 2 year-old seedlings were transplanted in 2006.

2. Experimental treatments

Similar height and root collar diameter (rcD) seedlings were planted at 30 L-plastic pots in April, 2007. Each pot had 5 cm depth gravels in the bottom and filled with soils. We randomly collected three samples to analyze soil chemical and physical properties. The soil analysis methods were the same as below. The soil was sandy and neutral in pH (Table 1). It had low organic matter and infertile in most nutrients.

We applied four treatments including no treatment as a control after four weeks planting (Table 2). We dug a gully with 3 cm in depth and 3 cm in width around the seedling and then the fertilizer was manually spread. Nitrogen was applied as urea ($CO(NH_2)_2$) at 3.0 g tree^{-1}, phosphorus as soluble superphosphate at 6.9 g tree^{-1}, and potassium as potassium chloride (KCl) at 1.4 g tree^{-1}. We randomly distributed all treatments with 15 replicates. Total number of pots was 240 (4 species×4 treatments ×15 replicates).

Table 1. Soil texture and chemical characteristics of the pot soil before fertilizer application. Total N is the sum of organic N and inorganic N. Available P and CEC represent $H_2PO_4^-$ and cation exchange capacity, respectively. Parenthesis is standard error (n = 3).

Texture	
Sand (%)	88.3 (0.4)
Silt (%)	5.5 (0.5)
Clay (%)	6.2 (0.1)
Chemical properties	
pH	7.0 (0.1)
Organic matter (%)	0.11 (0.01)
Total N (g kg^{-1})	0.19 (0.00)
Available P (mg kg^{-1})	15.7 (1.9)
Exchangeable K^+ ($cmol_c$ kg^{-1})	0.23 (0.01)
Exchangeable Ca^{2+} ($cmol_c$ kg^{-1})	2.5 (0.2)
Exchangeable Mg^{2+} ($cmol_c$ kg^{-1})	0.56 (0.04)
Exchangeable Na^+ ($cmol_c$ kg^{-1})	0.23 (0.01)
CEC ($cmol_c$ kg^{-1})	4.1 (0.4)

Table 2. Properties of applied fertilizer.

Treatments	Applied amount (g tree^{-1})
Control	0
N	N 1.4
P	P 0.6
K	K 0.7

One liter water was applied in each pot every two days. We removed all herbaceous plants in the pots during experiment. Initial height and rcD were measured on two weeks after planting. rcD were measured at 1 cm above the ground, which were marked with a white paint to measure the same position repeatedly.

3. Growth measurements

Height and rcD were measured on twenty weeks after the fertilization treatment. After measuring height and rcD, we randomly harvested six pots out of 15 ones for each treatment to measure biomass. Roots were cautiously excavated from the pots not to damage roots. Roots were washed with tap water several times to remove soil particles from the root surface. We separated harvested seedlings into foliage, stem, and roots. Unfortunately, we could not collect foliages of *F. rhynchophylla* and *F. mandshurica* because of abrupt freezing leaf fall. The divided tissues were oven dried at 65°C for one week and weighed.

4. Soil and plant analysis

Soil samples were collected before excavating seedlings from the pots. One hundred g soil from each pot was collected at 0-10 cm in depth and six samples per treatment were pooled to make one sample. All soil samples were kept in cool temperature until the analysis.

Soil texture was measured by hydrometer method at 30ºC and organic matter amount were measured by Tyurin method. Soil acidity (pH) was analyzed by 10 g soil mixing with distilled water with 1:5 ratio. Total nitrogen was analyzed by Micro – Kjeldahl method with 1 g soil. Available phosphorus (P_2O_5) was measured by Lancaster method. Exchangeable K^+, Ca^{2+}, and Mg^{2+} were determined in 1 N NH_4OAc extracts with Atomic Absorption Spectrometer (AA280FS, USA). CEC was determined in 1 N HN_4OAc and 1 N CH_3COOH extracts by Brown method.

We pooled two seedlings by tissue to produce one sample per tissue. Oven-dried tissues were ground in a Wiley mill to pass 1 mm screen. Concentrations of N, P, and K were determined. Block digester (BD-46, Lachat Ins., USA) with combination of H_2SO_4 and $HClO_4$ was used to digest organic matter. Total N and total P were determined by Automated Ion Analyzer (Quik Chem AE, Lachat Ins., USA) and K by Atomic Absorption Spectrometer (AA280FS, USA).

5. Dickson's quality index and vector analysis

Dickson's quality index (Deans *et al*., 1989; Bayala *et al*., 2009) was calculated as follows: Quality index = SD/(HD+SR), where SD is seedling dry weight (g), HD is height (cm) to rcD ratio (mm), and SR is shoot dry weight (g) to root dry weight (g).

We used vector analysis (Haase and Rose, 1995; Timmer, 1996) to interpret changes in nutrient status in response to nutrient additions (N, P, and K) in the four species (Table 3, Figure 1). Nutrient deficiency is indicated when plant nutrient concentrations increase but not as much as mass and content (vector C). At optimal nutrition, concentrations remain constant while mass and content increase (vector B). Luxury consumption means that concentrations increase without changing mass (vector D). Toxicity is indicated if mass decreases (E, F). Dilution (vector A) is most likely when growth limitation has been relieved by another element. Because we didn't collect foliage samples from *F. rhynchophylla* and *F. mandshurica*, we used mass-weighted nutrient concentrations for relative concentrations.

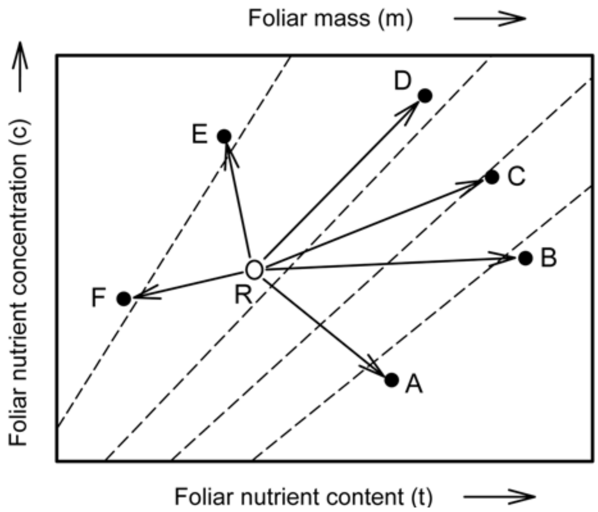

Figure 1. Vector interpretations of directional changes in relative dry mass (m), nutrient content (t), and nutrient concentration (c) of plants grown at different fertilizer applications. Vector length reflects the magnitude of differences among individual plant parameters (modified from Timmer and Stone, 1978; Salifu and Timmer, 2003). See table 3 for more vector interpretations.

6. Statistic analyses

We did not compare soil organic matter, pH, total N, available P, extractable K^+, Ca^{2+}, Mg^{2+}, and CEC concentrations among treatments because only one sample were collected from each treatment. Analysis of variance (ANOVA) with Duncan's multiple comparison tests was applied to test the effects of fertilization treatment and species on seedling height and rcD growth, biomass, and nutrient status. All probabilities were tested at the significant level at 0.05.

Table 3. The interpretation for vector analysis. The reference status (R) is usually normalized to 100. Vector shifts (A to F) indicate an increase (+), decrease (–) or no change (0) in dry mass and nutrient status relative to the reference status (Timmer, 1996).

Vector shift	Change in relative			Interpretation	Diagnosis
	mass	concentration	content		
A	+	–	+	Dilution	Growth dilution
B	+	0	+	Sufficiency	Steady state
C	+	+	+	Deficiency	Deficiency
D	0	+	+	Luxury	Accumulation
E	–	–, +	–	Excess	Toxic accumulation
F	–	–	–	Excess	Antagonism

Results and Discussion

1. Soil chemical properties

We could not analyze the change of soil properties before and after treatments and compare among treatments because of one sample per treatment, but cautiously say the patterns as below. Soil pH was not changed by treatments in *F. rhynchophylla* and *F. mandshurica*, but fertilization treatment reduced pH in *P. koraiensis* (Table 4). In *A. holophylla*, soil pH was reduced in all treatments including the reference after fertilization. Total nitrogen and exchangeable Ca^{2+}, Mg^{2+}, Na^{+}, and CEC in soil were not influenced by species and fertilization treatments. Available P was the highest in P treatment and exchangeable K^{+} was higher in K treated pots than others.

Because nutrient uptake rate and amount depend on species and soil properties (Ingestad and Ågren, 1995; Brady and Weil, 2002; Marschner, 2002), a understanding of the mechanisms by fertilization and species is needed to optimize seedling performances to fertilization (Jacobs and Timmer, 2005). Applied fertilizer is released into soil solution as ions, which are uptaken by roots or attached soil particles or leached out. Trees can uptake both NH_4^+ and NO_3^- forms for nitrogen source. If trees uptake NO_3^- over NH_4^+ and release of OH^- from the root, soil pH is subsequently raised (Neumann and Romheld, 2001; Brady and Weil, 2002). In contrast, trees uptake NH_4^+ over NO_3^-, which leads to release H^+ and results in soil acidification.

Table 4. Soil characteristics after fertilizer application and planting seedlings for 20 weeks.

	Species	Treatments			
		Control	N	P	K
pH	*Fraxinus rhynchophylla*	7.2	6.9	6.9	7.1
	Fraxinus mandshurica	6.5	7.1	7.1	7.2
	Pinus koraiensis	7.0	6.0	6.1	6.0
	Abies holophylla	6.3	6.2	6.1	6.2
Total N ($g\ kg^{-1}$)	*Fraxinus rhynchophylla*	0.2	0.2	0.3	0.2
	Fraxinus mandshurica	0.2	0.3	0.2	0.3
	Pinus koraiensis	0.2	0.2	0.2	0.2
	Abies holophylla	0.2	0.4	0.3	0.2
Available P ($mg\ kg^{-1}$)	*Fraxinus rhynchophylla*	21.1	26.6	75.2	11.0
	Fraxinus mandshurica	12.8	10.1	53.2	11.0
	Pinus koraiensis	11.9	10.1	44.0	11.0
	Abies holophylla	11.0	14.7	97.2	11.9
Exchangeable K ($cmol_c\ kg^{-1}$)	*Fraxinus rhynchophylla*	0.12	0.16	0.14	0.18
	Fraxinus mandshurica	0.12	0.12	0.11	0.15
	Pinus koraiensis	0.12	0.15	0.10	0.16
	Abies holophylla	0.13	0.11	0.11	0.15
Exchangeable Ca ($cmol_c\ kg^{-1}$)	*Fraxinus rhynchophylla*	1.9	1.8	1.9	1.7
	Fraxinus mandshurica	2.1	1.7	2.0	1.8
	Pinus koraiensis	2.0	2.2	2.4	2.2
	Abies holophylla	2.5	2.0	1.9	2.0
Exchangeable Mg ($cmol_c\ kg^{-1}$)	*Fraxinus rhynchophylla*	0.29	0.29	0.35	0.25
	Fraxinus mandshurica	0.27	0.24	0.35	0.28
	Pinus koraiensis	0.26	0.32	0.39	0.29
	Abies holophylla	0.34	0.28	0.38	0.29
Exchangeable Na ($cmol_c\ kg^{-1}$)	*Fraxinus rhynchophylla*	0.08	0.08	0.08	0.07
	Fraxinus mandshurica	0.08	0.09	0.09	0.07
	Pinus koraiensis	0.07	0.08	0.08	0.08
	Abies holophylla	0.07	0.07	0.08	0.08
CEC ($cmol_c\ kg^{-1}$)	*Fraxinus rhynchophylla*	0.9	0.7	0.7	0.7
	Fraxinus mandshurica	1.3	0.9	0.9	0.7
	Pinus koraiensis	1.3	0.4	0.7	1.5
	Abies holophylla	1.8	1.8	1.8	0.7

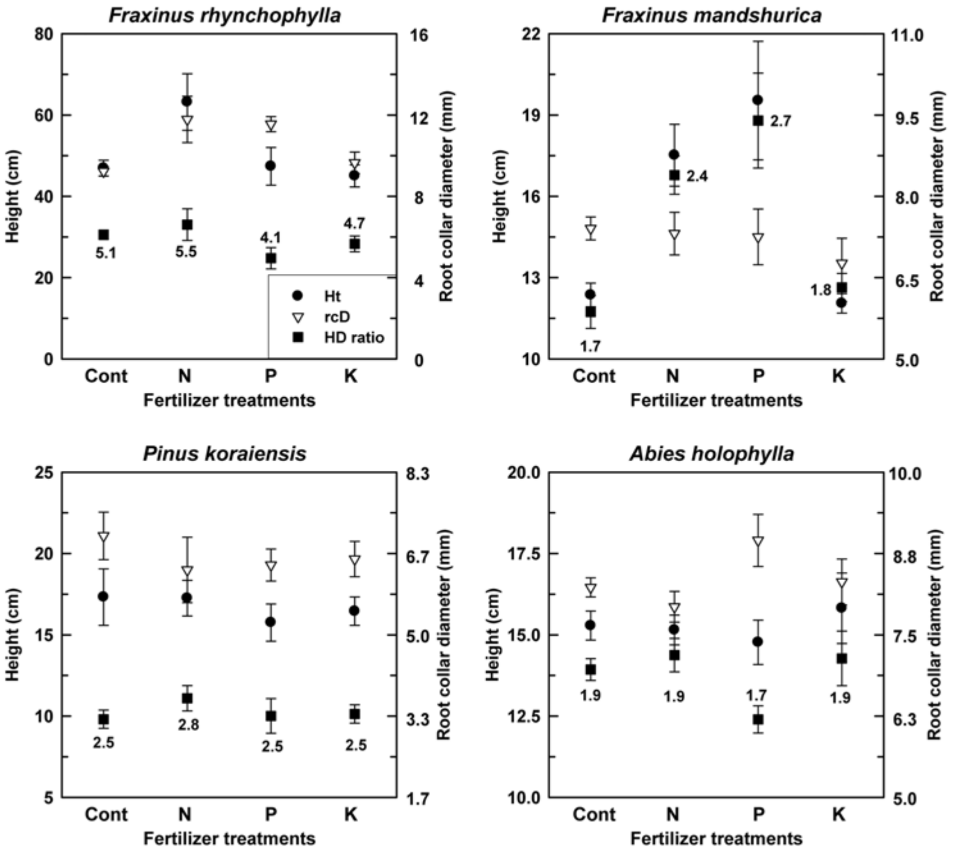

Figure 2. Height, root collar diameter (rcD), and height to rcD ratio (HD ratio) after fertilizer application.

2. Growth responses

Nitrogen treatment reduced the survival rate by 77% only in *P. koraiensis*, but did not affect in other species. N treatment increased height growth in *F. rhynchophylla* and *F. mandshurica*, however, did not in *P. koraiensis* and *A. holophylla* (Figure 2). The patterns of rcD growth after N fertilization were similar to those of height growth.

In *F. rhynchophylla*, stem and root biomass were the highest in N treatment (Figure 3). In *F. mandshurica*, P treatment increased stem and root biomass. However, N treatment significantly reduced total biomass of *P. koraiensis* and *A. holophylla* (Figure 3). Nitrogen fertilization of 1.4 g per seedling seems to be excess for the seedlings of *P. koraiensis* and *A. holophylla* resulting in biomass reduction and N toxic accumulation (Table 5, Figure 4). Similar results were reported in coniferous species as the growth of white spruce (*Picea glauca*) seedlings fertilized with ammonium nitrate was decreased due to soil acidity and Al toxicity (Teng and Timmer, 1995) and fertilization with high levels of ammonium-based fertilizer decreased root biomass and root length of Douglas-fir (*Pseudotsuga menziesii*) seedlings (Olsthoorn *et al*., 1991; De Visser and Keltjens, 1993). Because *P. koraiensis* and *A. holophylla* have fixed growth form, these may use nutrients inside the body (or tiny nutrients

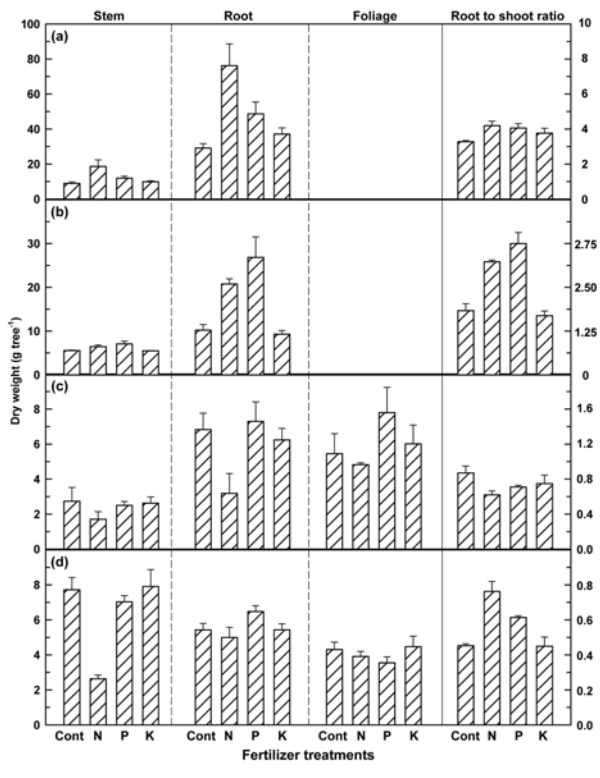

Figure 3. Foliage, stem, root dry weight, and root to shoot ratio after fertilizer application. (a) *Fraxinus rhynchophylla*, (b) *Fraxinus mandshurica*, (c) *Pinus koraiensis*, and (d) *Abies holophylla*.

Table 5. Mean dry weight, height to root collar diameter ratio, shoot to root ratio, and Dickson's quality index of *Fraxinus rhynchophylla*, *Fraxinus mandshurica*, *Pinus koraiensis*, and *Abies holophylla*.

Species	Treatments	Total dry weight (g tree^{-1})	HT to rcD ratio (cm mm^{-1})	Shoot to root ratio (g g^{-1})	Quality index
Fraxinus rhynchophylla	Control	38.0	5.09	0.31	7.0
	N	94.8	5.51	0.24	16.5
	P	60.6	4.13	0.25	13.8
	K	46.9	4.72	0.27	9.4
Fraxinus mandshurica	Control	15.8	1.68	0.55	7.1
	N	27.2	2.40	0.31	10.0
	P	33.9	2.69	0.27	11.5
	K	14.8	1.81	0.59	6.2
Pinus koraiensis	Control	15.0	2.45	1.15	4.2
	N	11.3	2.77	1.62	2.6
	P	17.6	2.50	1.41	4.5
	K	14.9	2.53	1.34	3.8
Abies holophylla	Control	17.4	1.86	2.21	4.3
	N	11.5	1.92	1.31	3.6
	P	17.0	1.65	1.63	5.2
	K	17.8	1.90	2.23	4.3

Table 6. Tissue nutrient concentrations (g kg^{-1}) after fertilizer application (n=3). Foliage nutrient concentrations of *F. rhynchophylla* and *F. mandshurica* were not available because of abrupt freezing leaf fall. Different letters represent significant differences between treatments at *P* = 0.05.

Elements	Species	Treatments			
		Control	N	P	K
Foliage					
N	*Pinus koraiensis*	6.50 (0.30)	6.69 (0.21)	7.47 (0.26)	6.52 (0.15)
	Abies holophylla	8.10 (1.94)	8.62 (0.99)	13.03 (0.67)	8.69 (1.62)
P	*Pinus koraiensis*	0.93 (0.06) b	0.90 (0.06) b	1.52 (0.18) a	0.91 (0.00) b
	Abies holophylla	0.98 (0.14) b	0.87 (0.09) b	2.20 (0.07) a	1.05 (0.32) b
K	*Pinus koraiensis*	5.14 (0.06)	5.24 (0.75)	5.61 (0.28)	6.09 (0.82)
	Abies holophylla	3.15 (0.59)	3.35 (0.24)	5.11 (0.14)	3.89 (0.72)
Branch					
N	*Fraxinus rhynchophylla*	5.79 (0.50)	5.93 (0.34)	5.33 (0.54)	4.98 (0.71)
	Fraxinus mandshurica	8.76 (0.28) ab	8.53 (0.45) ab	6.73 (0.71) b	9.68 (0.63) a
	Pinus koraiensis	3.59 (0.68)	5.82 (2.01)	4.10 (0.29)	2.60 (1.14)
	Abies holophylla	5.00 (0.89)	5.22 (0.41)	7.00 (0.20)	5.09 (0.55)
P	*Fraxinus rhynchophylla*	0.59 (0.05) b	0.61 (0.02) b	0.82 (0.07) a	0.62 (0.03) b
	Fraxinus mandshurica	1.06 (0.09)	1.03 (0.03)	1.10 (0.08)	1.03 (0.07)
	Pinus koraiensis	0.63 (0.06)	0.79 (0.21)	0.91 (0.08)	0.67 (0.06)
	Abies holophylla	0.86 (0.15) b	0.71 (0.06) b	1.43 (0.05) a	0.82 (0.16) b
K	*Fraxinus rhynchophylla*	4.01 (0.11)	4.15 (0.35)	3.30 (0.36)	4.01 (0.50)
	Fraxinus mandshurica	4.15 (0.44)	5.05 (0.23)	4.67 (0.59)	4.92 (0.16)
	Pinus koraiensis	3.02 (0.33)	2.30 (0.64)	2.97 (0.17)	3.51 (0.40)
	Abies holophylla	4.11 (0.42) ab	2.93 (0.20) b	5.17 (0.40) a	4.55 (0.53) ab
Root					
N	*Fraxinus rhynchophylla*	6.52 (0.81)	6.03 (0.30)	4.54 (0.92)	6.10 (1.64)
	Fraxinus mandshurica	8.59 (0.52)	8.75 (0.25)	8.14 (0.71)	9.56 (0.62)
	Pinus koraiensis	4.89 (0.06)	5.97 (1.04)	5.17 (0.21)	5.21 (0.21)
	Abies holophylla	6.47 (1.49)	6.30 (0.55)	6.05 (0.32)	5.22 (0.28)
P	*Fraxinus rhynchophylla*	0.77 (0.08) ab	0.70 (0.09) b	1.04 (0.07) a	0.90 (0.05) ab
	Fraxinus mandshurica	1.13 (0.22)	1.15 (0.04)	1.55 (0.07)	1.18 (0.18)
	Pinus koraiensis	0.84 (0.00) b	0.74 (0.05) b	1.42 (0.08) a	0.96 (0.08) b
	Abies holophylla	1.11 (0.36)	0.84 (0.10)	1.63 (0.08)	1.02 (0.31)
K	*Fraxinus rhynchophylla*	8.94 (0.89)	6.91 (0.73)	7.48 (0.93)	9.17 (0.54)
	Fraxinus mandshurica	12.26 (1.02)	11.18 (0.70)	12.30 (0.51)	11.26 (0.76)
	Pinus koraiensis	3.75 (0.15)	2.58 (0.89)	4.01 (0.43)	3.77 (0.25)
	Abies holophylla	4.48 (1.08)	4.44 (0.36)	5.50 (0.14)	5.34 (0.61)

from outside) rather than uptake from outside for the planting year. To identify source of nutrient is above the present study, but more researches to trace nutrient retranslocation are needed to profoundly understand seedlings performances to fertilization (Salifu and Timmer, 2003). However, N or P fertilization improves photosynthesis and hence tree growth of *F. rhynchophylla* and *F. mandshurica*, which have free growth form (Ingestad and Ågren, 1992).

The order of seedling quality index (QI) was N > P > K > control for *F. rhynchophylla*, P ≥ N > Control ≥ P for *F. mandshurica*, P > Control ≥ K > N for *P. koraiensis* and *A. holophylla* (Table 5). QI is one of the best indices to evaluate seedling quality, however, to predict future seedling performance is difficult (Bayala *et al*., 2009). In the light of QI, N or P fertilization may improve outplanting performances of *F. rhynchophylla* and *F. mandshurica*, but N fertilization may decrease those of *P. koraiensis* and *A. holophylla*. QI has two weak points: one is a relatively complex formula and the other is that seedlings should be destructed for measuring dry weight. Simple non-destructive measures should be developed as a good predictor of future outplanting performance of seedlings.

3. Vector analysis and interpretation

Total dry weight of *F. rhynchophylla* seedlings were increased 149% by N treatment, 59% by P treatment, and 23% by K treatment (Table 6). Total dry weight of

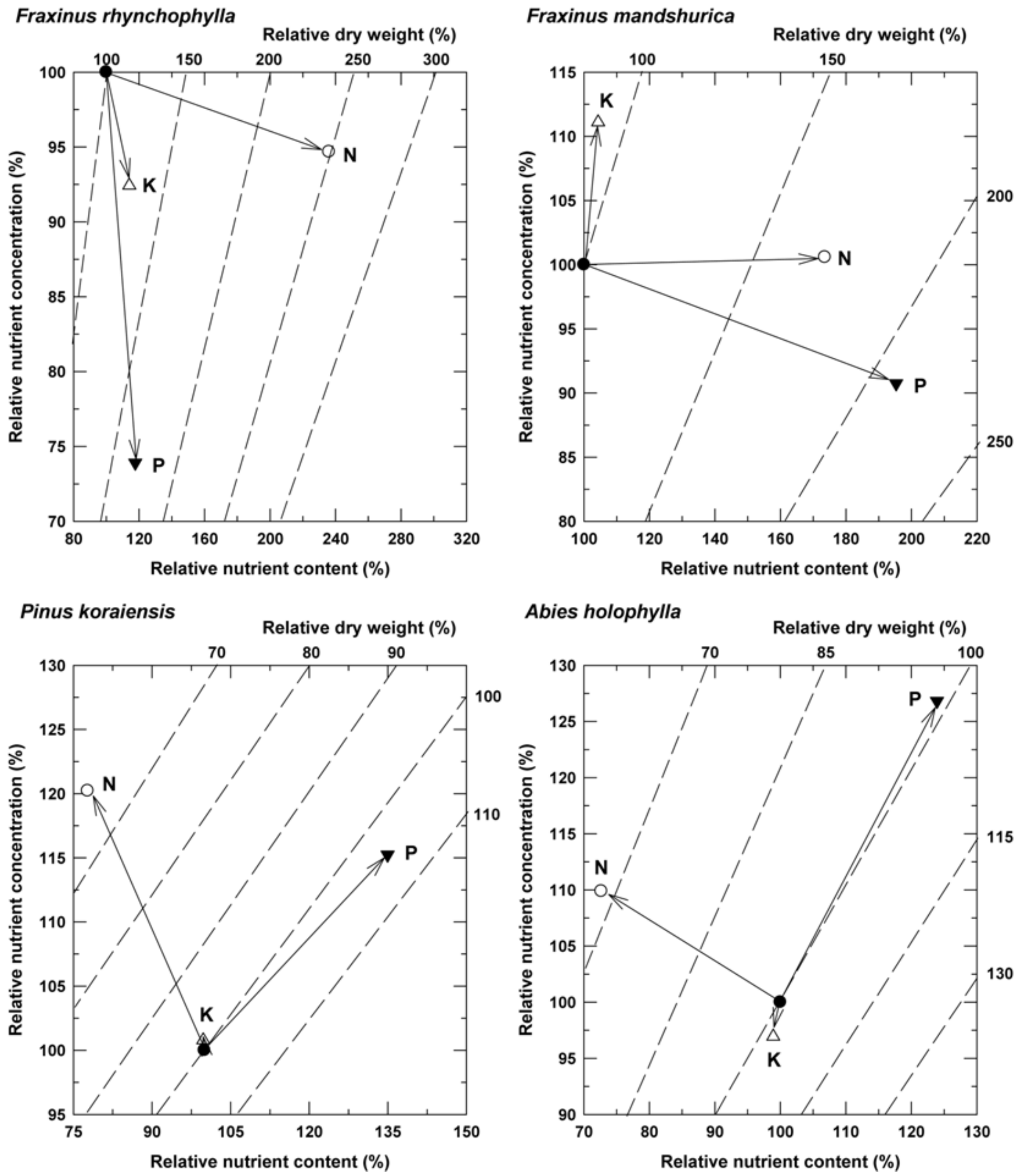

Figure 4. The relationship between N concentration, N content, and dry weight of *Fraxinus rhynchophylla*, *Fraxinus mandshurica*, *Pinus koraiensis*, and *Abies holophylla*.

F. mandshurica were the highest at P treatment with 115% increase. However, N fertilization decreased total dry weight of *P. koraiensis* and *A. holophylla* by 25% and 34%, respectively. The substantial response in growth rate to N fertilization suggests that N may be the most effective fertilizer for *F. rhynchophylla* and *F. mandshurica.*

In *F. rhynchophylla*, growth responses were higher than fertilization uptake indicating that fertilization diluted N concentration of the tissue (Figure 4). The N dilution was the highest in P fertilization. In *F. mandshurica*, P fertilization diluted N concentration, but N fertilization was sufficient because of no increase in N concentration with biomass increase. In *P. koraiensis* and *A. holophylla*, N fertilization increased N concentration by 20% and 10%, respectively (Figure 4). These trees showed N excess showing "toxic accumulation". P fertilization increased N concentration without biomass increase showing N luxury consumption. K fertilization rarely influenced on vector movements.

P fertilization increased P concentration and P content in all species even though the biomass of *P. koraiensis* and *A. holophylla* was decreased (Figure 5). *F. rhynchophylla* and *F. mandshurica* responded to P supply implying that they were under P deficiency, however, *P. koraiensis* and *A. holophylla* showed luxury accumulation. N fertilization showed steady state in P concentration for *F. rhynchophylla* and *F. mandshurica*, but made

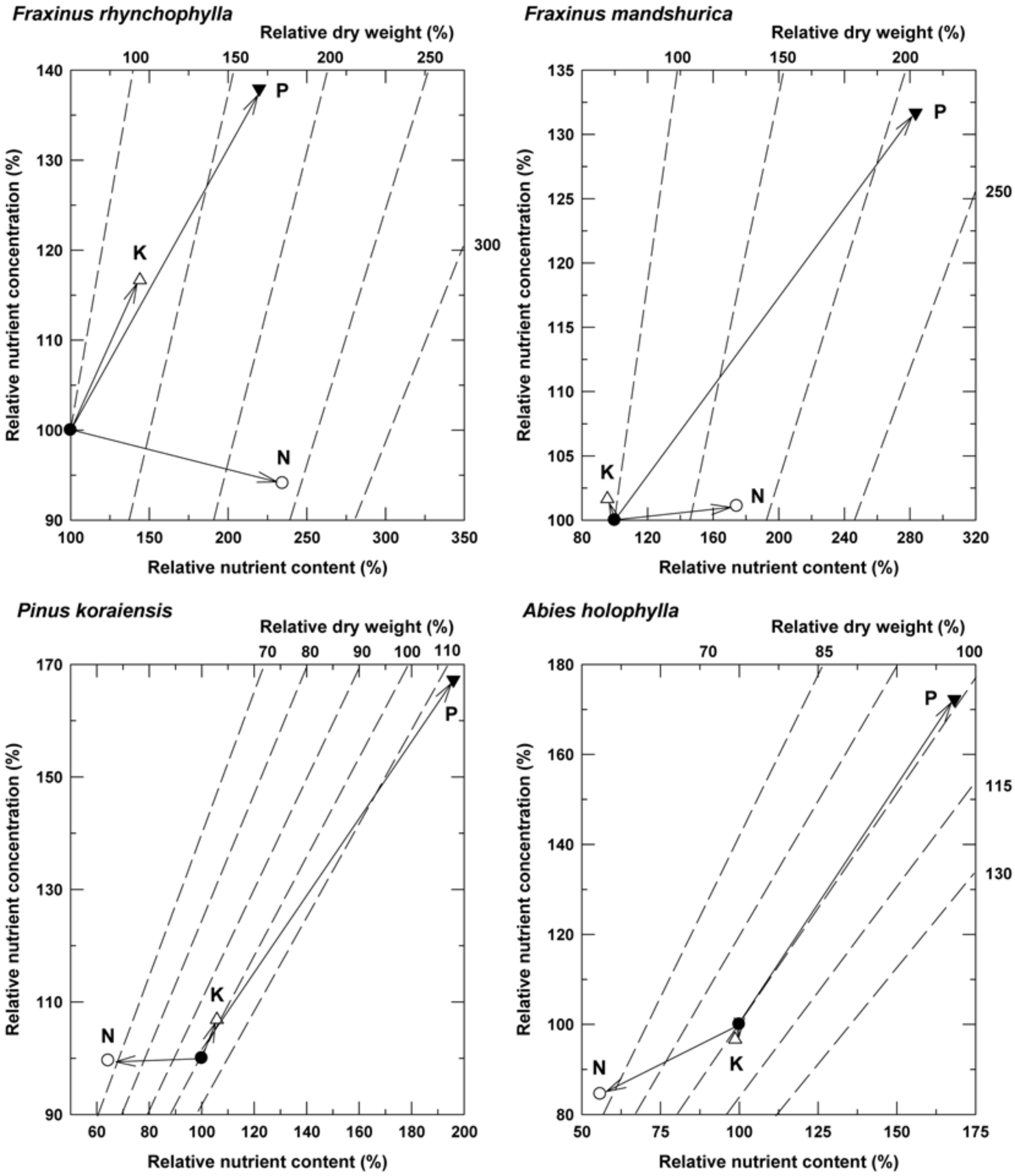

Figure 5. The relationship between P concentration, P content, and dry weight of *Fraxinus rhynchophylla*, *Fraxinus mandshurica*, *Pinus koraiensis*, and *Abies holophylla*.

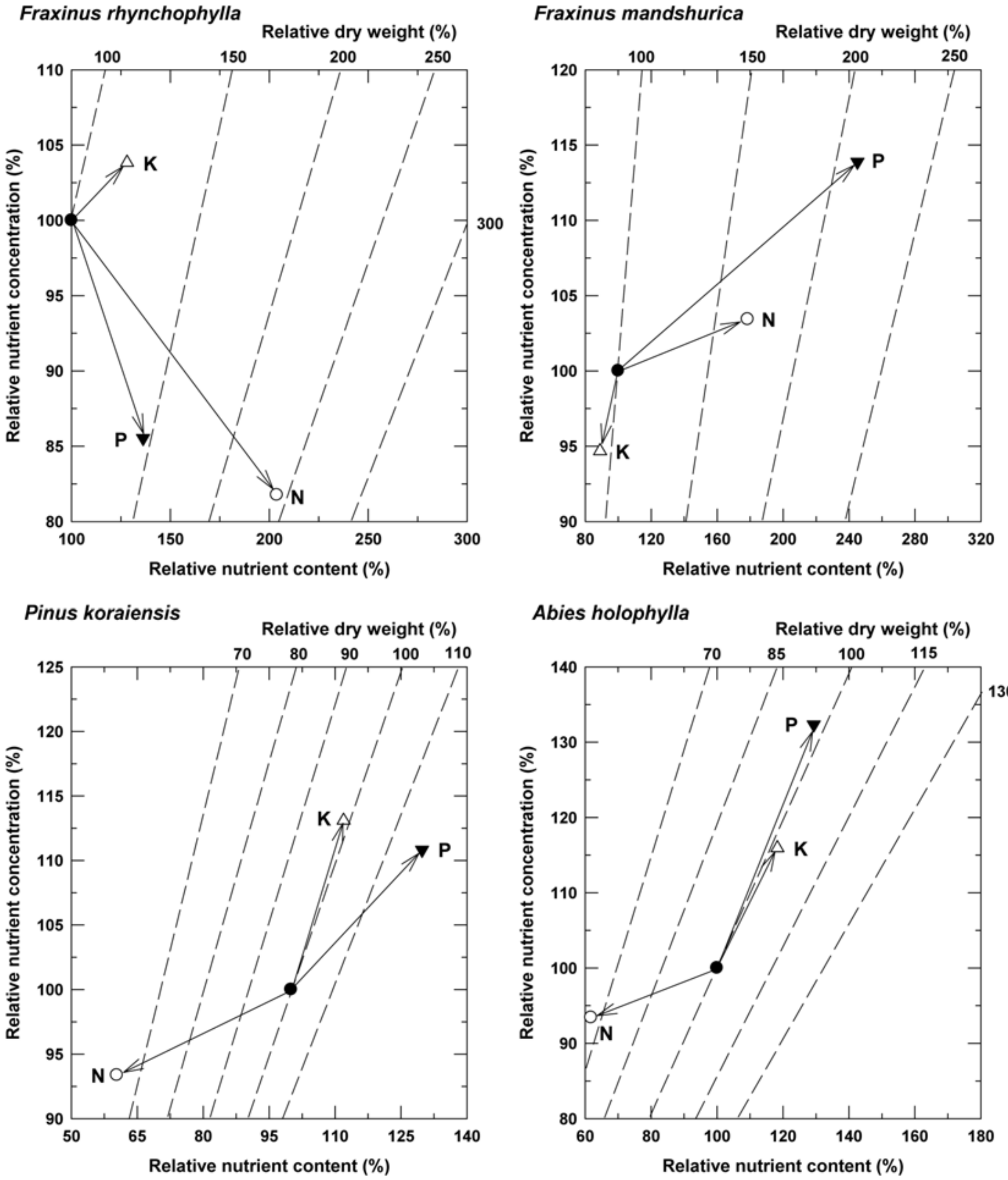

Figure 6. The relationship between K concentration, K content, and dry weight of *Fraxinus rhynchophylla*, *Fraxinus mandshurica*, *Pinus koraiensis*, and *Abies holophylla*.

toxic accumulation with antagonism for *P. koraiensis* and *A. holophylla.*

In *F. rhynchophylla,* N and P fertilization diluted K concentration, but K deficiency occurred in K fertilization (Figure 6). In *F. mandshurica*, N and P fertilization made K deficiency because of higher biomass increase than K uptake. In *P. koraiensis* and *A. holophylla*, all fertilizations showed K excess or luxury accumulation (Table 3).

In *F. rhynchophylla* and *F. mandshurica*, growth rate is much higher than uptake rate, so nutrient concentration in the tissue was diluted. For these trees, more fertilization can be applied. Vector diagnosis of *P. koraiensis* and *A. holophylla* indicated that high application rates of N, P, or K are inefficient for short-term growth and nutrient responses. Therefore, low-frequent dosages are better than a single heavy application for those seedlings.

Conclusion

We cannot recognize not only luxury consumption but also dilution by only concentration data. The vector diagnosis, a graphical technique, seems well suited for illustrating changes in nutrient concentration, nutrient content, and dry weight in a single graph. It reduces subjective interpretation, even though in huge experimental variability.

The effects of fertilization depend on species, which mask the effects of different nursery management practices. It is not easy to generalize good indicators with only morphological traits. More integrated approaches and ecophysiological evaluations in correlating with field performance should be studied.

QI and vector diagnosis seem to be the most appropriate indicators to predict the outplanting performance of studied trees, but non-destructive, simple and reliable nursery grading system should be developed to increase economic gains for reforestation.

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