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Positive effects of wood ash fertilization and weed control on the growth of Scots pine on former peat-based agricultural land – a 21-year study

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Highlights

- Weed control decreased and fertilization increased vegetation height and shading of seedlings.
- Weed control decreased mortality, but fertilization had no effect.
- Despite improved foliar K concentration though ash fertilization, all trees in the trial had severe K deficiency after 21 years.
- Weed control increased growth by 20 m^3 ha^{-1} and fertilization by 35 m^3 ha^{-1} in 21 years.

Abstract

The impacts of weed control, ash fertilization and their interaction were tested for the afforestation of former agricultural peat-based soil with Scots pine (*Pinus sylvestris* L.) in northern Finland in a factorial arrangement of four treatments. Weed control with herbicides was carried out in July 1 and 2 years from planting, and wood ash (5 Mg ha^{-1}) was applied in the spring of the 2nd year. Various vegetation, tree growth and nutrient assessments were made over the 21-year study period. Weed control decreased the weed cover by 36–56 percentage points, vegetation height by 4–26 cm and thus shading of seedlings by vegetation for at least 4 years after planting. For the same period, ash fertilization increased vegetation height by 6–15 cm and shading of seedlings. Weed control reduced seedling mortality by 27 percentage points in 21 years, but ash fertilization had no significant effect. Ash fertilization increased foliar potassium and boron concentrations, but its effect declined, and severe K-deficiency was recorded 21 years after planting. Up to the 9th year, weed control had a greater influence on growth than fertilization. Later the significance of fertilization increased due to an aggravated K-deficiency. Stand volume at year 21 for the untreated control plots was 8 m^3 ha^{-1}. Weed control and fertilization increased stand volume by 20 and 35 m^3 ha^{-1}, with a combined effect of 55 m^3 ha^{-1}. The effects of weed control and fertilization were additive and no significant interactions were found. Due to severe K-deficiencies, re-fertilization of all treatments would be necessary for the continued survival and growth of Scots pine.

Keywords agricultural soil; fertilization; overgrowth; potassium deficiency; production potential; shading; vegetation management; *Pinus sylvestris*
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1 Introduction

The area of peat-based agricultural fields (organic matter content > 40%) in Finland under cultivation was estimated to be over 500 000 ha in 1950. Fifty years later this area had decreased to 85 000 ha (Myllys and Sinkkonen 2004) due to field afforestation and the change of soil type, resulting from the decomposition of organic matter and its mixing with underlying mineral soil in shallow-peated agricultural fields. At the end of 1960's, state funds were made available to support field afforestation as one of the means of reducing the area of land under cultivation so as to reduce agricultural surpluses (Selby 1990). Afforestation focused on low-yielding fields, which were often former peatlands (Mustonen 1990; Petäjistö et al. 1994; Selby and Petäjistö 1994). Afforestation has resulted in a significant land-use change in Finland since the end of 1960's, the current total afforestation area being 267 980 ha (Official Statistics of Finland 2016). Moreover, a large area of uncultivated agricultural land is under slow natural succession. Due to changes in agricultural policy, annual afforestation areas have been decreasing since the turn of the century (1314 ha in 2013).

During afforestation, tree seedlings compete with other species for space, light, water and nutrients. The morphological diversity of these different species, combined with their modes of competition, results in varying levels of competition for these resources, both in space and time. The impact of competition on tree growth is generally greater on sites with a higher productive capacity (Little and Rolando 2008; Rolando and Little 2009), as well as on sites with historical anthropogenic inputs (including former agricultural lands) (Little and Rolando 2008; Little et al. 2007; McCarthy et al. 2010). This increase in competition may result in increased seedling mortality, poor tree form due to overgrowth, delayed stand development and reduced timber volume (e.g. Wagner et al. 2006; Willoughby et al. 2009; Watt et al. 2014).

Agricultural practices may alter the soil physical and chemical status, such that any imbalances need to be corrected when converting from annual to slower growing forest stands (Wall 2005). For example, agricultural practices have been found to compact soil, increase the pH and phosphorus and calcium concentrations of the former tillage layer (Wall and Hytönen 1996; Hytönen and Wall 1997; Hytönen and Ekola 2003). These changes can be long-lasting, with nutritional and floristic differences detected after decades or even centuries in afforested agricultural lands (Koerner et al. 1997; Dupouey et al. 2002; Falkengren-Grerup et al. 2006; Ritter et al. 2003; Wall and Hytönen 2005; Plue et al. 2008). In addition, the repeated application of agricultural practices (mechanical, cultural and/or the use of agricultural pesticides), may result in a weed complex that is adapted to rapid and vigorous growth in a disturbed environment, as well as an increased weed seed bank (Paatela and Erviö 1971; Törmälä 1982; Kiirikki 1993).

European studies dealing with early post-planting years have documented the effects of weed competition on plantation establishment and seedling growth (Willoughby et al. 2009). In North America, South Africa, South America, New Zealand and Australia, 30–500% increases in stand volume have been reported following various weed control treatments (Wagner et al. 2006). According to Balandier et al. (2006) the competition process is never constant in time or space. In addition the longevity of the gains in growth and yield through the management of vegetation may be inconsistent (Amner et al. 2010), especially as the benefits of weed control can diminish as seedlings grow and become more competitive. In the review by Wagner et al. (2006), the time span of the European studies was less than 10 years. Subsequent studies have shown that the effects of weed control on stand growth may remain for at least 10–15 years (Hytönen and Jylhä 2005, 2008, 2011; Jylhä and Hytönen 2006; Stokes and Willoughby 2014). Although natural forest regeneration may fail on former agricultural lands due to intensive competition, stands can be successfully established by planting, provided the competing vegetation is adequately managed.

Globally, afforestation is increasingly being favoured as a means of C-sequestration (e.g. Winsten et al. 2011; Holubík et al. 2014). To meet European Union targets for reducing greenhouse gas emissions, Finland has focused on substituting fossil fuels with wood-based fuels. In 2015, 8.3 million m^3 of forest chips were used for energy production. This increased consumption of wood biomass also increases ash production. Wood ash contains plant-derived nutrients in the form of basic elements, which can act as liming agents reducing soil acidity, and as a fertilizer by supplying nutrients to plants (Huotari et al. 2015). Nitrogen is lost during the combustion of the wood chips, however most agricultural soils are rich in nitrogen bound in the organic matter and do not require nitrogen fertilization (Paavilainen 1977; Hytönen and Wall 1997; Hytönen and Ekola 2003). However, wood ash contains phosphorus and potassium (Silfverberg 1996), the two key nutrients which limit the growth of peatland forests (Moilanen et al. 2010). In Finland, the utilisation of ash as a forest fertilize is regulated by the Fertilizer Product Act (539/2006) and related decrees, which specify the permitted minimum concentrations for P, K and calcium (Ca), as well as maximum concentrations for harmful heavy metals. Deficiencies of potassium and also boron, indicated by foliar analyses, are typical of trees growing on former afforested agricultural peat soils (Ferm et al. 1992; Hytönen and Ekola 1993; Hytönen and Wall 1997; Hynönen and Makkonen 1998). Fertilization experiments using wood ash on nitrogen-rich peatland forests have resulted in long-lasting (30–50 years) improvements in tree nutrient status and the growth of forest stands (Silfverberg and Hotanen 1989; Moilanen et al. 2002, 2004, 2005, 2015). In addition, the application of wood ash as a surface, broadcast application for afforestation of former agricultural land is cost-effective and does not require more advanced technology. However, any additional nutrient inputs onto a site could result in increased competition from other species and thus lead to an increased need for weed control.

In the present study we determined the long-term effects of wood ash fertilization and weed control on the development and nutrition of Scots pine (*Pinus sylvestris* L.) on peat-based agricultural land. The follow-up period covered 21 years.

2 Material and methods

2.1 Experimental design

A wood ash fertilization and weed control experiment was established on former agricultural land located in Vuolijoki, Northern Ostrobothnia (64°05´N, 25°58´E). The peat-based soil had a mean organic layer depth of 0.7 m (range 0.4–1.5 m). During agricultural cultivation, mineral soil (silt loam: sand 17%; silt 66%; clay 16%) had been spread over the peat layer to improve soil quality. The field was abandoned in 1971 and remained uncultivated for 19 years. During this period, any natural regeneration of trees were confined to the edges of drainage ditches. Topsoil (0–10 cm) of the unfertilized plots contained 5100 kg ha^{-1} of total nitrogen (N), 980 kg ha^{-1} phosphorus (P), 140 kg ha^{-1} potassium (K), 1030 kg ha^{-1} calcium (Ca) and 180 kg ha^{-1} of magnesium (Mg) and 1.0 kg ha^{-1} of boron (B) (Hytönen 2003). The amounts of acid ammonium acetate extractable P, K, Ca and Mg in the top soil were 5, 35, 580 and 110 kg ha^{-1} respectively (Hytönen 2003).

In October 1990, the site dominated by grass vegetation, was mounded in preparation for planting. Three-year-old bare rooted Scots pine seedlings (ca. 15 cm in height) were planted on the mounds in early June 1991, aiming at a planting density of 3000 seedlings ha^{-1} recommended for afforestation of former agricultural lands (Metsänhoitosuositukset 1989), but actually resulting in an average of 2900 seedlings ha^{-1}.

The trial consisted of a two-level factorial experiment where two factors were replicated four times on plots 450 m^2 in size (15 × 30 m) and arranged in a randomised complete blocks design. The two main factors and their levels were weed control (weed control carried out: WC; no weed control: NWC) and ash fertilization (fertilizer applied: F; no fertilization: NF). The four treatments were 1) untreated control (NWC + NF), 2) fertilization only (NWC + F), 3) weed control only (WC + NF), and 4) both fertilization and weed control (WC + F). The weed control plots received a broadcast application of foliar active glyphosate (Roundup®, 360 g a.i. l^{-1} applied at 7 l ha^{-1}) and soil active terbuthylazine (Gardoprim®, 500 g a.i. l^{-1} applied at 3 l ha^{-1}) in July 1991 and the treatment was repeated in July 1992. The herbicides were mixed and applied with a knapsack sprayer. Tree seedlings were protected from spray drift with inverted cones. Manual application of wood ash (5 Mg ha^{-1}) was carried out one growing season after planting of the seedlings, in April 1992. The ash application resulted in an addition of 48 kg ha^{-1} of P, 124 kg ha^{-1} of K, 1010 kg ha^{-1} of Ca, and 75 kg ha^{-1} of Mg.

2.2 Measurements

Two circular sample plots (100 m^2) were established within each treatment plot. Scots pine height (h) was measured from years 1 to 10, with both tree heights and diameters at breast height (d) measured at years 10, 16 and 21. The stem volumes of trees measured in the sample plots for years 16 and 21 were computed using the model of Laasasenaho (1982). Causes for treatment-related damage occuring to tree were recorded at years 1, 2, 3, 10, 16 and 21. Of the variates assessed, only browsing (by moose) and damage through the overgrowth of deciduous trees on mounds (years 16 and 21) were observed at levels such that the data could be analysed and interpreted.

The assessment of tree vigour and stem form (years 1, 2, 3, 10, 16 and 21 after planting) allowed for the determination of the number of trees having adequate development potential for future growth (stems ha^{-1}).

Five circular sub-sample plots (1 m^2) for vegetation observations were established within each sample plot of 100 m^2 (4 on the circumference, 1 in the centre). Within these, vegetation cover, the mean height of the ground vegetation as well as the three main weed species were visually estimated during the 2nd, 3rd and 4th growing seasons after planting. In the inventories conducted in the 2nd and 3rd year, the potential impact of overgrowth and shading by vegetation within a 0.3 m radius around each seedling was scored representing 0, 25, 50, 75 and 100% shading.

To determine the nutritional, treatment-related responses of Scots pine, foliar samples were taken in years 4, 8 and 21 during the dormant season. The foliar samples were taken from the top whorls of five trees in each plot, from the south-facing side of each tree. The samples were dried to constant mass at 70 °C and ground. Nutrient analysis involved microwave digestion of the ground needles in $HNO_3 + H_2O_2$ solution (CEM MDS2000 Microwave Digestion System). The N concentration of the needles was measured using the Kjeldahl method (Halonen et al. 1983). The concentrations of P, K, Ca, Mg, Fe, Mn, Zn, Cu and B were then analyzed using inductively coupled plasma (ICP).

2.3 Statistical analyses

Analysis of variance (ANOVA), appropriate for a 2 × 2 factorial design was used to test for the effects of weed control and fertilization and their interaction on stand volume. A repeated measures ANOVA was used for those variables which were measured on several occasions during the study period. An arcsine transformation was carried out for the variables which were expressed as a percentage. Prior to analysis, the assumptions underlying a valid analysis were checked. Where the assumption of sphericity (according to Mauchly's test) had been violated for the repeated measures ANOVA, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. All statistical analyses were carried out using IBM SPSS Statistics 22 software.

3 Results

3.1 Vegetation

The most common species occurring on the site after afforestation were *Deschampsia cespitosa* (L.) P. Beauv., *Agrostis* spp., *Epilobium* spp., *Rumex* spp., *Ranunculus* spp. and *Juncus* spp. Two growing seasons after planting, 50% of the species occurring in the untreated control (NWC+NF) plots, and 29% of those growing in the WC plots were grasses. The grasses became more abundant with time, and when assessed at year 4, the proportion of vegetation occupied by grasses was 92 and 59% in the untreated control and weed control plots respectively. Ash fertilization did not alter the weed composition.

There was an increase with time in the abundance and height of the vegetation (Fig. 1A and 1B). WC decreased vegetation cover ($p=0.031$), but neither F ($p=0.684$), nor WC × F interaction ($p=0.300$) had a significant influence on vegetation cover. Vegetation cover differed significantly between the assessment years ($p=0.003$), but the WC × year interaction was not significant ($p=0.070$). WC decreased the vegetation cover by 36, 43 and 12 percentage points (absolute percentage difference) in years 2, 3 and 4 (Fig. 1A).

Both WC ($p=0.016$) and F ($p=0.044$) had a significant impact on the vegetation height (Fig. 1B). WC reduced the mean vegetation height by 21, 19 and 6 cm in years 2, 3 and 4, resulting in a significant ($p<0.001$) reduction in the shading of seedlings.

Fertilization increased the mean vegetation height by 6, 9 and 15 cm in years 2, 3 and 4 (1, 2 and 3 growing seasons after wood ash fertilization). This resulted in a significantly higher ($p=0.028$) number of seedlings that were shaded (>50%) (Fig. 2A). There was no interaction between the main factors (WC × F) ($p=0.470$). WC significantly reduced the number of Scots pine seedlings impacted (shading and/or overgrowth) by deciduous trees (birches and willows) ($p=0.005$), but

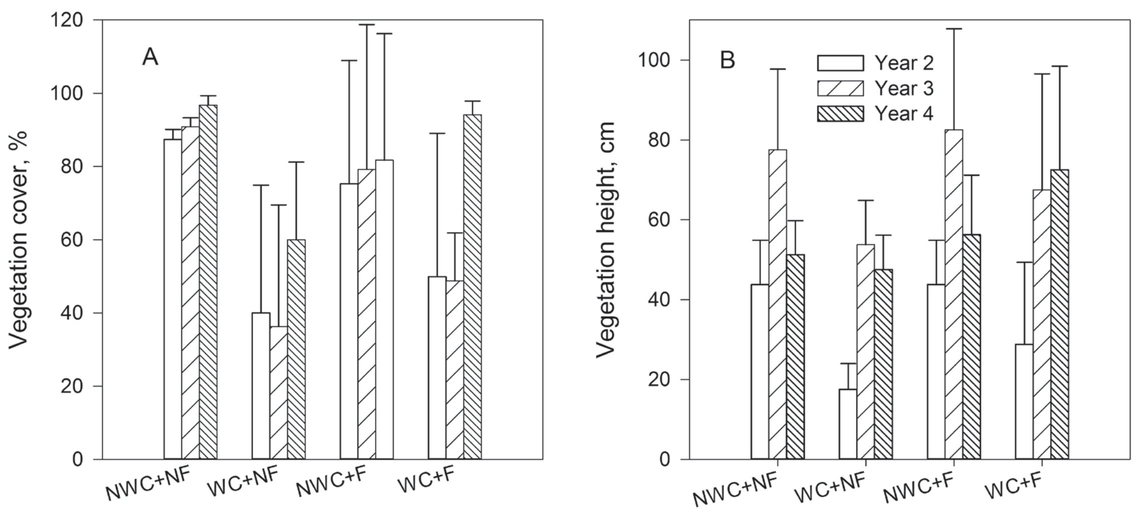

Fig. 1. Development of vegetation cover (%) (A), and height (cm) (B) over time. Bars indicate standard deviation. NWC = no weed control; WC = weed control; NF = no fertilization; F = fertilization.

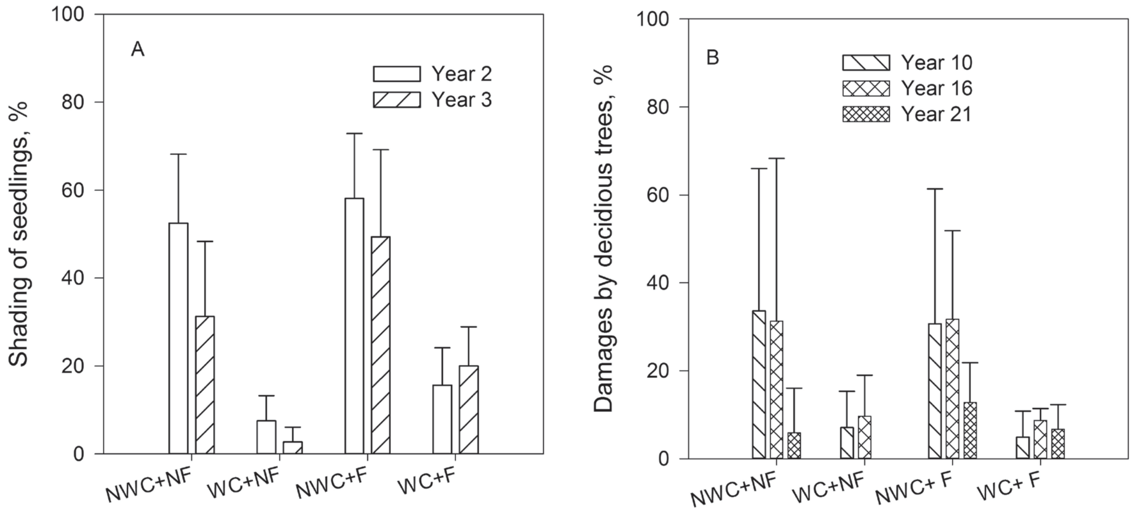

Fig. 2. The influence of vegetation in terms of shading (%) (A), and damage by broadleaved trees (%) to Scots pine seedlings (B). Bars indicate standard deviation. NWC = no weed control; WC = weed control; NF = no fertilization; F = fertilization.

fertilization had no effect (p = 0.475) (Fig. 2B). Relative to the NWC plots, there was a mean reduction of 26, 22 and 6 percentage points in the share of Scots pine seedlings impacted by deciduous trees 10, 16 and 21 years from planting.

3.2 Mortality and damage

During the first two years, seedling mortality was low, with no significant differences detected between treatments (Fig. 3). In year 3, highly significant differences ($p < 0.001$) in mortality

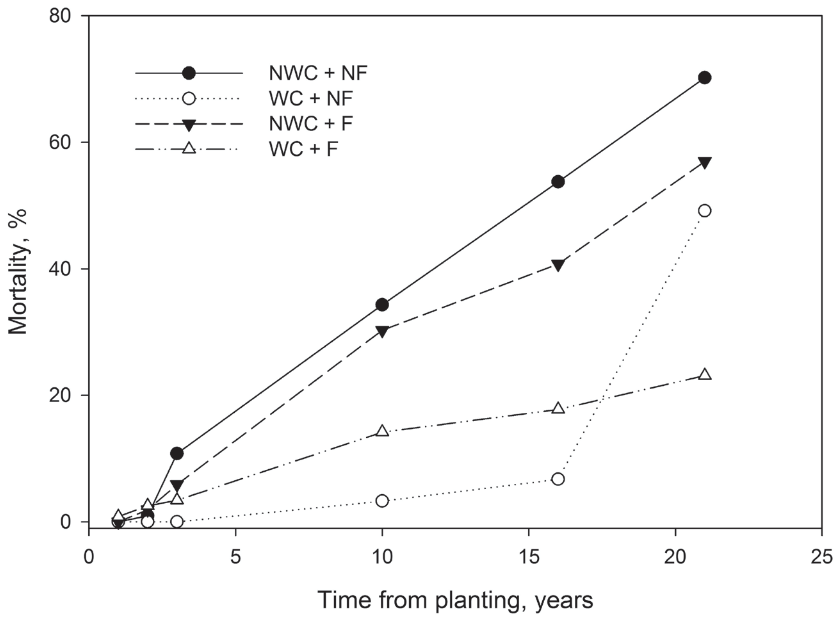

Fig. 3. Changes in Scots pine mortality (%) over time by treatment (NWC = no weed control; WC = weed control; NF = no fertilization; F = fertilization).

were detected, with the lowest mortalities (0% and 3%) recorded on the herbicide-treated plots (WC+NF, WC+F). In year 10, seedling mortality in the plots without WC varied from 30–34%, but remained low in the WC+NF plots (3%). However, when WC was combined with F, mortality increased to 14%. When analysed using repeated measures ANOVA, a significant increase in mortality over time was detected for the whole trial ($p<0.001$). The main effect of WC had a significant effect on mortality ($p=0.001$), but fertilization ($p=0.862$) and the WC × F interaction ($p=0.100$) did not. Mortality in the plots that did not receive any herbicide increased from 34% in year 10 to 54% and 70% in years 16 and 21. Mortality was reduced by applying herbicide, by 7, 24, 35 and 27 percentage points in years 3, 10, 16 and 21 (Fig. 3). In addition there was also a significant WC × year interaction ($p=0.007$), indicating changes in mortality in the WC and NWC treatments over time. The higher increase in mortality in the WC+NF plots from years 16 to 21 could probably be attributed to nutrient deficiency.

Although browsing by moose (mostly side branches) was detected in the trial (39% of the trees showing symptoms of browsing in year 10, declining to 12% in year 16 and to 5% in year 21), analysis of the browsing assessments indicated that this was not treatment-related.

3.3 Height, diameter and volume of trees

Both WC ($p=0.045$) and F ($p=0.017$) affected Scots pine height but there was no WC × F interaction. In addition, there was a significant F × year interaction ($p<0.001$), indicating changes in the effect of fertilization over time. The main effect of WC on Scots pine height increased from 27 cm in year 5, to 49, 82 and 94 cm in years 10, 16 and 21 (Fig. 4A). The initial and smaller impact of F on height (6 cm year 5, 40 cm year 10), relative to WC, remained till year 10, after which the main effect of F, relative to WC, increased over time being 135 and 272 cm in years 16 and 21. The combined effect of WC and F was 365 cm at year 21. There was a significant impact of F on diameter at breast height ($p=0.011$) but not for WC ($p=0.246$) (Fig. 4B). There was also a significant F × year interaction ($p=0.019$) indicating that the effect of F decreased with time.

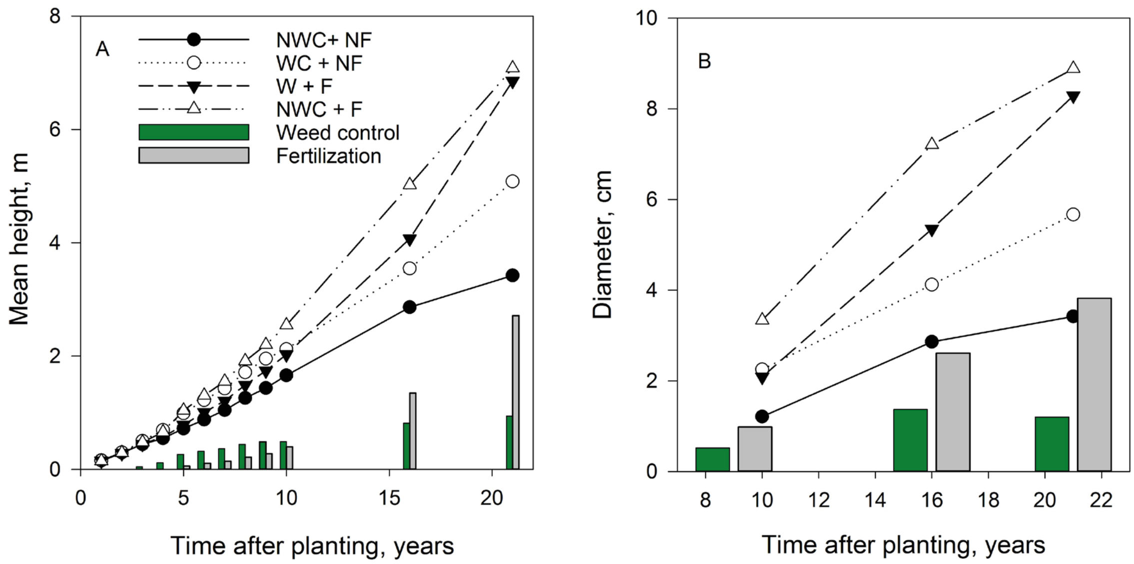

Fig. 4. Changes in Scots pine height (m) (A), and diameter at breast height (cm) (B) over time. Bars show the factorial main effects of weed control and fertilization. NWC = no weed control; WC = weed control; NF = no fertilization; F = fertilization.

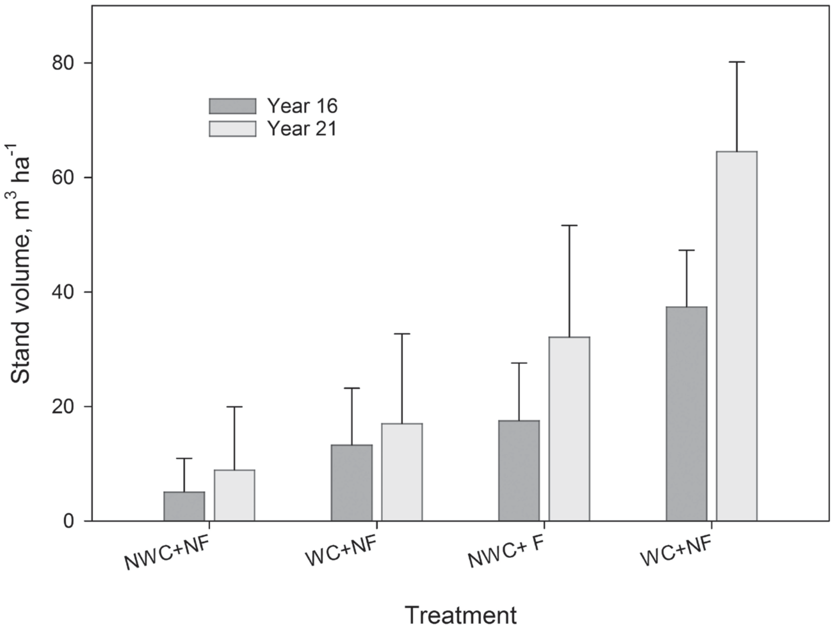

Fig. 5. Scots pine stand volume (m^3 ha^{-1}) at years 16 and 21 by treatment (NWC = no weed control; WC = weed control; NF = no fertilization; F = fertilization).

Both WC and F had a significant and positive impact on Scots pine volume when assessed at years 16 and 21, with F having a greater impact than WC (Fig. 5). At year 16 the volume of the NWC+NF treatment was 5 m^3 ha^{-1}, and that of NWC+F treatment, 37 m^3 ha^{-1}. Weed control (WC) increased stand volume by 14 m^3 ha^{-1} and F by 19 m^3 ha^{-1}, with a combined effect of 33 m^3 ha^{-1}. Five years later (year 21), all treatment volumes had increased, with the highest volume recorded for those treatments that were fertilized (NWC+F 33 m^3 ha^{-1}, WC+F 65 m^3 ha^{-1}), and the lowest for the NWC+NF treatment (9 m^3 ha^{-1}). At 21 years, WC had increased stand volume by 20 m^3 ha^{-1}, and F by 35 m^3 ha^{-1}. Compared to the NWC+NF treatment, applying fertilizer and carrying out weed control resulted in a 7.2 fold stand volume production by year 21.

3.4 Development potential of trees

Both WC ($p=0.005$) and F ($p=0.009$) had a significant effect on the number of trees assessed as having good development potential (Fig. 6). There was no interaction for the main effects of WC and F ($p=0.607$), however the significant WC × year interaction ($p=0.021$) indicated a change in the impact of WC over time. Weed control (WC) increased the number of trees estimated to have good development potential up to year 16 by 1138 ha^{-1}, with a subsequent decline from this time due to an increase in mortality. For the WC+NF treatment, the number of trees with good development potential decreased from 2200 trees ha^{-1} in year 16 to 1000 trees ha^{-1} in year 21. At year 21 the number of trees with good development potential was 2300, 1175, 1000 and 625 ha^{-1} for the WC+F, NWC+F, WC+NF and NWC+NF treatments, respectively.

3.5 Foliar nutrient status

With the exception of N (16 g kg^{-1}), Fe (22 mg kg^{-1}) and Cu (3.2 mg kg^{-1}), there were significant treatment-related variations in the Scots pine foliar nutrient concentrations between sampling events

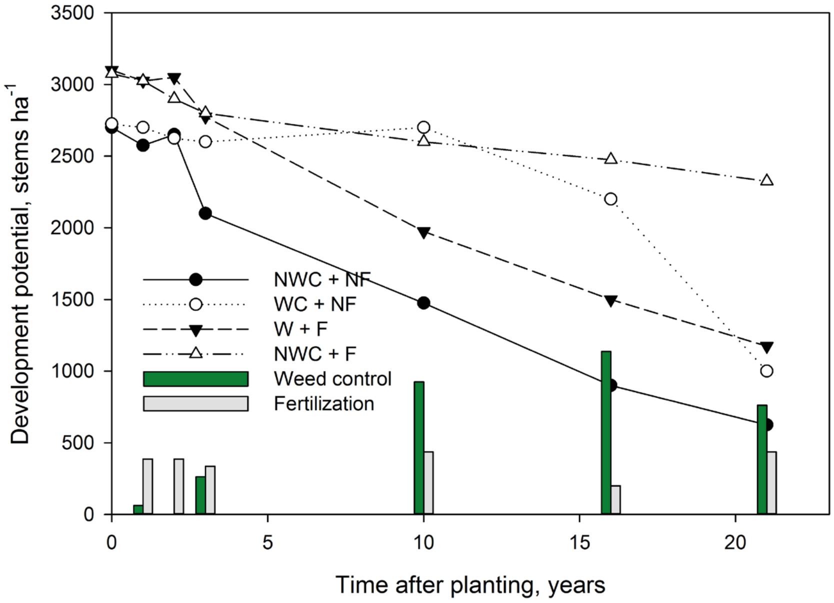

Fig. 6. Changes in Scots pine trees exhibiting good development potential (stems ha^{-1}) by treatment. The bars show the factorial main effects of weed control and fertilization. NWC = no weed control; WC = weed control; NF = no fertilization; F = fertilization.

(Table 1). The foliar P-concentrations in all treatments and over all the sampling events exceeded 1.4 g kg^{-1} and were above the deficiency limit (Paarlahti et al. 1971; Reinikainen et al. 1998). WC ($p=0.019$), but not F ($p=0.863$) resulted in a small, but significant increase of 0.03 to 0.16 g kg^{-1} in foliar P-concentrations (Fig. 7).

Even though F resulted in a significant increase in foliar K-concentration ($p=0.036$), this benefit declined over time from 0.7 g kg^{-1} to 0.3 g kg^{-1} by year 21 (Fig. 7). In addition, foliar K-concentrations decreased in all treatments over time (Fig. 7). Despite the initial elevated K-concentrations in the fertilized plots (NWC+F, WC+F), the levels (2.8 g kg^{-1}) recorded at year 21 were close to those recorded on unfertilized plots (2.5 g kg^{-1}) and K deficiency was considered severe on all plots according to Paarlahti et al. (1971) and Reinikainen et al. (1998).

Table 1. The effect of weed control and fertilization on Scots pine foliar nutrients in a trial established on a peat-based, former agricultural land, northern Ostrobothnia, Finland. "Year" indicates changes in nutrient concentrations over time. Values marked in bold are significant at $p<0.05$.

Variable	Weed control	Fertilization	Weed control × Fertilization	Year	Year × Weed control	Year × Fertilization	Year × Weed control × Fertilization
N	0.590	0.227	0.443	0.182	0.728	0.941	0.445
P	**0.019**	0.863	0.207	**0.000**	0.384	0.166	0.129
K	0.392	**0.036**	0.831	**0.000**	0.157	0.184	0.782
Ca	0.428	0.439	0.602	**0.001**	0.106	**0.001**	0.254
Mg	**0.039**	0.280	0.588	**0.000**	**0.001**	**0.005**	**0.002**
Mn	0.824	0.123	**0.046**	**0.000**	0.661	**0.001**	0.686
Fe	0.485	0.532	0.898	**0.000**	0.790	0.847	0.912
Cu	0.272	0.880	0.124	**0.011**	0.373	0.743	0.574
Zn	0.851	**0.020**	**0.002**	**0.008**	0.148	0.049	0.698
B	0.806	**0.001**	1.033	**0.000**	0.061	**0.001**	0.341

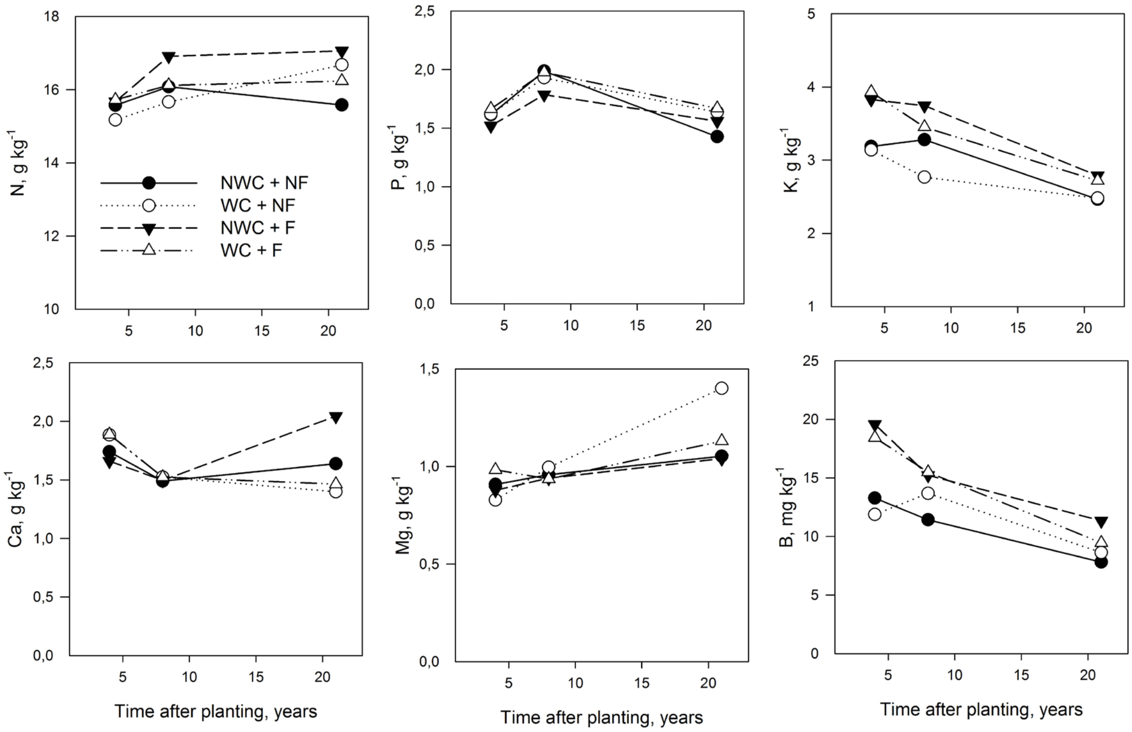

Fig. 7. Changes in Scots pine foliar N, P, K, Ca Mg and B concentrations by treatment (NWC = no weed control; WC = weed control; NF = no fertilization; F = fertilization).

Magnesium concentrations tended to increase over time for all treatments (Fig. 7), with a small, but significant increase associated with weed control ($p=0.039$). Neither WC or F affected Ca-concentrations, however there was a significant F × year interaction due to a decline in Ca-concentrations in those treatments that received ash application.

Boron concentrations decreased over time for all treatments. F increased B-concentrations ($p=0.001$), but the initial benefit (6 mg kg^{-1} at year 4) associated with fertilization had declined by year 21 to 2 mg kg^{-1}. The final mean B concentration (9.0 mg kg^{-1}) was considered to be below the optimum level for Scots pine grown on peat-based soils (Fig. 7) (Reinikainen et al. 1998).

4 Discussion

4.1 Site properties and foliar nutrient concentrations

The surface layer of soil in this trial had similar amounts of total N, P and Ca to those reported earlier for afforested peat-based agricultural soils (Ekola and Hytönen 1993; Wall and Hytönen 1996), but higher than those recorded in drained peatland forests (Kaunisto and Paavilainen 1988; Kaunisto and Moilanen 1998; Laiho and Laine 1994, 1995). The Scots pine foliar N and P concentrations were above deficiency limits for all treatments, and mostly within the optimum range (N 15–16 g kg^{-1}; P 1.6–2.0 g kg^{-1}) (Paarlahti et al. 1971; Reinikainen et al. 1988) as reported also in other studies (e.g. Ferm et al. 1992; Hytönen and Ekola 1993). The reason for the high P concentrations was probably the residual carryover from the application of fertilizers containing P during the agricultural use of the site.

Although the amounts of total and acid ammonium extractable K and Mg were lower than those observed from studies on similar sites, they were still higher than in drained peatland forests (Kaunisto and Paavilainen 1988). The addition of mineral soil, as on this site, has been observed to increase the topsoil bulk density, ash content and most nutrient levels, but not N, Ca or B (Wall and Hytönen 1996; Hytönen and Wall 1997). Since the mean depth of the peat layer on the site was as deep as 0.7 m, mounding inverted the soil and most likely brought nutrient-poor peat from deeper layers to the top of the mounds, thus decreasing the amount of plant available K for the seedlings growing on the mounds.

Foliar K-deficiencies have been reported for Scots pines planted in peat-based agricultural soils (Ferm et al. 1992; Hytönen and Ekola 1993; Hytönen 2003). In year 4 the Scots pine foliar K-concentrations (4.0 g kg^{-1}) were already marginally deficient (Paarlahti et al. 1971; Reinikainen et al. 1988). In accordance with other studies, ash fertilization increased foliar K concentrations (Silfverberg and Issakainen 1987; Silfverberg and Hotanen 1989; Moilanen et al. 2015). Regardless of fertilization (F vs. NF), foliar K-concentrations continued to decrease with time and were considered to be severely deficient at year 21 (F plots = 2.8 g kg^{-1}). Low K concentrations can lead to increased mortality (Kaunisto and Tukeva 1984). Re-fertilization with fertilizers containing K would be required for maintaining survival and growth of trees on sites such as this.

Trees growing on former agricultural land have been shown to be susceptible to growth disorders associated with B-deficiencies (Veijalainen 1983; Ferm et al. 1992; Hytönen and Ekola 1993; Hytönen 1999; Hytönen 2003). Liming increases soil pH, which in turn increases B-fixation and absorption in soils (Saarela 1985; Lehto 1995), thus decreasing B-availability for uptake by trees (Lehto and Mälkönen 1994). The proportion of trees exhibiting visible symptoms associated with B-deficiencies (leader dieback and loss of apical dominance, deformed new shoot growth etc.) increases when foliar B-concentrations fall below 6–7 mg kg^{-1} (Reinikainen and Veijalainen 1983; Hytönen and Ekola 1993). Wood ash is considered a good source of B and is recommended for the alleviation of B-deficiencies in Scots pine when grown on peatlands (Silfverberg and Issakainen 1987, 2001; Ferm et al. 1992). Initially fertilization resulted in elevated B-concentrations in those treatments that received wood ash (NWC+F, WC+F), however B-concentrations in these treatments declined over time, and at year 21 were close to deficiency limits, supporting the need for the re-application of a fertilizer containing B, such as wood ash.

4.2 Vegetation

One of the concerns associated with the afforestation of former agricultural lands is severe competition from weeds. Not only is this important in terms of the species and their abundance, but also in terms of their growth relative to the seedling/tree. These impacts are mainly direct, such as shading, a restriction in branching and crown development and overgrowth. Although the seedlings were planted into mounds free from vegetation, the mounds were rapidly colonized by annual weeds emerging from the agricultural soil seed bank, but after the first year, perennial weeds became more dominant. Later deciduous trees (willow, birches) also started to colonize the mounds in accordance with a model describing secondary succession of uncultivated fields (Törmälä 1982). Weed control decreased both the vegetation cover and mean height of weeds resulting in reduced competition for at least 3–4 years. A single application of soil-active terbuthylazine has been shown to control vegetation for 2–3 growing seasons (Jylhä and Hytönen 2006), but in some cases repeated applications are needed (Hytönen and Jylhä 2008, 2011). The two weed control applications (years 2 and 3) made in this study decreased competition for 3–5 years as recommended by Davies (1987). Although fertilization did not increase weed cover it did increase the height of the weeds, and thus the shading of the seedlings. Fertilization during establishment can increase competition from weeds, resulting in negative effects on overall afforestation success. Weed control not only restricted the development of grasses, but also decreased the emergence of woody vegetation (willows, birches), thus limiting their negative impacts.

There has been a significant reduction in herbicide use in Finnish forestry, with only 282 ha treated in 2013 (Juntunen and Herrala-Ylinen 2014). In addition, many herbicides, such as terbuthylazine used in this study, have been withdrawn from the market. Althought mulching has been the most most widely studied alternative weed control method in Finland, variable results on the effects of mulching on seedling mortality and growth have been reported (e.g. Ferm et al. 1994; Siipilehto and Lyly 1995; Siipilehto 2001; Hytönen and Jylhä 2005, 2013) indicating that further studies are needed, for example on the effect of mulch sizes and materials. In addition, the development of integrated weed management practices that include aspects such as appropriate site preparation and optimum seedling size is needed (Little et al. 2006).

4.3 Mortality and development potential of trees

In the absence of weed control, seedling mortality increased from year 3 onwards. The seedlings planted were of 3-yeard old bare-rooted stock, similar to those used for the afforestation of agricultural land in Finland in the early 90's (Jylhä and Hytönen 2006; Hytönen and Jylhä 2008, 2011). Currently, smaller, containerized seedlings are being used for afforestation in Finland. Smaller seedlings are more susceptible to competition from vegetation (Van der Driessche 1992; South et al. 2001; Hytönen and Jylhä 2008), which could result in a high mortality and sub-optimal growth if they were to be planted on agricultural sites. Scots pine mortality increased over time for all the treatments, with a higher rate of mortality recorded in the plots lacking weed control. Weed control, but not fertilization, resulted in a significant reduction in mortality. The 27 percentage point decrease in seedling mortality in the weed control treatments at year 21 emphasizes the importance of weed control in afforestation of former agricultural lands to ensure seedling survival. In Britain, Stokes and Willoughby (2014) recorded a significant effect of weed control on survival in 15–25 year old Sitka spruce stands. In the present study, an unexpected increase in mortality in the WC+NF plots was detected after 16 years (from 6 to 50%), probably due to K deficiency.

For the duration of the trial, there was a general decline across all treatments in terms of trees exhibiting good development potential. At 21 years the WC+F treatment had the highest number of trees with good development potential (2300 ha^{-1}), followed by WC+NF (1000 ha^{-1}) and NWC+F (1175 ha^{-1}). Besides the initial benefits of reduced shading and overgrowth, weed control improved the development potential of Scots pine, especially when combined with fertilization (WC+F). Initially weed control on its own (WC+NF) was as good as the weed control combined with fertilization (WC+F), but from year 16 to 21, there was a rapid decline from 2200 to 1000 stems ha^{-1}, most likely due to nutrient availability becoming a limiting factor. In the absence of weed control and fertilization the number of trees having good development potential was only 625 trees ha^{-1}. Similar low numbers of Scots pines with good development potential (400–800 stems ha^{-1}) have been reported in inventories of the outcome of practical afforestation of peat-based agricultural land in Finland (Hynönen 1997; Hynönen and Saksa, 1997; Hytönen 1999; Rossi et al. 1993). Based on the results of this study the application of weed control and fertilization would considerably improve the outcome of practical afforestation.

4.4 Height, diameter and volume of trees

The main effect of weed control on height and diameter increased between years 10 and 21. Initially these differences could be attributed to the management of competing vegetation, and as the stand developed, these initial differences remained. The significant improvement in the mean annual volume increment (MAI) from 0.8 m^3 ha^{-1} a^{-1} in year 16 to 1.1 m^3 ha^{-1} a^{-1} in year 21 could be attributed to higher survival in the weed control treatments. Similar benefits to the once-off weed control treatment have been recorded for the growth of Scots pine on former agricultural lands (Jylhä and Hytönen 2006; Hytönen and Jylhä 2011).

Although wood ash was applied one year later than the weed control, by year 10 the main effects of weed control and fertilization on tree growth were similar. From year 16, fertilization had a larger influence on growth than weed control, with an increased mean annual volume growth at year 21 of 1.7 m^3 ha^{-1}. Similar increases (0.5–1.4 m^3 ha^{-1}) have been reported for Scots pine growth 15 years after ash application in drained peatland forests (Moilanen et al. 2005). Our results confirm the positive effects of wood ash fertilization on Scots pine growth on former peat-based agricultural soils (Ferm et al. 1992; Hytönen 2003). In the present study, the effect of wood ash lasted only for 16 years, indicating the need for re-fertilization. This is in contrast to studies from peatland forests where longer-term benefits of ash fertilization have been reported (30–50 years) (e.g. Silfverberg and Hotanen 1989; Moilanen et al. 2002, 2005, 2015). In the present study the combination of fertilization and weed control lead to a seven fold volume compared to untreated plots (NWC + NF) in 21 years.

The effects of WC and F were additive, with no interaction detected. Similar responses have been reported by South et al. (1995), Rose and Ketchum (2002, 2003) and Haywood et al. (2003) for weed control × fertilization studies.

5 Conclusions

The present study emphasizes both the need for a reduction of competition through weed control and an improvement of soil nutrient status through fertilization for the success of afforestation of peat-based agricultural soils. Weed control was necessary for stand establishment and resulted in a long-lasting (21 years) decrease in Scots pine mortality. Mortality was found to be the main determinant of wood production productivity if K-deficiency had not become a limiting factor from years 5–6 onwards. Increased mortality due to K-deficiency occurred in unfertilized plots. Although fertilization had a significantly positive impact on Scots pine growth, by year 16 the K deficiency had become severe, with the need for re-fertilization becoming apparent. On peat-based agricultural soils prone to K- and B-deficiencies, it would be advisable to delay the first application of fertilizer until the 5–6th growing season. During this phase of growth, competition control is of prime importance. An additional benefit of delayed fertilization would be a delay in the enhanced development of competing vegetation.

On nutrient deficient sites such as in the present study, both weed control and fertilization are necessary for successful afforestation with Scots pine. In particular for sites with a thick peat layer, re-application of fertilization may be required for sustained growth. The profitability of such a silvicultural management regime will need to be examined, as would the need for developing alternative weed control methods, such as mulching.

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