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Research Article

Inconsistent Growth Response to Fertilization and Thinning of Lodgepole Pine in the Rocky Mountain Foothills Is Linked to Site Index

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Fertilization of conifers often results in highly variable growth responses across sites which are difficult to predict. The goal of this study was to predict the growth response of lodgepole pine (*Pinus contorta var. latifolia*) crop trees to thinning and fertilization using basic site and foliar characteristics. Fifteen harvest-origin stands along the foothills of the Rocky Mountains of Alberta were subjected to six treatments including two levels of thinning (thinning to 2500 stems per hectare and a control) and three types of fertilization (nitrogen-only fertilization, complete fertilization including nitrogen with added P, K, S, Mg, and B, and no fertilization). After three growing seasons, the growth response and foliar status of the crop trees were examined and this response was related to site and foliar characteristics. There was a small and highly variable additive response to fertilization and thinning; diameter growth of crop trees increased relative to the controls an average of 0.3 cm with thinning, 0.3 cm with either N-only or complete fertilization and 0.6 cm when thinned and fertilized. The increase in diameter growth with thinning and nitrogen-only fertilization was positively related to site index but not to any other site factors or pretreatment foliar variables such as nutrient concentrations, ratios, or thresholds.

1. Introduction

Lodgepole pine (*Pinus contorta var. latifolia* Loudon) is the dominant tree species in the foothills of Alberta and is capable of growing on a wide range of site types. Precommercial thinning of juvenile high density lodgepole pine stands can be used to avoid stand repression [1] and increase the growth of individual trees [2, 3]. Fertilization is used to increase both individual tree growth and total stand volume [4]. Fertilization of lodgepole pine in North America usually focuses on nitrogen (N) but limitations of other nutrients, including sulfur (S), phosphorus (P), boron (B), and zinc (Zn), have been identified in some sites in British Columbia [5, 6].

Fertilization of lodgepole pine and other conifers has been extensively studied around the world and a common finding has been that, on average, fertilizing conifer stands result in a significant increase in growth but there is usually high variability across sites. For example, five-year stem growth of *Pinus sylvestris* increased on average 45% after fertilization, but the growth response ranged from 11–104% across 28 sites in Scandinavia [7] with no obvious connection between growth response and site characteristics.

For lodgepole pine, pretreatment foliar nutrient concentrations, their ratios with foliar N [8–10] and adequate foliar nutrient concentrations [11] have shown promise as diagnostic tools to predict site response to fertilization. For example, pretreatment foliar sulfate concentration and N/S ratios were successful in predicting lodgepole pine growth response to N and N + S fertilization in British Columbia [4]. Other site variables including site index and soil type have been used to predict the response to midrotation fertilization

Table 1: Site properties for each of the 15 stands.

Site number	Site index (m @ 50 years)	Age (at breast height)	Density (stems ha^{-1})	Basal area (m^2 ha^{-1})	Elevation (m)	Ecological subregion
1	20.3	18	8000	23.0	1238	Upper foothills
2	20.4	16	11040	24.6	1281	Upper foothills
3	19.5	9	5740	5.8	1197	Upper foothills
4	21.7	6	5060	3.9	1104	Lower foothills
5	19.7	22	8300	17.0	1064	Lower foothills
6	21.6	21	8667	29.9	1041	Lower foothills
7	19.3	12	11160	15.3	1341	Upper foothills
8	21.4	7	6533	8.3	1255	Upper foothills
9	18.2	15	2420	11.1	1346	Lower foothills
10	16.6	19	3027	11.2	1473	Upper foothills
11	18.7	4	9200	1.2	1480	Upper foothills
12	20.8	18	6960	21.9	1084	Upper foothills
13	18.8	18	9280	15.3	1169	Upper foothills
14	18.4	18	14640	22.1	1208	Upper foothills
15	22.5	9	10080	14.9	1096	Lower foothills

of loblolly pine (*Pinus taeda*) in the southern United States [12], and these types of relationships between fertilization response and basic site and foliar characteristics may be applicable in Alberta.

Our study examines tree growth in relation to both thinning and fertilization applied to harvest origin lodgepole pine stands across a range of sites within the same ecological region. We examined site and foliar characteristics that might be used to predict response to treatment. Previous lodgepole pine thinning and fertilization studies have generally only examined a single site [1, 3] or compared stands from different ecological regions [13]. Our approach uses sites from a 350 km north-south transect across most of Alberta's foothills region and allows us to examine the differential growth benefits of thinning and fertilization over a large number of sites differing in productivity.

2. Methods

We studied 15 relatively pure lodgepole pine stands in the foothills of the Rocky Mountains in Alberta, Canada (Figure 1). Stands were of harvest origin, ranging in breast height age from 6 to 22 years, and were dominated by lodgepole pine (pine made up over 95% of the stand density in all but three of the stands). Site index, elevation, age, density, and other characteristics are given in Table 1. Within each stand, six 200 m^2 square plots were established and randomly assigned to a thinning (2 levels) and fertilization treatment (3 levels). The thinning treatments were no thinning and a low thinning to a density of 2500 stems per hectare with all deciduous trees removed. The fertilization treatments were control (no fertilization), N-only fertilization, and complete fertilizer blend with N and added P, K, S, magnesium (Mg), and B (Table 2).

Within each plot, all conifer trees were measured before treatment for height and diameter at breast height (DBH). Thinning and fertilization treatments were carried out by hand in May of 2006. All trees were remeasured the following winter and again after three growing seasons. After the first and third growing seasons, foliar samples were also collected during the winter from the upper third of the crown of three dominant or codominant lodgepole pine trees. A sample of 100 needle fascicles of the youngest age class was isolated from each tree and the dry weight was determined after drying at 68°C. Samples were ground and pooled for foliar nutrient analysis, including foliar N, P, K, S, calcium (Ca), Mg, sulfate (SO_4), B, copper (Cu), Zn, manganese (Mn), and iron (Fe) concentrations. Nitrogen concentration was determined colourimetrically using an autoanalyzer after digestion with H_2SO_4 while K, Ca, Mg,

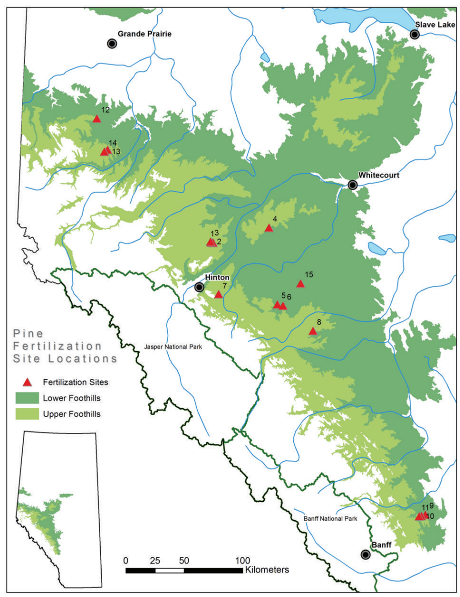


Figure 1: Map of the study region in the foothills of Alberta.

Table 2: Fertilizer formulations for N-only and complete fertilizers.

	Ingredient	Nutrients (kg ha^{-1})					
		N	P	K	S	Mg	B
N-only fertilizer	Urea	300					
	Total	300	0	0	0	0	0
Cbmplete fertilizer	Urea	251					
	Monoammonium phosphate	49	100		7		
	Muriate of potash			46			
	Sulphate potassium magnesia			54	68	33	
	Borate granular						3
	Total	300	100	100	75	33	3

Cu, Zn, and Mn were determined by atomic absorption after the same digestion. The azomethine-H method was used to determine B concentration after dry ashing. Available SO_4 was determined colourimetrically on a HI-bismuth reducible distillate after 0.1 N HCl extraction. Active Fe concentration was determined by atomic absorption after 1 N HCl extraction.

Growth rate per tree was determined for each plot based on the largest 12 stems (600 stems per hectare). This approach was taken because a snow storm damaged 9 of the 15 of the stands, with damage concentrated on the medium- and smaller-sized trees [14]. Only in the thinning + fertilization treatments were some of the larger trees affected. By concentrating on the largest trees, the impact of the snow damage on growth responses can be greatly reduced and still allows for meaningful comparisons among treatments. Analyzing the growth response of the largest trees in stands has been done previously [1, 15] and is relevant as these trees can be considered the crop trees that will likely survive to final harvest. Growth increment was calculated as tree size (DBH and volume) after three growing seasons minus the initial tree size prior to treatment. Stem volume was calculated using a taper volume equation developed for the area [16]. Foliar N mass per 100 fascicles was determined by multiplying N concentration by the mass of 100 fascicles. Foliar N uptake as a result of the treatments was estimated by subtracting the foliar N mass per 100 fascicles of the control plot from the foliar N mass of the treatment plots.

Statistical analysis involved comparing growth and foliar characteristics among treatments using two-way ANOVAs (3×2) blocked by site. Tukey's HSD test was used to further examine differences among treatment levels. To evaluate the differential response to fertilization and thinning between sites, differential growth increment (treatment growth-control growth) was regressed against site conditions, including site index, density, elevation, and age, and foliar properties, including foliar mass, nutrient concentrations, ratios, uptake, and adequate nutrient values, of the control plots. Statistical analysis was conducted using JMP 8.0 (SAS Institute Inc., Cary, NC, USA).

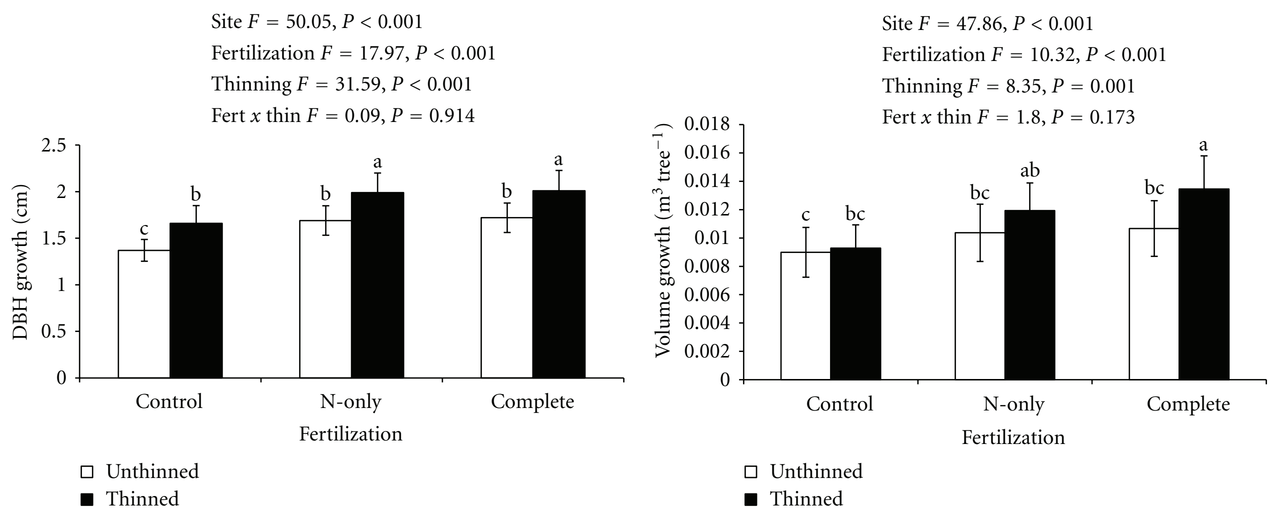
3. Results

Thinning and fertilization had an additive impact on individual tree growth of the 600 crop trees ha^{-1} after the third growing season, increasing diameter growth from 1.4 cm in the control plots to an average of 1.7 in the thinned or fertilized plots to greater than 2.0 cm in the thinned + fertilized plots (Figure 2(a)). However, the differential diameter growth increment was highly variable ranging from −0.12 to 1.27 cm diameter growth across treatments. Relative to the control plots, this corresponds to a diameter growth increase of 22% with thinning, 24% with N-only fertilization, 25% with complete fertilization and 47% with thinning and fertilization combined. For volume growth, only the thinning + fertilization treatments resulted in significantly greater growth than the controls (Figure 2(b)). Overall, there was a positive effect of thinning and fertilization on both diameter and volume increment, but there was no difference in average growth response between N-only and complete fertilization either with or without thinning.

Initial foliar N concentrations ranged from 1.02–1.23% N. The first year after treatment, foliar N concentration increased with complete fertilization (both with and without thinning) and thinning + N-only fertilization reaching an average of 1.48% N, while the N-only treatment without thinning was 1.35% N and the control fertilization plots (either unthinned or thinned) were less than 1.14% N (Figure 3(a)). After three growing seasons, foliar N concentrations were not significantly different from the control plots in all but the unthinned + complete fertilization plots (Figure 3(a)).

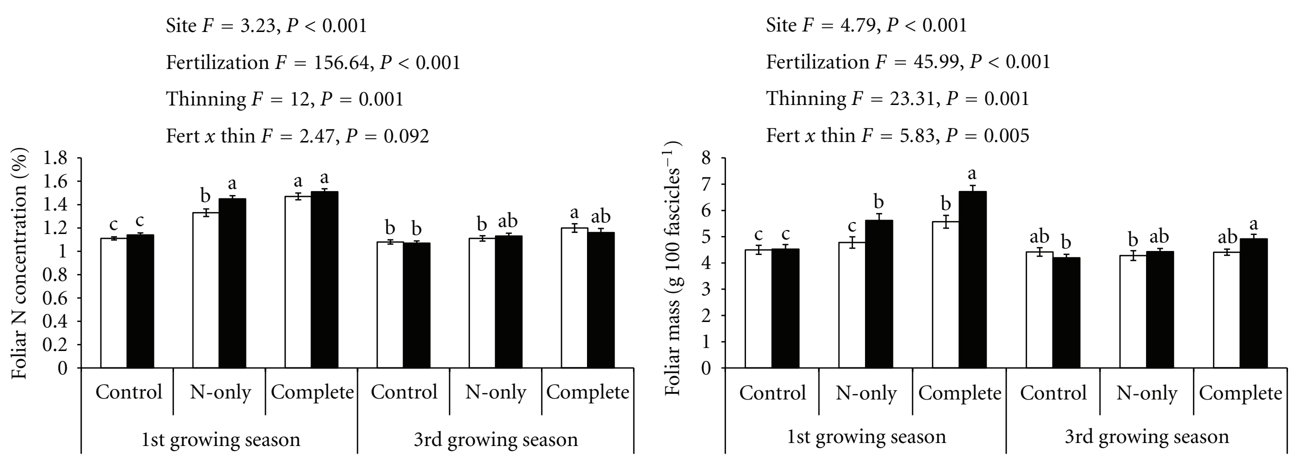
Foliar mass responded strongly to the combination of thinning and fertilization the first year after treatment (Figure 3(b)). Thinning or N-only fertilization alone did not increase foliar mass while the highest foliar mass was in the thinning + complete fertilization treatment. After three growing seasons, foliar mass was not significantly different from the control plots in any of treatments. Crop tree foliar nitrogen uptake increased with fertilization with the greatest average uptake in the thinning + complete fertilization treatment (Figure 4). There was great variability among sites, however, with 4 of the 15 sites showing no foliar N uptake with N-only fertilization alone, 8 of the 15 sites showing no foliar N uptake with thinning only and many other treatment units showing very little foliar N uptake.

After one growing season, foliar P concentration increased in response to complete fertilization (Table 3). Foliar S concentration increased with complete fertilization



(a) Diameter (b) Volume

Figure 2: Three-year crop tree diameter (a) and volume (b) growth in relation to thinning and fertilization treatments. Letters represent differences in total growth among the six treatments.



(a) (b)

Figure 3: Response of (a) foliar nitrogen concentration and (b) mass of 100 fascicles to thinning and fertilization treatments after 1 and 3 growing seasons. White bars represent unthinned stands and black bars represent thinned stands. Different letters represent significant differences among treatments for each growing season. ANOVA statistics are given for the 1st growing season data.

but SO_4 concentration decreased with N-only fertilization. Foliar base cation concentrations (K, Ca, and Mg) did not respond significantly to either fertilization or thinning but foliar K concentration tended to increase with complete fertilization while Mg tended to decrease with all fertilizer treatments. Foliar B concentration increased with complete fertilization but tended to decrease with N-only fertilization. Foliar Fe decreased with complete fertilization while Zn, Cu and Mn did not respond to the treatments. After three growing seasons, only B and SO_4 concentrations were still significantly different from the controls.

We could not detect any correlations between growth differential (treatment growth—control growth) and prethinning density, elevation, age, foliar mass, foliar nutrient concentrations, nutrient ratios, or nutrient thresholds of the controls. Further, the growth differential was not related to estimated foliar N uptake among sites for any of the treatments (Figure 4). We did, however, find that diameter growth differential increased with site index in the thinning only, N-only fertilization, and thinning + N-only fertilization treatments (Figures 5(a) and 5(b)); there was no correlation of diameter growth differential with site index in the complete fertilization treatments (Figure 5(c)).

4. Discussion

Thinning and fertilization produced an additive growth response in lodgepole pine with the best growth occurring when plots were both thinned and fertilized—diameter growth after three growing seasons increased on average

Table 3: Foliar nutrient concentrations after the first growing season in relation to thinning and fertilization treatments. Letters represent significant differences between treatments.

Thinning	Fertilization	P (%)	K (%)	S (%)	Ca (%)	Mg (%)	So_4^- (ppm)	B (ppm)	Cu (ppm)	Zn (ppm)	Fe (ppm)	Mn (ppm)
Unthinned	Control	0.132[c]	0.409	0.089[bc]	0.187	0.082	127.7[a]	11.16[b]	3.49	45.6	53.3[ab]	370.3
	N-only	0.133[bc]	0.407	0.088[c]	0.182	0.075	48.7[b]	8.67[b]	3.29	43.8	47.7[bc]	360.7
	Complete	0.149[a]	0.435	0.108[a]	0.189	0.075	94.9[a]	34.29[a]	3.23	42.7	44.5[c]	360.7
Thinned	Control	0.135[bc]	0.413	0.091[bc]	0.211	0.084	121.2[a]	11.78[b]	3.54	45.4	54.9[a]	400.8
	N-only	0.143[ab]	0.405	0.096[b]	0.187	0.077	48.6[b]	8.93[b]	3.77	44.7	48.9[abc]	360.5
	Complete	0.150[a]	0.447	0.111[a]	0.189	0.075	97.8[a]	32.10[a]	3.48	43.5	46.6[c]	378.0

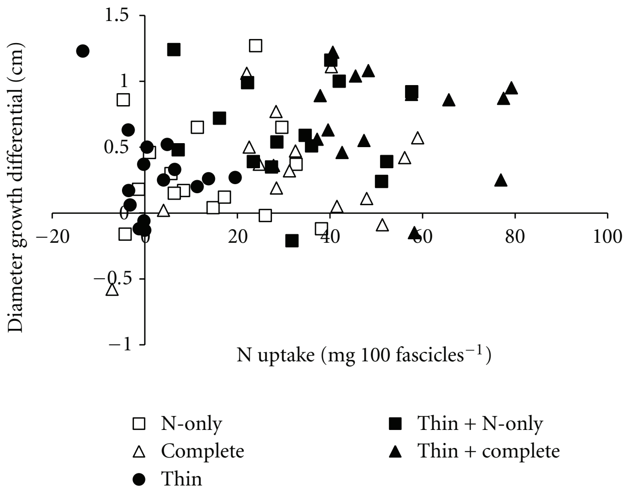


Figure 4: Diameter growth differential of thinning and fertilization treatments relative to the controls in relation to nitrogen uptake by the foliage in year 1 (N content of treated trees—N content of control trees). Diameter growth differential is the difference between DBH growth after three years of the treated stand and DBH growth of the associated control stand.

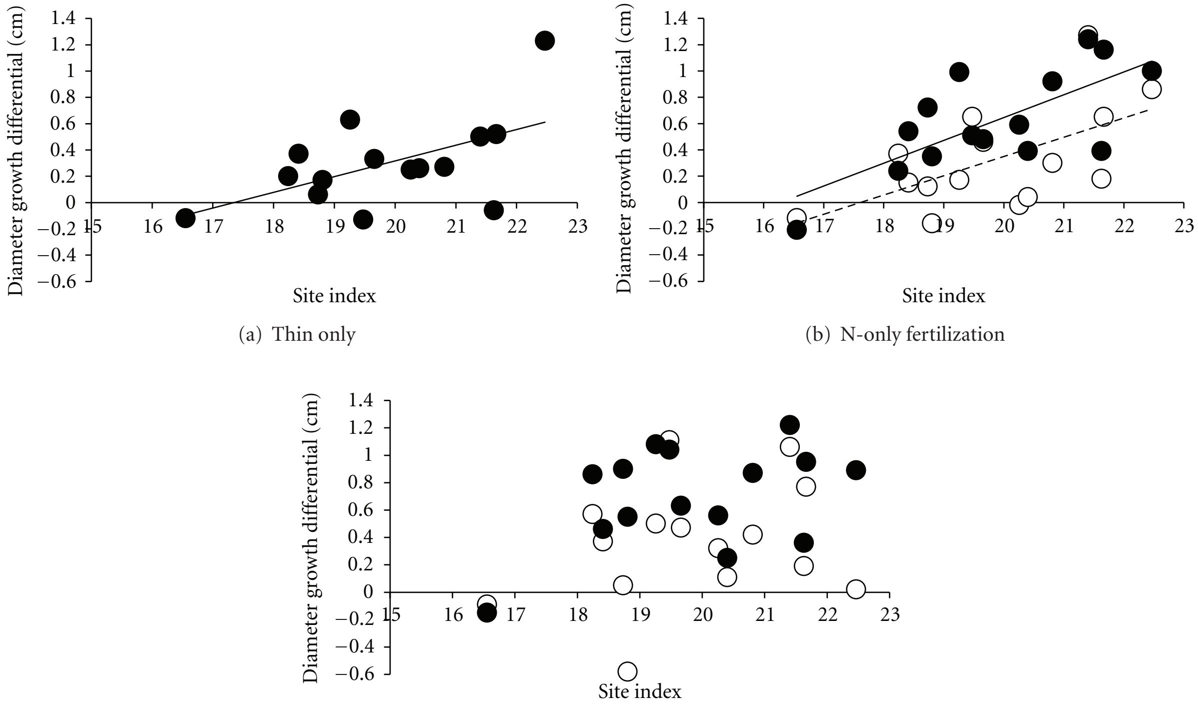
0.3 cm with thinning, 0.3 cm with either N-only or complete fertilization, and 0.6 cm with thinning and fertilization combined. This additive crop tree growth response to thinning and fertilization has been recorded before in lodgepole pine stands [1, 3, 13]; however, the real story of our study relates to our inability to diagnose which stands would respond to treatment, particularly for the complete fertilization treatment.

All stands had low foliar N concentrations prior to treatment (average 1.1%) compared to the adequate value of 1.35% N [11]. We therefore expected a greater growth increase as a result of the fertilization. Further, many of our sites showed little or no positive growth response to our treatments which is a disappointing result given that all of the sites were below the critical level of foliar N prior to treatment and the high rate of fertilizer applied (300 kg N ha^{-1} along with other nutrients). This inconsistent response to fertilization is similar to what has been found in other conifer fertilization studies (e.g., in lodgepole pine [4, 17], *Picea glauca* [18], *Picea abies* [19], *Pseudotsuga menziesii* [20], and mixed conifer stands of the Pacific Northwest [21]).

Foliar nutrient concentrations and ratios have been successfully used in predicting the growth response of lodgepole pine to fertilization [4, 6] but did not work in our study. We believe that the main reason that these techniques were not useful in our study is that in many of the sites the nutrients supplied by the fertilizer were not successfully taken up by the trees. These diagnostic tests can only work well if the tree actually takes up the nutrients. In our study, at 4 of the 15 sites, trees showed no uptake of N in the N-only treatment and another 4 sites had only a small amount of uptake.

The uptake of N may be related to the type of fertilization applied with the complete formulation resulting in greater N uptake, even though the total amount of N applied was the same between the N-only and complete fertilization treatments. This increased N uptake with complete fertilization could simply be related to increased tree growth stimulating greater uptake of N. The addition of other potentially limiting nutrients can also increase N uptake as has been seen previously in *Eucalyptus grandis*, where fertilization with P increased N absorption through a mechanism not related to increased N demand [22]. The difference in fertilizer formulation may have also affected N uptake; in the N-only fertilizer urea was the single source for N while in the complete fertilizer 49 kg N ha^{-1} was derived from monoammonium phosphate. This direct addition of NH_4 could have made N more readily available for uptake since the N from monoammonium phosphate may have been less likely to be volatilized than the N derived from urea [23] in these forests with thick organic layers. It is likely that ammonium nitrate is a better formulation than urea for N fertilization in boreal forests [24].

Even when N was increased in the foliage, there were sometimes poor tree growth responses and we suggest that these were related to internal nutrient imbalances. With the addition of N-only fertilizer, macronutrient imbalances can be induced in lodgepole pine [4] and other conifers [25]. Micronutrient deficiencies (Cu and Zn) have also developed after repeated N fertilization of lodgepole pine, thereby limiting potential growth [5]. In our study, the idea that nutrient imbalances limit growth response is supported by the fact that only the N-only and thinning-only treatments had a positive relationship between growth differential and



(a) Thin only

(b) N-only fertilization

(c) Complete fertilization

Figure 5: Diameter growth differential of thinning and fertilization treatments relative to site index of the control stands. The response variable, diameter growth differential, is the difference between DBH growth after three years of the treated stand and DBH growth of the associated control stand. White dots represent unthinned plots and black dots represent thinned plots. (a) Thin only, $P = 0.032$, $r^2 = 0.254$, (b) N-only, $P = 0.020$, $r^2 = 0.303$, N-only + thinning, $P = 0.003$, $r^2 = 0.469$, and (c) complete fertilization, $P = 0.334$, complete + thinning, $P = 0.110$.

site index. We argue that sites with low site index are likely limited by several nutrients so thinning or N-only fertilization will not result in increased growth. On better-quality sites, other nutrients such as P, S, and micronutrients, are likely in higher supply so N-only fertilization and thinning will increase growth without causing internal nutrient imbalances or inducing other nutrient deficiencies. In contrast, the differential growth response to complete fertilizer was not related to site index, likely because any potential nutrient imbalances were eliminated.

The link between site index and growth response to silvicultural treatments has been varied. For example, growth response to competition control in hybrid poplar plantations was positively correlated to site productivity [26], while in jack pine plantations the growth response to site preparation treatments was negatively correlated to site productivity [27]. The positive relationship between lodgepole pine growth response to thinning and N-only fertilization and site index has not previously been documented but appears to be related to site nutrient availability and nutrient imbalances.

In summary, the combination of fertilization and thinning is likely to result in the greatest growth response of lodgepole pine crop trees. On better quality sites it may be possible to use N-only fertilizer but the poorer sites may also need other nutrients in order to stimulate a growth response. We recommend caution in extrapolating the growth results in our study to yield at the stand level because our study focused on the response of only the largest trees in the stand, that is, the crop trees. Future work should concentrate on identifying specific fertilizer formulations, particularly the forms of N, and their delivery methods to enhance nutrient uptake of trees in the field.

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