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Arginine phosphate (ArGrow©) treatment on Norway spruce and Scots pine seedlings at different planting times and under varying planting site conditions in boreal forests

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ABSTRACT

Climate change increases the likelihood of extreme weather events and the risk of damage to seedlings. At the same time, forest growth and thus carbon sequestration should be increased to mitigate climate change. A decrease in the number of forest workers requires an extension of the planting season from the traditional spring to fall. These changes in the operating environment can also affect root growth and early performance of seedlings. Granular arginine phosphate has been developed to improve root growth of tree seedlings and may be a potential tool to improve field performance of seedlings after planting. The aim was to study the effects of arGrow® Granulat (ARG) on the field performance of Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* L.) seedlings planted at different planting dates and under different site conditions in boreal forests. Container seedlings were planted in mounds on the forest regeneration sites and under the harsh conditions in the former gravel pits in Central Finland. Pine seedlings were planted in May 2021 and spruce seedlings in May and September 2021 and in June 2022. ARG granules were added to the planting hole for half of the seedlings, while the other half remained the untreated control. In the former gravel pits, there was a lot of drought damage, more in spruce than in pine. Under these harsh conditions, ARG treatment increased root growth in Scots pine seedlings and height growth in both species when damage level was moderate. In the forest sites, the exceptionally warm and dry early summer of 2021 and severe night frosts in June 2023 damaged spruce seedlings in particular, and animals pine seedlings. The ARG treatment affected damage levels only in fall planted spruce, with slightly less severe damage in treated than in untreated seedlings. No other differences in damage levels between seedling treatments were found in forest sites. Damage found at most sites made it difficult to reliably compare seedling treatments, and differences in height between treatments varied. On sites with the least damage, ARG treatment increased seedling height of healthy seedlings in both pine and spruce, but the effects were clearer in pine. In conclusion, it is difficult to study true growth effects of ARG treatment under relevant forest conditions, but there was some evidence that arGrow® could increase seedling growth, more so in pine and under harsh planting conditions.

1. Introduction

Scots pine (*Pinus sylvestris* L.) (later pine) and Norway spruce (*Picea abies* (L.) H. Karst.) (later spruce) are the main tree species in Northern European forests. From planted seedlings 98% in Norway, 51% in Sweden and 70% in Finland were Norway spruce and the percentage of Scots pine seedlings were 45 and 27 in Sweden and Finland in 2019 (Solvin et al. 2021). After clear-cutting, most tree seedlings are planted

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in mechanically prepared soils in Nordic boreal forestry. The two most used mechanical site preparation (MSP) methods are disc trenching and mounding (Sikström et al. 2020). Disc trenching produces the continuous furrows and berms. The berms are formed from turned organic layers and it consists of a double humus layer under the uniform mineral soil cover. The mounds are also elevated planting spots, but they are either made by an excavator (Ramantswana et al. 2020) or by a continuously advancing mounder (Saksa et al. 2018). They consist of turned single or double humus layer covered by the mineral soil layer. The planting place in these mounds are like the berms in disc trenching but at single points (see Sikström et al. 2020 for more information on MSP methods). In Finland, pine container-grown seedlings are planted either in disc trenched furrows or mounds and spruce container seedlings mainly in mounds.

In Finland, the planting season is extended from conventional spring planting to whole growing season (Luoranen et al. 2005, 2006). This is needed from an operational point of view to ensure both, that all seedlings can be planted with diminishing labor resources, and that the regeneration areas can be planted as soon as possible after the clearcut. To increase the productivity of planting machines and cost-effectiveness of mechanized planting, a planting season lasting the entire growing season is also required (Ersson et al. 2018).

For rapid establishment the fast growth of roots in the surrounding soil is important (Grossnickle, 2000). Root growth of newly planted, healthy seedlings in moist, warm soils during in spring and summer is normally rapid (Luoranen et al. 2005, 2006). However, if pine or spruce seedlings are planted in September, there is no root growth before the winter (Luoranen, 2018). Due to this, root growth starts slower in the following spring, reducing the height growth of conifer seedlings planted in the fall in comparison to the summer or spring (Luoranen, 2018). The risk of abiotic damage is also greater in fall plantings compared to other planting dates (Luoranen et al. 2022).

Due to climate change the drought periods during spring and early summer has been predicted to become more common in the future in the Nordic boreal region (Ruosteenoja et al. 2018) and the risk of drought damage in the forests may increase (Venäläinen et al. 2020). This can also increase the drought damage risk of newly planted seedlings, which already occurred in Finland during the summer of 2021 (Luoranen et al. 2023). From the forest carbon sequestration point of view, clearcuts should be planted as quickly as possible, minimizing the risk of damage, and the growth of planted seedlings should be as fast as possible, so that regeneration areas can be rapidly transformed from a source of carbon into sinks. Thus, all applications or treatments that can increase root growth might help an early development of planted seedlings, especially in harsh growing conditions, and later also increase shoot growth.

Organic nitrogen (N) has been shown to enhance root growth and mycorrhizal colonization in planted Scots pine and Norway spruce seedlings when applied to seedlings in the nursery (Gruffman et al. 2012). According to Gruffman et al. (2013), if carbohydrate supply of roots is reduced for some reason (as probably in case of fall planted and poorly rooted seedlings), the roots can utilize organic N for their nitrogen nutrition. Thus, the arginine phosphate treatment at the time of planting might ensure a better establishment of newly planted conifer seedlings as roots can utilize the N from arginine phosphate. Arginine can bind to the peat and leaching is low (Öhlund and Näsholm, 2002), which makes it possible that the arginine phosphate that is added to the planting hole at the time of fall planting, is probably usable in the following spring when seedlings are starting their growth leading to improved field performance of seedlings. Under forest regeneration site conditions, the effects of arginine phosphate, and especially its commercial product arGrow® Granulat (Arevo AB, Umeå, Sweden; later used abbreviation ARG) on survival and growth of pine and spruce seedlings has differed between tree species (Häggström et al. 2023; Luoranen and Saksa, 2023), site preparation methods (Häggström et al. 2021; Luoranen and Saksa, 2023) and geographical areas (Häggström et al. 2023)

The aim of this study was to investigate the effects of arginine phosphate on the field performance of spruce and pine seedlings planted either in spring or fall and under varying planting site conditions in boreal forest conditions in Central Finland. To study these effects, i) spruce and pine seedlings were planted at the normal forest regeneration areas and to harsh conditions in former gravel pits in spring, and ii) spruce seedlings were planted either in spring, early summer or fall at forest regeneration areas. The hypothesis was that by the addition of ARG (ArGrow© Granulat) to the planting hole at the time of planting of container seedlings of both tree species i) treated seedlings grow better in normal forest conditions and ii) the addition of granules increases the survival potential of seedlings, especially in harsh conditions (gravel pits). The further hypothesis in spruce seedlings was that the advantage of the ARG treatment is greater in fall than in spring plantings, and it increases the survival potential of fall planted seedlings.

2. Material and Methods

2.1. Seedling material

Seedlings to the experiment were grown in the Saarijärvi nursery of FinForelia Oy. One-year-old pine (grown from seed-orchard seeds for Central Finland use) and two-year-old spruce (grown from seed-orchard seeds for Central Finland use) seedlings were grown in hard-walled plastic containers (Plantek PL81F, 81 seedlings per container, cell volume: 85 cm^3, surface area of a cell: 18.3 cm^2, growing density: 546 cells m^{-2}; BCC Ab, Landskrona, Sweden), which were filled with base-fertilized and limed light sphagnum peat. Seedlings were grown according to the nursery practices used in Finnish nurseries (Lilja et al. 2010). For plantings in May 2021 and September 2021, the seedlings were packed into low, grating-based seedling trays from Lännen Plant Systems in late autumn 2020, where they overwintered outdoors under the snow. For June 2022 planting, seedlings were packed in cardboard boxes in the previous fall and freezer-stored over winter until the middle of June, about 10 days before planting. Seedlings were transferred in boxes to the planting sites. All seedlings were treated chemically against pine weevil feeding in the nursery.

2.2. The establishment of experiments

Pine seedlings were planted in four and spruce seedlings in eight forest regeneration sites and both tree species in two former gravel pits in Central Finland (Fig. 1). Clear-cut had been done at least a year before planting (Table 1). Site preparation method was spot mounding (double humus layer covered by mineral soil), and it was done in the previous summer for regeneration sites planted in May 2021. Other sites were mounded in summer 2021. In gravel pits, seedlings were planted in coarse sandy soil. Pine sites (Experiment Pine21M) and gravel pits (PineG and SpruceG) and four of spruce sites (Spruce21M) were planted in the middle of May 2021. For four sites, spruce seedlings were planted in September 2021 (Spruce21S) and in the end of June 2022 (Spruce22J). The experiments Spruce21S and Spruce22J were adjacent to each other in the same regeneration sites.

The study design was a split plot with 10 blocks within each experimental site. Seedling treatments, either the addition of arginine phosphate (ARG) or the untreated control (CO), were used as randomized subplots with each block. The plot size was 12 m x 12 m. The aim was to plant 25 seedlings to each plot but due to the uneven distribution of mounds in regeneration sites, the actual numbers of planted seedlings varied between plots. A total of 2620 pine and 6140 spruce seedlings were planted. Seedlings were planted in the middle of mounds using a standard planting tube (Pottiputki, BCC AB, Landskrona, Sweden). Planting depth was 5 cm (the length of the underground part of the stem). The target was that there should have been about 10 cm intact mineral soil layer around a planted seedling.

One dose of arginine phosphate granules (ArGrow©, Arevo AB,

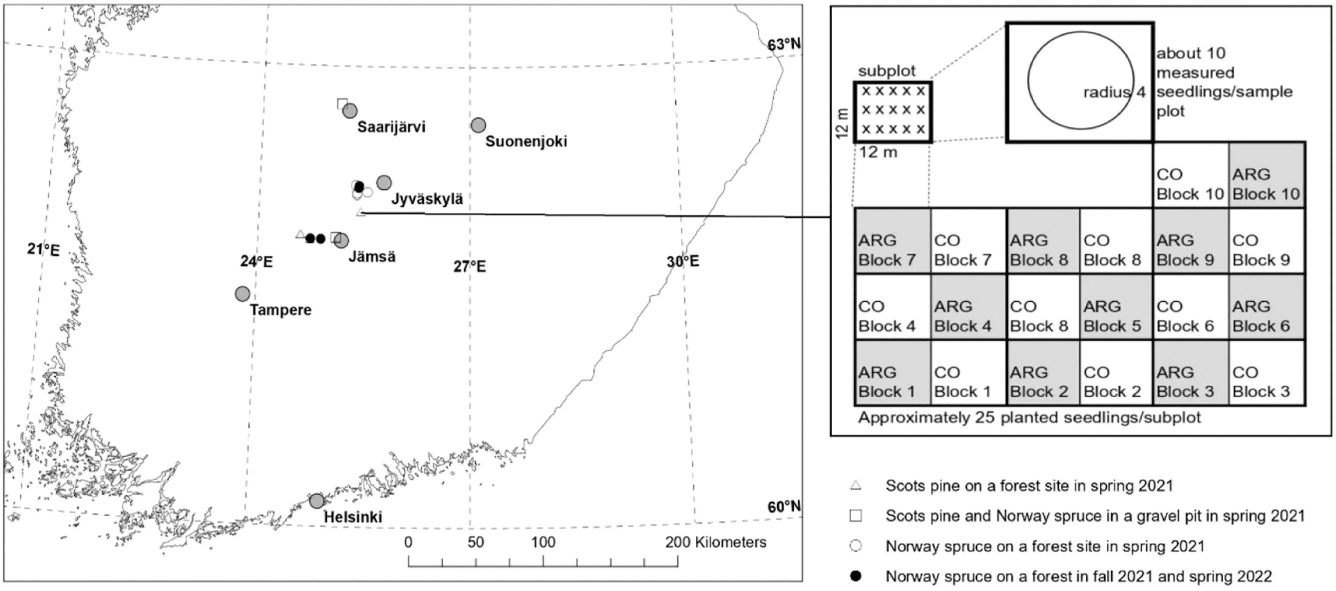

Fig. 1. Locations of experimental sites in central Finland and the experimental design of the study. Different symbols in the map indicate sites planted in spring 2021, fall 2021 or spring 2022, as well as forest regeneration sites or former gravel pits (harsh conditions) planted with either Scots pine or Norway spruce seedlings. Seedling treatments [addition of arginine phosphate (ARG) to the planting hole; untreated control (CO)] were randomized into the 10 blocks within each site. In the experimental design, there were ten blocks and two subplots within the block in each site. Within each subplot approximately 25 seedlings were planted but the real number of seedlings depended on the number of mounds within the 12 m x 12 m plot. In each plot, seedlings were measured inside the circular 4 m-radius sample plot.

Table 1
Description of the regeneration sites used in the different experiments in the study. In the site type classification, OMT is *Oxalis-Myrtillus* (mesic), MT *Myrtillus* (sub-mesic), VT *Vaccinium* (sub-dry) and CT (dry) type according to the forest site type classification of Cajander (1949) and Tonteri et al. (1990) has been applied. Month (if know) and year are presented for time of clear-cutting, mounding and planting. Soil texture type was assessed based on grain size classifying sites as coarse, medium coarse and fine. Stoniness was assessed using the classification of Viro (1952).

Experiment	Site code	Location	Tree species	Time of clear-cut	Time of mounding	Time of planting	Site type	Soil texture type	Stoniness
Pine21M	M01	Jyväskylä	pine	1/2020	7/2020	5/2021	CT	medium	normal
	M02	Jämsä	pine	10/2019	7/2020	5/2021	CT	medium	few stones
	M03	Jämsä	pine	2019	5/2020	5/2021	VT	medium	normal
	M04	Jämsä	pine	2019	5/2020	5/2021	VT	fine	very stony
PineG	M05	Jämsä	pine	-	-	5/2021	former gravel pit	coarse	few stones
	M06	Saarijärvi	pine	-	-	5/2021	former gravel pit	coarse	few stones
Spruce21M	K01	Jyväskylä	spruce	12/2018	7/2020	5/2021	MT	medium	normal
	K02	Jyväskylä	spruce	12/2018	7/2020	5/2021	MT	medium	very stony
	K03	Jyväskylä	spruce	7/2019	8/2020[a]	5/2021	MT	medium	normal
	K04	Muurame	spruce	2019	5/2020	5/2021	OMT	medium	normal
SpruceG	K05	Jämsä	spruce	-	-	5/2021	former gravel pit	coarse	few stones
	K06	Saarijärvi	spruce	-	-	5/2021	former gravel pit	coarse	few stones
Spruce21S	K07S	Jämsä	spruce	9/2020	7/2021	9/2021[b]	MT	fine	few stones
	K08S	Jämsä	spruce	9/2020	6/2021	9/2021[b]	MT	fine	normal
	K09S	Jyväskylä	spruce	8/2020	7/2021[a]	9/2021[b]	MT	medium	few stones
	K10S	Jyväskylä	spruce	8/2020	7/2021	9/2021[b]	MT	medium	normal
Spruce22J	K07J	Jämsä	spruce	9/2020	7/2021	6/2022[b]	MT	fine	few stones
	K08J	Jämsä	spruce	9/2020	6/2021	6/2022[b]	MT	fine	normal
	K09J	Jyväskylä	spruce	8/2020	7/2021[a]	6/2022[b]	MT	medium	few stones
	K10J	Jyväskylä	spruce	8/2020	7/2021	6/2022[b]	MT	medium	normal

[a] Collection of logging residues.
[b] Seedlings were planted in the same regeneration sites in the fall 2021 and summer 2022, side by side with each other within a site.

Umeå, Sweden) was added to the planting hole at the time of planting, using a dosing feeder mounted to the Pottiputki (0.4 g per seedling). The structure of the granules differed between plantings in 2021 and 2022 but in the small-scale field tests there were no statistically significant differences in shoot or root growth between these versions (data not shown). In all experiments, 40 mg of N and 22 mg of P in the form of L-arginine phosphate ($C_6H_{17}N_4O_6P$) granules were added in the planting hole. In both versions of the granules, the amount and the active ingredient was the same (L-arginine phosphate), however different binders had been used.

2.3. Measurements

In each plot, total height and height growths in current and previous years of seedlings within the circular sample plots (radius 4 m) in each plot (see Fig. 1) were measured (accuracy of 0.5 cm) at planting (not in Spruce22J), in the fall 2021 (only for sites planted in May 2021), 2022 and 2023. Seedlings for monitoring was marked with sticks. During the assessments, marked seedlings were measured in the same order every time. Seedling conditions [healthy, slightly damaged (some small needle damage that was not predicted to have any effect on the further development of a seedling), weak (browned or dropped needles, at least a part of stem alive and a seedling was predicted to be survive), dying (seriously damaged, still alive seedling was predicted to die), dead] and the damage causing agents [pine weevil (*Hylobius abietisI* L.), drought (dried, brown needles, all or a part of needles dropped off, partly or totally dried shoot; this category includes all damages that had caused the drying of needles or stems, i.e., both drought and winter damages), early summer frost (damaged new growth), frost heaving (root plug rose up from the ground), field vegetation, animal browsing (including both fowls and mammals, exact herbivore species was not recognized, and both the bud damage and stem and needle browsing), unknown reason] were also determined in the June 2022 and the falls in 2022 and 2023 from the same seedlings from which the height was measured. Damage to the leader shoot was also registered as to be healthy shoot, multiple leader or dried shoot. In one of the former gravel pits (M06, K06), some seedlings had been destroyed by the use of vehicles in the experimental field. The destroyed seedlings were not measured, and they were registered as missing values in the data. The height and seedling condition assessments were done a total of 910 pine and 2143 spruce seedlings. Stem base diameter (measured at the height of 2 cm from ground level; accuracy of 0.1 mm) of the two seedlings closest to the central stick of the sample plots were also measured in former gravel pits.

In forest sites, the quality of each mound within the sample plot was evaluated in the fall 2022 using two variables. Mound cover material was classified to be mineral soil, a mixture of mineral soil and humus (mixture) or humus. Another variable looked at was whether there were stones or logging residues under the mound that could weaken the chances of seedling survival.

To study the effects of the ARG treatment on the seedlings' morphology and especially on the root growth, two seedlings from each subplot in the gravel pit in Jämsä (M05, K05) were sampled in October 2021. A total of 20 spruce and 10 pine seedlings were dug up from the north and south side of the circular sample plots, outside of the sample plot. For the sampled seedlings, total height, current-year height growth, planting depth, stem base diameter, dry masses of current and previous year needles, stems and branches as well as roots grown out from the peat plugs (new roots) and grown within a plug (old roots) were determined. After separating the plant parts and washing of the new and old roots, samples were dried in 60 °C for 48 h. After weighing, the current-year needles of seedlings in three (or four) blocks were combined in three samples per seedling treatment for both tree species. The needles of several seedlings were pooled to get enough biomass for nutrient analysis. From the samples, the nitrogen (N) concentration was determined with a CHN analyzer (modified ISO13878 standard; LecoCN Trumac, LECO Corp., St. Joseph, MI, USA) in Luke's laboratory in Jokioinen, Finland.

2.4. Weather conditions

Weather data from the airport in Jämsä Halli Lentoasemantie (61.86°N; 24.81°E), the database (1 km x 1 km grid data) of the Finnish Meteorological Institute (FMI) and the long-term average values for monthly mean temperatures and precipitation from FMI statistics were collected. In 2021, June, July and October were warmer and July and September drier when compared to the long-term average temperatures and precipitation sums (Table A1). In August 2021, the precipitation was high, and September was colder than the average. Winter 2021–2022 as well as the winter 2022–2023 were otherwise warmer than average, but December 2021 and March 2022 were colder with lower precipitation sums. In 2022, June, August and October were warmer and June and August also drier. On the 6th of June 2023, a minimum temperature at 2 m height at the weather station of Jämsä Halli airport was 0.3°C, being equivalent to -1.3°C on ground level.

2.5. Data analysis

Statistical analysis was done separately for different experiments. Differences in annual seedling heights, height growths and stem base diameters (only in gravel pits) between seedling treatments and experimental sites within experiments were analyzed with a linear mixed model analysis (MIXED) in IBM SPSS Statistics Version 29.0.0.0 and the probability of binary variables [damage causing agents (animal, drought, frost, frost heaving, pine weevil), damaged (combined weakened, dying and dead seedlings) or serious damage (dying and dead), healthy shoot] was analyzed with a generalized linear mixed model (GLIMMIX) in SAS 9.4 for Windows. For seedling condition and damage agent variables, the fixed factors in the GLIMMIX models were seedling treatment (T), experimental site (S) and their interaction (T x S) and random factors were experimental sites, block within an experimental site, and seedling treatment within a block and experimental site. The maximum likelihood method used in GLIMMIX produces irrational results when the observed number in a group is zero: both the estimate and its standard errors are zero. Tests declare clearly significant differences as nonsignificant. To get meaningful results, zero observations were changed into one. Then meaningful results were obtained. Tests are then in principle conservative, which is quite sensible: significant differences in conservative test are more reliable than in anticonservative tests.

Damage affected the health of seedlings in the second and third growing seasons and height analysis was done using only health seedlings with healthy and normal leader shoot. Due to the damage, the number of observations varied among forest experimental sites. Variances in growth variables varied also between sites. Thus, to get more reliable comparisons between seedling treatments, differences in height, height growth and diameter (only in former gravel pits) between treatments were analyzed with MIXED models separately for each site using seedling treatment as the fixed factor and block and treatment within a block as random factors. For continuous variables, normal distribution was analyzed with the Kolmogorov–Smirnov test, and homogeneity of variance with Levene's test. In the first MIXED analysis seedlings' heights at planting between seedling treatments differed at some experimental sites and height at planting was used as a covariate in the model. Multiple comparisons were based on the Sidak method. In some cases, normal distribution was not achieved, and statistical significances in treatment differences were analyzed also by nonparametric Mann Whitney U test. A difference with a p-value of <0.05 was considered significant.

Differences in the proportions of different mound cover classes and good-quality mounds between seedling treatments within an experimental site were analyzed with GLIMMIX using block and seedling treatment within a block as random factors. Correlations and differences between seedling treatments in mound quality and mound cover classes and drought damage in 2022 were analyzed by Chii^2 and Pearson's R tests in SPSS.

Morphology samples were collected only from one former gravel pit and differences in different variables between seedling treatments were analyzed using UNIANOVA of SPSS in the case of planting depth, height at planting, total height, current-year height growth and N concentration. The variances were heterogeneous for dry masses of different plant parts, and the differences between treatments were analyzed using nonparametric Mann Whitney U test.

3. Results

3.1. Quality of site preparation in forest sites

Approximately 89% of pine seedlings were planted in mineral soil covered mounds, 7% in mounds covered by mixture of mineral soil and humus, and 4% in humus covered mounds without statistically significant differences between seedling treatments within an experimental site (Table 3). More variation in mound quality was found in spruce sites. In very stony site K02 ($p=0.020$) and very fertile site K04 ($p=0.035$), more ARG-treated than control seedlings were planted in humus covered mounds, meaning that less ARG seedlings were in mineral soil covered mounds ($p=0.015$ for K02). In the experiments Spruce21S and Spruce22J, mound cover varied between sites, but seedling treatments were planted in quite similar mounds within sites (Table 2).

Proportions of poor-quality mounds (obstacles under mounds) varied between sites (Table 3). The poorest mounds were in very stony K02 where 25% of seedlings were planted in mounds with stones under them. The best mounds were in sites M03, K07J and K09J were only 1% of seedlings were planted in poor-quality mounds. Statistically significant difference in the proportions of poor-quality mounds between seedling treatments was seen only in very stony site M04. In that site, more ARG-treated seedlings were in poor quality mounds than control seedlings ($p<0.001$).

3.2. Survival and damage in forest sites

In the experiment Pine21M, mortality and damage of seedlings were low in all sites and both treatments (data not shown). There were no statistically significant differences in the occurrence of any damage agents or seedling condition classes between seedling treatments (Table 3). Animal damage was found after the first winter especially in site M04 and damage increased also in the site M01 by the fall of 2023. These browsing damage decreased the proportion of seedlings with healthy shoots.

In Spruce21M, drought damage was more probable in ARG-treated (overall means for ARG 17% and 12.5% in the measurements in early summer 2022 and at the end of the third season) than in CO seedlings (8% and 4.5%) (Table 3). Drought damage also increased the mortality and proportions of damaged seedlings in the second and third years. More damage caused by early summer frosts was found in site K02 than in other sites and less total drought damage in K03 than in other sites.

In the experiment Spruce21S, only few seedlings with drought damage were found after the first winter, but later more drought and pine weevil feeding damage was found in fine textured site K08S than in other sites (Table 3). These damages also increased the probability of

Table 2
Proportion of seedlings planted in mounds covered by mineral soil, mixture of mineral soil and humus and humus, or proportion of seedlings planted in poor quality mounds which had stones or slashes under them. Proportions are presented for each site and treatments (the first value for control and the last one for seedlings treated with arginine phosphate). Bolded values indicate statistically significant differences between seedling treatments given by the generalized linear mixed model.

		Mound cover material			Mound quality
Experiment	Site code	Mineral	Mixture	Humus	Poor
Pine21M	M01	85/91	15/7	0/3	7/1
	M02	97/100	3/0	0/0	3/1
	M03	85/93	11/5	4/2	0/2
	M04	81/79	6/7	13/15	**4/8**
Spruce21M	K01	97/96	3/3	0/1	4/4
	K02	**92/75**	2/4	**6/21**	22/28
	K03	80/80	17/20	3/0	12/16
	K04	**90/72**	6/11	4/14	9/11
Spruce21S	K07S	85/73	15/27	0/0	15/8
	K08S	54/56	36/34	10/10	6/7
	K09S	97/94	3/6	0/0	10/3
	K10S	78/80	21/19	1/1	2/4
Spruce22J	K07J	69/58	31/40	**0/1**	1/0
	K08J	5/0	95/100	0/0	4/4
	K09J	92/87	7/13	1/0	1/0
	K10J	100/96	0/3	0/1	3/0

Table 3
Observed proportions (%) of mortality in 2022, damaged (including weak, dying and dead) seedlings and severe damage (only dying and dead seedlings) at the end of the season 2023, major damage causing agents in different inventories in control (values before slashes) and arginine phosphate treated (values after slashes) Scots pine and Norway spruce seedlings planted in forest regeneration sites in May 2021 (Pine21M and Spruce21M), September 2021 (Spruce21S) or June 2022 (Spruce22J). In the three last columns are statistical significances (p-values) of seedling treatment (T), experimental site (S) and interaction of treatment and site (T x S) given by the generalized linear mixed model. Lowercase letters indicate statistically significant ($p<0.05$) differences between experimental sites and letters in parenthesis p-values almost significant ($p=0.055$ and 0.057) in pairwise comparison.

Variable	Experimental site				Effect		
	Percentage of seedlings				T	S	T x S
Pine21M	*M01*	*M02*	*M03*	*M04*			
Animal damage in the winter 2022	$4/4^{a}$	$0/0^{a}$	$13/7^{a}$	$40/39^{b}$	0.600	**<0.001**	0.863
Animal damage in the fall 2022	$3/0^{a}$	$0/0^{a}$	$5/2^{a}$	$38/33^{b}$	0.382	**<0.001**	0.851
Total animal damage in 2023	$19/25^{a}$	$0/0^{b}$	$9/2^{b}$	$39/47^{a}$	0.632	**<0.001**	0.334
Healthy shoot in 2022	$88/89^{a}$	$97/93^{a}$	$93/96^{a}$	$69/62^{b}$	0.900	**<0.001**	0.519
Healthy shoot in 2023	$55/45^{a}$	$74/76^{b}$	$81/80^{b}$	$82/71^{b}$	0.285	**<0.001**	0.764
Spruce21M	*K01*	*K02*	*K03*	*K04*			
Mortality in 2022	0/10	0/27	0/0	6/9	**0.011**	0.214	0.119
Damaged in 2023	0/10	3/28	1/0	6/10	**0.012**	**0.047**	0.292
Severe damage in 2023	0/10	0/27	0/0	6/9	**0.015**	0.194	0.156
Drought damage in the winter 2022	7/12	21/40	0/8	6/9	**0.023**	**<0.001**	0.770
Drought damage in the fall 2022	$1/12^{ab}$	$11/28^{a}$	$1/2^{b}$	$5/8^{ab}$	**0.041**	**0.005**	0.510
Drought damage in the fall 2023	$4/12^{ab}$	$11/30^{a}$	$1/2^{b}$	$12/8^{ab}$	0.235	**0.009**	0.140
Early summer frost in 2023	$0/0^{a}$	$17/10^{b}$	$0/0^{a}$	$11/9^{ab}$	0.731	**0.003**	0.924
Healthy shoot in 2022	$90/94^{a}$	$90/77^{a}$	$99/100^{b}$	$95/93^{ab}$	0.543	**0.012**	0.390
Healthy shoot in 2023	$100/98^{a}$	$90/82^{b}$	$96/98^{a}$	$97/97^{a}$	0.994	**0.001**	0.621
Spruce21S	*K07S*	*K08S*	*K09S*	*K10S*			
Damaged in 2023	$14/10^{a}$	$42/38^{b}$	$5/0^{a}$	$2/1^{a}$	0.134	**<0.001**	0.803
Severe damage in 2023	$7/2^{a}$	$29/17^{b}$	$5/0^{a}$	$2/0^{a}$	**0.044**	**<0.001**	0.936
Drought damage in the fall 2022	$17/16^{a}$	$13/7^{ab}$	$3/1^{b}$	$5/2^{b}$	0.227	**<0.001**	0.835
Drought damage in the fall 2023	$17/17^{a}$	$13/7^{ab}$	$4/1^{b}$	$8/4^{b}$	0.068	**<0.001**	0.520
Total pine weevil feeding	$1/1^{a}$	$63/61^{b}$	$1/3^{a}$	$0/0^{ab}$	0.945	**<0.001**	0.829
Early summer frost in 2023	$15/11^{a}$	$26/31^{a}$	$0/0^{b}$	$11/13^{a}$	0.963	**<0.001**	0.770
Frost heaving	$9/8^{(a)}$	$0/0^{(b)}$	$1/0^{(b)}$	$4/0^{ab}$	0.459	**0.004**	0.800
Healthy shoot in 2023	$91/91^{a}$	$82/74^{b}$	$78/70^{b}$	$89/88^{a}$	0.253	**0.001**	0.867
Spruce22J	*K07J*	*K08J*	*K09J*	*K10J*			

(*continued on next page*)

Table 3 (*continued*)

Variable	Experimental site				Effect		
	Percentage of seedlings				T	S	T x S
Damaged in 2023	22/ 18^{a}	13/ 16^{ab}	5/4^{b}	6/6 b	0.740	**<0.001**	0.811
Drought damage in the fall 2023	65/ 56^{a}	21/ 22^{b}	9/4^{c}	5/8^{bc}	0.545	**<0.001**	0.628
Total pine weevil feeding	0/0^{a}	32/ 35^{b}	1/1^{a}	1/0^{a}	0.976	**<0.001**	0.999
Healthy shoot in 2023	65/ 49^{a}	73/ 47^{a}	90/ 92^{b}	99/ 93^{b}	**0.027**	**<0.001**	0.240

damaged and seriously damaged seedlings in that site at the end of the second growing season. Early summer frost in June 2023 damaged seedlings in all other sites but not in K09S. Frost heaving was more probable in the fine textured K07S site. In the experiment Spruce22J, pine weevil feeding damage was more probable in K08J, and drought damage in the fine textured K07J and K08J sites than in medium coarse sites K09J and K10J. Early summer frost damaged seedlings in all Spruce22J sites, but no frost heaving damage was found. For the variables described above, there were no statistically significant differences between seedling treatments in either experiment.

Drought and frost damaged the top of shoots or killed the new growth and affected the health of shoots in all spruce experiments. Differences between seedling treatments were statistically significant only in Spruce22J experiment. There were more healthy top shoots in the control than in ARG-treated seedlings. Otherwise, the differences in the proportion of healthy shoots were between experimental sites (Table 4).

There was a correlation between drought damage observed in 2022 and mound quality (all experiments combined): in good quality mounds the proportion of drought damage decreased, especially in ARG-treated seedlings (Pearson's R for ARG -0.105 ($p < 0.001$); for CO -0.034 ($p = 0.250$); overall -0.069 ($p < 0.001$). On the other hand, when mound cover was humus, the proportion of drought damage slightly increased, and again more in ARG-treated seedlings than in CO (Pearson's R: for ARG 0.087 ($p = 0.003$); for CO -0.012 ($p = 0.684$); overall 0.047 ($p = 0.023$)). In spruce experiments, there were also correlation between total pine weevil feeding damage and mound cover: in mineral soil covered mounds proportion of feeding damage decreased (-0.204; $p < 0.001$).

3.3. Seedling growth in forest sites

Although seedlings were randomly planted in different treatments, for some reason ARG-treated seedlings were slightly taller than control seedlings in all Spurce21M sites and sites M01 and K10J at planting, and height at planting was used as a covariate in height analysis in these sites. Reponses of seedlings varied between experimental sites. ARG-treated seedlings grew better than control in sites M02, K07S and K07J in the first season, in sites M02, K03 and K07S in the second and in

Table 4

Number of observations included to the analysis and statistical significances (p-values) of differences between seedling treatments given by the linear mixed model or Mann Whitney U test (p-values in brackets) for the height and height growth at planting, at the end of first, second and third (for Pine21M and Spruce21M) growing seasons in healthy Scots pine (Pine) and Norway spruce (Spruce) seedlings planted in the forest regeneration sites in May 2021(21 M), September 2021 (21 S) or June 2022(22 J). The first values for seedling numbers are for control seedlings and the last values after slashes for seedlings treated with arginine phosphate at the time of planting. For height growths, the number of observations is the same as for total height in each measurement year. Significant p-values are shown in bold.

Variable	Numbers of observation in each experimental site and p-values															
	Pine21M								***Spruce21M***							
	M01		***M02***		***M03***		***M04***		***K01***		***K02***		***K03***		***K04***	
Height at planting	67/ 70	**(0.015)**	87/ 80	0.745	54/ 55	0.164	64/ 59	0.036	70/ 69	**<0.001**	63/ 57	**(0.037)**	69/ 64	**(0.001)**	67/ 64	**(<0.001)**
Height at the end of the 1st year	67/ 69	**(<0.001)**	85/ 83	**<0.001**	55/ 55	0.107	69/ 61	0.573	70/ 64	(0.087)	63/ 41	**0.037**	69/ 58	0.195	63/ 59	**0.016**
Height at the end of the 2nd year	64/ 66	0.593	83/ 76	**(<0.001)**	48/ 52	0.325	42/ 35	0.244	63/ 56	0.635	54/ 33	0.461	67/ 55	0.121	58/ 54	0.507
Height at the end of the 3rd year	34/ 27	0.986	63/ 61	**0.034**	42/ 44	0.638	40/ 25	0.457	69/ 60	0.703	43/ 29	0.161	65/ 56	0.063	49/ 49	0.067
First-year height growth		0.115		**(<0.001)**		0.344		(0.065)		0.761		0.972		0.105		0.221
Second-year height growth		0.924		**0.046**		0.704		0.749		0.100		(0.782)		**(0.019)**		0.146
Third-year height growth		0.910		**(0.007)**		**0.037**		0.995		0.311		0.329		0.123		0.147
	Spruce21S								***Spruce22J***							
	K07S		***K08S***		***K09S***		***K10S***		***K07J***		***K08J***		***K09J***		***K10J***	
Height at planting	88/ 91	0.683	78/ 89	0.967	79/ 87	(0.064)	86/ 85	0.415		0.469		0.914		0.351		**(0.007)**
Height at the end of the 1st year	68/ 70	**(0.003)**	64/ 67	0.501	68/ 78	0.344	73/ 72	0.861	61/ 58	0.518	48/ 44	0.240	61/ 69	0.708	69/ 68	0.861
Height at the end of the 2nd year	51/ 56	**(<0.001)**	14/ 16	0.214	56/ 58	0.998	65/ 64	0.910	15/ 15	0.637	25/ 12	0.484	62/ 68	0.662	71/ 68	**0.024**
First-year height growth		**(<0.001)**		0.359		**(0.009)**		0.306		**(0.028)**		0.009		0.646		0.861
Second-year height growth		**(0.029)**		(0.058)		0.661		0.679		0.478		0.579		0.335		**0.023**

site M03 in the third season (Table 4, Fig. 2). Although the height growth of the control seedlings was statistically significantly better in site K09S in the first season, sites K08S and K10J in the second and in site M03 in the third season, the total height of the seedlings in these sites did not differ between treatments at the end of each season. Statistically significant differences in the total heights between treatments were observed in sites M01, M02, K04 and K07S at the end of the first season, when ARG-treated seedlings were 0.5, 1, 3 and 2.5 cm taller than controls, respectively. On the other hand, the control seedlings were 0.5 cm taller in site K02. At the end of the second season, ARG-treated seedlings were 4 cm taller than control seedlings in sites M02 and K07S. In addition, at the older sites M02, K03 and K04, ARG-treated seedlings were 9, 6 and 4 cm taller than controls at the end of the third season (almost statistically significantly when $p<0.07$).

Table 5
Statistical significances (p-values) of seedling treatment (T), experimental site (S) and interaction of treatment and site (T x S) given by the generalized linear mixed model for the probabilities of damaged seedlings and severe damage, and linear mixed models for the diameter (D), height (H) and height growth (HG) measured at planting, and at the end of the first (1) and second (2) growing seasons of Scots pine and Norway spruce seedlings planted under harsh conditions in former gravel pits in the PineG and SpruceG experiments. Significant p-values are shown bold.

Variable	Effect T	S	T x S
Scots pine			
Damaged	0.560	0.201	0.938
Severe damage	0.632	0.986	0.643
D_planting	0.949	0.577	0.304
D2021	**<0.001**	0.367	0.339
D2022	**<0.001**	0.063	**0.017**
H_planting	0.813	0.804	0.375
H2021	0.112	0.692	0.627
H2022	**0.001**	0.215	0.639
HG2021	**0.012**	0.730	0.833
HG2022	**0.001**	**0.038**	0.801
Norway spruce			
Damaged	0.085	**<0.001**	0.378
Severe damage	0.304	**0.002**	0.518
D_planting	0.644	0.998	0.726
D2021	0.790	0.985	0.833
D2022	0.385	0.302	0.627
H_planting	0.787	0.217	0.833
H2021	0.966	0.428	0.667
H2022	0.250	0.866	0.644
HG2021	0.732	0.927	0.438
HG2022	0.337	0.614	**0.027**

3.4. *Damage and growth of seedlings in harsh conditions*

In experiments in former gravel pits (PineG and SpruceG), 80% of spruce seedlings in site K05 and 99% in site K06 suffered from drought until the end of the second growing season. Animal damage (species not recognized) was also found in 3% of seedlings in site K05 and 9% in sites K06. Damage was more severe in site K06 compared to site K05 and there were statistically significantly more damaged seedlings and severe damages (Table 5; Fig. 3b). Differences between seedling treatments were not statistically significant for any of the variables.

Pine seedlings were healthier than spruces and less than 10% of pine seedlings were damaged until the end of the second growing season without statistically significant differences between seedling treatments (Table 5, Fig. 3a). Most damage to pine seedlings was caused by the web-spinning sawfly (10% in site M06), drought (2% in site M05 and 14% in site M06) and animal browsing (3% in site M05 and 10% in site M06). Only the differences between sites were statistically significant (p-values are not shown).

At planting, no statistically significant differences in height or diameter between sites and treatments were found (Table 5). ARG treatment increased height and diameter growth of pine seedlings (Fig. 3c, e) and they were 3 cm taller in both sites and 1.5 mm thicker in site M05 site at the end of the second growing season than control seedlings. In spruce, ARG treatment affected statistically significantly

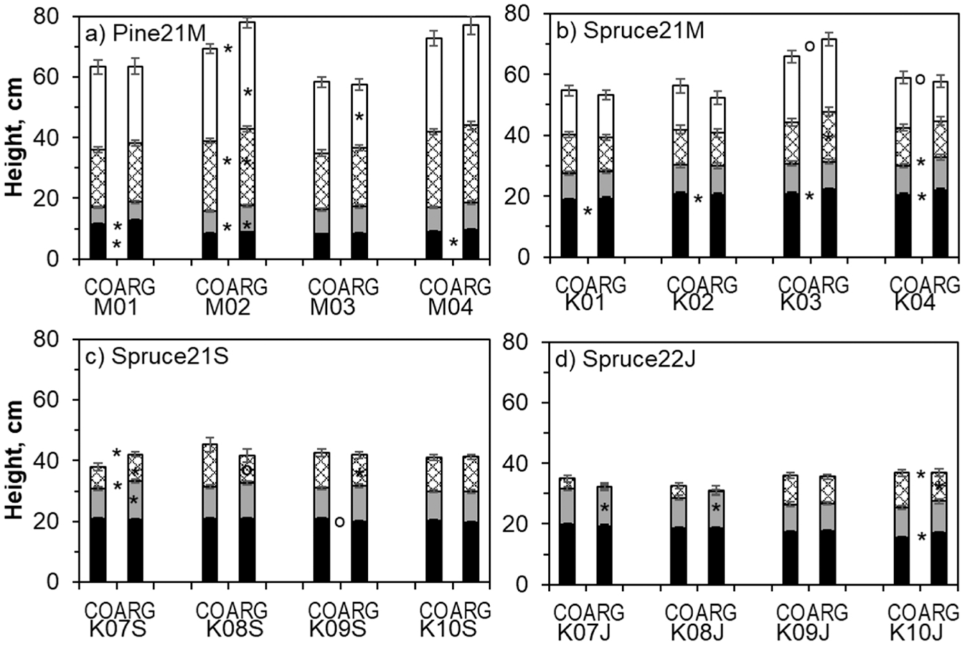

Fig. 2. Height of a) Scots pine and b-d) Norway spruce seedlings planted in a-b) May 2021 (Pine21M; Spruce21M), c) September 2021 (Spruce 21S) or d) June 2022 (Spruce22J) in four forest regeneration sites in each planting dates in Central Finland. To the half of seedlings, arginine phosphate granules (ARG) were added to the planting hole and the other half remained untreated as a control (CO). Asterisks (*) indicate statistically significant ($p<0.05$) and letter "o" almost significant ($p<0.07$) differences between seedling treatments within a site. The symbols between the bars indicate the statistically significant differences in the total height of each year and the symbols inside the bars indicate the differences in the growth of each year. Vertical bars indicate standard errors of means. Seedlings planted in June 2022 were not measured at planting.

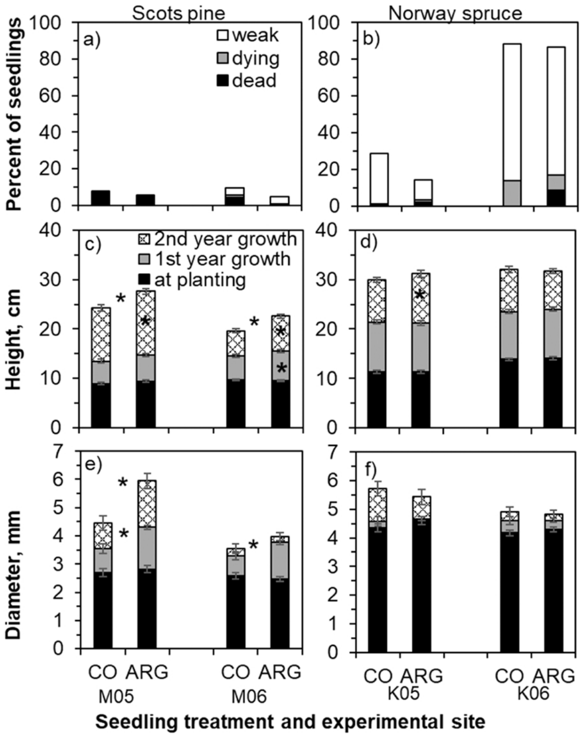

Fig. 3. a, b) Proportion of damaged (weak, dying and dead) a) Scots pine and b) Norway spruce seedlings and c, d) seedling heights (N 2–12 seedlings per treatment in 10 blocks within a tree species depending on seedling mortality) and e, f) stem base diameters (N two seedlings in 10 blocks per treatment) at planting and at the end of the first and second growing season when seedlings were planted under harsh conditions in former gravel pits. At the time of planting seedlings were planted normally (CO) or arginine phosphate-granules (ARG) were added to the planting hole. Symbols between bars are for differences in height or diameter and those within bars are for height growth between seedling treatments within an experimental site. Vertical bars are standard errors of the mean.

height growth only in site K05, where treated seedlings were 1 cm taller than control seedlings after two growing seasons (Fig. 3d).

Seedlings were sampled from M05 and K05 for morphological measurements at the end of the first season. From sampled seedlings, drought damaged especially spruces. Within tree species, there were no statistically significant differences in the drought damage between seedling treatments. Sampled seedlings were comparable in size and planted in same depth in both treatments in both tree species (Table 6). In spruce, drought damage probably increased the variation between seedlings and differences between treatments were not statistically significant in none of the measured morphology variables. In pine, ARG treatment increased height growth and the dry mass of the current-year stem and needles, and thus also the total dry mass of the shoots. Dry mass of roots grown out from peat plugs was also almost significantly greater in ARG-treated seedlings. N concentration was not statistically significantly different between treatments.

4. Discussion

4.1. General comments from data

In both establishment years, there were warm and dry periods during the summer months, in June and July 2021, and in late June 2022 (at the time of planting of the Spruce22J experiment). These periods clearly increased the drought damage, especially in spruce sites. In early June 2023, there was also a very cold period in early June that caused frost damage to fresh, succulent new growth in spruce seedlings. Animal browsing occurred at most of the pine sites. All these damage resulted in growth disturbances at the top of the seedlings and made it difficult to interpret the growth results in particular. However, some interpretations of ARG treatment effects on the field performance were possible by focusing on sites where only minor damage was found.

4.2. Drought damage

The influence of drought damage on the results was clearly seen in the gravel pit part of the study. In one gravel pit, drought damage was especially visible in spruce seedlings, but in the other one the damage levels were lower. The increased drought resistance of pine seedlings compared to spruce was also clearly seen in these gravel pit experiments, when experimental areas of tree species were adjacent: pine seedlings had less damage than spruce. Similarly in the plantings in 2021, less drought damage in pines than in spruces was found in forest sites. Results from artificial drought experiments performed in the greenhouse also support the observation that newly planted pine seedlings are more resistant to drought than spruce seedlings (unpublished results of M. Kivimäenpää). Pine is adapted to grow on drier sites than spruce, so this difference in drought tolerance, already visible at the seedling stage, is a

Table 6

Proportion of healthy Scots pine and Norway spruce seedlings planted under harsh conditions at experimental sites M05 and K05 planted in spring 2021 and sampled in October 2021, and means and their standard errors (in brackets) of morphological variables and nitrogen concentrations in untreated control (CO) and arginine phosphate treated (ARG) seedlings. P-values obtained by GLIMMIX*, UNIANOVA** or Mann Whitney U tests are also presented. Values in bold are statistically significant.

Variable	**Scots pine**			**Norway spruce**		
	CO	**ARG**	**p-value**	***CO***	***ARG***	***p-value***
Proportion of healthy seedlings, %	*80*	*90*	0.391*	5	15	0.306*
Planting depth, cm	6 (0.2)	6 (0.3)	0.118**	7 (0.3)	7 (0.2)	0.789**
Height at planting, cm	14 (0.4)	14 (0.4)	0.532**	24 (0.6)	25 (0.7)	0.662**
Total height, cm	19 (0.5)	20 (0.5	0.172**	34 (0.9)	36 (1.4)	0.406**
Height growth, cm	**5 (0.3)**	**7 (0.3)**	**0.014****	10 (0.5)	11 (1.2)	0.474**
Diameter, mm	3.1 (0.1)	3.4 (0.1)	0.060	4.6 (0.1)	4.8 (0.1)	0.314
Dry masses, g						
- Old stem, g	0.49 (0.03)	0.56 (0.04)	0.183	2.49 (0.18)	2.58 (0.21)	0.659
- Current-year stem	**0.14 (0.01)**	**0.22 (0.01)**	**<0.001**	0.67 (0.05)	0.79 (0.08)	0.314
- Old needles	0.67 (0.03)	0.67 (0.05)	0.925	1.70 (0.09)	1.71 (0.15)	0.862
- Current-year needles	**0.75 (0.08)**	**0.96 (0.06)**	**0.017**	1.89 (0.13)	1.99 (0.17)	0.602
- Total mass of shoot	**0.63 (0.04)**	**0.78 (0.05)**	**0.035**	3.16 (0.22)	3.37 (0.27)	0.620
- Old roots	0.41 (0.02)	0.46 (0.04)	0.445	1.45 (0.12)	1.48 (0.11)	0.495
- New roots	0.16 (0.02)	0.23 (0.03)	0.063	0.56 (0.05)	0.62 (0.06)	0.478
- Total mass of roots	0.57 (0–04)	0.69 (0.04)	0.165	2.01 (0.16)	2.09 (0.16)	0.620
Nitrogen concentration, %	1.52 (0.05)	1.57 (0.05)	0.527**	0.67 (0.01)	0.81 (0.09)	0.100

natural response, although less often studied under comparable conditions.

In our study, ARG treatment increased the proportion of drought damage in spruce seedlings planted in the spring 2021. In this experiment, more ARG-treated seedlings had been planted in poor quality mounds consisting of humus instead of mineral soil. We also found a significant correlation between mound cover and drought damage, such that the probability of drought damage increased with decreasing proportion of mineral soil cover mounds (i.e. increasing proportion of humus mounds). In the other studies, the humus mounds have been very susceptible to abiotic damage, such as summer drought and winter damage (Luoranen et al. 2018, 2023). Therefore, the difference between treatments in this case was probably caused by the structure of the planting place and not by the ARG treatment.

4.3. Growth of seedlings

The quality of the mounds probably affected the differences in height at planting between seedlings treatments as ARG-treated seedlings were more often planted in mounds with stones or logging residues underneath. These obstacles could prevent seedlings from being planted deep enough, resulting greater height at planting when measured from the ground. Differences in planting depth were so small that they did not affect the further development, although deep-planted spruce seedlings have been observed to grow better in later years (Luoranen and Viiri, 2016). The planting place itself may be more important if stones can prevent proper water and nutrient uptake. Logging residues in the rooting zone can bind N and negatively affect seedling growth (Hallsby, 1994, 1995). This complicates the comparison of seedling treatments in our study.

The most reliable growth comparisons between seedling treatments can be made in the gravel pits, although also in there the drought damage may have affected the growth of the seedlings. Previously, Turtola et al. (2003) observed that drought reduced the growth of pine and spruce seedlings in the second season after drought. In our study, the growth of both species was less pronounced in the gravel pit, where the damage was more intense in the year of planting. In these dry conditions, ARG treatment increased both height and diameter growth of pine seedlings in both places two years after planting. the height growth of ARG-treated spruce seedlings also increased in the gravel pit with less drought damage. The height growth of ARG-treated pine and spruce seedlings also increased in the forest sites with low level levels of damage. In the other sites, the differences between seedling treatments were small. In a few sites, control seedlings and some other sites ARG-treated seedlings grew slightly better without clear trends. Only healthy seedlings were included to the statistical analysis and when damage levels were high, the number of observations varied a lot between treatments and sites, being extremely low in some cases. This cause uncertainty to the growth results in most of experimental sites.

Morphological measurements in the gravel pit at the end of the first growing season showed evidence of better root growth of ARG-treated seedlings was found in pine, but not in spruce. Similarly, in the study of Luoranen and Saksa (2023), there was better root growth of pine seedlings in unprepared soil but not in mounds, and no effects were found in spruce seedlings. Larger root systems of pine seedlings probably explained the better height growth of seedlings in the second year observed in gravel pits and in the second and third years observed in forest sites with low levels of damage. Similarly to the study of Luoranen and Saksa (2023), ARG treatment increased the shoot dry mass in pine but not in spruce.

The varying effects of arginine phosphate on the growth of conifer seedlings corresponds to other studies. Häggström et al. (2021, 2023) found small positive effects on growth in some sites and none in others. As in our study, the different types of damage to planted seedlings in the studies of Häggström et al. (2021, 2023) made it difficult to make proper growth comparisons under forest conditions. The study by Luoranen and Saksa (2023) was conducted under controlled conditions, and in that study the height growth of pine and spruce seedlings treated with arginine phosphate was slightly better in pots simulating unprepared forest soil and in spot mounds. As a conclusion of this and earlier studies, it seems that positive effects of the product used, the increased growth of conifer seedlings are easier to detect under harsher conditions, i.e., gravel pits in our study, and clearer for pine than spruce seedlings. However, all published studies are conducted under forest conditions and include a high proportion of damaged seedlings, which may easily miss any relevant growth effects of arginine phosphate. In our study, the follow-up period was two or three years after planting and differences in growth more pronounced in older experiments. Thus, the longer monitoring period is probably needed, also with respect to the question whether arginine phosphate affects the recovery of seedlings from damage.

4.4. Pine weevil feeding damage

Häggström et al. (2023) found a higher proportion of pine weevil feeding damage in pine seedlings treated with arginine phosphate in southern Sweden with a high pine weevil population. In our study, a high proportion of pine weevil feeding damage was only observed at one spruce site with no differences between seedling treatments. In our study, there was at least one growing season between clearcut and planting which is known to reduce the probability of pine weevil feeding (Örlander et al. 1997; Örlander and Nilsson, 1999; Luoranen et al. 2017). Why the pine weevil feeding was high in site K08 is unclear. In this site, the percentage of feeding damage was higher in seedlings planted in the fall than in seedlings planted in June, corresponding the observations of Wallertz et al. (2016) that the risk of pine weevil damage is higher in seedlings planted in the fall.

4.5. Animal damage

Animals caused a lot of damage to pine seedlings. We found no differences between seedling treatments. Previously Häggström et al. (2023) found less browsing damage in spruce and pine seedlings treated with arginine phosphate in northern Sweden, but more in spruce in southern Sweden. In our case, most of the damage was bud damage, probably caused by bank voles or fowls, while Häggström et al. (2023) thought it was caused by deer browsing. Animal damage can occur very occasionally in different regions, so it is not possible to draw very far-reaching conclusions about differences in results between studies.

4.6. Fall vs. spring planting

In fall-planted spruce seedlings, the probabilities of drought and severe damage were smaller in ARG-treated seedlings than in control ones. This suggests that ARG treatment may enhance the root growth of fall-planted seedlings the following spring and help seedlings better withstand drought and warm conditions, as observed in our study in 2022.

Early summer frost damage was more common in fall-planted seedlings than in June-planted seedlings, but the difference in planting dates may be an artefact. A lot of drought damage was also observed in June planted sites at the end of the second season. When needles and stems of seedlings were already dead in winter, proper flushing and frost damage caused by night frost in early summer was not possible. However, the difference in drought damage between planting dates within the same experimental sites was true and it was probably caused by the rather late planting date of seedlings in June 2022. The proportion of drought damaged seedlings was higher especially in the experimental site with fine textured soils. There were damages in both fall and June planted parts, but more and more severe damages were in the June planted parts.

Seedlings planted in June were freezer-stored and were not growing at the time of planting. In other studies, the risk of drought-like shoot damage was increased when freezer-stored seedlings were planted in late June and early July (Luoranen et al. 2022). If the remaining growing season is too short, the seedlings do not have time to grow and harden properly before winter (Hänninen et al. 2009). The accumulated temperature sum in 2022 was low compared to other years, and the growing season ended quite early when temperatures in September 2022 were lower than average. Seedling measurements in October 2022, after the first growing season at these experimental sites, did not show large differences between planting dates or no exceptionally high proportions of damage in seedlings planted in June. Thus, the shoots of the seedlings were probably damaged by the winter weathers. The reason, why shoot damage was more likely to occur on fine textured sites than on medium coarse textured sites in both fall and June plantings may be due to frost heaving. Frost heaving can cause seedlings to rise in mounds and cut the roots, exposing the seedlings to drought. In our study, frost heaving was found in fall-planted seedlings but not in June-planted seedlings. However, this does not mean that freezing and thawing of the soil could not have moved the root system in the mounds in the fine-textured soil, even if the root plugs did not rise to the soil surface. This could have cut the roots, preventing proper water and nutrient uptake during the growing season and increasing the effects of drought damage.

5. Conclusions

The effect of arginine phosphate on the survival potential was small in years with exceptionally warm and dry early summers when there was a high proportion of drought damage especially in spruce sites. In healthy, undamaged seedlings, arginine phosphate increased seedling height two to three years after planting especially in pine seedlings, but also to some extent in spruce seedlings. Arginine phosphate had a mild protection effect against severe damage in spruce seedlings planted in the fall. A late spring planting date and the resulting damage made it difficult to compare the effects between planting dates and does not provide a clear answer to our hypothesis whether arginine phosphate is more useful in fall planting than in spring planting. Arginine phosphate had no effect against animal browsing, pine weevil feeding or drought. We received some evidence of increased root growth in seedlings treated with arginine phosphate, but to clarify its effects on growth and recovery of damaged seedlings in later years, we would need a longer monitoring period.

Role of the funding source

The study was undertaken in cooperation with Natural Resources Institute Finland (Luke), Arevo AB, FinForelia Oy, and Metsähallitus Metsätalous Oy. People from Arevo AB and FinForelia Oy participated in the establishment of the experiments and data collection according to the study design together with people from Luke. Authors from Luke made the study design, analysis, and interpretation of data, wrote the first draft of the report and decided to submit the article for publication.

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CRediT authorship contribution statement

Timo Saksa: Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Jaana Luoranen:** Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Timo Salminen:** Writing – review & editing, Investigation, Conceptualization. **Regina Gratz:** Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jaana Luoranen reports financial support was provided by Arevo AB. Jaana Luoranen reports financial support was provided by FinForelia Oy. Jaana Luoranen reports financial support was provided by Metsähallitus Metsätalous Oy. Timo Saksa reports financial support was provided by Arevo AB. Timo Saksa reports financial support was provided by Fin Forelia Oy. Timo Saksa reports financial support was provided by Metsähallitus Metsätalous Oy. Regina Gratz reports a relationship with Arevo Oy that includes: employment. Timo Salminen reports a relationship with Fin Forelia Oy that includes: employment and equity or stocks. Timo Salminen: Fin Forelia Oy is a nursery company, but also one of Arevo AB's products' retailers in Finland. Jaana Luoranen and Timo Saksa: The study was carried out as a collaborative study, with other participating organisations supporting the work done at the Natural Resources Institute of Finland (Luke) financially through the Luke project. However, Luke was the main funder and the research design, the work instructions, the analysis of the results and the first version of the manuscript, as well as the decision to publish the manuscript, were all made by Luke staff.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122012.

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