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Optimization of Environmental Factors Affecting Initial Growth of Norway Spruce Seedlings

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The purpose of the study was to create a near optimal environment for seedling establishment and growth, without the restrain of water and nutrients but under climate conditions typical for the region. This to give us valuable knowledge about the growth potential of different seedling types in the field. The experimental site was situated in southern Sweden. Six treatment combinations were applied including two site treatments; 1) soil inversion, i.e. the control treatment, and 2) soil inversion, drip irrigation and fertilization combined with plastic cover mulch, i.e. the optimization treatment, and three seedling types of Norway spruce (*Picea abies* L. Karst.), (a) a 2-year-old Plug+1 seedling, (b) a 1.5-year-old containerized seedling and (c) a 10-week-old mini seedling. Effects on seedling nutrient status and growth were studied during the first three years after planting. Height, diameter and biomass of the seedlings grown in the optimized environment were significantly greater than for seedlings grown in the control. The Plug+1 seedlings grown in the optimization treatment had, after three years, reached a height of 124 cm, while the containerized seedlings were 104 cm and the mini seedlings 45 cm. In practical plantations, this height is usually gained after 5–10 years depending on planting conditions. Biomass partitioning did not differ between optimization treatments, but between seedling types. The mini seedlings allocated less biomass to the roots and more biomass to needles and stem in comparison with the two other seedling types. Mini seedlings also broke bud earlier. Throughout the experimental period, seedling nutrient status for all treatment combinations was followed and a balanced nutrient supply of macro- and micronutrients was given in the optimization treatment. Nutrient concentrations were constantly higher in seedlings grown in the optimization treatment, but the difference decreased over time. Results from this study shows that, by improving site conditions associated with fast establishment, growth check can be avoided.

Keywords establishment, fertilization, irrigation, regeneration, seedling types, vegetation management

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1 Introduction

The greatest challenge for a forester when planting a reforestation area is to achieve a fast seedling establishment. During the establishment phase, the seedlings are exposed to a lot of stress. Availability of water and nutrients are often limited and the seedlings are exposed to a number of factors, both biotic and abiotic, that may cause seedling growth check and in the worst case even severe damages and mortality (Burdett 1990, Grossnickle 2000). Growth check, also referred to as planting shock or planting check, is the restricted field growth in recently planted seedlings that occurs the first years after planting (Grossnickle 2000). A high initial growth is important when it comes to reduce the period when seedlings are exposed to factors causing stress, among which the most common in Sweden are pine weevils, frost, competing vegetation and browsing (Nilsson et al. 2010). Therefore, both vital seedlings and methods that improve site conditions are necessary to reduce seedling stress and to increase the seedlings ability to, as fast as possible, respond to its new environment. Another important aspect regarding fast seedling establishment is the fact that there is an increasing demand from the society to increase forest production and to reduce the rotation periods from regeneration to final cutting (Regeringens proposition… 2008). A shorter rotation will result in earlier incomes and reduced costs. Therefore, already in the regeneration phase measures to increase production should be taken.

In practice, site preparation is the most common method used in Sweden to improve site conditions. Depending on the method used, site preparation increases water availability, nutrient mineralization and temperature in the soil (Örlander et al. 1990). It also reduces the amount of competing vegetation and reduces the risk of damages caused by pine weevils (Peterson et al. 2005) and frost (Langvall et al. 2001). Soil inversion is the site preparation method that has shown to create the most optimal conditions for seedling establishment in field (Örlander et al. 1998). The choice of seedling type has also shown to be important and it depends on the type of site preparation method used as well as on the climatic conditions at the regeneration area (Thiffault 2004, Johansson et al. 2007). Containerized seedling types usually show a lower rate of growth check than larger bare-root seedlings (Nilsson et al. 2000), supposedly due to differences in root system morphology. For example, mini seedlings have shown to have a greater growth potential when planted in soil inversion than larger seedling types (Johansson et al. 2007). This is probably due to a better balance between root and shoot and a greater proportion of fine roots. Larger bare-rooted and Plug+1 seedlings have more suberized roots and therefore are more likely to experience water stress (Becker et al. 1987). However, smaller seedlings have a higher probability to suffer from early summer frost events (Langvall et al. 2001) and herbivore browsing (Bergström and Bergqvist 1999) since they have a smaller shoot biomass.

Choosing the right site preparation method and seedling type is not always enough. The nutrient status of the seedlings planted and the fertility of the regeneration area has shown to be of importance for the growth response, and both are factors that can be manipulated. For example, nutrient loading of seedlings before planting in field is an alternative that may increase seedling performance (Imo and Timmer 1999), although it has been shown to be relatively short-lived (Heiskanen et al. 2009). Some experiments with slow release fertilizers applied at planting have shown positive effects on conifer seedling growth (Thiffault et al. 2005, Thiffault and Jobidon 2006). Also, the use of hydrogel or water-absorbent polymers in combination with fertilizers can be used to improve seedling performance (Del Campo et al. 2011). Broadcast application of fertilizers is a rather simple and inexpensive method that can be used to increase the fertility of the regeneration site. However, a positive response in seedling growth is many times lacking due to an increase in uptake by other herbaceous and woody species (Nordborg and Nilsson 2003, Johansson et al. 2007). In those cases, fertilization has to be combined with vegetation management; otherwise seedling growth can be suppressed rather than improved (Imo and Timmer 1999, Bergh and Willén 2006).

Although several factors can be manipulated to increase the growth of newly planted seedlings, the question remains on how close to optimal growth we are in the field. Can growth check be reduced by altering the planting environment and if so, which are the optimal combinations of silvicultural measures at different regeneration sites?

The purpose of this experiment was to study establishment and growth of different Norway spruce (*Picea abies* L. Karst.) seedling types planted in a near optimal environment, where the availability of nutrients and water was almost unrestricted and competition from vegetation heavily reduced. Knowledge about the potential growth of seedlings could be used as a reference to further improve growth-enhancing methods used in practical forestry today. It also has potential to improve modeling of early growth of Norway spruce. We hypothesized that:

1) Seedlings planted in an optimized environment grow considerably higher in comparison with seedlings planted only with ordinary site preparation.
2) Growth rate and biomass partitioning differ between seedling types.
3) In a near optimal environment, despite seedling type, growth check does not occur.
4) Seedlings in the optimization treatment grow bigger when compared to seedlings grown in other regeneration studies in the same area.

2 Material and Methods

2.1 Experimental Design

The experiment was located in the Asa Experimental Forest in southern Sweden (57°10’N, 14°47’E). The study site had earlier been used for grazing and the vegetation was dominated by grass. By using this type of site instead of a newly felled clear-cut, the risk of pine weevil damages was significantly reduced. The soil was a sandy loam and the site quality index (Hägglund och Lundmark 1981) was estimated to be a G30, which is considered to be moderately to highly productive for this region. Mean annual precipitation at Asa was 800 mm during the years of this study.

The experimental site was divided into 20 blocks of the size 4 × 10 m. In summer 2005, all blocks were prepared with the soil inversion method using an excavator. By soil inversion, the upper 20 cm of the soil was inverted and thereafter put back into the original hole, creating planting spots with bare mineral soil covering a buried humus layer (Örlander et al. 1998). Each block was hereafter split into two subplots. Two site treatments were randomly applied to the subplots, 1) control or 2) optimization. In the control treatment, the subplots were left without any further treatment. In the optimization treatment irrigation, fertilization and weed control were applied to the subplots. Irrigation and fertilization was applied by using a drip irrigation system (RAM 17D c/c 50 cm, Netafim Ltd, Israel), to which a fertilizer injector was connected (Dosmatic Inc., USA). Liquid fertilizer was applied in the proportion of 1 ml per liter water. The fertilizer used was Wallco (Cederroth Int., Sweden) with the proportion N-P-K 51-10-43 plus micro nutrients. Approximately 16.7 g nitrogen (N) per seedling was applied each growing season during three consecutive years, i.e. a total of 50 g during the experimental period. To reduce the amount of competing vegetation in the subplots where irrigation and fertilization were applied, woven polypropylene mulch (Mypex, Proturf Ltd, UK) was used to cover the soil.

In early June 2006, three different seedling types of Norway spruce were planted, (a) a 2-year-old Plug+1 seedling – grown 10 weeks in a container and hereafter transplanted to a seed bed, (mean height 22 cm), (b) a 1.5-year-old containerized seedling – grown in a Hiko 93 ml container, (mean height 25 cm) and (c) a 10-week-old mini seedling – sown in March 2006 and grown in a Hiko 50 ml container, (mean height 4 cm). The two first seedling types were dormant at the time of planting, while the mini seedlings were in growth. The seedlings were all of the same origin, from the Maglehem seed orchard (latitude 55.8°). The seedlings were planted in rows of five in each subplot, one row per seedling type and subplot. The rows with different seedling types were randomly applied to each subplot. A total of 5 seedlings × 3 seedling types × 2 treatments × 20 blocks = 600 seedlings were used in the experiment.

2.2 Measurements

2.2.1 Site Conditions

Eight soil moisture sensors (electrical resistance blocks) and eight thermo elements of the copper-constantan type were installed in the seedling root zone, i.e. 5–10 cm below ground. Four of each of the sensor types were installed in each subplot treatment, one in each of four randomly selected blocks. Furthermore, eight thermo elements (Cu-constantan with a diameter of 0.1 mm) were installed in the air 25 cm above the ground at the same place as the other sensors. All sensors were connected to a data logger (CR10, Campbell Scientific, USA). Scan interval was set to 1 minute and average values for 30-minute periods were stored from June to September.

It was both drier and warmer during the growing season the year of planting, especially in June and July, compared to the normal for the site. The precipitation during the vegetation period was 483 mm and the mean temperature in June–August was 16.8°C. The opposite conditions prevailed the second year and the precipitation during the vegetation period was 562 mm and the mean temperature in June–August was 15.2°C. The corresponding values were 482 mm and 15.1°C during the third year.

2.2.2 Seedling Growth

Seedling height, root collar diameter, top shoot length and damages were assessed on the seedlings at the time of planting and after the three first growing seasons following planting. In the fall/winter after each growing season, a random sample of seedlings, eight per seedling type and treatment, were harvested for measurements of biomass both above and below the ground. The seedlings were dried at 70°C to constant weight and dry weights of roots, stems and needles were measured.

The development of buds and new shoots on the seedlings was assessed in spring 2007 and 2008 by estimating the average for the whole seedling on the Krutzsch index, an index from 0–8 where 0 = dormant buds, 3 = bud break and 8 = fully elongated. For more details, see Krutzsch (1973).

2.2.3 Seedling Nutrition

Current year needles were sampled in October–November after the two first growing seasons and in May the year after the third growing season. Shoots were cut from eight seedlings in each of the six different treatment combinations for nutrient analyses. Before the analyses were made, the eight samples were pooled. Samples were dried at 85ºC at 48 hour before they were sent to laboratory for the analysis. At the laboratory needles were dried (70°C, 48 h) and ground in a cyclone mill (Cyclotec 1093 sample mill, Tecator, Sweden). Sub-samples were then dried under vacuum (70°C, 24 h). A part of each sub-sample was wet-digested in nitric and perchloric acid in an open digestion system and then analyzed for elements on an ICP/MS (Elan 6100, PerkinElmer, Norwalk, CT, USA). Between 4 and 7 mg of each sub-sample was weighed into tin capsules. These samples were analyzed for relative nitrogen (N) and carbon (C) content in a continuous flow isotope ratio mass spectrometer (model 20-20 Stable Isotope Analyzer, Europa Scientific Ltd, Crewe, UK) interfaced with an elemental analyzer unit (ANCA-NT solid/liquid preparation module, Europa Scientific Ltd).

2.3 Calculations and Statistical Analyses

A model for biomass based on the harvested seedlings was developed to be able to calculate biomass for all seedlings in the experiment:

$$\text{Biomass} = \beta_0 + \beta_1 \times d^2\, h \quad (1)$$

where biomass (g) was the total dry biomass (sum of root mass, stem mass and needle mass), β_0 the intercept, β_1 the parameter coefficient, d the root collar diameter (mm) and h the height (cm). The same parameters could be used for all seedling types and treatments and the R^2-value for the model was 0.90.

Nutrient concentrations were given in percent dry weight of the needle samples. The nutrient concentrations were analyzed as pooled samples for each optimization and seedling type. Therefore, only the main effects of optimization treatment and seedling type could be tested for significant differences. Needle nutrient content was achieved by multiplying the over-all nutrient concentration with the needle dry weight.

All analyses were made using SAS software (SAS Institute, USA). Analyses of variance were made with the mixed model procedure (PROC Mixed) and the following model was used:

$$Y_{ijk} = \mu + \phi_i + \alpha_j + (\phi\alpha)_{ij} + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{ijk} \qquad (2)$$

where μ is the general mean, ϕ_i is the block effect ($i = 1–20$), α_j is the main effect of the optimization treatment ($j = 1–2$), β_k the main effect of the seedling type ($k = 1–3$) and ε_{ijk} the experimental error. The interactions between block and optimization $(\phi\alpha)_{ij}$ and optimization and seedling type $(\alpha\beta)_{jk}$ were also included in the model. Optimization treatment, seedling type and their interaction were set as fixed factors, while block and block x optimization were random factors. Mean values of the five seedlings per seedling type in each subplot were calculated and used as the input values in the ANOVA analyses. Where significant treatment differences were detected, means were separated by overall pair-wise comparisons using Tukey's test. For all tests, an α-value of 0.05 was used to show significance.

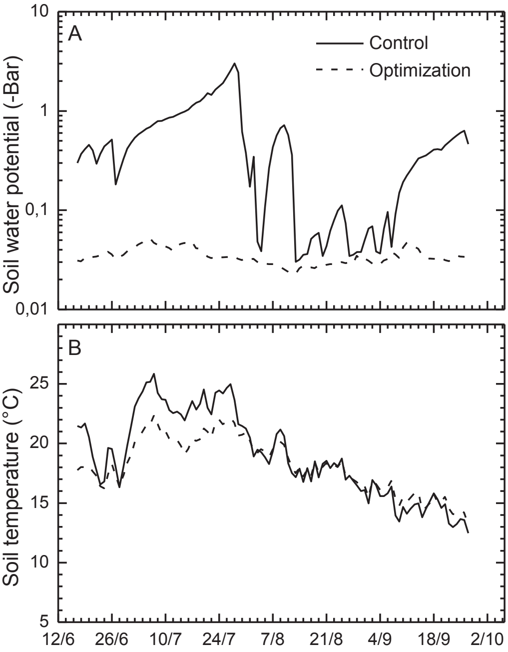

Fig. 1. Daily average soil moisture potential (A) and soil temperature (B) in the optimization treatment and the control during the first growing season.

3 Results

3.1 Site Conditions

Soil moisture conditions the year of planting were significantly ($p < 0.001$) affected by optimization treatment (Fig. 1a). The soil water potential remained stable around –0.02 to –0.08 Bar throughout the growing season in the optimization (irrigated) subplots. In the control, the soil water potential varied more and in one period in July the daily average potential reached –3 Bar.

The soil temperature was also affected by the mulch and the irrigation in the optimization treatment during the first year after planting (Fig. 1b). Compared to the control, the temperature was slightly lower in the beginning of the growing season and slightly greater in the end, resulting in a lower variation, ±2.6°C and ±4.0°C around the seasonal mean for the optimization treatment and the control, respectively. The seasonal mean temperature differed significantly ($p = 0.010$) between the treatments and was higher in the control, 18.9°C, compared to 18.1°C in the optimization treatment.

3.2 Seedling Growth

Seedling height, root collar diameter and total biomass were all significantly affected by the optimization treatment, seedling type and their interactions the first three growing seasons after planting ($p < 0.001$ for all factors). The Plug+1 and containerized seedling types were significantly higher in the optimization treatment compared to the control and the difference increased over time ($p < 0.001$) (Fig. 2a). The Plug+1 seedlings showed the greatest response in the optimization treatment, and in three years it had reached a mean height of 124 cm. After three years, the Plug+1 seedlings in the control had reached the same height, 80 cm, as the Plug+1 seedlings in

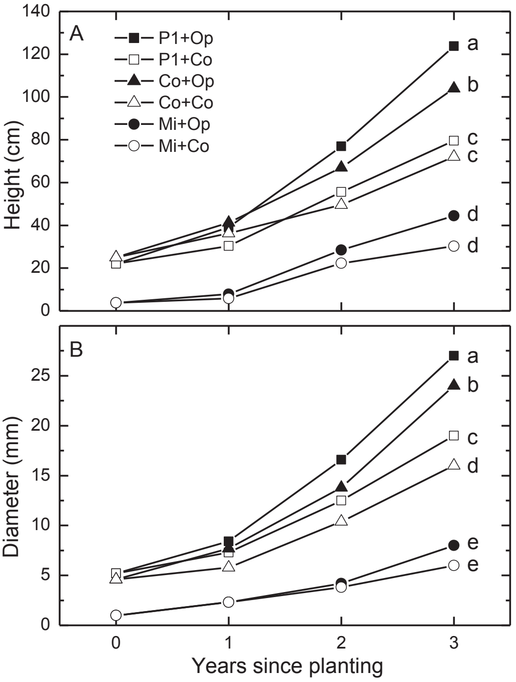

Fig. 2. Height (A) and diameter (B) development for seedlings in different treatment combinations the three first years after planting. Treatment combinations are

P1+Op = Plug+1 seedlings+optimization,
P1+Co = Plug+1 seedlings+control,
Co+Op = containerized seedlings+optimization,
Co+Co = containerized seedlings+control,
Mi+Op = mini seedlings+optimization and
Mi+Co = mini seedlings+control

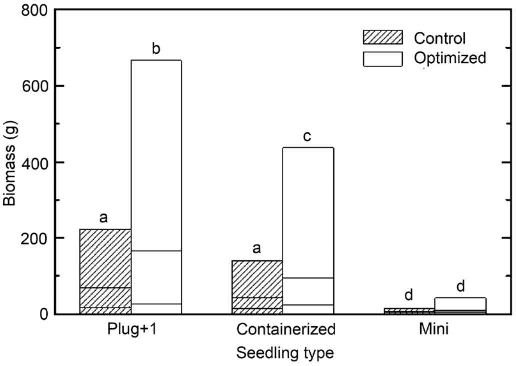

Fig. 3. Biomass of the first three years after planting for the different seedling types grown in the optimization treatment and in the control. Bars are broken into three parts, one for each growing season. Bars with different letters are significantly different after the third growing season ($p<0.05$).

the optimization treatment had reached after two years. Thus, the time gain in height growth was one year in the optimization treatment. In the control treatment, seedling height was not significantly different between Plug+1 and containerized seedlings ($p=0.738$). The survival three years after planting varied between 96–98% for Plug+1 and containerized seedling types in both treatments.

For the mini seedlings, the difference in height between optimization and control was not significant ($p=0.342$; Fig. 2a). Soon after planting, a large amount, of the mini seedlings set buds, 70% in the control and 35% in the optimization treatment. Also, the survival of the mini seedling differed between treatments. Three years after planting it was 88% in the optimization treatment and 70% in the control.

Diameter development followed the same patterns as the height development (Fig. 2b). Significant differences between the control and optimization treatment were found for the Plug+1 and containerized seedlings ($p<0.001$) but not for the mini seedlings ($p=0.363$). The greatest diameter three years after planting was obtained by the Plug+1 seedling (27 mm), followed by the containerized seedling (24 mm), both grown in the optimized environment. The difference between the optimization treatment and the control was 8 mm for both seedling types. For mini seedlings, the diameter differed 3 mm between treatments.

The biomass of all seedlings was doubled after the second growing season. After the third growing season, significant main effects of both optimization treatment ($p<0.001$) and seedling type ($p<0.001$) occurred. The biomass was three times as high in the optimization treatment as in the control for both Plug+1 and containerized seedlings (Fig. 3). No differences were found between Plug+1 seedlings and containerized seedlings in the control treatment ($p=0.168$). For the mini seedlings, the biomass was more than doubled after three years, but this difference was not significant due to large variation between seedlings ($p = 0.992$).

Table 1. Relative biomass partitioning in needles, stem and roots of three seedling types after one and two growing seasons after planting. Different letters show significant differences for each fraction and year ($p < 0.05$).

Seedling	Treatment	Relative biomass per fraction (% of dry weight)					
			1st			2nd	
		Needles	Stem	Roots	Needles	Stem	Roots
Plug+1	Optimization	34 a	35 a	31 a	29 a	39 a	32 a
	Control	30 a	37 a	33 a	30 a	39 a	31 a
Containerized	Optimization	36 a	28 a	36 a	29 a	39 a	32 a
	Control	30 a	37 a	33 a	30 a	39 a	31 a
Mini	Optimization	45 b	25 b	30 a	38 b	36 b	26 b
	Control	48 b	19 b	33 a	40 b	35 b	25 b

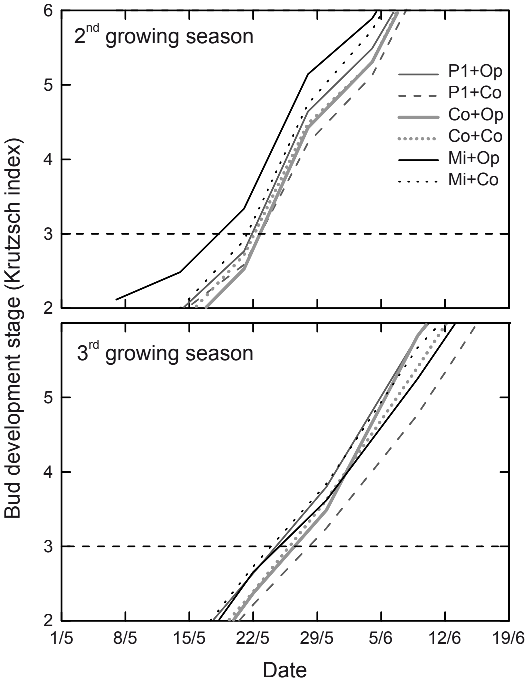

Fig. 4. Bud development according to the Krutzsch Index (Krutzsch 1973) of different combinations of seedling types and treatments. Aritmetic means of the assessed indices for each assessment date of the second (above) and third (below) growing season are shown.Treatment combinations are
P1+Op = Plug+1 seedlings+optimization,
P1+Co = Plug+1 seedlings+control,
Co+Op = containerized seedlings+optimization,
Co+Co = containerized seedlings+control,
Mi+Op = mini seedlings+optimization and
Mi+Co = mini seedlings+control.
The Krutzsch index level 3 indicates the seedling bud burst.

Biomass partitioning of the seedlings differed significantly ($p<0.001$ for all seasons and fractions) between seedling types during the first two growing seasons (Table 1). The seedling biomass at the end of the first growing season was rather evenly distributed among needles, roots and stem for both Plug+1 and containerized seedlings. The second growing season a little more of the biomass was allocated to the stem compared to needles and roots. The partitioning of biomass for the mini seedlings was different in relation to the two other seedling types, since less biomass was allocated to roots and the stem in favor for needles. No significant differences were found between the optimization treatment and the control ($p=0.443$).

Bud development and shoot elongation, assessed with the Krutzsch index, showed that mini seedlings in the optimization treatment on average reached bud break (stage 3 of the index) five days earlier than the other treatments the second growing season ($p=0.014$, Fig. 4). The third growing season, all seedling types planted in the optimization treatment broke bud earlier than seedlings planted in the control and there were significant interaction effects between seedling type and treatment ($p=0.009$). The biggest difference occurred for the Plug+1 seedlings, for which the seedlings in the control broke buds about 5 days later than in the optimization treatment. In both years, all new shoots of the seedlings had reached full elongation in the beginning of July (data not shown).

Table 2. Nutrient concentration for different seedling types and optimization treatments. The two first growing seasons are means from samples collected in fall, while values for the third growing season are from samples collected in the spring the year after.

Seedling	Treatment	1st N	1st P	1st K	2nd N	2nd P	2nd K	3rd N	3rd P	3rd K
Plug+1	Optimization	2.6	0.26	0.71	2.3	0.24	0.76	1.8	0.21	0.56
	Control	2.2	0.24	0.69	2.2	0.31	0.78	1.7	0.23	0.62
Containerized	Optimization	2.7	0.25	0.82	2.3	0.25	0.83	1.8	0.21	0.53
	Control	1.9	0.21	0.72	2.2	0.27	0.78	1.7	0.20	0.53
Mini	Optimization	2.6	0.31	1.00	2.1	0.25	1.00	1.7	0.21	0.65
	Control	2.1	0.25	0.68	1.9	0.31	0.77	1.5	0.20	0.68

Nutrient concentration (% dry weight)

Table 3. Needle nitrogen content in different seedling types and optimization treatments the first three growing seasons after planting. The two first growing seasons are means from samples collected in fall, while values for the third growing season are from samples collected in spring the year after. Different letters show significant differences for each growing season ($p < 0.05$).

Seedling	Treatment	Nitrogen content (g/needles) 1st	2nd	3rd
Plug+1	Optimization	0.21 a	1.09 a	4.52 a
	Control	0.13 b	0.44 b	1.68 b
Containerized	Optimization	0.18 a	0.63 c	3.09 c
	Control	0.10 c	0.29 b	1.00 b
Mini	Optimization	0.08 d	0.09 d	0.30 d
	Control	0.06 d	0.06 d	0.10 d

3.3 Seedling Nutrition

Overall, the N concentrations were relatively high, around 2%, in the seedlings (Table 2). The N concentration was higher in seedlings planted in the optimization treatment compared to the control at the end of the first growing season ($p = 0.042$). However, these differences leveled out the following years and only small differences (0.1–0.2%) could be found between the treatment combinations after the second and third growing season. The N-concentrations were considerably lower at the last sampling time compared to the first two sampling times. Concentrations of phosphorus (P) and potassium (K) were also rather stable over time and treatments (Table 2). After the third growing season, the K:N ratio was 0.31 for the Plug+1 seedlings in the optimization treatment and 0.31 and 0.29 for containerized seedlings in the control and optimization treatment, respectively. For all other combinations of seedling types, treatments and growing seasons, the K:N ratio was above the target value 0.35.

P+1 and containerized seedlings grown in the control and the optimization treatment differed in needle N-content (Table 3). The N-content in the needles was two times higher after the first two growing seasons and almost three times higher after the third growing season for seedlings planted in the optimization treatment compared with the control. For the mini seedlings, the difference in needle N-content also increased over time between the optimization treatment and the control, but the difference was not significant. The needle N-content followed the same pattern as biomass development, indicating a similar use of N in the seedlings among both treatments and seedling types. On average, 4.52 g N was found in the needles of the Plug+1 seedlings in the optimization treatment at the end of the third growing season, which was 10% of the amount of N added in the treatment (50 g), compared to 0.10 g in the mini seedling grown in the control with no added N.

4 Discussion

As expected, growth of seedlings planted in the near optimal environment was significantly higher in comparison with seedlings planted only in soil inversion. Site preparation usually increases growth in comparison with seedlings planted directly in untreated soil. Results from other regeneration studies made in the same area show that seedlings planted in site preparation will be one to two years ahead in height growth three years after planting in comparison with seedlings planted without any site preparation (e.g. Nilsson and Örlander 1999, Johansson et al. 2007). This study shows that seedling growth can increase even further by improving the establishment environment with irrigation, fertilization and vegetation control. After three growing seasons, the Plug+1 seedlings had almost reached breast height (130 cm), which is typically reached after 5–10 years in the same region in southern Sweden (e.g. Nordborg et al. 2006, Johansson et al. 2007). Thus, in the long run, increased initial growth of seedlings in an optimized environment during seedling establishment may result in a shorter rotation period.

Earlier bud break is another effect of a higher nutrient supply (Floistad and Kohmann 2004), that could increase growth. In this study the bud-break for seedlings in the fertilized treatment occurred up to five days earlier, which might be too small to have an effect on the total growth. Also, timing of growth cessation often occurs later in seedlings with a higher nutrient content, thus resulting in a longer growing season (Murray et al. 1994). This could have had a positive growth effect on the seedlings planted in the optimized treatment, but also increase the risk for proleptic growth (second flushing) and frost damages in fall.

It is common that the seedlings experience a growth check the first years after planting. This is especially true for larger seedlings due to a low initial quality of their root systems (Lamhamedi et al. 1998), and bare-rooted seedlings are more likely to experience water stress than containerized seedlings (Becker et al. 1987). Containerized seedlings with a well-balanced root system may not experience this type of growth reduction, and if the peat plug is well-watered, early seedling establishment can be enhanced even further (Helenius et al 2005). The results from this study indicate that growth check for large types of seedlings can be reduced if the planting environment can support the seedlings with sufficient amount of water and nutrients. The difference in height for the containerized seedlings in this study and other containerized seedlings planted in site preparation in other studies in the same area (e.g. Nilsson and Örlander 1999), was somewhat lower than the difference in height for the Plug+1 seedlings in this study compared with other studies of Plug+1 seedlings in the same area (Johansson et al. 2007). This supports the idea that an improved planting environment could have an even greater effect on larger seedling types or seedlings with low quality root systems. The survival of these two seedling types in the study was high, 96–98% after three growing seasons, indicating a low level of damages. In other studies and in practical forestry, damages caused by for example pine weevils, frost and browsing animals can affect growth of the planted seedlings considerably (Nilsson et al. 2010). Thus, to achieve fast establishment and high growth when planting it is important to improve and reduce both abiotic and biotic factors affecting seedling growth, as well as using proper regeneration methods adapted to the specific site.

The growth response of the mini seedlings was lower than expected. In earlier studies, the mini seedling has shown a high growth response when planted in favorable environments (Lindström et al. 2006, Johansson et al. 2007). In this study, the variation between seedlings was high and mainly caused by a large amount of seedlings setting buds directly after planting instead of a continuous growth throughout the first growing season. In the control treatment, the number of seedlings setting buds was higher than in the optimization treatment, which could indicate a less stressful establishment and growth environment in the latter. Also, the survival rate was lower in the control. Due to their low height at planting, the mulch in the optimization treatment covered some of the mini seedlings and eventually obstructed further height development. However, some individuals showed a great growth response indicating their potential. The mini seedlings broke bud earlier compared to the other seedling types, which is common for younger seedlings (Langvall et al. 2001), and they allocated more of the biomass to the needles instead of the root system in difference to the two larger seedling types. The delayed bud break for Plug+1 seedlings in the control the third growing season could be due to an effect of seedling age (4 years), when compared to the other seedling types. Also, a lower nutritional status could have delayed the bud burst in the control treatment. The differences in bud burst were rather small in this experiment, and had therefore probably no effect regarding the risk of suffering from early summer frosts. But, the buds can be influenced by low temperatures even before bud break, although these effects have to be further investigated according to Luoranen et al. (2010).

In this experiment, we could not separate the effects of irrigation, fertilization and vegetation control. However, only weak effects of irrigation on seedling growth have been shown in other studies (Nilsson and Örlander 2003). Problems with drought stress are probably more related to the functioning of the root system and poor establishment, which is described above, than with soil moisture content in this region. Regarding the effects of fertilization, it is very important that the applied nutrients are available for the seedlings. Several studies have shown that, when fertilizers are added to newly planted stands, the field vegetation rather than the seedlings increase in growth (Imo and Timmer 1999, Nilsson and Örlander 2003, Nordborg and Nilsson 2003, Johansson et al. 2007). Fertilization at the time of planting should therefore be combined with vegetation control or applied by a method that concentrates the nutrients to the planting spot. Also, liquid fertilizers will probably improve seedling uptake in comparison with granulated solid fertilizers.

When nutrients are limiting, the relation between roots and the shoot changes and the seedling allocates relatively more resources to the root system (Ingestad and Ågren 1991). In this experiment, allocation patterns for the seedlings did not differ between the treatments. Similar results were found by Johansson et al. (2007), where different seedling types and site preparation methods were compared. However, only root mass was determined and compared with above ground biomass. No measurements regarding fine root distribution or root system morphology were made. On the other hand, no nutrient deficiencies or unbalanced proportions were detected in any of the treatments. The increased growth in the optimization treatment was a result of a higher nutrient uptake and thus a higher nutrient content and greater needle biomass in the seedlings, which favors photosynthesis and growth (Allen et al. 1990). The lower N-concentration after the third year could be explained partly by older seedlings, and partly due to the fact that they were sampled in spring instead of fall. In spring, the concentration of carbohydrates and starch increases, and this causes a dilution effect on needle nutrient concentrations (Linder 1995). Furthermore, an improvement of the nutrient status can occur after growth cessation in fall, which also affects the comparison of seedling nutrient status between years. No signs of luxury consumption were found in this study. Instead, a balanced nutrient concentration in the seedlings in the optimization treatment showed that the seedlings were not exposed to an excess of nutrients, according to earlier findings for Norway spruce by Linder (1995). One exception was the K:N ratio that was somewhat below the target value after three growing seasons. Due to this fact, we could not state whether adding more nutrients would have further increased growth or not. We were only able to determine the total nitrogen content of the needles in this study, and of the total amount of nitrogen added at most 10% was found in the needles of seedlings. Roughly, the total amount of N in the needles corresponds to around 50% of the total N content (Nilsson and Wiklund 1994), so we can assume that only about 20% of the N added was used by the seedlings.

A high initial seedling growth is important from many aspects, both biological and economical. Newly planted seedlings are exposed to a lot of stress in terms of damages caused by insects, browsing animals, competing vegetation and climatic factors. Fast establishment and high growth will reduce the time of high vulnerability. Results from this study show that seedling growth check can be reduced by altering the planting environment. Also, the time gain due to higher growth could be used to reduce the rotation period and give earlier incomes from both thinnings and final harvest. But not only height and biomass growth are important for the seedlings. Diameter growth has shown to be very important for newly planted seedlings since a large diameter reduces the risk of damages caused by the Pine weevil (*Hylobius abietis*) (Thorsén et al. 2001). A seedling with a fast establishment and high diameter growth, in combination with other silvicultural measures that reduces the risk of pine weevil damages (see Petersson and Örlander 2003), might therefore reduce the need of chemical treatments in the plantations. Thus, the results from this study can help to improve planting measures now and in the future. For example, techniques for adding nutrients to each specific seedling in combination with site preparation would increase both survival and growth and probably reduce damages to the seedlings.

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