THE EFFECT OF ARTIFICIAL DRAINAGE IN WATERLOGGED SITES ON THE FOLIAR NUTRIENT STATUS OF PLANTED INTERIOR SPRUCE SEEDLINGS IN THE CENTRAL INTERIOR BC

by

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Abstract

Drainage of waterlogged sites following harvest is a silvicultural treatment to reduce water table levels; therefore, potentially improving seedling growth. The goal of this study was to assess foliar nutrient status changes of planted hybrid interior spruce (*Picea glauca x Picea englemannii* [Moench] Voss) seedlings as a result of artificial drainage of waterlogged sites located in the central interior of British Columbia. Ditches were constructed near the end of the 2007 growing season, and foliar samples were collected and analysed for foliar unit mass and macronutrient concentrations and contents in the fall of 2007 (pre-ditching conditions) and in the fall of 2008 (post ditching conditions). Two way ANOVA and correlation analyses were used to determine and interpret significant responses. Concentration and content of foliar B and Al decreased and foliar K increased near and away from the ditch. These trends can be used as immediate indicators of ditch effects. The effect of distance from the ditchline on changes of foliar nutrient status was not conclusive. Overall, ditching appeared to be detrimental to health of seedlings in the short term. Longer term trends need to be examined for an understanding of any improvement in plant productivity and establishment of a new steady state.

Keywords: ditching, waterlogged sites, foliar macronutrient, foliar concentration, foliar content, distance effect, Interior Spruce

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Introduction

Drainage of waterlogged sites is a remedial activity to manage higher water table levels or excess soil moisture after forest harvesting in order to improve tree growth. Flooding and water saturated soil conditions results in limited above-ground growth and usually stunted growth of commercially important species. Thus artificial drainage schemes to increase aeration of the root zone, by lowering of the water table, have been advocated. Questions emerge regarding the potential effects of the increased aeration on species growing on the site, and whether the amount of aeration within the root zone has an effect on nutrient dynamics of established plant species.

During the growing season, flooded soil conditions can inhibit seedling growth by depleting soil oxygen and uptake of nutrients such as K and P (Kozlowski et al. 1991, Kozlowski 1984). Also, plants intolerant to flooding have reduced foliar nitogen (N) status (Kozlowski 1984). Yet foliar iron (Fe) and manganese (Mn) concentrations may be very high under saturated conditions (Kozlowski et al. 1991) due to potentially toxic concentrations of Mn and Fe in waterlogged environments (Huang 2006). Therefore, it follows that tree health may be positively affected by lowering of the water table in waterlogged sites in the long term.

However, in the short term, drainage of waterlogged sites may be detrimental to plant health. Artificial drainage of waterlogged areas may decrease nutrient availability for plant uptake in the short term as a result of some combination of the following:

- nutrient leaching resulting from increased drainage;
- nutrient precipitation resulting from increase in soil acidity/oxidation;
- soil microbial immobilization;
- slow development of new roots with mycorrizal associations with access to the increased soil volume;
- initial plant water stress.

The first objective of this study was to estimate the foliar element status of hybrid interior spruce (Sx) (*Picea glauca x Picea englemannii* [Moench] Voss) seedlings before and after ditching logged and waterlogged valley bottom sites in the Vanderhoof Forest District of the central interior of British Columbia. The second objective of this study was to compare Sx foliar element status at two distances from ditchline (i.e., near versus away from the ditchline). The assumption is that water table is lower closer to the ditchline, and thus distance from the ditchline is a proxy measure of water table level.

QUESTIONS:

(i) Does drainage affect the foliar element status of Sx?

H1: Drainage decreases the foliar element content of planted Sx seedlings

H0: Drainage does not decrease the foliar element content of Sx seedlings

(ii) Does the distance from the ditchline (as a proxy of the water table level or amount of drained soil volume after ditching) affect foliar element content of Sx?

H1: Proximity to the ditchline (i.e., greater water table decrease) decreases the foliar nutrient element of planted Sx seedlings

H0: Proximity to the ditchline does not decrease the foliar element content of planted Sx seedlings

There has not been any study on foliar nutrient content changes of interior spruce seedlings during the first year after ditching. Some related studies of other commercial conifer species have been reported. Roy et al. (1999) found no ditching effect on black spruce (*Picea mariana*) seedling growth one and two years after ditching and suggested limiting nutrients as a potential cause. Rothwell et al (1993), however, reported positive drainage effects on seedling growth and foliar N concentration, yet deficient foliar nutrient levels in white spruce (*Picea glauca*) planted four years after ditching and analyzed one and two growing seasons after planting.

Macdonald and Lieffers (1990) reported that black spruce trees had significantly higher foliar N content in peatlands 3-4 years after drainage than in undrained peatlands. Also, Mugasha et al. (1993) showed that foliar N, P and K status of black spruce trees increased four years after drainage. These results are not surprising as black spruce is known to be more tolerant to saturated conditions than interior spruce species and the black spruce trees would have deeper stabilized roots.

1. Ditching effects on nutrient availability

The immediate effect of successful artificial drainage on waterlogged sites is a more aerated soil volume resulting in warmer soils in the growing season and potentially colder soils during the remainder of the year. Artificial drainage will also change soil processes from mainly anoxic to oxic. Drainage will also initially increase soil volume available for root growth, but still over time may decrease pore space as organic materials subside. Furthermore, drainage will increase leaching potential of water soluble compounds, such as inorganic salts and simple organic chelates (i.e.: fulvic compounds) and increase the nutrient retention potential, such as inorganic P.

Artificial drainage will change the microorganism community size, composition and soil respiration rate. The microbial community will change from largely anaerobic to aerobic after drainage of waterlogged sites. Warmer and more aerated soils will increase soil organic matter decomposition rate by the increased microbial organisms' population and activity (Kozlowski et al. 1991). In contrast, soil and root respiration decreases immediately after irrigation as demonstrated by Bouma and Bryla (2000).

Increased decomposition of organic matter will increase available nutrients, such as nitrogen (N), phosphorus (P) and sulphur (S), in the soil medium. Prévost et al. (1999) reported that ditching of a forested peatland in Quebec increased nutrients in soil solution, and this effect was proportional to the closeness of the ditch and soil surface.

Yet, various studies have shown that ditching wetlands also results in leaching of nutrients into run-off waters, especially during the first year of treatment (Prevost et al. 1999, Joensuu et al. 2002, Nilsson and Lundin 1996, Astrom et al. 2001). Joensuu et al. (2002) reported that NH_4, Na, K, Ca, Mg, Fe, Al and S concentrations in the water run-off increased during the first year after ditch maintenance in Finnish peatland forest sites. The authors also reported that P concentration increased in the run-off at some of the sites during the first year after ditching maintenance (Joensuu et al. 2002). Astrom et al. (2001) reported a Ca, Mn and Mg concentration increase in run-off waters after ditching operations in a boreal forest site in western Finland. Nilsson and Lundin (1996) reported a concentration increase of sulphates, Fe, Al, NH_4 and organic C release into peat groundwater and stream water immediately after ditching bog sites in Sweden. Prévost et al. (1999)

reported an increased electrical conductivity due to increased leaching of mineral N, Ca, Mg, Na and S into surface waters after ditching a Quebec peatland site.

1a. How can artificial drainage enhance nutrients in soil medium while potentially leading to nutrient losses?

Leaching through the soil solution is part of the biogeochemical cycling of nutrients, such as N, S and P (Brady et al. 2004). For instance, dry followed by wet conditions may cause leaching of inorganic P (Sardans et al. 2008, Baum et al. 2003). Acid and alkaline phosphatases are groups of enzymes released by soil microbes (bacteria and fungi). These enzymes are found mainly in acidic and alkaline soils, respectively, and catalyze the breakdown of organically bound P, releasing inorganic P (i.e., phosphate ions) which are then available for plant and microbial uptake (Eivazi and Tabatabai 1977). A decrease in soil moisture content reduces soil acid and alkaline phosphatase activity (Sardans et al. 2008). Yet during these drier periods, soil inorganic P does not decrease and may even increase in the short term since plant nutrient uptake is also reduced (Sardans et al. 2008). However, dry periods followed by rainfall will increase the risk of P losses by leaching and run-off of the stored phosphorus from the dry season (Sardans et al. 2008).

Also, when acid phosphatase activity is high, re-wetting of peatlands can increase the risk of P losses through leaching of P incorporated in microbial biomass and inorganic P in soil solution (Baum et al. 2003). During the growing season, such drying-wetting patterns are common in the Sub Boreal Spruce zone.

A summary of the literature covering the effects of soil environment change from anoxic to oxic, resulting from ditching, on element form and solubility is given in Table 1. Overall, anions, resulting from increased mineralization, have a higher potential to leach out the system whereas cations, resulting from oxidation, become less water soluble.

Table 1. The effects of soil environment change from anoxic to oxic on element form and solubility from Brady and Weil (2004) and Buol et al. (1989).

element - main element source	processes from an anoxic to an oxic environment	Product	Drainage effect on solubility/leaching of elements in the soil
C - organic matter	increased respiration	CO_2	NA
N - organic matter	increased mineralization	NH_4^+ to NO_3-	negatively charged nutrient results in more potential leaching
S - organic matter	increased mineralization	SO_4^{2-}	negatively charged nutrient results in more potential leaching
P - organic matter	increased mineralization	$H_2PO_4^-$ to PO_4^{2-} to PO_4^{3-}	negatively charged nutrient results in more potential leaching
Cu – mineral	Oxidation	Cu^+ to Cu^{2+}	positively charged element decreases water solubility
Zn – mineral	Oxidation	Zn^+ (unstable) to Zn^{2+}	positively charged element decreases water solubility
Fe – mineral	Oxidation	Fe^{2+} to Fe^{3+}	positively charged element decreases water solubility (precipitates)
Al – mineral	no effect		remains largely insoluble
B – mineral	no effect		remains largely insoluble
K – mineral	no effect		remains largely insoluble
Ca – mineral	no effect		remains largely insoluble
Mg – mineral	no effect		remains largely insoluble, but less soluble than Ca^{2+}

1b. Eluviated nutrients from uplands into drained valley-bottoms

Nutrients eluviated from higher elevations to ditched valley bottom sites will not be accessible to Sx seedling roots where the water table has decreased below the root zone, whereas prior to ditching these nutrients would have been accessible to Sx seedling roots.

1c. Limiting nutrient retention after ditching

NUTRIENT PRECIPITATION IN ACIDIC SOILS

Artificial drainage of wetlands decreases soil pH, increasing the potential of mineral retention. Under acid conditions, positively charged minerals, such Fe and Al oxides, will bind to negatively charged humic materials and clay particles (Kozlowski et al. 1991, Buol et al. 1989). Moreover, as discussed above, more oxic conditions will increase P mineralization increasing inorganic P forms, such as phosphates, into soil solution. These newly decomposed inorganic P forms can leach out of the ecosystem, be taken up by microorganism or plants, or precipitate under acidic soil conditions. In such an environment, phosphates react with Fe and Al oxides and precipitate, decreasing the mineral P availability to plant uptake (Huang 2006, Yuan and Lavkulich 1994).

MICROBIAL DECOMPOSITION AND IMMOBILIZATION

Fall and winter microbial communities die off and provide nutrients primarily to summer microbial communities rather than to plant uptake and/or leaching (Schmidt and Lipson 2004, Schmidt et al. 2007). A pulse of nutrient immobilization by the increased soil microbial community could occur in a recently drained and nutrient poor ecosystem. Inorganic nitrogen, for instance, is immobilized in the microbial biomass in the beginning phases of decomposition (i.e.: low rates of net mineralization) especially in low N, wide C to N ratio ecosystems (Attiwill and Adams 1993, Finzi and Berthrong 2005). Soil fauna populations, in addition, may be lagging behind the increased microbial community in the first year after drainage, which, in turn, could lower the available nutrients, such as ammonium, for plant uptake (i.e.: soil fauna grazing on microbial biomass). As a consequence, there would be a lower amount of available inorganic nutrients for plant uptake during the first growing season than the following growing seasons as a new steady state is being reached after drainage.

2. Ditching effect on soil water availability

Artificial drainage may lead to soil surface dehydration especially during prolonged dry periods (i.e., little or no precipitation). Rothwell et al. (1993) reported higher mortality of white spruce seedlings in drained sites, especially on hummock tops, than on undrained sites and attributed this to higher soil temperature and lower moisture after artificial drainage. Also, nutrient uptake can decrease under water deficit conditions since water stressed plants decrease their uptake of water through reductions in transpiration (Farooq et al. 2009, Kramer and Boyer 1995, BassiriRad 2005). Since nutrients can move by mass flow (Nasholm and Persson 2001), the rate of delivery to roots will be decreased. This suggests that drier soil conditions during the growing season may result in decreased soil solution flow towards roots and consequently reduced foliar nutrient status of Sx seedlings.

3. How do seedlings cope with low soil nutrient and water status?

Root growth and development

Various studies, cited in Schimel and Bennett (2004), show that plant roots with mycorrizal fungi associations do compete with the microbial community and can take up both inorganic and depolymerized organic nitrogen sources, in low N ecosystems. Indeed, plant roots and mycorrhizae have amino acid transporters (Nasholm and Persson 2001). The availability of organic N forms to plants is, nevertheless, dictated by production by microbial agents (including mycorrizal fungi) and their protease exoenzymes which depolymerize polymeric organic N forms (Nasholm and Persson 2001, Schimel and Bennett 2004).

Temperate and boreal forest trees species have the physiological capacity to take up amino acid N (Finzi and Berthrong 2005, Nasholm and Persson 2001, Nasholm et al. 1998). Additionally, Kranabetter et al. (2007) reported that the inorganic forms of N are very low and dissolved organic N forms are predominant in soils in the southern boreal forests and inferred that uptake of the latter by plants through fungal association can support this forest ecosystem.

Root exudation is high in younger plants and increases in soil with low available nutrients and water for plant uptake (Brady et al. 2004, Pinton et al. 2007); therefore, more resources could be allocated from foliage to roots after ditching, decreasing foliar nutrient status. Increased aerated soil volume and lower soil nutrient and water supply may also induce development of new roots, again decreasing the nutrient allocation to needles.

Root exudates attract microbial organisms. In fact, there are 2 to 10 times more microbial organisms in the rhizosphere than bulk soil, providing a high source of inorganic nutrients for plant uptake (Brady et al. 2004). About 40% of plant photosynthates are secreted into the rhizosphere, providing a source of energy for microbial activity (Kumar et al. 2006, Lynch and Whipps 1990). The density of bacterial communities, for instance, is higher at the root tips where sucrose exudation is more prominent (Jaeger et al. 1999). The result of the accumulation of microbial communities attracted to plant rhizodeposition will in turn favour inorganic nutrient availability for plant uptake, such as N (Attiwill and Adams 1993), Cu (Cloutier-Hurteau et al. 2008) and Fe (Crowley et al. 1991).

These active microbial populations in the rhizosphere may also function as bio-control agents against plant diseases (Whipps 2001).

Exuded organic acids can also solubilize phosphorus (Attiwill and Adams 1993) and Fe (Jones et al. 1996) from low solubility compounds into inorganic forms which can then be taken up by plant roots.

Plants, furthermore, form extensive fine root systems (root clusters) to increase root absorption of minerals found in low concentration and low mobility in the soil (Kozlowski et al. 1991, Huang 2006, Attiwill and Adams 1993). As root density increases so would the amount of root exudates and sequestration of low solubility inorganic nutrients (Attiwill and Adams 1993).

Therefore, to counterbalance the decrease of soil minerals and water availability to plant uptake during the first year after drainage, the development of new roots with mycorrizal associations and rhizosphere inhabitants could be enhanced until a new steady state is established.

Methods and Materials

Project layout

This study was conducted at 4 selected sites (labelled sites A, C, E and F) located in lower topographic relief positions within the Sub Boreal Spruce (SBS) and Engelmann Spruce – Subalpine Fir (ESSF) biogeoclimatic zones (Figure 1) (Heemskerk et al. 2004). Sites exhibited near-saturated water conditions in the rooting zone for a large portion of the growing season and were representative of high water table areas currently encountered throughout the Mountain Pine Beetle-infested areas of the Vanderhoof Forest District (Rex and Dubé 2009). These sites were previously ditch mounded between 1996 and 2001 (Heemskerk et al. 2004). However, drainage has had limited effect on water table levels due to less than optimal planning (Dubé 2004). And, as a result, the sites remained waterlogged until ditching maintenance (sites A, C and F) and construction of a new ditch (site C) was carried out between the end of summer and fall of 2007. Interior spruce seedlings were operationally planted between 1996 and 2000 (Heemskerk et al. 2004). A complete vegetation and soil description was performed at all sites by Heemskerk et al. (2004).

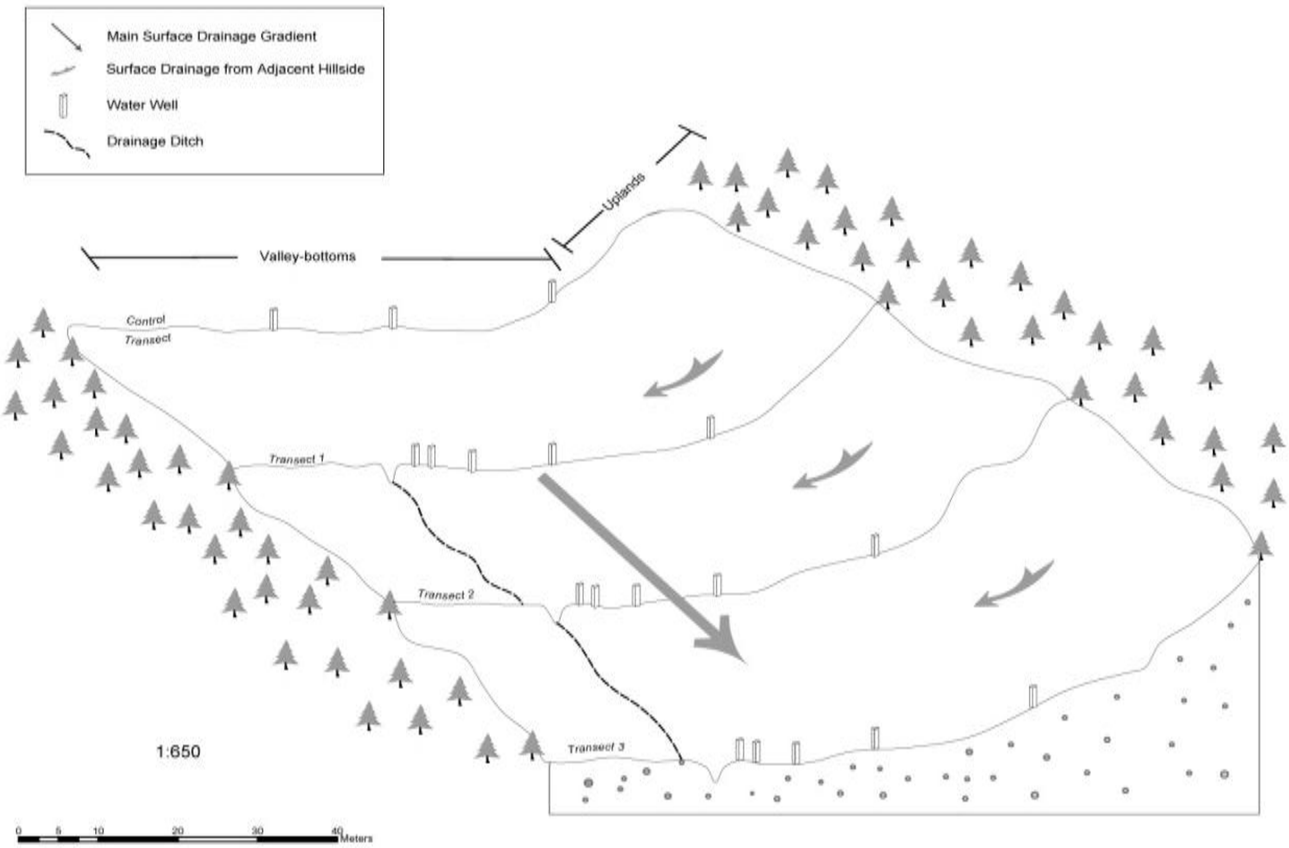

Figure 1. Site layout showing location of waterlogged soils and ditchline. Transects were established to install wells in various distances from the ditchline.

Site description

Site A

Site A is in the SBSmc2 subzone and is classified as a forested swamp (Table 2) (Heemskerk et al. 2004). Primary sources of on-site water include groundwater, precipitation and snowmelt. Prior to ditch maintenance, the soil moisture regime was hygric, and the soil nutrient regime was rich. The soil is classified as Orthic Humic Gleysol.

Natural drainage is poor as a result of the level topography (slope 1%) and location (valley bottom) (Heemskerk et al. 2004). Artificial drainage and mounding was completed in 2001 to promote tree growth; however, ditching had not proven to be effective due to the shallow depth and narrow width of the ditch that quickly filled with eroded material (Dubé 2004). Remedial drainage was completed at the end of July 2007. The new ditch is on average one meter deep and 2 meters wide.

Site C

Site C is in the SBSmc2 subzone and is classified as being a forested wetland (Table 2) (Heemskerk et al. 2004). Primary sources of on-site water include groundwater, precipitation and snowmelt. Prior to construction of the new ditch, the soil moisture regime was subhygric and the soil nutrient regime was medium. The soil is classified as Dystric Brunisol.

The drainage is poor as a result of the topography (slope 0%) and location (toe of the slope) (Heemskerk et al. 2004). Ditching and mounding had been completed in 2000. However, ditching had limited effects on water table levels since the site remained waterlogged throughout a wet summer (Dubé 2004). A new ditch was dug in a better location at the end of July 2007. The new ditch is on average one meter deep and 2 meters wide.

Site E

Site E is in the ESSFmv1 subzone and is classified as being a forested swamp (Table 2) (Heemskerk et al. 2004). Primary sources of on-site water include groundwater, precipitation and snowmelt. Prior to ditch maintenance, the soil moisture regime was hygric and the soil nutrient regime was rich. The soil is classified as Orthic Gleysol.

The drainage is poor due to the topography (slope 1-2 %) and location (lower slope with a concave surface profile) (Heemskerk et al. 2004). Ditching and mounding had been completed in 1996, but drainage was not effective due to the undersized ditch that restricted flow of water (Dubé 2004). Ditch maintenance was completed in September 2007. The re-constructed ditch is on average one meter deep and 2 meters wide.

Site F

This site is in the ESSFmv1 subzone and is classified as being a forested swamp (Table 2) (Heemskerk et al. 2004). Primary sources of on-site water include groundwater, precipitation and snowmelt. Prior to ditch maintenance, the soil moisture regime was hygric and the soil nutrient regime was rich. The soil is classified as Orthic Humic Gleysol.

The drainage is poor as a result of the topography (slope 1-2 %) and location (depression on a mid-slope bench) (Heemskerk et al. 2004). Drainage and mounding were completed in 1996. Despite the shallow depth of the ditch, it had a positive effect on Sx height growth within 6 m of the ditch edge (Dubé 2004). The ditch was cleaned in September 2007 and its dimensions were 1 meter deep and 2 meters wide.

Table 2. Summary of study sites adapted from Heemskerk et al. (2004) and artificial drainage construction and maintenance date of the four research sites in Vanderhoof Forest District.

	Classification			Before Re-ditched		Date	
Site	**BEC**	**Site**	**Soil**	**Moisture Regime**	**Nutrient Regime**	**Ditched**	**Re-ditched**
A	SBSmc2	forested swamp	Orthic Humic Gleysol	hygric	rich	2001	Jul-07
C	SBSmc2	forested wetland	Dystric Brunisol	subhygric	medium	2000	Jul-07
E	ESSFmv1	forested swamp	Orthic Gleysol	hygric	rich	1996	Sep-07
F	ESSFmv1	forested swamp	Orthic Humic Gleysol	hygric	rich	1996	Sep-07

Sampling and laboratory analyses

Samples of foliage developed in the current growing season were randomly collected (i.e., simple random sampling) from planted interior spruce seedlings in October (dormant phase) of 2007 (control) and 2008 (post treatment) at sites C, E and F (Figure 2). At site A, samples were randomly collected in 2008 from both a ditched plot and a control plot (located parallel to the ditched plot) (Figure 2). Samples were randomly collected between 3 and 7 meters from the ditch (labelled 'near the ditch') and between 38 and 42 meters from the ditch (labelled 'away from the ditch') at sites C, E and F (Figure 2). At site A, samples were randomly collected between 3 and 7 meters from the ditch (labelled 'near the ditch') and between 28 and 32 meters from the ditch (labelled 'away from the ditch') (Figure 2).

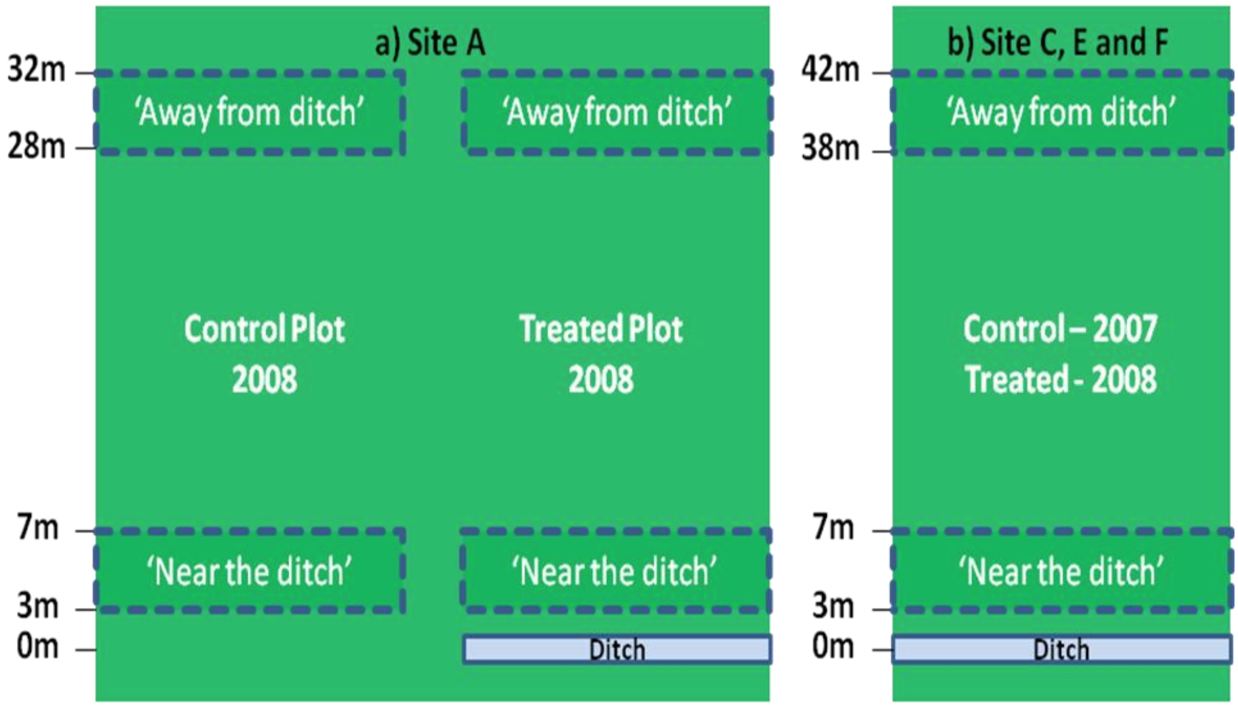

Figure 2. a) Samples randomly selected from within area marked by dashed line in 2008 after ditch maintenance at treated plot at site A. b) Samples randomly selected within area marked by dashed line in 2007 (control) and after ditch maintenance (Site E and F) or construction of a new ditch (Site C) in 2008.

Foliage was collected between the top one-quarter and bottom one-half of the crown. Samples were oven-dried at 75°C for 24 hours. Each sample was weighed (foliage mass/100 needles) and milled. A total of 136 samples were analysed for total N and C content by the Total Elemental Analyses method (Carter 1993) using a NA-1500 analyzer and 248 samples were analysed for macronutrient analyses (Al, B, Ca, Cu, Fe, Mg, Mn, P, K, S and Zn) (Kalra and Maynard 1991) using an ICP Spectrometer by the BC Ministry of Forests and Range laboratory (Victoria, BC) (Table 3).

Eight composite samples (Table 3) were ground and analysed for their stable carbon isotope ratio. Because isotope discrimination during photosynthesis is directly related to the diffusion gradient for CO_2 from the atmosphere to the sites of carboxylation at rubisco, the carbon isotope ratio of plant tissue provides an index of water-use efficiency integrated over the period of carbon fixation ((Farquhar et al. 1982). The ratios of $^{13}C/^{12}C$ are expressed as del (δ) values in parts per mil (‰) with respect to the Vienna Peedee Belemnite (V-PDB) carbonate standard:

$$\delta^{13}C = ((^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{VPDB}) / (^{13}C/^{12}C)_{VPDB} \times 1000$$

After the composite samples were ground to a fine powder in liquid N_2 with a mortar and pestle, 2–2.5 mg homogenized sub-samples were packed in tin capsules and sent to the University of California, Davis, Stable Isotope Facility. The samples were combusted in an online continuous flow dual analyzer coupled to an isotopic ratio mass spectrometer (Europa Scientific Integra). Overall, sample preparation and analysis error between repeated analyses of the same ground tissue was less than ±0.11‰.

T**able 3**. Sample size and analyses type for the four research sites

Site	**1. Total N and C**	**2. Macronutrients**	**3. C isotope**
A	None	$N_{c.n} = 14$ $N_{c.a} = 14$ $N_{t.n} = 14$ $N_{t.a} = 14$	$N_{c.n} = 1$ (composite of 5 samples randomly selected from Site A **2.** – $N_{c.n}$) $N_{t.n} = 1$ (composite of 5 samples randomly selected from Site A **2.** - $N_{t.n}$)
C	$N_{c.n} = 17$ $N_{c.a} = 17$ $N_{t.n} = 17$ $N_{t.a} = 17$	$N_{c.n} = 17$ $N_{c.a} = 17$ $N_{t.n} = 17$ $N_{t.a} = 17$	$N_{c.n} = 1$ (composite of 5 samples randomly selected from Site C **2.** – $N_{c.n}$) $N_{t.n} = 1$ (composite of 5 samples randomly selected from Site C **2.** - $N_{t.n}$)
E	$N_{c.n} = 17$ $N_{c.a} = 17$ $N_{t.n} = 17$ $N_{t.a} = 17$	$N_{c.n} = 17$ $N_{c.a} = 17$ $N_{t.n} = 17$ $N_{t.a} = 17$	$N_{c.n} = 1$ (composite of 5 samples randomly selected from Site E **2.** – $N_{c.n}$) $N_{t.n} = 1$ (composite of 5 samples randomly selected from Site E **2.** - $N_{t.n}$)
F	None	$N_{c.n} = 14$ $N_{c.a} = 14$ $N_{t.n} = 14$ $N_{t.a} = 14$	$N_{c.n} = 1$ (composite of 5 samples randomly selected from Site F **2.** – $N_{c.n}$) $N_{t.n} = 1$ (composite of 5 samples randomly selected from Site F **2.** - $N_{t.n}$)
All sites	$N_{c.n} = 34$ $N_{c.a} = 34$ $N_{c.a} = 34$ $N_{t.a} = 34$ $N_{total} = 136$	$N_{c.n} = 62$ $N_{c.a} = 62$ $N_{t.n} = 62$ $N_{t.a} = 62$ $N_{total} = 248$	$N_{c.n} = 4$ $N_{t.n} = 4$ $N_{total} = 8$

N= sample size, $_c$ =control, $_t$ =treatment, $_n$ =near the ditch, $_a$ =away from ditch

Statistical analyses

In the analyses for ditching and distance effects, two-way ANOVA (Kutner et al. 2005) conducted using R v.2.8.1 (R Development Core Team 2008) was used to compare treatment and control data from both near the ditch and away from ditch. An alpha value of 0.05 was used in these analyses. Element concentrations for Al, B, Ca, Cu, Fe, Mg, Mn, P, K, S and Zn data had unequal sample sizes while total C and N data had equal sample sizes.

The same analysis as above was conducted for element content. Element content was calculated with the following formulas:

1. Element content (μg of a mineral/needle) is equal to: (mineral (%)/100)*(μg/100 needles) when mineral was expressed in percentage.
2. Element content (μg of a mineral/needle) is equal to: (mineral (PPM)/1,000,000)*(μg/100 needles) when mineral was expressed in PPM.

Also, to interpret the ditching effect analyses, correlation analyses (Kutner et al. 2005) for element concentration in PPM and percentage and element content in μg of a mineral/needle were conducted in Microsoft Office Excel 2007.

Results

Element concentration (PPM and %)

Ditching caused a significant ($p<0.05$) increase in foliar C and K concentration but significantly decreased foliar B, Al and Mg concentration both near and away from the ditchline. Additionally, away from the ditchline, ditching also caused a significant decrease in foliar Fe, Ca and S concentration. Near the ditch, however, there were no significant changes in concentrations of these nutrients. Furthermore, ditching caused no significant effect on foliar Zn, Mn, P, N and Cu concentration and foliar C to N ratio both near and away from the ditch. The summaries of element concentration results are given in Tables A1a and A1b (Appendix 1).

Element content (μg of a mineral/needle)

Ditching significantly increased foliar K content but decreased foliar Al and B content independently of drainage distance. Furthermore, ditching caused a significant increase in foliar S content near the ditch and foliar Mn and P content away from ditch. No significant changes in foliar Fe, Ca, Cu, Mg, Zn, C and N content were found after ditching. Furthermore, ditching caused no significant effect on foliar Mn and P content near the ditch and foliar S content away from the ditch. The summaries of element content results are described in Tables A2a and A2b (Appendix 2).

Carbon Isotopes

Data from C isotopes were not available by the time of submission of this paper. The data will be described in a subsequent paper.

Correlation

Changes in relationships between foliar elements occurred both close to and away from ditchline. The following are some of the foliar element relationships that changed after ditching:

- Foliar Fe and Al concentration and content were strongly positively correlated before ditching, but these nutrients were only weakly correlated after ditching;
- Foliar Cu and Ca concentrations were positively correlated before and after ditching, but the correlation became weaker after ditching;
- Foliar Cu and B contents were positively correlated before and after ditching, but the correlation became weaker after ditching;
- Positive relationships between foliar Zn concentration and content and foliar Ca concentration and content became weaker after ditching;
- A positive relationship between foliar C content and foliar S content became stronger after ditching;
- A positive relationship between foliar C content and foliar N content became stronger after ditching.

All changes in relationship among foliar element concentration and content after ditching are given in Table A3 (Appendix 3).

Discussion

Changes in relationships between some foliar nutrients after ditching are concurrent with the effects of changes from mainly anoxic to mainly oxic soil conditions on the element solubility (Table1). The relationship between foliar Fe and Al concentration and content, for instance, is not significant after ditching. This may be due to the fact that Fe precipitates while Al is insoluble both before and after ditching. The decrease in correlation also occurs between foliar Cu, in which the element has a decreased solubility after ditching (i.e., oxic conditions), and foliar Ca and B where the latter elements remain largely insoluble after ditching. Similar patterns are observed between foliar Zn and Ca concentrations.

Average foliar element concentrations in which ditching caused a significant effect were compared to critical values of one of the "parental" species, white spruce, from Ballard and Carter (1986) (Tables A1a and A1b). There were no critical values for Al found in the literature to identify Al toxicity or deficiency for white spruce or interior spruce. For all elements, except for Al (i.e., no critical values found in the literature) and Ca, for which the ditch caused a significant decrease, possible pre-existing nutrient deficiencies were exacerbated (Tables A1a and A1b). The ditch effect, furthermore, significantly increased K concentration; yet, a possible slight K deficiency was observed before and after ditching (Tables A1a and A1b). Rothwell et al. (1993) found similar results for white spruce seedlings, in which drainage significantly increased foliar N concentration but foliar N, P, K levels were deficient both on undrained and drained sites. Similarly, Roy et al. (1999) reported limiting foliar P and Mg concentrations in black spruce seedlings two years after ditching.

Artificial drainage caused significant decreases in foliar Al and B concentrations and contents and significant increases in foliar K concentration and content for seedlings both near and away from the ditch. This suggests that Al, B and K minerals can be used as potential foliar nutrient indicators for drainage effects in the short term.

Foliar S concentration decreased away from the ditch, but it remained unchanged near the ditch. This pattern could have been caused by the pre-existing intermittent lowering of water table near the old ditch at sites A, E and F. Nearly all natural sources of S are returned to the soil as organic matter (Brady et al. 2004). Thus, slow S decomposition, while the soil was aerated, may have released inorganic S. Therefore, a longer period of aerobic decomposition and subsequent plant S uptake near the old ditch could have counterbalanced S leaching resulting from the new ditch. Foliar Fe and Ca concentrations were affected similarly to foliar S concentration. Prior to ditch maintenance, precipitation of Fe and leaching of Ca were probably already taking place near the original ditch due to temporary water table drops at sites A, E and F.

The effect of ditching appears not to be proportional to the degree of drainage as influenced by the site water table decrease (inferred by distance from the ditchline). Ditching of waterlogged sites thus causes a change on foliar nutrient status of planted Sx seedlings from the ditchline to at least about 32 to 42 meters away from the ditchline. This is in agreement with Roy et al. (Roy et al. 1999) who reported no distance to ditchline effect on foliar nutrient concentrations of black spruce seedlings.

The literature suggests that artificial drainage may reduce seedling productivity in the short term; this study demonstrates that artificial drainage of logged wetlands may be detrimental to planted interior spruce seedlings during the first year after drainage. Initial negative effects on seedlings could, however, be just a transitional stage. Therefore, the effectiveness of ditching and drainage on seedlings health and productivity improvement should be measured only after the system reaches a new steady state. The effect of artificial drainage on foliar nutrients over a longer term should be examined. Monitoring changes in foliar nutrient concentration and content through time could be conducted until the system reaches a new steady state.

Conclusion

The goal of this research was to better understand the short term effects of artificial drainage on the foliar nutrient status of planted interior spruce seedlings. Ditching caused an effect on foliar nutrient concentration and content of seedlings both near and away from the ditchline. The results of the study show a detrimental effect on this plant species and a system not in equilibrium during the first year after ditching. Therefore, the benefits of ditching on plant productivity, if any, may only be apparent over a longer term study.

The future direction of this research is to analyse the site differences in which ditching had a significant effect on foliar nutrient status. For each site, foliar element contents and concentrations in which ditching caused a significant effect could then be compared to water table levels, soil moisture content and aeration measured weekly during the 2007 and 2008 growing season. These analyses could explain the postulated differences in foliar element concentrations and contents at different distances from the ditch as discussed above. Furthermore, C isotope data will be analysed to look for signs of either an increase or decrease in stomatal limitations to growth, as may be expected in the short term following abrupt changes in water table.

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