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Effects of cutting size and exogenous hormone treatment on rooting of shoot cuttings in Norway spruce [*Picea abies* (L.) Karst.]

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Abstract The effects of cutting length, cutting diameter, and exogenous hormone pre-treatment on rooting were studied in comparative experiments to improve the efficiency of cutting propagation in Norway spruce. The results showed that cutting length, diameter, and the interaction between cutting length and diameter significantly affected rooting efficiency. Higher rooting efficiency was obtained by cuttings of 0.3–0.4 cm diameter and 9–12 cm length. Hormone type significantly affected all measured rooting traits, and moderately higher measurements were observed in the indole butyric acid treatment than those of the control, whereas all measurements in the α-naphthalene acetic acid treatment were significantly lower than those of the control, which may have been an inhibitor of *Picea abies* in stem cuttings. The cutting size effect on rooting efficiency is discussed and an optimal cutting size is suggested, which provide valuable information for propagating Norway spruce.

Keywords *Picea abies* · Shoot cutting size · Hormone · Rooting efficiency

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Introduction

The vegetative propagation of superior genotypes is the basis of clonal forestry to create intensive plantations with large genetic gains. Norway spruce [*Picea abies* (L.) Karst.] is a coniferous species suitable for clonal forestry, and cutting propagation has been give priority over vegetative propagation. Propagation from shoot cuttings is relatively easy in spruce and can lead to a high rooting percentage (>90 %) (Kleinschmit et al. 1973; Bentzer 1981). Chun et al. (2009) reported that the rooting percentage of shoot cuttings from 5-year-old Norway spruce stock plants is >89 %. Norway spruce has a documented relatively long history of introduction in China and grow better and exhibit stronger adaptation than *Picea crassifolia* Kom. and other local spruces (Zhang and Zhang 1995; Dong et al. 2007). Moreover, conventional breeding programs have generated a considerable number of excellent clones, but more efficient cutting techniques are required for mass propagation.

Nevertheless, Norway spruce belongs to the callus rooting species as its roots initiate from a callus; thus, rooting is relatively more difficult than species that root from bark. The physiological conditions of the stock plants (Mitchell et al. 2004), time and place of cutting collection (Hannerz et al. 1999; Jurásek and Martincová 2004), and environmental conditions (Ragonezi et al. 2010; Repáč et al. 2011) significantly affect the efficiency of Norway spruce cutting propagation. Initial cutting size is a very important factor involved in rooting ability and growth performance (Burgess et al. 1990; Foster et al. 2000; Vigl and Rewald 2014). Cuttings with a larger diameter and longer length result in better survival and growth under normal conditions (Leakey 1983; Hannerz et al. 1999; Vigl and Rewald 2014), but cutting size is not a simple variable affected by cutting origin and age (Hoad and Leakey 1992; Leakey 2004). Moreover, the leaf area × cutting length interaction (Tchoundjeu and Leakey 1996) and an interaction between cutting length and cutting diameter may be critical factors that affect rooting (Hoad and Leakey 1992; Leakey et al. 1992; Tchoundjeu and Leakey 1996). The relationships between rooting efficiency and cutting size are well known in tropical hardwood species (Leakey 2004) but not in spruce species.

Adventitious rooting is a complex developmental process that can be affected by internal and external factors (Leakey 2004). Auxins play a critical role in the formation of adventitious root by increasing initiation of the root primordium and growth via cell division (Fogaça and Fett-Neto 2005). Auxins promote starch hydrolysis and mobilize sugars and nutrients to the cutting base (Das et al. 1997). During cell division and auxin transport, auxins act primarily through selective proteolysis and cell wall loosening with receptor protein transporting inhibitor response 1 and auxin-binding protein 1 (da Costa et al. 2013). However, the combined effects of auxin type, auxin concentration, and soaking time on rooting of Norway spruce cuttings have not been reported.

The objectives of our study were to estimate the effects of cutting length, cutting diameter, and their interaction on rooting cuttings; study the effects of exogenous auxin type, exogenous auxin concentration, and soaking time on rooting success; and establish an optimum cutting propagation scheme for Norway spruce to produce more elite clone plants for clonal forestry.

Materials and methods

Experimental site, plant material, and stock plant environment

The experiment was conducted in a nursery at the Research Institute of Forestry of Xiaolongshan Mountain in Gansu Province, China (34°28′50″N, 105°54′37″E) in May

Fig. 1 Cutting orchard of 5-year-old Norway spruce

2007. The altitude is 1,160 m with an annual rainfall of 600–800 mm. The average annual temperature is 10.7 °C.

Norway spruce shoot cuttings were collected from mixed clones of 5-year-old trees (Fig. 1), of which 20 or more ortets were involved. The shoot cuttings were harvested from the first branch whorl of the ortets. Ortets of clones were watered regularly and fertilized twice monthly using foliar nutrients at an application rate of 5 kg/m^2 (0.4 % monopotassium phosphate, 0.0002 % diammonium phosphate, and calcium phosphate with urea). The concentrations of nitrogen (N), phosphorus (P), and potassium (K) in the soil were 62.55, 32.32, and 186.9 mg/kg, respectively. Soil organic matter content was 0.64 % at a pH of 7.96.

Rooting medium and rooting pots

The rooting medium was prepared with a 1:1 (v:v) mixture of peat:rice hulls. Rooting pots were 5 cm in diameter and 10 cm long, made of non-woven paper (bottom open), and set on the seedbed (Fig. 2) in the nursery.

Cutting management

Cuttings for each treatment were managed across both experiments. After planting, cuttings were immediately sprayed with fungicide (1,000 mL/m^2 carbendazim) and treated again every 10 days. The cuttings were watered regularly and fertilized twice monthly

Fig. 2 The seedbed and mix device of the experiment

using foliar nutrients with 0.3 % monopotassium and 0.2 % urea at a dosage of 0.5 kg/m^3. A mist device (Fig. 2) was used to maintain humidity.

Experimental design

Cutting size experiment

Cuttings were divided into five groups by diameter. The groups were 1 (1.0–1.9 mm), 2 (2.0–2.9 mm), 3 (3.0–3.9 mm), 4 (4.0–4.9 mm), and 5 (5.0–7.9 mm). In total, 661 cuttings were used. The range of cutting length was 3.2–17.5 cm. The cutting samples for each diameter group were $n = 26$, 146, 201, 141, and 55, respectively. A randomized complete block design was set up for the diameter group experiment with three replications and eight or more cuttings in each diameter plot.

Exogenous hormone experiment

A short cutting size (length, 5.0–8.0 cm; diameter, 0.2–0.35 cm) was selected for the hormone experiment. An orthogonal experimental design [$L_{16}(4^5)$], with three factors (hormone types, concentration, and soaking time) and four levels each were set, which generated 16 treatments (Table 1). Twenty cuttings were in each treatment plot, with three plot replications per treatment. The base of each cutting was dipped into an aqueous solution of auxins with corresponding concentrations and soaking times.

Table 1 Orthogonal experimental design [L_{16} (4^5)] for the exogenous hormone pretreatment

Treatment	Number				
	1 Hormone type	2 Hormone concentration (mg kg^{-1})	3 Soaking time (h)	4 Blank	5 Blank
1	1 (Control)	1 (100)	1 (0.5)	1	1
2	1 (Control)	2 (150)	2 (1)	2	2
3	1 (Control)	3 (200)	3 (1.5)	3	3
4	1 (Control)	4 (300)	4 (2)	4	4
5	2 (IBA)	1 (100)	2 (1)	3	4
6	2 (IBA)	2 (150)	1 (0.5)	4	3
7	2 (IBA)	3 (200)	4 (2)	1	2
8	2 (IBA)	4 (300)	3 (1.5)	2	1
9	3 (NAA)	1 (100)	3 (1.5)	4	2
10	3 (NAA)	2 (150)	4 (2)	3	1
11	3 (NAA)	3 (200)	1 (0.5)	2	4
12	3 (NAA)	4 (300)	2 (1)	1	3
13	4 (ABT)	1 (100)	4 (2)	2	3
14	4 (ABT)	2 (150)	3 (1.5)	1	4
15	4 (ABT)	3 (200)	2 (1)	4	1
16	4 (ABT)	4 (300)	1 (0.5)	3	2

The four different hormones types were distilled water (control), *IBA* indole-3-butyric acid, *NAA* α-naphthalene, acetic acid, and ABT ABT-1 rooting powder. The hormone concentrations were 100, 150, 200, and 300 mg kg^{-1} and the soaking times were 0.5, 1.0, 1.5, and 2.0 h

Rooting traits measurements

Measurements of rooting efficiency for each treatment for both the cutting size and hormone experiments were assessed after 3 months of growth. The measured indices included the number of roots (NR, roots > 0.2 cm), length of the longest root (LLR, 0.1 cm), total root length (TRL, 0.1 cm), and mean root length (MRL, 0.1 cm) for each plant; the root effect index (REI); aging callus percentage (ACP, %); rooting percentage (RP, %); and rotting percentage (RoP, %) for each treatment plot. The REI [the plot mean of (MRL × NR)] was also evaluated. Rooting success was expressed as the percentage of cuttings that rooted in each plot, whereas rooting failure was expressed as the percentage of cuttings that rotted or the percentage of cuttings that callused in each plot.

Statistical analysis

Rooting traits were transformed to obey a normal distribution using SPSS 16.0 software (Norušis and SPSS Inc. 1994) before analysis of variance (ANOVA). The analysis of rooting traits among cutting sizes was performed using the multiple analysis of variance program in the vegan package of R 2.15.3 (Oksanen et al. 2011), where cutting length, diameter, and length × diameter were fixed factors. The ggplot2 package in R 2.15.3 (Wickham 2009) was used to plot the relationship between the cutting length and diameter affecting the rooting traits. In total, 660 cuttings, which were divided into five diameter groups, were used to plot the relationship among cutting length affecting NR, LLR, TRL, and MRL. Thirty-three data values, which were generated by calculating 20 cuttings from small to large of the 660 cuttings, were divided into three diameter groups to plot the relationship between cutting length and REI, ACP, RP, and RoP.

The analysis of rooting traits for the hormone orthogonal experiment was conducted using a specially designed program in DPS 7.5 software (Tang 1998), where hormone type, concentration and soaking time were fixed factors. Traits with significance differences were verified using Duncan's test in DPS 7.5 software. The effects of hormone type on rooting traits were plotted using Microsoft Excel 2007 and Adobe Illustrator CS5 software (Press 2010).

Results and analysis

Influence of cutting size

Based on the ANOVA, cutting length significantly affected NR, TRL, MRL, and ACP, whereas NR, LLR, TRL, and MRL were significantly affected by cutting diameter. The interaction between cutting length and cutting diameter significantly affected LLR, TRL, MRL, RP, RoP, and REI (Table 2). However, no significant effect of cutting diameter was observed on the four percentage parameters.

Root initiation and length were lower in the thin and short cuttings (cutting diameter classes 1 or 2 and length < 6 cm), and associated with the lowest values of NR, LLR, TRL, MRL, RP, and REI and the highest values of RoP and ACP (Figs. 3, 4). Optimum rooting ability was obtained with thicker and longer cuttings (cutting diameter groups 3 and 4), and the NR, TRL, and RP values increased with increasing cutting length in the two diameter groups (Figs. 3, 4).

Number of roots and TRL decreased as the cutting length increased in the thinner diameter group 1 (Fig. 3), whereas TRL, RP, and REI values decreased and the RoP value increased with increasing cutting length in the thicker diameter groups (4 and 5) (Figs. 3, 4). LLR, MRL (Fig. 3), and ACP (Fig. 4) values decreased as the cutting length increased, regardless of the cutting diameter (Table 3).

The optimal cutting size for better rooting traits was a diameter of 0.3–0.4 cm and length of 9–12 cm.

Table 2 Analysis of variance for cutting size effect on shoot cutting rooting traits

Variance source	DF	NR	LLR (cm)	TRL (cm)	MRL (cm)	RP	ACP	ROP	REI
		MS	MS	MS	MS	MS	MS	MS	MS
Cutting length	1	24.97**	1.21	2.78*	6.63**	1.11	5.99*	0.40	0.74
Cutting diameter	1	13.72**	14.16**	16.15**	8.88**	0.47	0.89	0.02	0.55
Cutting length*cutting diameter	1	0.90	3.45*	3.84*	3.52*	7.25*	0.08	9.70**	6.30*
Error	29	0.59	0.63	0.62	0.63	0.68	0.67	0.44	0.79

NR number of roots, *LLR* length of the longest root, *TRL* total root length, *MRL* mean root length, *RP* rooting percentage, *ACP* aging callus percentage, *RoP* rotting percentage, *REI* root effect index

** Significant at 0.05; * significant at 0.01

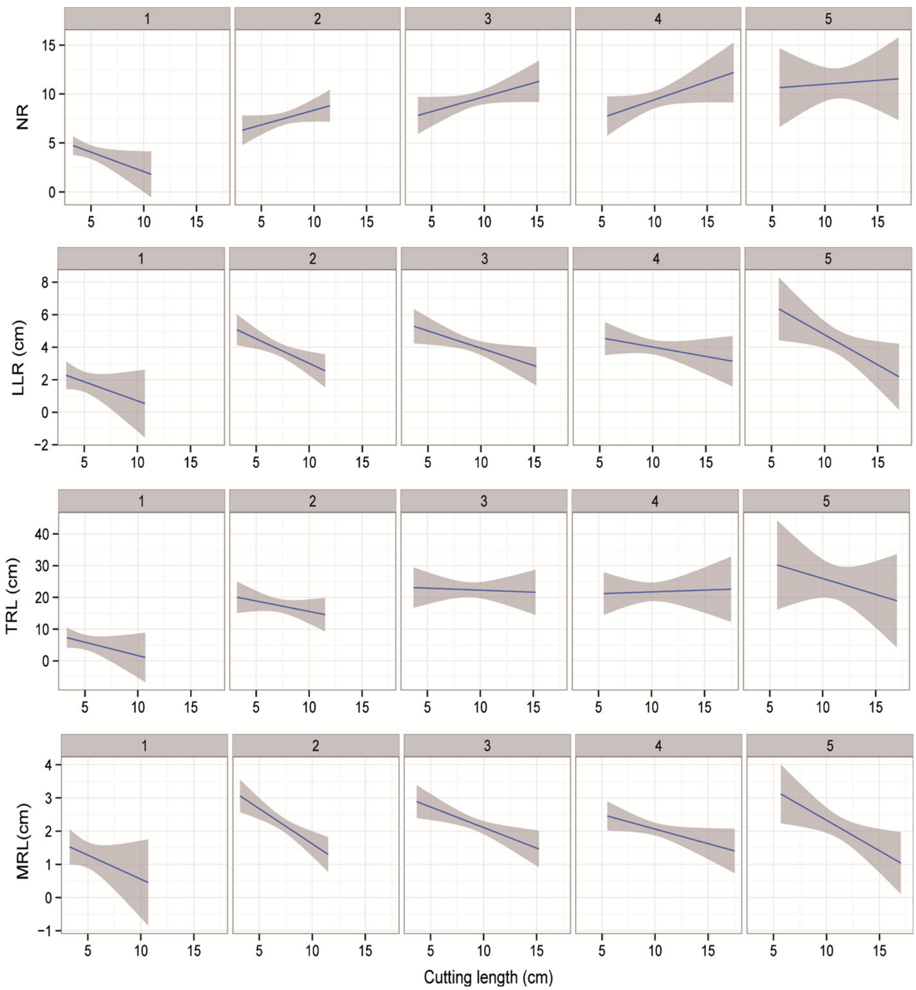

Fig. 3 Linear regression of the number of roots (NR), length of the longest root (LLR), total root length (TRL), and mean root length (MRL) with cutting length in each diameter group. The 1, 2, 3, 4, and 5 above each part represent the diameter groups: 1 (1.0–1.9 mm), 2 (2.0–2.9 mm), 3 (3.0–3.9 mm), 4 (4.0–4.9 mm), and 5 (5.0–7.9 mm)

Exogenous hormone pretreatment

Hormone type significantly affected all rooting traits, and soaking time significantly affected NR, TRL, MRL, and REI, whereas hormone concentration only significantly affected NR for all tested hormones (Table 3).

All root trait measurements in the IBA treatment were higher than those of the control, and variations were not significant (except TRL and REI), but all NAA measurements were significantly lower than those of the control, and the ABT-1 rooting powder (ABT, Chee 1995) measurements were similar to control values (Fig. 5).

Among the 16 treatments, treatments 6 (150 mg kg^{-1} IBA, soaking for 0.5 h) and 7 (200 mg kg^{-1} IBA, soaking for 2 h) were the optimum rooting trait combinations with the

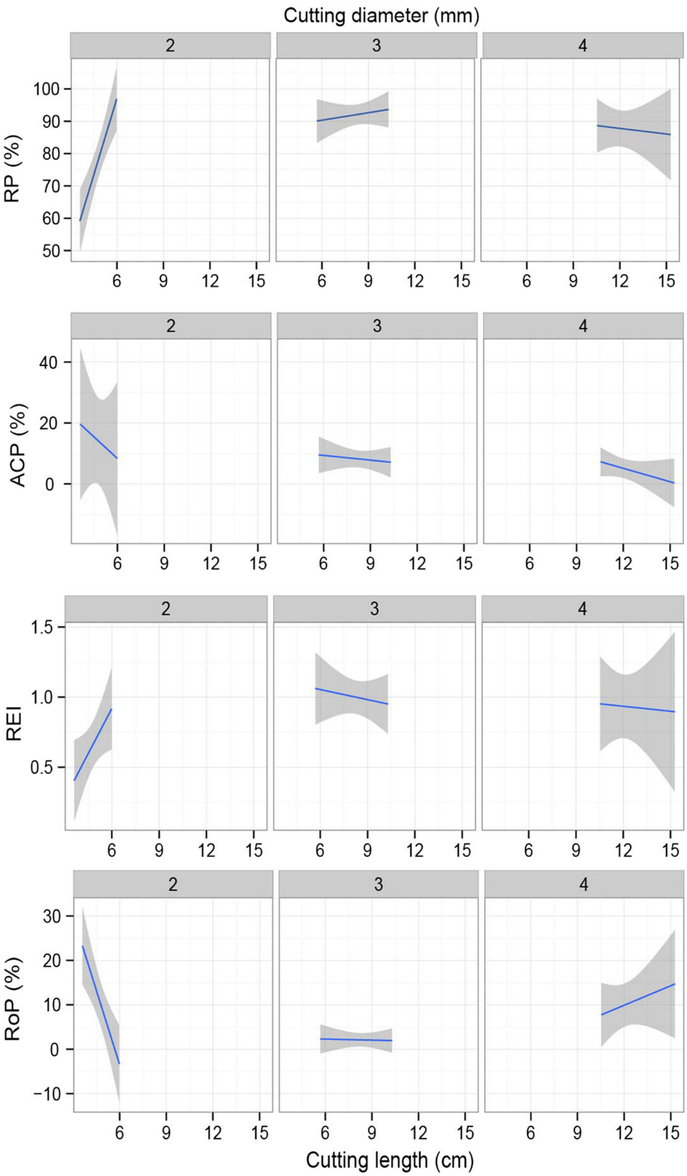

Fig. 4 Linear regression of the rooting percentage (RP), aging callus percentage (ACP), root effect index (REI), and rotting percentage (RoP) with cutting length in each diameter group. The 1, 2, 3, 4, and 5 above each part represent the diameter groups: 1 (1.0–1.9 mm), 2 (2.0–2.9 mm), 3 (3.0–3.9 mm), (4.0–4.9 mm), and 5 (5.0–7.9 mm)

significantly highest values (Table 4). Treatments 10 (150 mg kg^{-1} NAA, soaking for 2 h) and 12 (300 mg kg^{-1}, NAA soaking for 1 h) resulted in the significantly lowest rooting trait values (Table 4).

Table 3 Analysis of variance for hormone type, hormone concentration, and soaking time on the short shoot cutting rooting traits

Variance source	DF	NR MS	LLR (cm) MS	TRL (cm) MS	MRL (cm) MS	RP MS	REI MS
Hormone types	3	22.61**	6.56**	186.76**	0.38**	0.21**	0.47**
Hormone concentration	3	2.64*	0.81	23.34	0.14	0.006	0.06
Soaking time	3	3.11*	0.61	32.20*	0.23*	0.007	0.08*
Error	36	1.36	0.42	12.49	0.09	0.01	0.03

NR number of roots, *LLR* length of the longest root, *TRL* total root length, *MRL* mean root length, *RP* rooting percentage, *REI* root effect index

** Significant at 0.05; * significant at 0.01

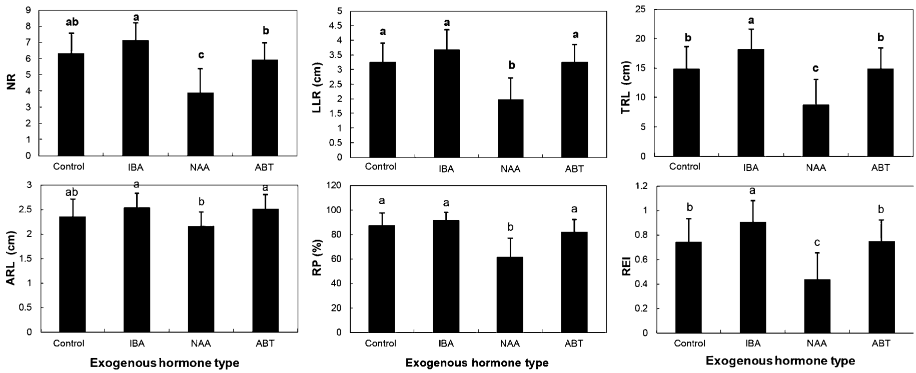

Fig. 5 Effect of hormone type on *Picea abies* rooting qualities. *a*, *b*, *c*, and *d* indicate the groups for Duncan's test

The rooting traits of cuttings that received the IBA pretreatment were all positively ($P = 0.10$–0.05) related with the cutting length and cutting diameter. Most of correlation coefficients between rooting traits and cutting length, cutting diameter with ABT, and the NAA pretreatment were lower than those for the IBA pretreatment (Table 5).

Discussion

Studies of cutting size effects on rooting in coniferous species have typically considered the cutting length (Miller et al. 1982; Hannerz et al. 1999; Foster et al. 2000) or diameter (Burgess et al. 1990; Foster et al. 2000) alone. Only a few studies have investigated both traits together. Our results show that both the cutting length and diameter significantly affected the rooting ability in Norway spruce cuttings, as well as the effect of an interaction between the cutting length and diameter (Table 2), which would provide a broader view of rooting effects in conifer species.

However, the effect of the cutting length on rooting in other studies was conflicting. Shorter cuttings (5.1 or 7.6 cm) of loblolly pine (*Pinus taeda* L.) rooted better and developed more roots than those of longer cuttings (Foster et al. 2000). The rooting

Table 4 Duncan's test on short shoot cutting rooting traits among the 16 treatments in the orthogonal experiment [L_{16} (4^5)]

Treatment	Hormone type	Concentration (mg kg^{-1})	Soaking time (s)	Length (cm)	Diameter (mm)	NR	LLR (cm)	TRL (cm)	MRL (cm)	RP	REI
1	CK	100	0.5	6.99	2.89	7.07^{abc}	3.26^{abc}	15.58^{abc}	2.17^{bc}	83.33^{abc}	0.78^{abc}
2	CK	150	1	5.56	2.22	5.47^{bcde}	2.87^{bc}	11.34^{bcdef}	2.08^{c}	91.67^{a}	0.57^{bcdef}
3	CK	200	1.5	7.31	2.47	6.03^{abcd}	3.51^{ab}	15.76^{ab}	2.67^{ab}	85^{abc}	0.79^{ab}
4	CK	300	2	6.53	2.72	6.7^{abc}	3.36^{ab}	16.67^{ab}	2.47^{abc}	88.33^{ab}	0.83^{ab}
5	IBA	100	1	6.21	2.34	6.65^{abc}	3.15^{bc}	15.83^{ab}	2.4^{abc}	85^{abc}	0.79^{ab}
6	IBA	150	0.5	6.65	3.21	8.1^{a}	4.39^{a}	20.13^{a}	2.48^{abc}	93.33^{a}	1.01^{a}
7	IBA	200	2	7.25	3.43	7.4^{ab}	3.97^{ab}	20.81^{a}	2.82^{a}	96.67^{a}	1.04^{a}
8	IBA	300	1.5	6.86	2.97	6.33^{abcd}	3.18^{abc}	15.64^{abc}	2.46^{abc}	90^{ab}	0.78^{abc}
9	NAA	100	1.5	7.48	2.45	4.98^{cde}	2.71^{bcd}	12.13^{bcde}	2.29^{abc}	68.33^{bcde}	0.61^{bcde}
10	NAA	150	2	6.60	3.07	3.8^{ef}	1.61^{de}	8.15^{ef}	2.13^{bc}	58.33^{de}	0.41^{ef}
11	NAA	200	0.5	5.93	2.94	4.22^{def}	2.11^{cde}	8.9^{cdef}	2.08^{c}	65^{cde}	0.44^{cdef}
12	NAA	300	1	6.57	2.37	2.58^{f}	1.43^{e}	5.49^{f}	2.1^{bc}	53.33^{e}	0.27^{f}
13	ABT	100	2	6.46	2.51	6.92^{abc}	3.76^{ab}	18.07^{ab}	2.61^{abc}	91.67^{a}	0.9^{ab}
14	ABT	150	1.5	6.90	2.40	5.43^{bcde}	3.13^{bc}	14.23^{abcde}	2.59^{abc}	76.67^{abcd}	0.71^{abcde}
15	ABT	200	1	5.27	2.51	5.87^{abcde}	3.34^{abc}	15.17^{abcd}	2.6^{abc}	81.67^{abc}	0.76^{abcd}
16	ABT	300	0.5	6.09	2.49	5.47^{bcde}	2.74^{bcd}	12.14^{bcde}	2.22^{bc}	78.33^{abcd}	0.61^{bcde}

NR number of roots, *LLR* length of the longest root, *TRL* total root length, *MRL* mean root length, *RP* rooting percentage, *REI* root effect index. Superscript letters indicate the Duncan's test groups

Table 5 Correlation analysis among cutting length, cutting diameter, soaking time, hormone concentration, and rooting traits under each hormone type

Hormone type	Cutting length				Cutting diameter			
	Control	IBA	NAA	ABT	CK	IBA	NAA	ABT
Soaking time	0.06	0.73	0.59	0.51	−0.12	0.35	0.17	−0.12
Concentration	0.03	0.63	−0.54	−0.41	0.01	0.43	−0.29	0.14
NR	0.58	0.20	0.41	0.01	0.99**	0.59	0.19	0.58
LLR	0.92*	0.38	0.53	0.02	0.53	0.74	−0.18	0.34
TRL	0.82	0.59	0.57	0.08	0.79	0.82	0.02	0.33
MRL	0.70	0.86	0.94*	0.07	0.11	0.74	−0.46	−0.12
RP	−0.92*	0.89	0.31	−0.04	−0.74	0.99*	0.09	0.63
REI	0.82	0.59	0.57	0.08	0.79	0.82	0.02	0.33

NR number of roots, *LLR* length of the longest root, *TRL* total root length, *MRL* mean root length, *RP* rooting percentage, *REI* root effect index

** Significant at 0.05; * significant at 0.01

percentage in Norway spruce is significantly and positively correlated with twig length before rooting among cuttings originating from the lower part of the crown (Hannerz et al. 1999). Long cuttings root at higher percentages than short cuttings in *Ayous* (*Triplochiton scleroxylon*) (Leakey 1983; Leakey and Mohammed 1985). However, in Fraser fir (*Abies fraseri*), no effect of cutting length on rooting percentage has been identified, but longer cuttings tend to initiate more and longer roots (Miller et al. 1982). Similarly, the cutting diameter significantly affects rooting ability (Leakey and Mohammed 1985; Burgess et al. 1990; Foster et al. 2000). However, *T. scleroxylon* cuttings of the same length and the largest diameter have the greatest rooting percentages, indicating that the cutting storage capacity (length × diameter = cutting volume) may be more critical than length (Hoad and Leakey 1992; Leakey et al. 1992; Tchoundjeu and Leakey 1996).

In our study, optimum rooting results were obtained for longer and thicker cuttings (cuttings of 0.3–0.4 cm diameter and 9–12 cm length). The effectiveness of rooting by larger cuttings can be explained by different factors. The first factor is that the level of endogenous auxins and other rooting-inducing factors may be lower in smaller cuttings, which leads to reduced rooting percentage (Fig. 4) or the absence of rooting in short cuttings (Palanisamy and Kumar 1997). The second factor is that larger cuttings store more carbohydrates (Tchoundjeu and Leakey 1996). Root growth is dependent on carbohydrates in the leaf and stem (Philipson 1988). The retention of leaves on cuttings is essential for rooting because it permits post-severance carbon assimilation (Reuveni and Raviv 1980; Leakey and Coutts 1989). The effect of nutrient status on rooting has been studied during adventitious root development in leafy cuttings (Dick and Dewar 1992). The accumulation of starch at the cutting bases in avocado improves its rooting capability (Reuveni and Raviv 1980), although starch-filled cuttings of *T. scleroxylon* develop very poor rooting due to inhibited post-severance photosynthesis (Leakey and Coutts 1989; Leakey and Storeton-West 1992; Mesén et al. 1997, 2001). The third factor is the lower elemental content of N, P, and K in large cuttings (Burgess et al. 1990), which is negatively correlated with rooting. However, other studies have shown positive relationships with N (Budiarto et al. 2006). Various data indicate that rapidly growing organisms commonly have low biomass N:P ratios (Elser et al. 2007; Güsewell 2004). All of these highly interactive factors are affected by the stock plant environment and management but are poorly understood (Leakey 2004).

Cuttings of the same diameter that are greater or less than a certain value (too small or too large) had a greater length and a larger cutting volume, whereas they had a lower NR, TRL, RP, and REI but higher RoP. Furthermore, the LLR, MRL, and ACP decreased as the cutting length increased, regardless of the cutting diameter. These results suggest that except for the cutting volume, leaf area (Aminah et al. 1997) and the leaf area by cutting length interaction (Tchoundjeu and Leakey 1996) may be factors affecting rooting. Cuttings with a 60-cm^2 leaf area appear to suffer water deficit as reflected by higher transpiration rates and leaf shedding compared to 15- and 30-cm^2 leaf areas (Aminah et al. 1997). Thus, striking a balance between photosynthesis and transpiration is necessary for optimum rooting to occur (Leakey and Coutts 1989). Another explanation is that cutting length affects water velocity and nutrient transfer. A cutting with the same diameter that was long showed a reduced rate of acropetal transport of cytokinins and basipetal transport of auxins (Friml and Palme 2002). This hinders the development of adventitious root primordia, which can only form when the ratio of auxins to cytokinins in the stem base is high (Bollmark and Eliasson 1990). Cutting size can often be attributed to the origin of a cutting within and between shoots, and to its position within the stock plant (Leakey 2004). The best way to regulate cutting size is by stock plant management, which affects the cutting morphology and physiology (Hoad and Leakey 1992).

The ability of auxins to promote adventitious root development in conifer stem cuttings is well known (Ragonezi et al. 2010). In the present study, applying IBA significantly enhanced TRL and REI, and other rooting traits were moderately higher than those of the control, which may enhance anchorage and absorption of water and nutrient elements when planted in the field. Applying IBA may have an indirect influence by enhancing the speed of translocation and movement of carbohydrates to the base of cuttings and consequently stimulate rooting (Davies et al. 1990; Aminah et al. 1995), so the rooting rate may be enhanced by the IBA treatment (Aminah et al. 1995). This may also be related to total phenolic content and peroxidase activity, which are higher in IBA-treated cuttings, particularly during the initiation and expression phases (Moncousin and Gaspar 1983; Rout 2006). Similar to IBA, NAA treatment promotes rooting in conifer stem cuttings (Copes and Mandel 2000; Ragonezi et al. 2010), but in the present study we found that NAA may be an inhibitor, which is in accordance with a study on apples (De Klerk et al. 1997). The reason may be that NAA is very stable (Dunlap et al. 1986) and more persistent than other auxins and remains present in the tissue in its free form. Thus, NAA decreases the rates of mobilization and translocation of nutrients to the growing root primordia (Husen and Pal 2006) and blocks the outgrowth of the initials. ABT-1 rooting powder contains 2.5 % IBA, 10 % NAA, and 25.8 % thiamine (Chee 1995), but has no significant effect on rooting (Fig. 5).

The hormone concentration and soaking time affected some of the rooting traits. The best rooting was achieved in cuttings treated with a low IBA concentration, soaking for a short time (treatment 6), or a high concentration of IBA and soaking for a long time (treatment 7), suggesting positive relationships among rooting traits, cutting length, and cutting diameter.

In conclusion, the cutting length, cutting diameter, and the interaction between the cutting length and cutting diameter all affected the rooting ability of Norway spruce. More rooting was obtained with thicker and longer cuttings; however, when the cutting diameter was greater than or less than a certain value, rooting decreased with increasing length. We conclude that an equilibrium between photosynthesis and transpiration and the rate of water and nutrient transport are important factors influencing rooting, and cuttings with a modest size (0.3–0.4 cm diameter and 9–12 cm length) were beneficial to rooting success. In the orthogonal experiment, 150 mg kg^{-1} IBA with soaking for 0.5 h and 200 mg kg^{-1} IBA with soaking for 2 h were the optimum rooting combinations among the 16 treatments, suggesting positive relationships among rooting traits, cutting length, and cutting diameter. NAA may have been an inhibitor of *P. abies* stem cuttings in the experiment.

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