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Original article

Response of newly planted Norway spruce seedlings to fertilization, irrigation and herbicide treatments

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Abstract – The effect of herbicide, fertilization and irrigation treatments on growth of planted Norway spruce seedlings were investigated in an experiment established in 1998 in southern Sweden. After three years, the amount of ground vegetation was about the same in fertilized, irrigated and fertilized + irrigated plots, but the amount was about double as in the control. Seedling growth was positively affected by the herbicide treatment. Fertilization increased growth when it was combined with herbicides. Irrigation did not have any significant effect on seedling growth. Results from this study indicate that competition for water between ground vegetation and planted Norway spruce seedlings is of little importance. However, this conclusion is restricted to seedling growth during years with at least normal precipitation. It was also indicated that increased nutrient availability is positive for seedling establishment and growth, but that the planted seedlings were not growing at their potential even when herbicide, irrigation and fertilization treatments were combined indicating establishment problems.

fertilization / irrigation / herbicide / seedlings / *Picea abies*

Résumé – Effets de la fertilisation, de l'irrigation et de traitements herbicides sur de jeunes plantations d'épicéa commun. Une expérimentation installée en 1998 dans le sud de la Suède a permis d'étudier l'effet de traitements par irrigation, fertilisation et application d'herbicide sur la croissance de jeunes plantations d'épicéa commun. Au bout de trois ans, l'importance de la végétation basse était à peu près la même dans les parcelles fertilisées, irriguées ou fertilisées et irriguées, mais cette végétation était deux fois plus développée que dans les parcelles témoins. L'application d'herbicide a eu un effet positif sur la croissance des plants. La fertilisation a favorisé leur croissance quand elle était combinée avec l'application d'herbicide. L'irrigation n'a pas eu d'effet significatif sur la croissance des plants. Les résultats de cette étude indiquent que la compétition pour l'eau entre végétation basse et plants d'épicéa est de faible importance. Néanmoins cette conclusion ne peut être tirée que pour la croissance de plants au cours d'années bénéficiant d'un niveau de précipitations au minimum normal. On a également démontré que l'augmentation des ressources en éléments nutritifs favorisait l'installation et la croissance des plants. Mais ces plants utilisés en reboisement n'exprimaient pas tout leur potentiel de croissance, même en combinant les traitements par irrigation, fertilisation et herbicide, ce qui implique l'existence de problèmes de reprise après transplantation.

fertilisation / irrigation / herbicide / plantations / *Picea abies*

1. INTRODUCTION

For planted Norway spruce in southern Sweden, it has been shown that competition from field vegetation is most important during the two first years after planting and is less important for established seedlings [16]. However, it has been debated whether competition for light, water, nutrients or a combination of these factors is the most limiting factor for newly planted seedlings [12]. Knowledge about the mechanism of competition between planted seedlings and field vegetation is important when modeling seedling establishment and growth, and when introducing new regeneration methods aiming at controlling the influence of competing vegetation.

Field vegetation on many clearcuts in southern Sweden is dominated by one grass species, Hairy grass (*Deschampsia flexuosa* (L) Trin.) [3]. Mowing experiments has shown that competition for light is of minor importance when the field vegetation mainly consists of grass [16] and that is probably also true for more fertile sites where vegetation is more dense [1, 14, 17].

Water availability in the soil may be a limiting factor during dry years and competition for water from field vegetation may therefore cause mortality among newly planted seedlings [5, 13]. Competition for water varies however significantly between regions. In southeastern Sweden, spring and early summer is often dry while precipitation is frequent during most years in southwestern Sweden.

Competition for nutrients has often been overlooked as an important factor for seedling establishment and growth [12]. The availability of nutrients is usually high on clearcuts as a

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result of decreased competition from removed trees, and decomposition of slash that are retained during the logging operation [4, 7]. However, despite the high nutrient availability, several studies have indicated that nutrients might restrict seedling establishment [1, 12, 16, 18, 19, 20]. Nordborg [17] found that competition from field vegetation might restrain nitrogen uptake during the first months after planting. Therefore, fertilization at the time of planting may be a practicable way to improve seedling establishment. However, studies have shown that fertilization without vegetation control may enhance competition from ground vegetation and could be negative for seedling growth [6, 9]. Fertilization at planting should therefore probably be combined with vegetation control to ensure its positive effect on growth.

The present study aimed at investigating the relative importance of competition between field vegetation and planted Norway spruce seedlings for water and nutrients and interaction between these factors. The hypotheses tested were that: (i) water availability during the first growing season do not affect seedling growth during years with normal precipitation (ii) increased nutrient availability during the first three growing seasons after planting enhance seedling growth if the competing vegetation is controlled but not otherwise. Varying levels of water and nutrient availability was obtained by irrigation, fertilization and herbicide treatments.

2. MATERIAL AND METHODS

The study was established in 1998 in Asa Experimental Forest, about 40 km north of the city of Växjö (57° 08' N, 14° 47' E). The clearcut was one-year-old at the start of the study. The soil moisture class was mesic and the soil texture was sandy-silty till. Site index (dominant height at 100 years) was estimated to 28, corresponding to an average production of Norway spruce of about 9 m^3 ha^{-1} $year^{-1}$, which is an average value for the area. Yearly precipitation in the area is about 700 mm and it is relatively evenly distributed throughout the year.

The experimental design was randomized blocks with sub-plots (split-split-plot). Four blocks were divided into one irrigated area and one that was not irrigated. Each irrigation treatment was divided into sub-plots, which were randomly assigned untreated control and herbicide treatment. Finally, half of the herbicide/not herbicide plots was fertilized and half was not.

Fertilization was done five times each growing season. At each fertilization occasion we applied 40 kg N ha^{-1} + other macro- and micronutrients in proportion to this [18]. The herbicide treatment consisted of two applications of glyphosate emulsion (12% a.i.) per growing season or whenever necessary. All vegetation on the herbicide-treated plots was treated except for an area of about 0.1 m^2 around each seedling, which was manually weeded.

The irrigation was done with an automatic irrigation system, keeping the soil constantly moist. Irrigation was performed if there was no precipitation, ca 4–6 mm day^{-1}, early in the morning. Mean precipitation (May-Aug.) was 70 mm $month^{-1}$ in 1998 and 68 mm $month^{-1}$ in 1999. In 1998, the mean monthly irrigation was about 112 mm. Because there was a tendency for flooding in the irrigation treatment during the growing season of 1998, irrigation was reduced during 1999 and mean irrigation amounted to about 44 mm $month^{-1}$. During the growing season of year 2000, no irrigation was done.

In late April 1998, each sub-plot was planted with 14 two-year-old containerized seedlings making a total of 14 × 4 × 8 = 512 seedlings. In late April 1999, five seedlings per subplot were replaced with new seedlings of the same provenance and seedling type. These seedlings were used as a replicate in time.

For seedlings planted in 1998, height, root collar diameter and damage (pine weevils, frost, vegetation, etc.) were registered directly after planting, in June, August and November the first growing season, and in August and November the second growing season. For seedlings planted in 1999, the same measurements were done directly after planting, in August and November the first growing season and in November the second growing season. Current-year needle colour was registered in June, August and November the first growing season and in November the second growing season for seedlings planted in 1998. For seedlings planted in 1999, current-year needle-colour was registered in November the first growing season. Current-year needle-colour was recorded using a seven-point scale, where 1 is yellow-green… 5 is green… 7 is very dark green [2]. For seedlings planted in 1998, the bud development was assessed according to Krutzsch index [10] two times during the period of shoot elongation (June and August) the first growing season. Krutzsch index defines stages and score them as follows: 0 = dormant bud; 1 = bud is slightly swollen; 2 = bud is swollen (grey-green colour); 3 = burst of bud scales, tips of needles emerging; 4 = needle elongation (double bud length); 5 = first spread of needles ("painters brush"); 6 = shoot elongation (basal needles not spread); 7 = differentiation of shoot (basal needles spread); and 8 = onset of new buds.

Five seedlings per treatment, block and planting year were harvested during dormancy in 1998 and 1999. Before harvest, the seedlings were sorted according to treatment, block, planting year and diameter. Thereafter each subgroup was divided into four diameter-classes with equal amount of seedlings in each class and one seedling per diameter-class was randomly chosen for harvest. The seedlings were carefully excavated and the roots washed under running water and dried at 70 °C for 48 h. The biomass for the following fractions was determined: current-year shoots; old shoots and stem; and roots.

In August of 1998, 1999 and 2000, the amount of field vegetation was estimated through destructive harvesting of all vegetation above ground on 0.5 m^2 sample plots. At each occasion, five sampling plots were harvested in each sub-plot (with exception for herbicide-treated plots). The harvested vegetation was dried at 70 °C for 48 h prior to weighing.

During the vegetation periods of 1998 and 1999, the soil water potential 10 cm below ground was measured weekly using gypsum blocks (Soil Moisture Inc., USA). Four gypsum blocks per treatments were installed in the center of the treatment-plots.

A regression function for dry weight of seedlings was estimated from the harvested seedlings. The regression function had the form:

$$DW = 2.55 + 0.00607\ HD^2 \qquad (R^2 = 0.931)$$

where DW = total seedling dry weight, H = seedling height and D = root collar diameter.

In the analysis of seedling growth, only seedlings that were alive at the final measurement were used. The SAS general linear model for split-split-plot designs (SAS Institute Inc., Cary, NC, USA) was used to perform the statistical tests. The model was:

$$y_{ijklm} = m + A_i + B_j + (AB)_{ij} + Ck + (AC)ik + BC_{jk} + D_l + BD_{jl} + CD_{kl} + BCD_{jkl} + e_{ijkl}$$

where m is the general mean, A_i is effects of the blocks, B_j is effects of irrigation, C_k is effects of herbicide treatment and D_l is effects of fertilization. The above model was a mixed model. The Ai effect and its interactions (AB)ij and (AC)ik were regarded as random effects and all others as fixed effects. The following mean squares (MS) were

Table I. Average dry mass of ground vegetation (kg ha^{-1}) in the middle of August 1998, 1999 and 2000 for the control (C), irrigation (I), fertilization (F) and irrigation + fertilization (IF) treatments. Figures in parenthesis are one standard error of the mean.

	1998	1999	2000
C	2365 *(1186)*	3105 *(851)*	1782 *(499)*
I	3511 *(1078)*	5164 *(570)*	4105 *(704)*
F	3386 *(942)*	6394 *(837)*	6403 *(1054)*
IF	3919 *(904)*	5014 *(779)*	5484 *(1106)*

used as denominators for the fixed effects and their interactions: $MS(AB)_{ij}$ for the B_j effect; $MS(AC)_{ik}$ for the C_k and $(BC)_{jk}$ effects; $MS(e)_{ijkl}$ for the Dl $(BD)_{jl}$, $(CD)_{kl}$ and $(BCD)_{jkl}$ effects.

3. RESULTS

The growth of ground vegetation increased as a result of the fertilization and irrigation treatments (Tab. I). The dry weight of ground vegetation was significantly greater in the irrigated and fertilized plots than in the control plots during 1999 and 2000, but not during 1998. The composition of species in the field layer changed as a result of the fertilization and irrigation treatments. The control plots were mainly dominated by *Deschampsia flexuosa*, a common grass species, whereas the irrigated and fertilized plots were dominated by *Rubus idaeus* (L.), *Carex sp.* or *Urtica dioca* (L.).

There was no effect of the irrigation, herbicide or fertilization treatments on soil water potential 10 cm below ground (data not shown). Soil water potential was registered weekly during the vegetation periods of 1998 and 1999, but there was no tendency for drought in any of the sub-plots at any of the measurement occasions.

Irrigation (I) had no significant effect on seedling dry weight increment in relation to the control, and there were no significant interaction between the irrigation and herbicide treatments (Fig. 1 and Tab. II). Both for seedlings planted in 1998 and 1999, seedling dry weight one year after planting was positively affected by the herbicide treatment (H). There was a positive interaction between herbicide and fertilization, fertilization in combination with herbicide treatment (FH) positively affected seedling growth whereas seedling dry weight was not affected by fertilization only (F) (Fig. 1). The same trends could be seen already three months after planting (August). For seedlings planted in 1998, growth during the first 1.5 months was not significantly affected by the herbicide and herbicide + fertilization treatments (Fig. 1). For seedlings planted in 1998, there was a significant effect of the herbicide only treatment but there was no significant interaction between fertilization and herbicide after the second and third growing season. For seedlings planted in 1999, there was a significant interaction between fertilization and herbicide also after the second growing season. In addition, there was a significant interaction between fertilization and irrigation for seedlings planted in 1999. Seedling growth was lower than the control treatment when fertilization was combined with irrigation but not when fertilization was applied without irrigation

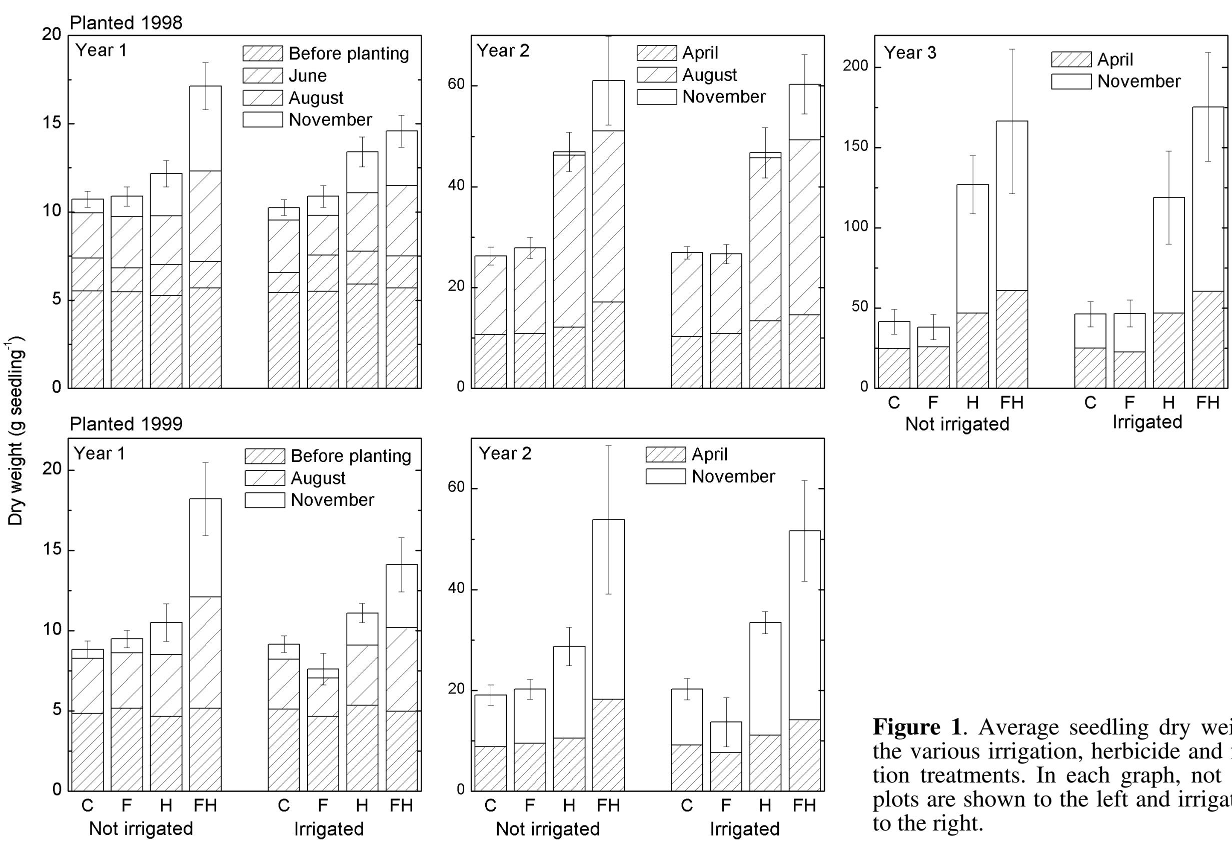

Figure 1. Average seedling dry weights for the various irrigation, herbicide and fertilization treatments. In each graph, not irrigated plots are shown to the left and irrigated plots to the right.

Table II. Probability values from the analysis of variance for seedling dry weight and length of the leading shoot for the various irrigation (I), herbicide (H) and fertilization (F) treatments.

	Seedling dry weight						Length of leading shoot		
	Year 1			Year 2		Year 3			
	June	Aug.	Nov.	Aug.	Nov.	Nov.	Year 1	Year 2	Year 3
Seedling planted in 1998									
I	0.5584	0.9373	0.5793	0.7431	0.8384	0.9202	0.1211	0.7385	0.9021
H	0.6988	0.0583	*0.0101*	*0.0241*	*0.0162*	*0.0130*	*0.0488*	0.0958	0.6493
I × H	0.7163	0.9207	0.7832	0.3776	0.2598	0.5075	0.6882	0.2123	0.7189
F	0.7528	*0.0392*	*0.0090*	0.3867	0.0985	0.1644	0.2876	0.1058	0.1698
H × F	0.6560	*0.0157*	*0.0161*	0.7815	0.1128	0.1387	0.3582	0.0909	0.3875
I × F	0.4319	0.0522	0.0823	0.8217	0.8389	0.8462	0.1287	0.8997	0.6444
I × H × F	0.1332	0.1431	0.1002	0.9911	0.9454	0.9750	0.3983	0.1878	0.3051
Seedling planted in 1999									
I		0.2099	0.1247		0.9268		0.4815	0.6142	
H		*0.0080*	*0.0049*		0.1169		*0.0286*	0.5921	
I × H		0.8323	0.8865		0.7165		0.9196	0.6354	
F		0.0723	*0.0013*		0.0765		*0.0116*	0.1830	
H × F		*0.0039*	*0.0001*		*0.0332*		0.4451	0.1945	
I × F		*0.0195*	*0.0064*		0.5551		*0.0376*	0.1101	
I × H × F		0.9087	0.4149		0.9132		0.0825	0.3279	

(Fig. 1). Seedling growth during the late part of the growing season (Aug.–Nov.) was increased by both herbicides and fertilization (Fig. 1).

The length of the leading shoot after the first growing season was positively affected by fertilization for seedlings planted in 1999, whereas the herbicide treatment affected the length of first year leading shoot negatively, both for seedlings planted in 1998 and 1999 (Fig. 2 and Tab. II). Second-year and third year leading shoot growth was not affected by any of the herbicide or fertilization treatments (Fig. 2 and Tab. II). For almost all treatments, second year leading shoot was shorter than first-year leading shoot (Fig. 2).

Needle colour index was not significantly affected by the various irrigation, fertilization or herbicide treatments (Tab. III). However, there was a tendency for a more deep green colour for fertilized seedlings at the end of the first growing season ($p = 0.0581$). There was no effect of the various irrigation, herbicide and fertilization treatments on bud development as described by the Krutzsch index (Tab. III).

Allocation of growth to roots was highest for the herbicide treatment and lowest for the fertilization treatment during the first growing season (Tab. IV), both were significantly different from the control ($p = 0.0085$ and 0.0109 for herbicide and fertilization, respectively). First-year root growth was on average less than 1.0 g seedling^{-1} for not herbicide treated plots. The corresponding growth for herbicide treated plots was 3.3 g seedling^{-1}.

4. DISCUSSION

Our results show that soil water was not the main limiting factor for early growth of the newly planted Norway spruce seedlings. This conclusion agrees with earlier studies of competition between ground vegetation and planted Norway spruce in similar climate [15, 16, 18, 20]. None of the years 1998–2000 was considered as a dry year, which is quite usual for the area. If the experiment had started during a dry year, we would have expected a greater effect of the irrigation treatment.

Notwithstanding that the irrigation treatment increased the amount of field vegetation, this treatment did not negatively affect growth of the planted seedlings as could have been expected if nutrients were limiting. Furthermore, the seedlings did not respond positively to irrigation if the competing vegetation was removed, indicating that irrigation did not increase nutrient availability for the seedlings. The increased biomass of field vegetation after irrigation might be due to a shift in species composition from grass to more densely growing herbs. Therefore, it seems reasonable that nutrient uptake in vegetation was higher in the irrigated plots. Why the increased nutrient availability in irrigated plots did not positively affect the seedlings remain to be explained.

The finding that competing vegetation reduce growth of planted Norway spruce and that herbicide treatment is an effective way to reduce this competition agrees with many other studies of Norway spruce [1, 11, 16]. However, we conclude that even though competing vegetation was removed by herbicides, availability of nutrients was still limiting seedling growth. The conclusion is based on the fact that fertilization affected seedling growth positively when combined with herbicides but not without. The ground vegetation seems to be much more efficient in taking up applied nutrients than planted Norway spruce seedlings, which is in accordance with results presented by Staples et al. [23]. The ground vegetation may act as a pool of immobilized nutrients which may be made available after canopy closure and result in improved growth

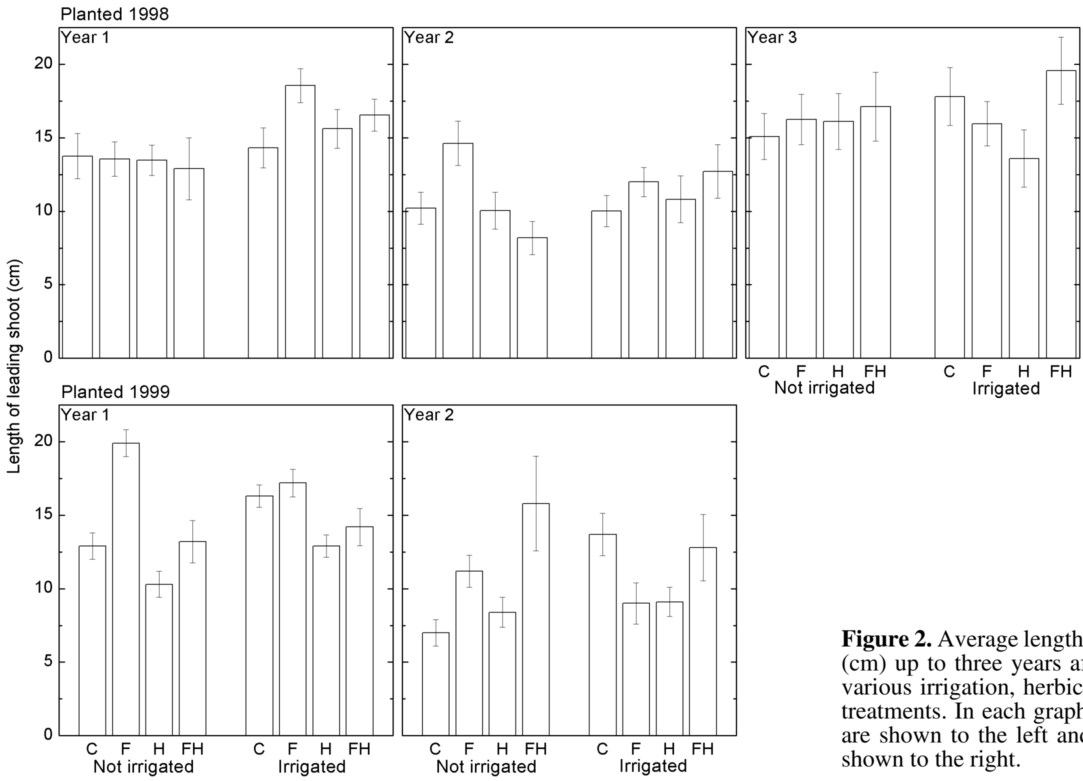

Figure 2. Average length of the leading shoot (cm) up to three years after planting for the various irrigation, herbicide and fertilization treatments. In each graph, not irrigated plots are shown to the left and irrigated plots are shown to the right.

Table III. Needle colour index (1 = yellow-green… 7 = dark-green) and Krutzsch index (1 = no bud development… 7 = shoot developed) for seedlings planted 1998 in the various irrigation, herbicide and fertilization treatments.

		Not irrigated				Irrigated			
		C	F	H	FH	C	F	H	FH
Needle colour									
Year 1	June	4.10	4.00	4.18	3.79	4.03	3.79	4.09	4.00
	Aug.	3.30	3.62	3.23	3.42	3.70	3.83	3.22	3.54
	Nov.	3.83	4.83	4.00	3.83	4.27	4.52	4.22	4.71
Year 2	Nov.	4.67	4.97	5.86	4.63	4.70	4.97	5.43	5.08
Krutzsch index									
Year 1	June	5.87	5.31	5.50	5.67	5.63	5.83	5.22	5.42
	Aug.	7.47	7.31	7.36	7.42	7.47	7.79	7.70	7.58

in future years [6]. Thus, both the irrigation and fertilization treatments might be found to be more positive if the experiment had been followed for a longer period of time. In our study it is possible that leakage of nutrients or immobilization in the soil had occurred since the amount of applied nutrients in the fertiliser treatment was much higher than what could be found in the vegetation.

Needle colour may be used as an indication of needle nitrogen concentration in newly planted seedlings [2]. There was little effect of the treatments on needle colour and that is an indication that the irrigation, herbicide and fertilization treatments did not affect nitrogen concentration of current needles. However, the total nitrogen uptake was probably affected by the treatments. Seedlings in herbicide, and especially in fertilization + herbicide treatments, probably had higher nitrogen uptake than other treatments since their needle colour (nitrogen concentration) was not diluted by the higher growth rate.

Shoot development, as described by Krutzsch index and growth of the 1998–seedlings during the first 1.5 months indicated that there were little difference between treatments in seedling growth during the first period after planting. During this time, the seedlings were probably more restricted by stress

Table IV. Average seedling dry weight (g) of current shoots, old shoots and roots, and root-shoot ratio for the various irrigation, herbicide and fertilization treatments before planting and after the first and second growing season. Standard error of the mean are given in italics

	Not irrigated				Irrigated			
	C	F	H	FH	C	F	H	FH
Before planting								
Old shoots	3.6 *0.22*							
Roots	0.9 *0.06*							
Root-shoot ratio	0.3 *0.01*							
Year 1								
Currrent shoots	3.1 *0.58*	3.6 *0.58*	4.3 *0.92*	8.8 *2.39*	2.9 *0.52*	2.8 *0.56*	4.7 *0.71*	7.3 *1.88*
Old shoots	4.1 *0.57*	4.1 *0.56*	5.2 *0.92*	7.2 *1.25*	3.8 *0.44*	3.9 *0.85*	6.5 *1.17*	7.1 *0.82*
Roots	2.4 *0.41*	1.9 *0.31*	3.3 *0.65*	5.2 *1.17*	1.8 *0.25*	1.4 *0.31*	4.2 *0.63*	4.1 *0.80*
Root-shoot ratio	0.3 *0.04*	0.3 *0.03*	0.3 *0.02*	0.3 *0.03*	0.3 *0.03*	0.2 *0.03*	0.4 *0.03*	0.3 *0.04*
Year 2								
Currrent shoots	12.0 *1.50*	16 *4.26*	24 *5.41*	32 *11.7*	10 *2.69*	8.2 *1.71*	23 *9.76*	26 *20.2*
Old shoots	16.4 *1.92*	18 *7.13*	25 *4.76*	35 *7.66*	14 *3.53*	13 *1.37*	32 *12.1*	24 *14.1*
Roots	5.6 *0.51*	8.1 *4.60*	16 *3.84*	19 *4.11*	4.8 *1.19*	4.3 *1.53*	19 *8.86*	13 *7.85*

of transplanting than by environmental constraints [5, 21]. The length of the second-year leading shoot was shorter than the first-year leading shoot for all treatments. This could be expected if there was a transplant shock, since an increasing length of the leading shoot over the years is normal if seedlings establish well [21]. Even though all competing vegetation was removed by herbicide treatment, nutrient was supplied by fertilization and water was applied by irrigation, the seedlings were still not growing at their potential. For spruce seedlings, the length of the current year leading shoot is partly dependent on conditions during shoot development and partly on conditions during bud development the year before [8]. For Norway spruce in southern Sweden, bud induction occurs in the beginning of July [18] with a rapid period of development for a period of up to six weeks [8]. The length of the leading shoot the second year after planting is therefore partly dependent on seedling establishment and resource availability during late summer the first year after planting. Therefore, one probable cause for the negative development of the length of leading shoots despite regeneration treatments was that the negative effects due to transplanting shock overshadowed changes of the environment [21]. This stresses the need examining interactions between seedling types, seedling handling and regeneration treatments in the field [22].

In conclusion, this study indicates that growth of newly planted Norway spruce seedlings is normally not restricted by water availability on clear-cuts in southern Sweden. In contrast, nutrient availability seems to be a limiting factor for seedling growth since seedling growth was positively affected by fertilization when it was combined with herbicides. However, when fertilization was done without vegetation control, there was no positive effect on seedling growth, probably because ground vegetation was more efficient to capture the added nutrients than the planted seedlings. This shows that regeneration treatments aiming at increasing below ground resources are efficient only when combined with vegetation control. Lastly, results from this study showed that even though vegetation is controlled and water and nutrients is added, the planted seedlings were not growing at their potential. This indicates a potential in improving nursery and handling practise.

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