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Predicting the effect of forest harvesting on soil nutrient availability in the boreal forest

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ABSTRACT

The main objective of this project is to gather information from different sources including field work, published scientific documents and information from collaborators in order to better identify forestry practices that would or would not allow the sustainable use of the soil resource. This process is intended to generate guidelines that can be used to address these issues for specific sites. The project is divided into three sections.

Inputs-outputs budgeting approach

The estimation of nutrient output rates in harvested products in relation to forest stand composition, site index, stand density, stand age and type of harvesting (stem-only versus whole tree) was completed using state of the art techniques for five major tree species of the boreal forest (balsam fir, black spruce, jack pine, paper birch, trembling aspen). These rates are compared to estimates of nutrient input rates which are dependant on location for atmospheric deposition, and on deposit for mineral weathering. This approach allows forest managers to address the question of sustainability of the soil nutrient capital using information that they usually have such as deposit and stand characteristics. General trends were observed such as potential problems using whole tree harvesting on shallow soils especially if stands are dense. The problematic situations encountered concerns mostly the Ca and Mg status of these soils while the N status does not appear problematic with the exception of severely burned stands.

Modelling soil N dynamics

Nitrogen (N) appears to be the elements that is the most limiting to boreal forest productivity despite the fact that the N budget approach (chapter 1) generally does not indicate any problems with N stocks. This information indicated that the controls over N dynamics within a forest stand must be considered carefully. Long term laboratory incubations have been used to determine the effect of soil type, temperature and vegetation type on N mineralization. These parameters are believed to be the key elements controlling N cycling and the latter two can be modified by forestry practices. The use of a large range of data provided by our laboratory as well as by other studies has permitted us to determine how these factors affect N mineralization and to derive general equations for representing their effect on N cycling. This information generates the backbone for modelling the impact of management on N cycling. The effect of soil type, soil temperature and vegetation type on soil N dynamics are analysed. The investigation of the effects of forest management on N availability with the use of simulation models will be provided in a following study.

Nutrient limitation of black spruce and Jack pine stands

The compositional nutrient deficiency index technique was used to determine nutrient imbalances and nutrient deficiencies for 30 jack pine and 30 black spruce sites covering a wide range of growing conditions in Quebec. For black spruce, the analysis revealed that site index

was influenced mostly by N on fine textured soil and on organic soils. On coarse textured soil, Ca and Mg appeared to be the elements that are most strongly related to the site index.

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INTRODUCTION

Forest harvesting can affect the maintenance of forest productivity by altering soil nutrient availability. While this has been known for a long time, there is yet no way for the forest managers to evaluate if the management that they are using could alter the long term productivity of their site and if corrective measures should be undertaken. Several case studies have examined nutrient budget issues but these studies have been conducted on very small areas and approaches that can extrapolate these results to a larger land base are needed.

The objective of this project was to provide tools to address the question of the sustainability of soil nutrient availability that would allow forest managers to know if some management operations, conducted on their specific sites, are potentially detrimental to the soil nutritional quality or if they maintain or improve it.

SUMMARY OF DATA ANALYSIS

Input-output budget for the boreal forest of eastern Canada

Introduction and Methods

A database containing estimates of the rates of nutrient export (nutrients that leave the forest ecosystem) caused by forest harvesting was completed. This database indicates the rate of nutrient export in kg per square meter per year and these values can be compared with estimates of nutrient input to the ecosystem in order to identify the most stressful situations and to determine which soil nutriment could become limiting to forest growth. The database provides rates of nutrient losses according to stand composition (5), methods of harvesting (2), rotation length and stand parameters (density and site index). These parameters can be evaluated by forest managers and therefore the nutrient budget can be estimated for specific sites.

Stand parameters were derived from production tables of the province of Québec (Pothier and Savard 1998) which is based on approximately 36 000 sampling points. It should therefore cover most growing conditions in the commercial boreal forest of eastern Canada. The biomass of plant compartments was estimated with the use of various published equations (Table 1). Nutrient concentrations in these components were derived mostly from a literature search and a single value per species and tissue was usually considered (Table 1). However, for the stemwood of aspen, paper birch, and balsam fir, the approach of Rochon et al. (1998) using a varying nutrient concentration with stem size, was used. This approach should generate results of a greater accuracy.

The estimates of atmospheric input are derived from Boulet and Jacques 1993. We estimated at 1kg/(ha*yr) the rate of N fixation and at 2 kg/(ha*yr) the rate of dry deposition output. N leaching was fairly constant when several sources in the literature were compared namely Lamontagne et al. (submitted), Paré and Bergeron (1997)and Titus et al. (1998). It was estimated at 2 kg/(ha*yr) . Weathering was estimated with different approaches. The model PROFILE (Alveted et al. 1994) was used but it generally generated values that were obviously two low since they were far from estimating net drainage losses. We therefore chose to use an empirical approach based on the rationale that element leaching from a watershed should be proportional to the amounts of element available and immobilised by the vegetation. This hypothesis was verified by a literature search of nutrient cycling on intensively studied forested watersheds that were approaching maturity. This analysis confirmed that K, Ca and Mg immobilisation was a fairly constant fraction of drainage losses. We therefore estimated weathering using published information on drainage fluxes from a watershed on thin till soil, another one for thick till soil and finally for clay soils (Plamondon 1993). Net element release from weathering were estimated using the following equation :

$$W = (\text{annual losses in drainage-precipitation inputs}) * A \qquad [1]$$

Where A is a coefficient specific to a given element , and W weathering in kg/(ha.yr). A was equal to 1.3 for Mg , 3 for K and 2 for Ca. Nutrient losses in drainage water was estimated from various sources (Lamontagne et al., submitted , Paré and Bergeron 1997, Plamondon 1993, Titus et al. 1998) but was not corrected for increased nutrient losses upon disturbance since over a rotation these rates appeared very small.

Results and discussion

The pattern of annual rate of nutrient output in harvested products for five stand types as a function of stand age are presented in Figures 1 (a, b, c, d, e). Using stand type, stand density as described by Pothier and Savard 1998, and site index (height at 50 years) one can determine nutrient output rates and observe how these rates vary according to the age at which the stand is harvested and according to the type of harvesting. Comparison with net rates of nutrient input (straight lines) are then possible using three deposit types namely clayey soils such as found in the Clay belt zone of Quebec and Ontario, thick till from the Canadian Shield and thin till from the Canadian Shield.   Nutrient budget can thus be examined for specific sites and stand types covered by the study. A nutrient biomass immobilisation rate (curves) exceeding input rates (straight lines) indicates a potentially problematic situation. Some general trends were also found. The rates of nutrient output generally increased in the following sequence: black spruce < paper birch < balsam fir < jack pine < aspen. Whole tree harvesting has an important effect on nutrient output except for jack pine where stand characteristics appear to have a greater effect because relatively small amounts of nutrient are found in branches and in needles. With age, nutrient output rate increases as the amount of harvested biomass increases. It then declines because nutrient concentrations in the stem generally decline with stem size and as foliage biomass stabilises. Figure 1 gives an indication of the effect of increasing the rotation age on nutrient outflow. When compared to nutrient inputs through different sources, nitrogen is in most cases sufficient. This information is also consistent with Bormann and Gordon (1989). In the case of intense forest fires, Brais et al. (submitted) estimated soil N losses at 600 kg/ha. This amount can be converted to a rate of 10 kg/(ha*yr) over a 60 year rotation and could significantly affect the N balance. The cumulative effect of intense fire and forest harvesting over short periods could cause a depletion of soil N.

Explanations for Figure 1 (a, b, c, d, e): Estimated rates (kg/(ha*yr) of nutrient output in harvested products and estimated net nutrient input rates (inputs minus leaching rates) for major stand types of eastern boreal forest of Canada in relation to stand age are presented in Figure 1. Each column represents a stand density (number of stem per hectare) which varies with stand age (see Pothier and Savard 1998). The original database for stand properties and changes through time is derived from Pothier and Savard (1998) and the equations for estimating the nutrient contents come from different sources (Table 1). Thin curves represent nutrient output rates caused by whole tree harvesting (whole aboveground portion of the tree) while thick curves represent nutrient output rates for stem-only harvesting (stem and stembark are harvested and branches smaller than 9cm diameter are left on site). Each curve represents a stand of a given site index (height at 50 years). For trembling aspen the site indices illustrated are 15, 18, 21 and 24 m; for paper birch they are for 12, 15, 18 and 21m ; for the coniferous species they are 9, 12, 15 and 18m. The horizontal lines represent the net input of nutrient to the ecosystem per year. A single line is used for N using average values for the boreal forest of Quebec. No estimate is available for P and for K, Ca, and Mg the horizontal lines represent the net nutrient input according to three deposit types (long dashes: clayey soils, small dashes: thick coarse till soil of the Canadian shield, and full line: thin till soils of the Canadian shield (<1m)). The absence of a horizontal line indicates that the value was much higher than the immobilisation in biomass and it was not presented for better clarity.

Table 1. Methods for estimating tree biomass and nutrient content

		Paper birch	Black spruce	Jack Pine	Trembling aspen	Bal.sam fir
Biomass (kg)	Stembark, Stem, Crown	Evert 1985	Evert 1985	Evert 1985	Evert 1985	Evert 1985
	Branch	(Crown-leaves)	(Crown-leaves)	(Crown-leaves)	(Crown-leaves)	(Crown-leaves)
	Leaves	Chatarpaul et al. 1985	Ter-Mikaelian and Korzukhin 1997	Hegyi 1972	Chatarpaul et al. 1985	Geron and Ruark 88
Nutrient	stem	Rochon et al. 1998	Foster and Morrison 1987 Conc. N=0.0578% P=0.00849% K=0.0336% Ca=0.204% Mg=0.0168%	Morrisson 1973 Conc in bark N=0.024% P=0.02% K=0.016% Ca=0.37% Mg=0.03% Conc in stemwood N=0.077% P=0.0063% K=0.063% Ca=0.07% Mg=0.01%	Rochon et al.1998	Rochon et al. 1998
	branches	Chatarpaul et al. 1985	Foster and Morrison 1987. Conc. N=0.351% P=0.0071% K=0.218% Ca=0.258% Mg=0.0627%	Morrisson 1973 Conc. N=0.26% P=0.016% K=0.16% Ca=0.19% Mg=0.0033%	Chatarpaul et al. 1985	Young 1971 Conc. N=0.31% P=0.011% K=0.36% Ca=0.84% Mg=0.08%
	foliage	Chatarpaul et al. 1985	Foster and Morisson 1997 and Weetman and Weber 1972 Conc. N=0.8295 % P=0.1263% K=0.3613% Ca=0.7367% Mg=0.1033%	Morrisson 1973 Conc. N=0.99 % P=0.10% K=0.32% Ca=0.29% Mg=0.11%	Chatarpaul et al. 1985	Brazeau and Bernier 1973. Conc. N=1.3533% P=0.17% K=0.4533% Ca=0.7967% Mg=0.1367%

Where b0, b_1, b_2, b_3, b_4, b_5, a, b, c are equation parameters found in the cited references. D= DBH and h= tree height.

Figure 1a: Aspen

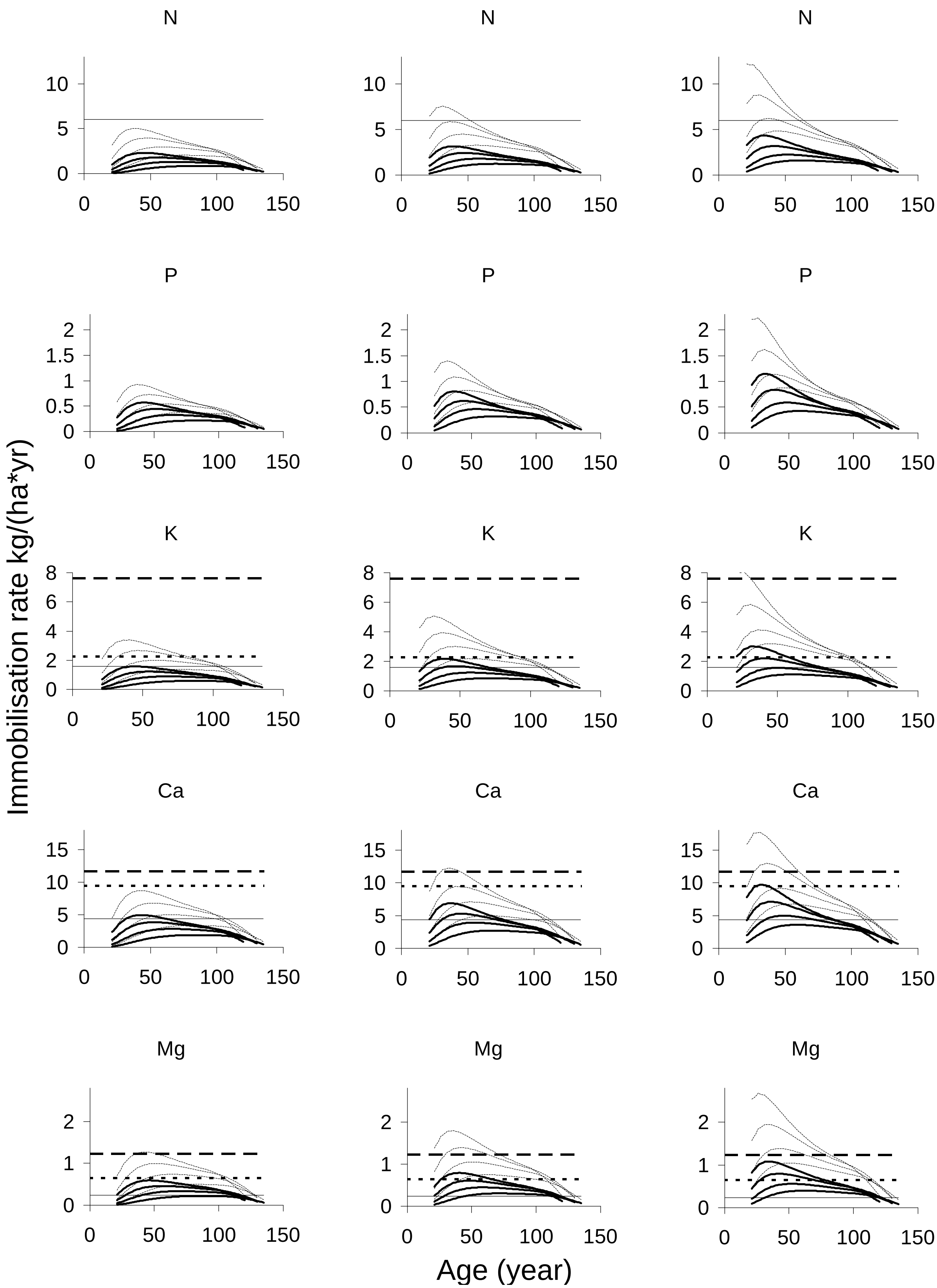


Figure 1b: Paper birch

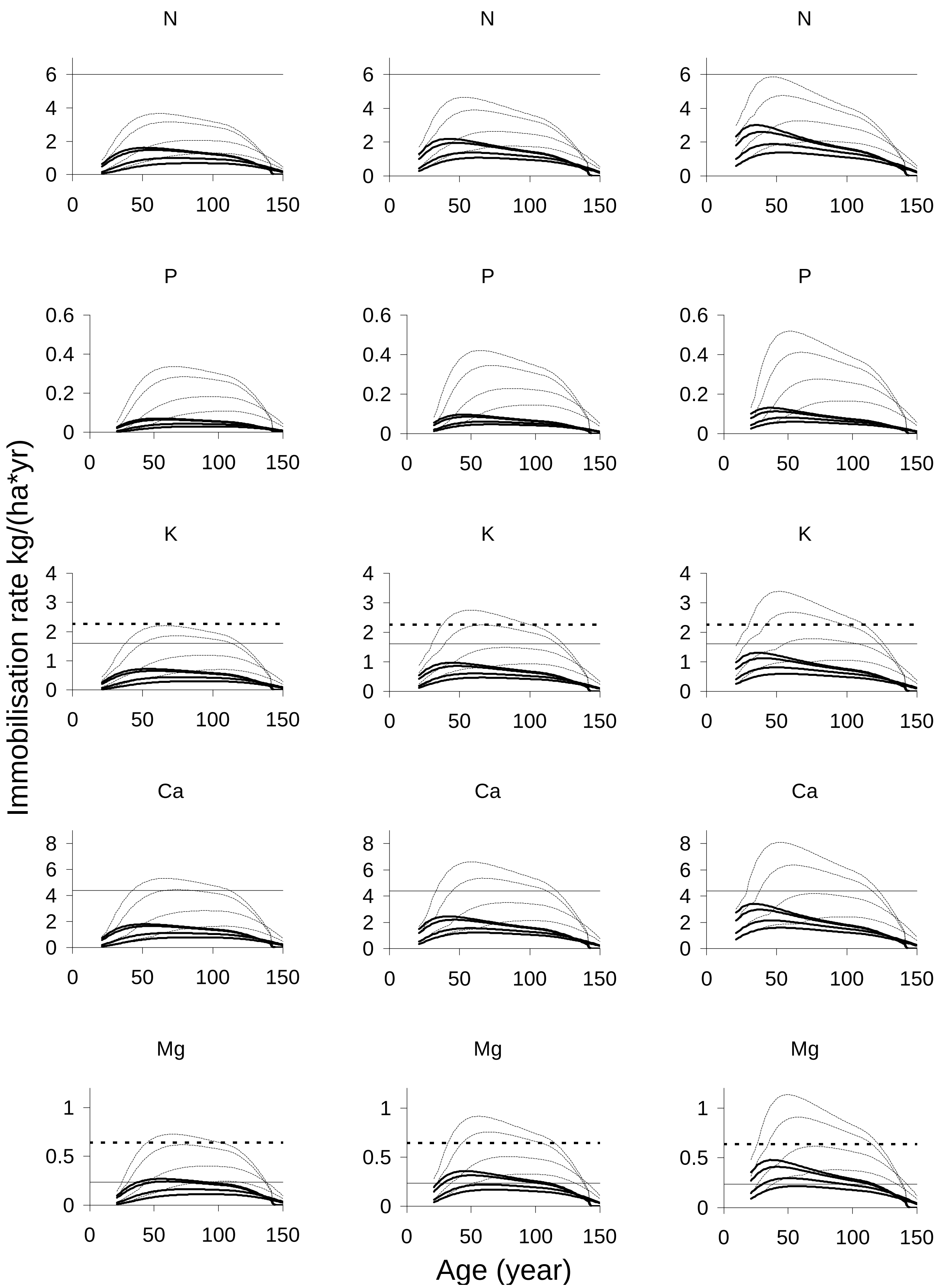


Figure 1c: Balsam fir

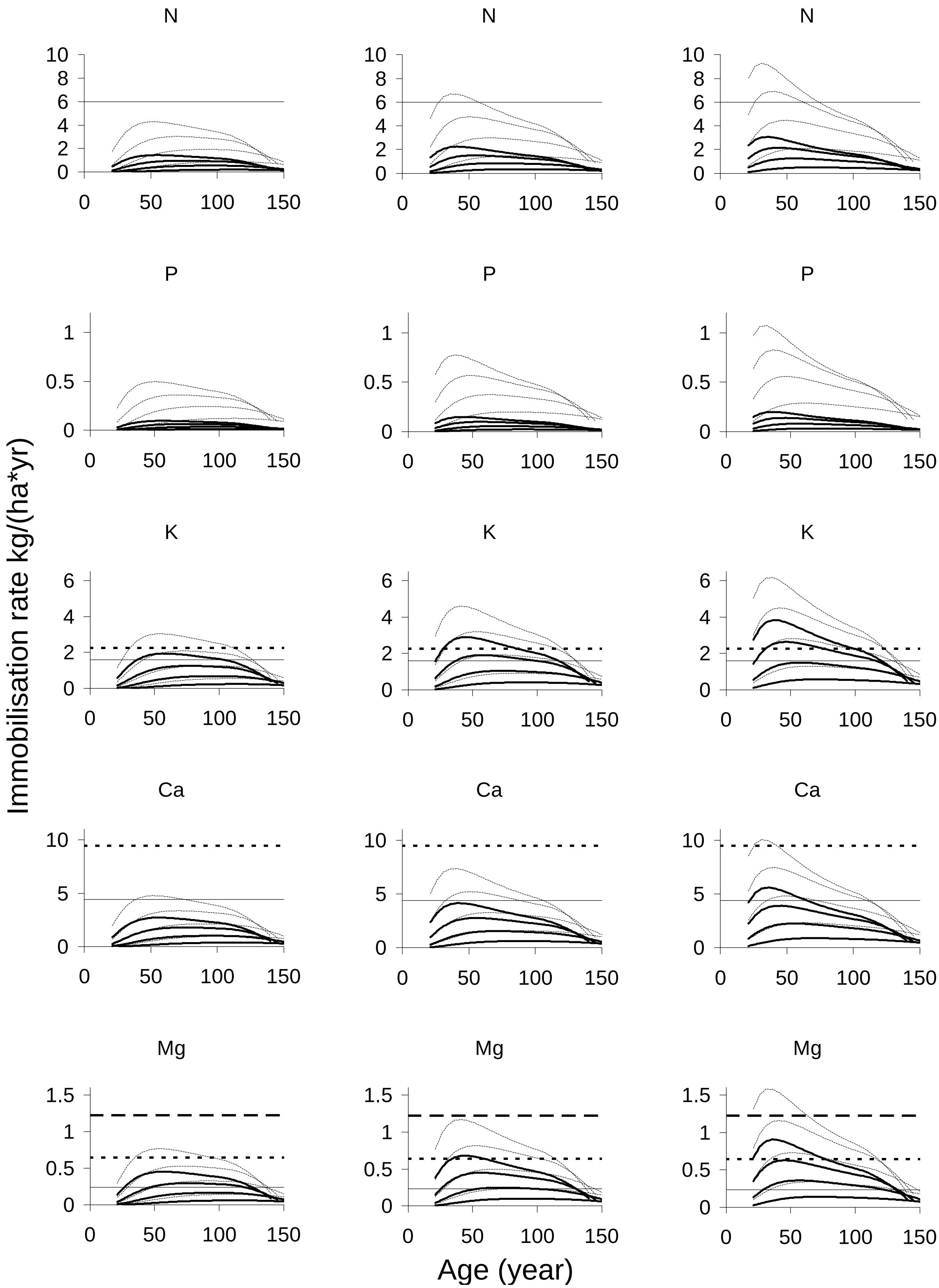


Figure 1d: Jack pine

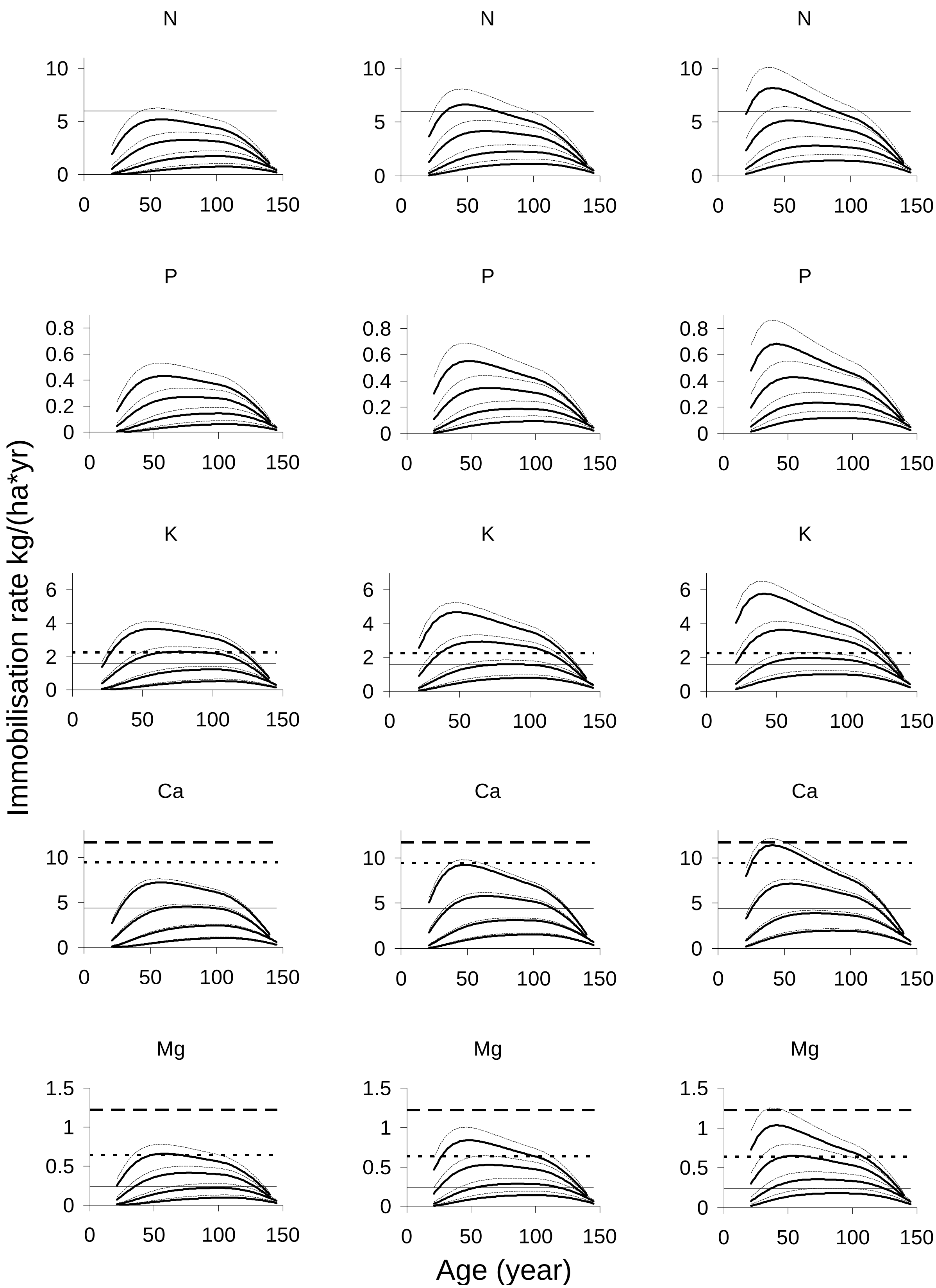
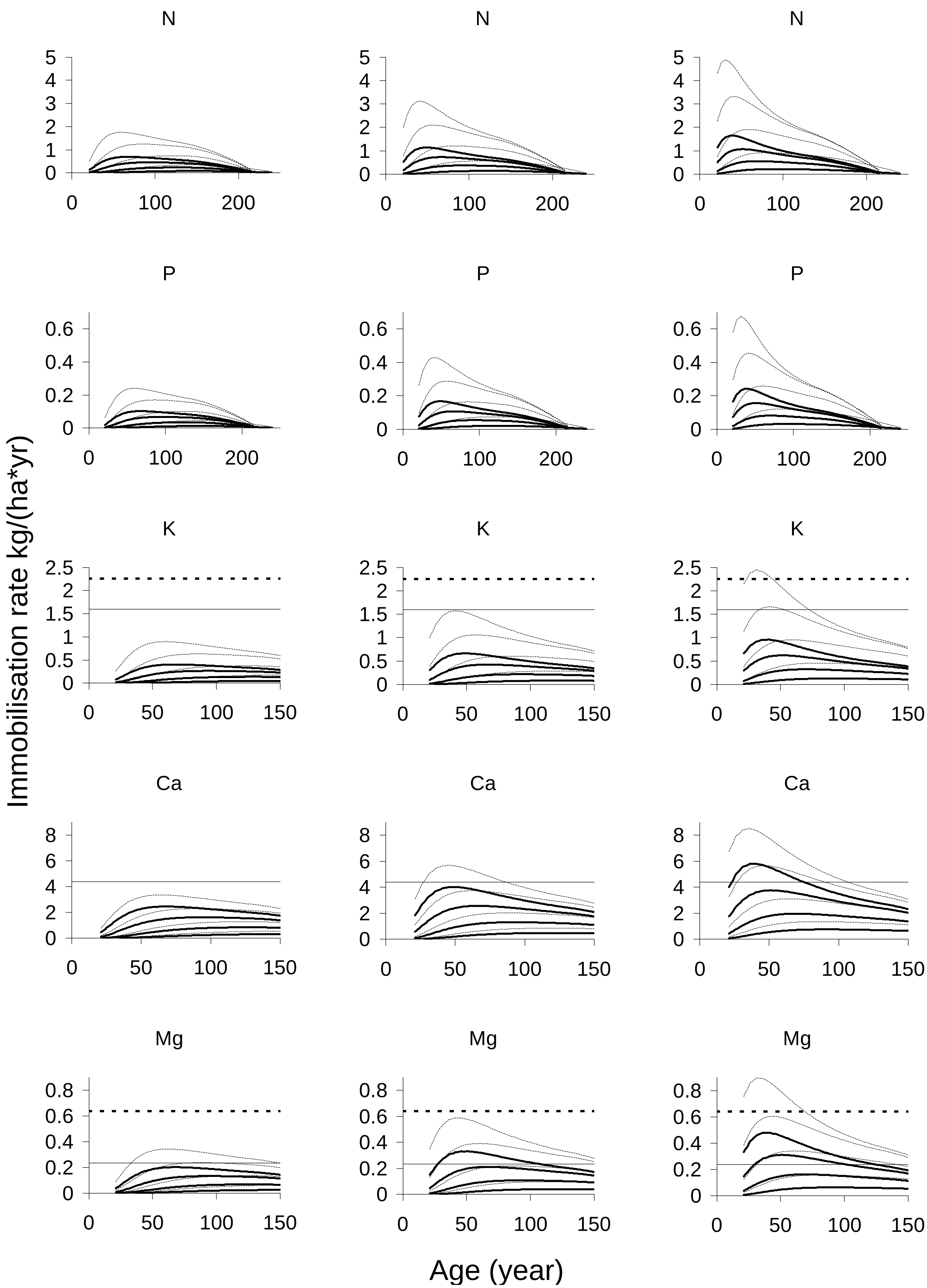


Figure 1e: Black spruce



Modelling soil N dynamics

Introduction and Methods

Nitrogen (N) is a crucial element to forest productivity as most forests will positively increase their productivity upon N addition. While boreal forest soils generally contain large reserves of this element and the nutrient budget of these ecosystems generally points out to a state of sufficiency, only a small portion of soil N is available to plants. It is therefore important to consider the effect of several factors that may affect the availability of this element to plants. Among the potential factors controlling N availability, soil texture, soil temperature and soil organic matter quality which is related to plant composition can influence the rate of N release in a form available to plants. In order to study these effect we gathered information from our lab and from different sources (for references see table 2) to examine : 1-the effect of soil horizon and soil texture, 2- the effect of the composition of plant communities growing on specific sites as well as the effect of recent soil disturbances, 3-the effect of soil temperature. The pattern of N release in the form of ammonium and nitrate over time was examined over the course of long term incubation under different temperature conditions. The amounts of potentially available N and the rates of N mineralization were estimated using the Gompertz model (France and Thornley 1984). The Arrhenius equation was used to examine the relationship between these parameters and temperature of incubation.

Results and discussion

The source of the data used is presented in Table 2 together with the total amounts of N mineralised. The results expressed by weight of soil organic matter give an indication of the quality of soil organic matter for N release and when expressed by hectare, they give an indication of the amounts available. One striking feature is that N availability in the forest floor of clay soils is much higher than in any other soil types. The quality of soil organic matter for N release is significantly affected by tree species on clay soils (Côté et al. Submited) as it varies in the following order birch>aspen>spruce/fir both in the forest floor and the mineral soil. However in terms of N release per hectare, these differences are not significant. No clear trends appeared in soil organic matter quality when comparing harvested or burned sites suggesting that the quality of soil organic matter is not affected by disturbance. The amounts of total organic matter therefore reflects the soils ability to provide inorganic N on coarse textured soils.

The relationships between soil temperature and N mineralization was examined (Table 3). Again fine-texture soils were different from other soils as the N mineralization rate of these soils were more strongly affected by a temperature change both in the organic layer and in the mineral soil.

These results will be used to model soil N dynamics. They indicated that deposit type has a major effect on soil organic matter quality for N release especially in the forest floor. The results suggested that fine texture soils should be rapidly colonised in order to limit nutrient losses by leaching, while coarse soils would be more resistant to N losses. The results also suggest that fine texture soils are the most sensitive to a change in soil temperature which can be significantly affected by site preparation (Mallik and Hu 1997). On some sites not only the rate of mineralization of N is affected but also the amount available suggesting that a change in soil temperature could impact on the pool of N available to plants. The best management strategy to allow soil N mineralization to match plant requirements will be addressed with the use of modelling in a following report.

Table 2. Average and standard deviation of N mineralised over the course of a 282 days incubation expressed in weight of N per weight of soil C and in weight of N per hectare.

N mineralised (20°C/ 282 days)

DEPOSIT	FH		N	Min Soil		N	References
	gN/gorg.C	KgN/ha		gN/gorg.C	KgN/ha		
Clay	7088 (2070)	218 (64)	59	5178 (2278)	211 (93)	20	Côté et al. (submitted) and Brais et al. (unpublished)
Loam	1647 (336)	73 (15)	3	3949 (1238)	107 (34)	3	Offord 1999
Silty loam	1296 (386)	48 (14)	3	5254 (1005)	66 (13)	3	Offord 1999
Sand	1358 (1040)	58 (44)	53	1699 (1072)	27 (17)	51	D.paré et al. (unpublished), Offord 1999, and Brais et al. (unpublished)

CLAY	FH		N	Min Soil		N	References
	gN/gorg.C	KgN/ha		gN/gorg.C	KgN/ha		
Aspen	7177 (1504)	173 (36)	16	5452 (2803)	244 (125)	8	Côté et al (submitted)
Mixed fir	7515 (2274)	202 (61)	3				Brais et al. (unpublished)
Birch	8800 (2022)	177 (41)	16	5184 (2066)	198 (79)	8	Côté et al (submitted)
Spruce-fir	5704 (1861)	385 (125)	16	4576 (1707)	179 (67)	6	Côté et al (submitted)
Recent cut	5870 (384)	71 (5)	3	9554	389	1	Brais et al. (unpublished)
Recent cut (scaped)	6345 (1403)	51 (11)	3	5382 (580)	219 (24)	2	Brais et al. (unpublished)
Recent cut plantation	6064 (570)	73 (7)	2	5372	219	1	Brais et al. (unpublished)
SAND							
Burned	923 (420)	20 (9)	4	1256 (209)	13 (2)	4	D.paré et al. (unpublished)
Cut	800 (544)	33 (23)	10	1633 (979)	23 (14)	8	D.paré et al. (unpublished)
Cut+burned	2537 (242)	54 (5)	9	1850 (1122)	19 (11)	8	D.paré et al. (unpublished)
Black spruce	1068 (756)	59 (42)	12	2079 (1301)	42 (26)	14	D.paré et al. (unpublished), and Offord 1999
Jack Pine	1369 (1305)	51 (49)	18	1451 (992)	18 (12)	17	D.paré et al. (unpublished), and Brais et al. (unpublished)
LOAM							
Jack pine +white spruce	1647 (336)	73 (15)	3	3949 (1239)	107 (34)	3	Offord 1999
White spruce +aspen	1296 (386)	48 (14)	3	5254 (1005)	66 (13)	3	Offord 1999

Nutrient limitation of black spruce and Jack pine stands

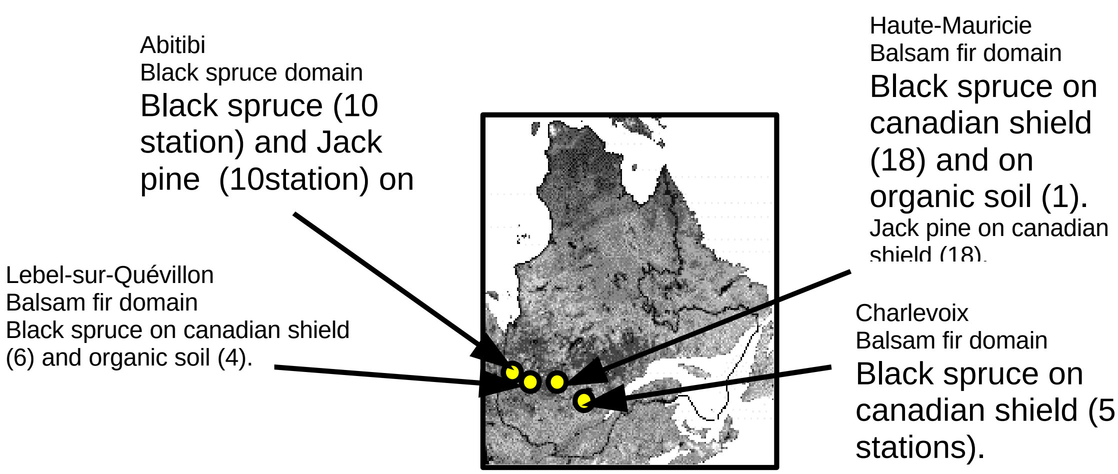
Introduction

The identification of nutritional constraints can help to better predict the impact of natural disturbances and forest management activities on future forest productivity. In the boreal forest, budget approaches have suggested that forest harvesting could cause limitations in Ca and Mg due to the exportation of these elements in the harvested biomass, while fire redistributes them in the ecosystem. Furthermore, fertilisation trials have generally shown that the addition of N and P increases productivity. The relationships between nutrition and growth and the balance between nutrients that permit an optimal growth are poorly known for boreal forests. The objective of this study is to evaluate the nutrient status of black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) with Compositional Nutrient Diagnosis (CND) and to predict potential productivity with CND index and edaphic factor.

Methods

Leaves of the upper third part of the crown of three trees were collected. Site productivity was estimated with site index curves (height at 50 years) of Pothier and Doucet (1998) for black spruce and Gekorviantz (1958) for jack pine. The soil type were evaluated with maps and field observations. The needles were oven dried at 70^{o}C and wet-digested (0,2 g) in sulphuric acid-hydrogen peroxide. N and P were analysed by Tecator FIA Star Analyser and K, Mg and Ca by flame emission spectrophotometry. Study sites covered a large territory extending from Charlevoix to the Ontario boarder. Sites of the Haute-Mauricie, Charlevoix and Lebel–sur Quevillon regions are characterised by coarse till soils while sites of the Abitibi region were found on Clayey till deposit (Fig. 2).

Figure 2. Study area



CND indices are multivariate nutrient ratios that express the relative abundance of an element in relation to all the others. They are used as a tool to interpret the nutrition of a given tree (or stand) in relation to the nutrition of a high-yielding population. Each sample is compared to a norm value, that is the mean obtained from a high-yielding population. For an optimal growth, all the nutrients should be in equilibrium.

Interpretation of CND index: positive (+) = sufficiency-excess [2]
zero (0) = sufficiency
negative(-) = deficiency

The site index (height at 50 years) that distinguish the high and the low-yielding populations were fixed at 13 m for black spruce and 20 m for jack pine. The CND approach needs intensive sampling of all kind of growth conditions and the presence of healthy and well growing populations for norm values calculations.

Results

The most significant relationships between CND indices and site index are presented in Table 4. Nitrogen appeared to be the most critical element for black spruce growing on clay soils as well as for black spruce on organic soils. Calcium and magnesium were related to site index on coarse texture soils.

Table 4 . Relationships between Compositional nutrient diagnosis (CND) indices and site index (height at 50 years) for black spruce.

Soil type and species	Nutrient	Nb of stands	Range (Si)	Range (CND)	Relationship CND and SI R2	prob.
Black spruce						
Clay	N	10	4.0 to 9.7	-4.0 to +1.5	0.65	0.01
Sandy loam	Ca	33	6.6 to 10.5	-1.5 to +1.5	0.32	0.001
Sandy loam	Mg	33	6.6 to 10.5	-3.5 to +2.0	0.22	0.01
Organic	N	5	3.5 to 6.6	-4.0 to –0.05	0.45	0.21

CONCLUSION

The input output budget approach provided a ready-to-use tool for evaluating the sustainability of forest harvesting based on tree species, site-type and stand characteristics. Such tools can be useful to provide guidelines for sustainable forestry practices and the figures presented could serve as indicators of sustainable management from the standpoint of the soil nutritional capacity. The weakest point of these figures is the amounts of nutrients provided by mineral weathering. It is however important to provide such a tool with the best estimate possible and further studies using modelling approaches and empirical evaluations will contribute to strengthen this approach. This analysis revealed that for all species except jack pine, leaving the branches and foliage on sites can make an important difference in the balance of the nutrient budget. It showed that on clay soil complete removal of the aboveground vegetation appears sustainable except for high density aspen stands. On thick till some stands can be whole tree harvested while some other cannot. On thin till most stands cannot be whole tree harvested except with very long rotations. The global analysis of N mineralization dynamics indicated that rich soils are more flexible than coarse acidic soil in their N providing capacity. Therefore they are likely to be manipulated more easily either favourably or not by management activities. A following study will evaluate how forest management and natural disturbances can affect soil N availability in the boreal forest.

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