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Will Whole-Tree Harvest of Jack Pine (*Pinus banksiana*) Deplete Soil Nutrients in Low-Productivity Sand Soils?

By:
Victoria L. Veach

A REPORT

Submitted in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE IN FOREST ECOLOGY AND MANAGEMENT

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ABSTRACT

In 2009 and 2010 a study was conducted on the Hiawatha National Forest (HNF) to determine if whole-tree harvest (WTH) of jack pine would deplete the soil nutrients in the very coarse-textured Rubicon soil. WTH is restricted on Rubicon sand in order to preserve the soil fertility, but the increasing construction of biomass-fueled power plants is expected to increase the demand for forest biomass. The specific objectives of this study were to estimate biomass and nutrient content of above- and below-ground tree components in mature jack pine (*Pinus banksiana*) stands growing on a coarse-textured, low-productivity soil, determine pools of total C and N and exchangeable soil cations in Rubicon sand, and to compare the possible impacts of conventional stem-only harvest (CH) and WTH on soil nutrient pools and the implications for productivity of subsequent rotations. Four even-aged jack pine stands on Rubicon soil were studied. Allometric equations were used to estimate above-ground biomass and nutrients, and soil samples from each stand were taken for physical and chemical analysis. Results indicate that WTH will result in cation deficits in all stands, with exceptionally large Ca deficits occurring in two stands. Where a deficit does not occur, the cation surplus is small and, chemical weathering and atmospheric deposition is not anticipated to replace the removed cations. CH will result in a surplus of cations, and will likely not result in productivity declines during the first rotation. However even under CH, the surplus is small, and chemical weathering and atmospheric deposition will not supply enough cations for the second rotation.

1. INTRODUCTION

Biomass utilization has increased in some regions of the world as the push for alternative and renewable energy sources has become stronger (Björheden 2006, Hakkila 2006). Forest residue is one of many types of biomass that can provide a renewable alternative to fossil fuels. Plant litter, however, is one of the most important sources of nutrients returned to the soil as it is an important source of soil organic matter (SOM) and provides much of the annual nutrients required for a forest ecosystem (Waring and Running 2007). SOM also has an important role in long-term site productivity, which can be greatly affected by forest management (Powers 1990, 2004). Intensive silvicultural systems, such as whole-tree harvesting (WTH), that remove fine and non-woody material (branches, foliage, etc.) may have a greater impact on soil productivity than conventional, stem-only, harvest systems (CH) as the concentration of many nutrients is greater in the foliage and branches than in the stem (Farve and Napper 2009). As a result, removing these components would dramatically reduce the amount of potentially mineralizable nutrients returned to the soil as tree litter.

Recent studies suggest that WTH can reduce above-ground productivity (e.g. Stone et al. 1998, Jacobson et al. 2000, Egnell and Valinger 2003, Walmsley et al. 2009, Helmisaari et al. 2011), and that carbon (C) and nitrogen (N) in shallow soil layers, especially the forest floor (FF), are more likely to show a stronger response than deeper soil horizons (e.g. Hendrickson et al. 1989, Olsson et al. 1996, Knoepp and Swank 1997, Nave et al. 2010, Saarsalmi et al. 2010). However, few of these field studies link soil nutrient loss and nutrient removal in harvest to growth reductions.

It is generally thought that WTH will be particularly detrimental to nutrient-poor, low organic matter sandy soils (Lundmark 1983 as seen in Jacobson et al. 1996, Page-Dumroese 2010), as significantly altering the nutrient status of the forest floor (FF) and upper mineral soil horizons could have severe negative implications for future forest and soil productivity. Precautionary biomass harvest guidelines, or best management practices (BMP's), have been developed to address this problem (Minnesota Forest Resource Council 2005, Herrick et al. 2009, MDNR 2010). These BMP's restrict biomass harvesting in certain site types, typically low-productivity sand or shallow soils, to promote long-term site productivity. However, large variation in study design, location, and tree species composition, and a low number of long-term monitoring studies make clear support for this idea relatively limited. For example, Jacobson et al. (2000) found growth reductions of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) following WTH regardless of climate and soil conditions in Sweden. Stone et al. (1998) found growth reductions of aspen growing on low fertility soil following WTH, but since this study was

not compared to aspen growing on more productive sites, it is not possible to conclude that productivity losses are worse on low productivity sites.

Determining the long-term impact of WTH is further complicated by the short-term nature of many studies. New long-term studies intended to determine the effects of soil disturbance on soil and forest productivity have been established in North America as part of the Long Term Soil Productivity (LTSP) project, but since the first experiment was established in just 1990 the majority of these studies are still in their infancy (Powers et al. 2005). Even the more established and extensive studies following tree growth from planting are barely 30 years old now, with the most recent reports coming from stands 20 to 24 years old (Egnell and Leijon 1999, Egnell and Valinger 2003, Walmsley et al. 2009).

Jack pine (*Pinus banksiana*) is an important commercial timber species in Michigan that is often found on coarse-textured low fertility soils, and is typically managed by clear-cut harvesting (Rudolph 1985). Many studies on jack pine have focused on determining the biomass and nutrient content of various tree components, and how nutrients cycle within the ecosystem (e.g. Morrison 1973, Foster and Morrison 1976, Maclean and Wein 1976, Alban et al. 1978, Green and Grigal 1980, Perala and Alban 1982, Alban 1988). Empirical and theoretical WTH studies on jack pine do suggest that this practice will have a negative effect on the soil nutrient status (Weetman and Algar 1983, Thiffault et al. 2006). Weber et al. (1985) concluded that removing the FF in jack pine stands results in reduced basal area and diameter increment. Still, Rothstein and Spalding (2010) conclude that soil and foliar nutrient content in stands treated with WTH will not be statistically different from those regenerating naturally after wildfire.

Currently, WTH of jack pine is widely used on Michigan Department of Natural Resource land at a rate of approximately 3,000 ha/year regardless of site and soil conditions (Mohney 2011, personal communication). In contrast, WTH is not widely used for jack pine management on the Hiawatha National Forest (HNF) in order to prevent declines in soil productivity on very sandy soils (USDA 2006). For example, just two WTH timber sales for jack pine have occurred in recent years (Keach 2011, personal communication).

With increasing construction of biomass-fueled power plants, the demand to maximize forest biomass utilization is expected to increase. Consequently, more information is needed on above- and below-ground nutrient pools in jack pine growing on sandy sites in the HNF, and the possible impact WTH could have on future soil productivity. Furthermore, most studies have determined the nutrient content of stands by chemical analysis of vegetation samples (Weetman and Algar 1983, Helmisaari et al. 2011). But this is cost and time intensive, and methods need

to be developed in order to quickly and accurately estimate nutrient content of management areas in order to make responsible silvicultural decisions.

1.1 Objectives

The objective of this study was to estimate the possible impact of WTH of jack pine on the nutrient status of a low productivity sand soil on the Hiawatha National Forest. Two harvest intensities are considered in this study: Conventional harvest (CH), in which boles to a 10 cm top are removed, and WTH, in which boles, limbs, and foliage are removed from the site. Due to differences in tree species composition, three further harvest scenarios were considered. The first assumes harvest of only jack pine, the second assumes harvest of jack and red pine, and the third assumes harvest of all merchantable trees (pines and hardwoods). All harvest scenarios assume 100 percent removal efficiency, that is, no residue is lost during transport. All WTH scenarios assume 100 percent removal with no snag or seed tree retention. This entailed:

- 1) Estimation of the biomass and nutrient content of above- and below-ground tree components in mature jack pine stands growing on a coarse-textured, low-productivity soil.
- 2) Determination of total soil C and N and exchangeable soil cation pools in four representative profiles of this soil.
- 3) Comparing the possible impacts of CH and WTH on subsequent soil nutrient pools.

2. METHODS

2.1 Study Location

This study was conducted in the Hiawatha National Forest (HNF) in Michigan's Upper Peninsula (Figure 2.1). The landforms in the HNF are highly influenced by glacial activity with the last event (the Greatlakean) occurring about 10,000 years ago (Jerome 2006). The growing season in the HNF lasts between 100 and 150 days, with average daily summer and winter temperatures of 17° and -7° C, respectively. The average total annual precipitation is 218 to 645 cm, with most occurring as snow (Jerome 2006).

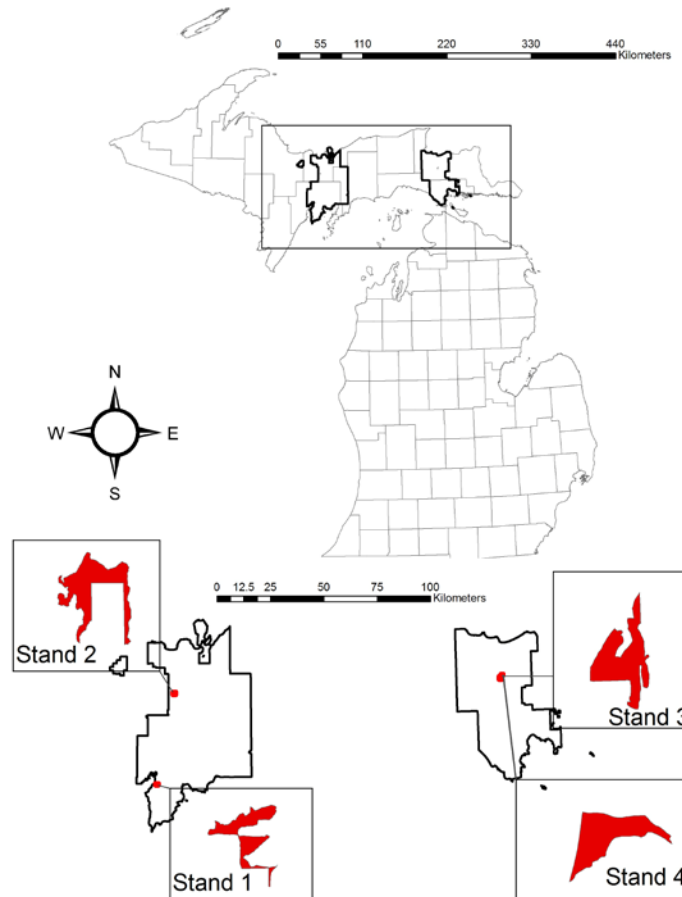


Figure 2.1: Location of study sites within the Hiawatha National Forest and in Michigan

2.2 Study Sites

Jack pine was chosen as the focus of this study as it is an important timber species (covering roughly 25,000 ha of the HNF) and is typically found on the low productivity sites where WTH is prohibited on the forest. All jack pine stands used in this study were growing on Rubicon sand, a deep, excessively drained, acid soil, classified as a sandy, mixed, frigid Entic Haplorthod. All stands are classified as Ecological Land Type (ELT) 20, and have a *Pinus strobus/Vaccinium angustifolium-Epigaea repens* (PVE) site type (Burger & Kotar 2003). Rubicon sand and ELT 20 are associated with outwash and lake plains, stream terraces, moraines, and beach ridges (USDA 2007, USDA NRCS 2009a), and are major components of the HNF, covering approximately 91,000 ha.

2.2.1 Stand 1 (HNF Stand ID 1/36/11)

Stand 1 (45°51'54" N, 86°55'57" W) was established in 1937 and is located on a lake plain in the southern portion of the West Zone of the HNF. Most of this stand is growing on the Grayling soil series, and only the small southern portion on Rubicon soil was sampled. The overstory is dominated by jack pine, and there is a scattered understory of serviceberry (*Amelanchier* spp.). Common groundflora include low sweet blueberry (*Vaccinium angustifolium*), bracken fern, bearberry (*Arctostaphylos uva-ursi*), wintergreen (*Gaultheria procumbens*), wild lily of the valley (*Maianthemum canadense*), sedge (*Carex* spp.), and ground cover mosses.

2.2.2 Stand 2 (3/89/72)

Stand 2 (46°15'14" N, 89°49'42" W) was established in 1940 and is located on a pitted outwash plain in the northwestern portion the West Zone of the HNF. The dominant overstory is jack pine with some quaking aspen (*Populus tremuloides*), pin cherry (*Prunus pensylvanica*), and red pine (*Pinus resinosa*) also occurring. The understory consists of scattered red maple (*Acer rubrum*), white pine (*Pinus strobus*), balsam fir (*Abies balsamea*), and serviceberry. Bracken fern is the most abundant groundflora species, but other common groundflora are wintergreen, sedge, low sweet blueberry, trailing arbutus (*Epigaea repens*), starflower (*Trientalis borealis*), ground cover mosses, and reindeer lichen (*Cladonia* spp.).

2.2.3 Stand 3 (4/90/03)

Stand 3 (46°17'40" N, 84°50'47" W) was established in 1947 and is located on an outwash plain in the East Zone of the HNF. The dominant overstory is jack pine with scattered red maple and red oak (*Quercus rubra*) also present. Understory is primarily pin cherry, red oak, and red maple. Common groundflora include bracken fern, low sweet blueberry, trailing arbutus, sedge, reindeer lichen, and ground cover mosses.

2.2.4 Stand 4 (4/89/01)

Stand 4 (46°18'36" N, 84°50'10" W) was established in 1961 and is located on an outwash plain in the East Zone of the HNF. The dominant overstory is jack pine with some red pine also present. Understory consists of scattered red maple. Groundflora is predominantly bracken

fern, low sweet blueberry, wild lily of the valley, wintergreen, sedge, reindeer lichen, and ground cover mosses.

2.3 Stand Sampling

2.3.1 Overstory

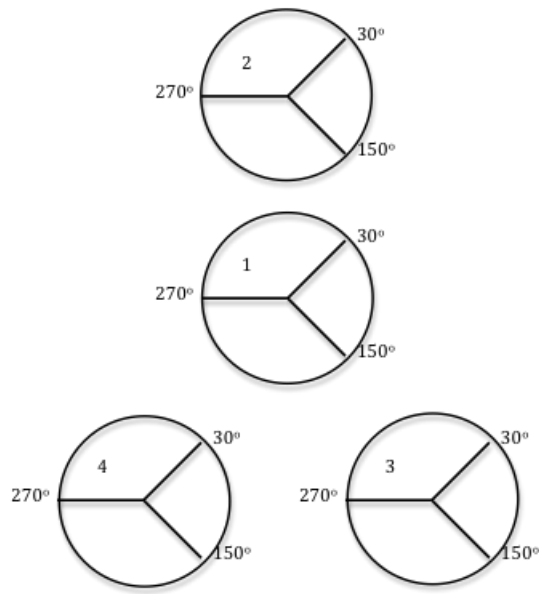
Above-ground stand data were obtained using a variable radius plot and a basal area factor 10 prism. Since the stands were relatively uniform in age and species, approximately one plot for every four hectares was established. Species, diameter, and status (live/dead) of each tree falling within each plot were recorded. The height of three dominant trees in each plot was also recorded.

2.3.2 Coarse Woody Debris (CWD)

Two or three multi-segment coarse woody debris plots were established in each stand, depending on the size of the stand. CWD (>2.5 cm) was inventoried according to the method utilized in the USFS Forest Inventory Analysis (Figure 2.2), which avoids bias associated with non-random CWD orientation (Woodall and Williams 2005). Mass and C content of CWD were estimated using equations from Woodall and Williams (2005). Nitrogen, Ca, K, and Mg content of CWD were estimated using the weight of the CWD and the stem wood nutrient concentration of jack pine stems (Alban 1988).

2.3.1 Forest Floor and Soil

Forest floor (FF) was collected using an 1830 cm² Daubenmire frame at five random locations in each stand. A 2.5 cm soil probe was used to collect mineral soil cores to a depth of 30 cm in each stand, and the horizon thickness in each core was measured. Soil horizons were separated and placed in plastic bags, and both soil and forest floor samples were stored in a cooler at 2° C until processing in the laboratory.



Distance between subplot center 1 and subplot centers 2, 3, and 4 is 36.5 m at 0°, 120°, and 240°, respectively. Each transect is 7.3 m.

Figure 2.2: Plot design to measure CWD biomass in jack pine stands on the Hiawatha National Forest (Adapted from Woodall and Williams 2005)

2.4 Sample Preparation and Analysis

All soil and forest floor samples were placed in an oven at 105° C until dry. Following drying, samples were weighed, and the mineral soil was passed through a 2 mm sieve. Forest floor samples were ground through a 1 mm screen. Organic matter was determined by loss-on-ignition at 400° C for 8 hours. Mineral soil texture was determined using the hydrometer method, and the pressure plate method was used to determine available water-holding capacity (AWHC). Nutrient analysis of the FF and mineral soil was conducted at the USDA Forest Service Sciences Laboratory in Moscow, Idaho. Total C and N in the FF and mineral soil were determined by dry combustion on a Leco TruSpec CN Analyzer. Mineral soil cations were extracted using pH 7.0 ammonium acetate. Cations in the FF were extracted using 2N nitric acid after ashing at 475 °C for 5 hours. Cations in the FF and mineral soil were analyzed on a PerkinElmer 5100PC Atomic Absorption Spectrometer.

2.5 Calculation of Biomass and Nutrient Pools

Height and above-ground dry weight biomass of foliage¹, live branches, dead branches, bole bark, bole wood, and stump and coarse root biomass for all tree species were estimated using allometric equations developed by Perala and Alban (1993). Above-ground nutrients for jack pine and red pine were estimated using nutrient concentrations from Alban (1988). Red maple, quaking aspen, red oak, and pin cherry nutrient concentrations were obtained from Rutkowski and Stottlemeyer (1993), and Marks (1974). Stem nutrient concentrations were used to estimate root nutrient concentrations of jack pine, red pine, quaking aspen, red oak, and red maple. Nutrient concentration of red maple was estimated using nutrient concentrations for sugar maple (*Acer saccharum*). Soil bulk density was estimated from percent sand content using equations developed by Broadfoot and Burke (1958).

3. RESULTS

3.1 Stand biomass and nutrients

The study sites range in age from 49-72 years (Table 3.1). All stands are jack pine dominated, but only stand 1 is pure jack pine. Stand 4 is a mix of jack pine and red pine, while the other two stands have various amounts of hardwoods. The hardwoods contribute little to total stand biomass, but contain an appreciable amount of cations (Tables 3.1 and 3.2, Figures 3.1 and 3.2). This was especially evident for Ca in the branches and roots of quaking aspen in stand 2, which contained 27 percent of the total above-ground Ca pool. The contribution of dead stems to stand biomass ranged from 2 to 10 percent, while the contribution to total stand nutrients ranged from 1 to 6 percent.

¹ Foliage biomass of quaking aspen was estimated using parameters developed for big-tooth aspen (*Populus grandidentata*) after determining an error existed in the parameters published for quaking aspen.

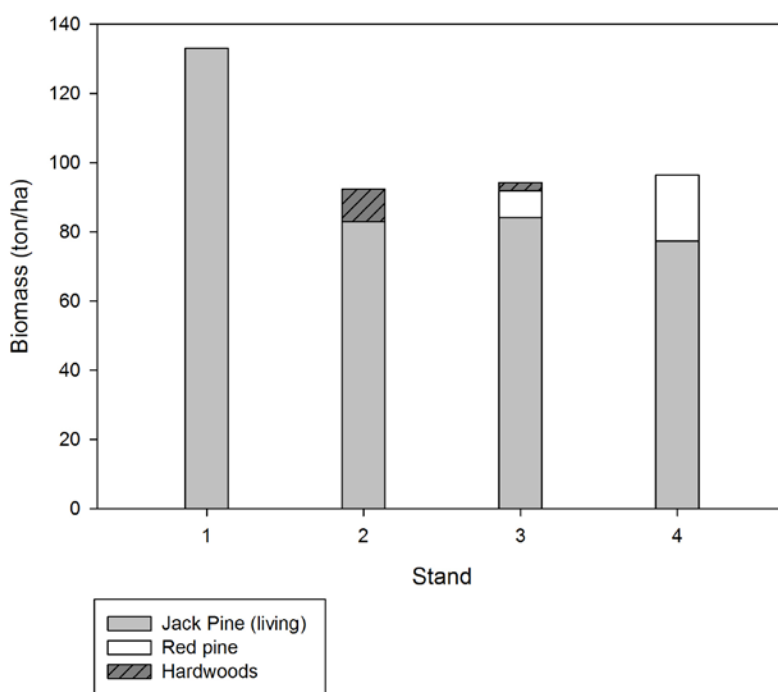


Figure 3.1: Above-ground biomass (ton/ha) of jack pine, red pine, and hardwood species of four jack pine stands in the Hiawatha National Forest

3.2 Soil Information

There is little variability in soil OM content, AWHC, texture, and pH among the four stands (Table 3.3). The mineral soil in stand 4 has slightly higher fine sand and silt content than the other stands, which is reflected in a slightly higher AWHC. The weight of CWD is highly variable among the sites, which could be related to differences in stand age (Table 3.3).

The amount of total soil C, N, and exchangeable Ca are lowest in stand 3. Since the concentrations of C and N are comparable to that of the other stands, these low values may be due to a thinner E horizon thickness in this stand (Table 3.3). The small E horizon will also contribute to the lower Ca content of this stand, but this can be better explained by the very low Ca concentration in the Bs₁ horizon (Table 3.4). In contrast to Ca, the K content of stand 3 is much higher than that of the others, which can be due to a high K concentration in the E horizon (Table 3.4).

The higher soil nutrients in stand 2 could be influenced by the presence of hardwoods, as the C and N content and the FF cation concentrations are higher than that of the other stands. The annual shedding of leaves will lead to higher yearly cation inputs to the FF. Shedding of leaves will also positively affect soil N, even though the hardwoods do not contain large amounts of N.

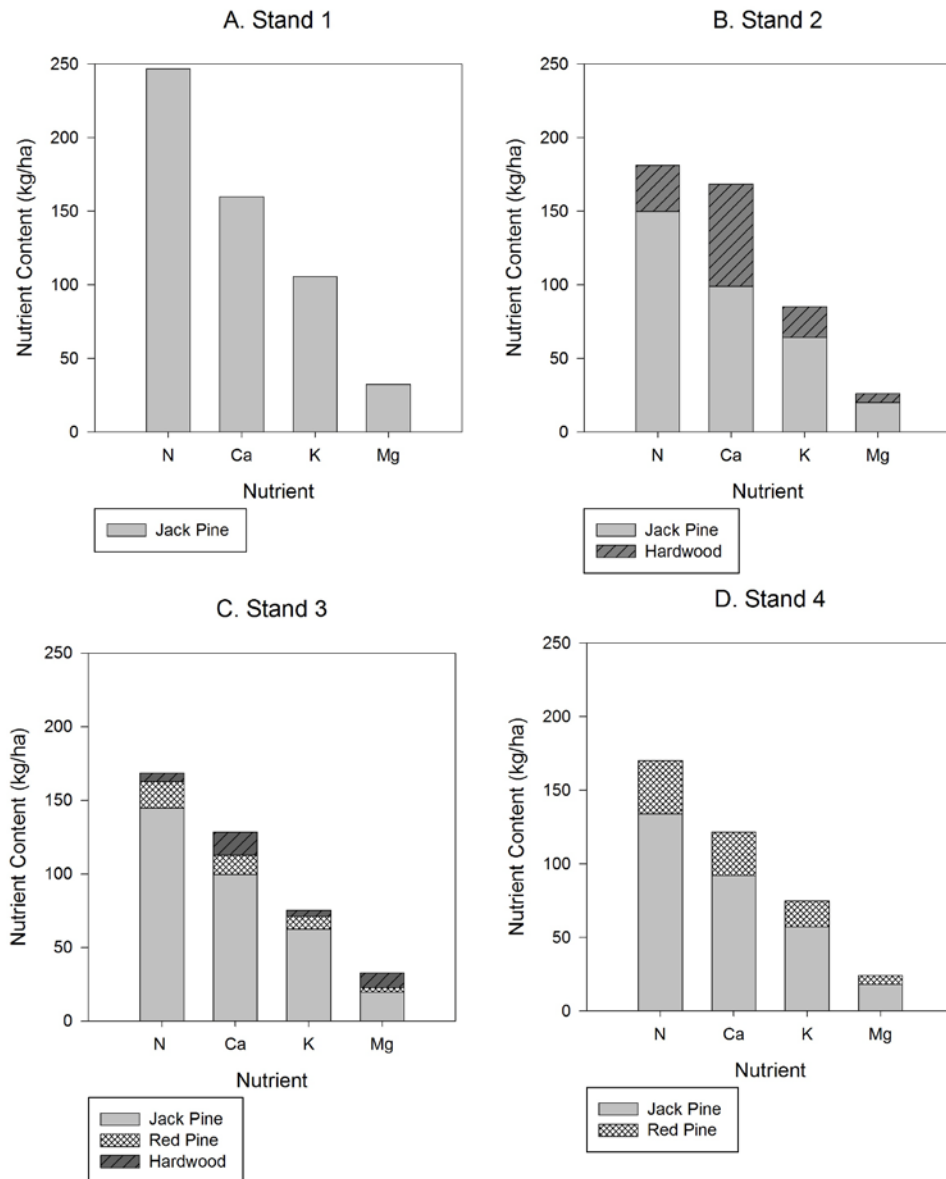


Figure 3.2: Nutrient content of jack pine, red pine, and hardwood species in four jack pine stands in the Hiawatha National Forest

Table 3.1: Mensuration data and biomass of four jack pine stands in the Hiawatha National Forest

Species	Age	Site Index (m)	Live Trees (stems/ha)	Dead Trees (stems/ha)	Height (m)	Diameter (cm)	Basal Area (m ² /ha)	-----Standing Biomass (ton/ha)-----					Total Standing Live Biomass (ton/ha)
								Foliage	Branch	Stem	Stump+ Root	Dead Trees ^a	
Stand 1 (1/36/11) <i>Pinus banksiana</i> (Live n=23, Dead n=2)	72	15	34 (132) ^b	18 (16)	20 (1.7)	27.7 (6.5)	17.6 (4.8)	5.4 (3.7)	21.6 (13.3)	86.5 (43.7)	19.5 (10.3)	5.7 (3.9)	138.7 (71.8)
Stand 2 (3/89/72) <i>Pinus banksiana</i> (Live n=57, Dead n=10) <i>Prunus pensyl/vanica</i> (n=2) <i>Populus tremuloides</i> (n=4) Total	69	15	258 (57) 16 (54) 53 (140) 330 (41)	44 (46) 0 0 44 (46)	19.4 (1.3) 12.1 (1.9) 10.6 (2.3)	25.6 (5.0) 19.2 (5.2) 17 (6.7)	11.9 (6.2) 0.4 (1.4) 0.8 (1.9) 13.1 (6.1)	3.2 (1.9) 0.1 (0.06) 0.1 (0.09)	13 (7.1) 0.6 (0.4) 1.6 (1.5)	54.6 (23.8) 2.1 (1.3) 3.2 (2.8)	12.1 (5.5) 0.4 (0.3) 1.4 (1.1)	10.4 (4.6) 0 0	82.9 (43.2) 3.2 (2.0) 6.3 (5.6) 102.8
Stand 3 (4/90/03) <i>Pinus banksiana</i> (Live n=143 Dead n=22) <i>Pinus resinosa</i> (n=2) <i>Quercus rubra</i> (n=2) <i>Acer rubrum</i> (n=2) Total	62	14	423 (142) 11 (56) 3 (14) 10 (51) 447 (33)	109 (133) 0 0 0 109 (133)	18.1 (1.2) 16.3 (9.0) 19.5 (1.1) 14.5 (0.5)	20.9 (3.8) 30.6 (28.5) 29.1 (3.4) 15.2 (1.1)	13.1 (3.5) 0.2 (0.9) 0.2 (0.9) 13.7 (3.7)	2.8 (1.6) 0.8 (1.1) 0.02 (0.003) 0.03 (0.004)	12.2 (6.3) 1.6 (2.1) 0.3 (0.09) 0.2 (0.03)	56.7 (23.4) 4.1 (5.4) 0.9 (0.3) 0.7 (0.1)	12.4 (5.4) 1.3 (1.7) 0.2 (0.06) 0.1 (0.02)	8.4 (5.1) 0 0 0	84.1 (49.3) 7.8 (10.3) 1.4 (0.4) 1.0 (0.1) 102.7
Stand 4 (4/89/01) <i>Pinus banksiana</i> (Living n=27, Dead n=3) <i>Pinus resinosa</i> (n=7) Total	49	13 12	542 (365) 93 (161) 635 (415)	86 (123) 0 86 (123)	17.1 (1.5) 14.9 (1.4)	18 (3.5) 23 (4.8)	12.4 (9.4) 3.2 (4.8) 15.6 (7.7)	2.8 (1.8) 1.2 (0.6)	10.6 (5.5) 2.9 (1.3)	52.6 (22.2) 11.1 (4.3)	11.3 (5.0) 3.9 (1.5)	1.7 (1.0) 0	77.3 (33.1) 19.1 (7.7) 98.1

^aAssumes sound stem

^b(SD)

Table 3.2: Nutrient content (kg/ha) of jack pine, red pine, and hardwoods in four jack pine stands in the Hiawatha National Forest

	Nitrogen (kg/ha)	Calcium (kg/ha)	Potassium (kg/ha)	Magnesium (kg/ha)
<i>Stand 1</i>				
Live Jack Pine				
Foliage	69.7	18.2	21.9	4.4
Branch	78.9	41.9	33.7	9.2
Stem	82.8	86.0	41.7	15.7
Stump+Coarse Root	15.3	13.8	8.4	3.1
Dead Jack Pine Stem ^a	4.5	4.1	2.5	0.9
Total	251.2	164.0	108.2	33.3
<i>Stand 2</i>				
Live Jack Pine				
Foliage	40.7	10.6	12.8	2.6
Branch	47.0	25.1	19.9	5.5
Stem	52.5	54.7	26.4	10.0
Stump+Coarse Root	9.6	8.6	5.2	2.0
Dead Jack Pine Stem ^a	8.2	7.4	4.5	1.7
Jack Pine Total	158.0	106.4	68.8	21.8
Hardwood				
Foliage	5.2	2.1	2.0	0.6
Branch	12.4	32.6	7.2	2.5
Stem	7.4	16	5.2	1.4
Stump+Coarse Root	6.5	18.8	6.5	1.7
Hardwood Total	31.5	69.5	20.9	6.2
Stand Total	189.5	175.9	89.7	28.0
<i>Stand 3</i>				
Jack Pine				
Foliage	36.2	9.5	11.4	2.3
Branch	43.7	23.6	18.1	5.1
Stem	55.1	57.7	27.6	10.4
Stump+Coarse Root	9.7	8.8	5.3	2.0
Dead Jack Pine Stem ^a	6.6	5.9	3.6	1.3
Jack Pine Total	151.3	105.5	66.0	21.1
Red Pine				
Foliage	7.8	2.4	3.2	0.7
Branch	5.1	5.2	2.8	0.9
Stem	4.1	4.6	2.1	0.9
Stump+Coarse Root	1.1	1.1	0.6	0.3
Red Pine Total	18.1	13.3	8.7	2.8
Hardwood				
Foliage	1.0	0.6	0.5	0.7
Branch	2.1	5.2	1.2	0.3
Stem	2.4	9.2	2.1	0.2
Stump+Coarse Root	0.4	0.4	0.5	0.04
Hardwood Total	5.9	15.4	4.3	1.2
Stand Total	175.3	134.2	79.0	25.1

Table 3.2 (cont.):

	Nitrogen	Calcium	Potassium	Magnesium
<i>Stand 4</i>				
Jack Pine				
Foliage	36.1	9.4	11.3	2.3
Branch	37.5	20.4	15.3	4.3
Stem	51.5	54.1	25.7	9.7
Stump+Coarse Root	8.9	8.0	4.9	1.8
Dead Jack Pine Stem ^a	1.3	1.2	0.7	0.3
Jack Pine Total	135.3	93.1	57.9	18.4
Red Pine				
Foliage	12.0	3.8	5.0	1.1
Branch	9.2	9.5	5.1	1.7
Stem	11.5	13.0	5.8	2.5
Stump+Coarse Root	3.4	3.2	1.7	0.7
Red Pine Total	36.1	29.5	17.6	6.0
Stand Total	171.4	122.6	75.5	24.4

^aAssumes sound stem

3.3 Nutrient Removal through Harvesting

The method used to harvest these low-fertility jack pine stands could have a major impact on soil nutrient pools and future stand growth, as a large portion of the available cation pool (to 30 cm mineral soil) is stored above-ground (Table 3.5). Harvest intensity will likely have a lesser impact on total soil N content. When all four stands are considered together, WTH of just jack pine will remove an average of 22% more biomass, 62% more N, 39% more Ca, 54% more K, and 44% more Mg than CH of jack pine only. Removing hardwoods during WTH of stands 2 and 3 will remove 17% more N, 27-56% more Ca, 20-24% more K, and 20-25% more Mg compared to WTH of just jack pine. The high Ca content of hardwood branches in stand 2 considerably increases the amount of Ca removed during total stand WTH. With the exception of Ca, leaving hardwoods but removing conifers during WTH of stand 3 will only slightly decrease nutrient removal. In stand 4, however, red pine has larger contributions to the above-ground nutrient pools, and removing red pine during WTH will remove 26% more N, 31% more Ca, 30% more K, and 33% more Mg as compared to WTH of jack pine only.

Table 3.3: Soil physical properties of four jack pine stands in the Hiawatha National Forest

Horizon	Weight (t/ha)	Thickness (cm)	Organic Matter (%)	pH	Available Water Holding Capacity (%)	Sand (%)					Total Sand (%)	Silt (%)	Clay (%)
						Very Coarse	Coarse	Medium	Fine	Very Fine			
Stand 1													
CWD	17.2 (0.7)												
FF (n=5)	12.4		76.8 (6.5)	4.07 (0.01)	--	--	--	--	--	--	--	--	--
E (n=15)	--	7.6 (1.9)	1.0	4.18	5.6	0.8	46.2	41.6	5.3	2.1	96	4	0
Bs ₁ (n=15)	--	11.7 (3.2)	1.0	4.52	5.9	0.8	53.8	37	3.7	1.6	97	2	1
Bs ₂ (n=15)	--	10.7 (4.5)	0.5	4.8	4.5	1	45.9	44.8	4.8	1.6	98	1	1
Stand 2													
CWD	11.6 (3.6)												
FF (n=5)	10.7 (2.4)		87.1 (9.3)	4.23 (0.10)	--	--	--	--	--	--	--	--	--
E (n=25)	--	9.0 (2.3)	1.2	4.29	7.6	1.8	50.5	38.9	2.4	1.4	95	4	1
Bs ₁ (n=25)	--	10.1 (2.3)	1.6	4.45	6.1	1.5	58.2	32.4	2.2	1.8	96	3	1
Bs ₂ (n=25)	--	10.9 (2.8)	0.8	4.79	3.1	2.1	55.1	37.2	2.3	1.3	98	1	1
Stand 3													
CWD	5.2 (0.6)												
FF (n=5)	11.9 (3.7)		84.7 (12.0)	3.93 (0.16)	--	--	--	--	--	--	--	--	--
E (n=25)	--	5.8 (2.4)	1.9	4.19	11.1	1.9	36.7	53.2	2.2	1	95	2	3
Bs ₁ (n=25)	--	10.0 (2.3)	1.7	4.45	7.6	1.7	41.3	48.2	4.2	0.5	96	4	1
Bs ₂ (n=25)	--	14.2 (3.4)	0.9	4.8	5.7	2	43.3	48.9	1.1	0.8	96	3	1
Stand 4													
CWD	2.5 (0.8)												
FF (n=5)	17.9 (5.3)		83.1 (9.4)	3.89 (0.13)	--	--	--	--	--	--	--	--	--
E (n=20)	--	11.1 (3.7)	2.6	4.1	12.3	2.6	36	39.9	7.6	4	90	9	1
Bs ₁ (n=20)	--	9.2 (2.6)	3.5	4.55	8.9	5.5	40.9	37.5	5.8	3.3	93	6	1
Bs ₂ (n=20)	--	9.7 (3.0)	2.1	4.78	6.7	7.5	40.7	40.4	3.6	2.6	95	4	1

^a(SD)

Table 3.4: CWD and soil nutrient content in four jack pine stands in the Hiawatha National Forest

Horizon	C		N		Ca ^a		K ^a		Mg ^a	
	%	ton/ha	%	kg/ha	mg/kg	kg/ha	mg/kg	kg/ha	mg/kg	kg/ha
Stand 1										
CWD										
FF (n=5)	42.1 (3.4) ^b	9.0 (0.4)	1.18 (0.13)	13.5	2924.4 (785.3)	12.2	350.5 (115.0)	7.4	1181.7 (471.8)	2.8
E	1.6	5.2	0.05	146.0	39.8	36.2	23.4	4.3	4.9	14.6
Bs ₁	1.7	17.9	0.06	595.0	17.0	43.5	21.4	25.6	2.1	5.3
Bs ₂	1.3	27.9	0.05	951.3	8.0	28.3	17.3	35.7	no detection	3.5
Total		79.8		2420.6		132.5		99.4		26.2
Stand 2										
CWD										
FF (n=5)	42.9 (5.2)	6.0 (1.9)	1.07 (0.14)	9.1	3084.6 (818.6)	8.2	451.7 (186.9)	5.0	1271.1 (470.7)	1.9
E	2.1	4.6	0.08	113.9	40.3	32.9	24.5	4.8	5.9	13.6
Bs ₁	1.7	26.2	0.07	1052.7	12.8	51.1	23.1	31.2	3.1	7.4
Bs ₂	1.4	24.9	0.04	973.0	1.6	18.3	16.1	33.1	0.8	4.4
Total		82.3		2826.1		112.9		98.8		28.5
Stand 3										
CWD										
FF (n=5)	44.4 (6.1)	2.7 (0.3)	1.28 (0.15)	4.1	1851.0 (590.5)	3.7	311.3 (141.5)	2.2	765.7 (297.7)	0.8
E	1.6	5.3	0.06	152.7	43.5	22.1	44.1	3.7	5.1	9.2
Bs ₁	1.4	13.1	0.05	456.8	3.3	35.2	27.1	35.8	1.9	4.1
Bs ₂	1.2	19.9	0.03	701.9	4.0	4.5	22.4	37.4	0.9	2.6
Total		64.0		1853.7		73.4		122.8		18.4
Stand 4										
CWD										
FF (n=5)	43.2 (4.1)	1.3 (0.4)	1.33 (0.22)	1.9	1769.0 (487.9)	1.7	305.4 (70.1)	1.1	175.8 (32.5)	0.4
E	1.9	7.7	0.05	238.1	34.3	31.6	23.8	5.5	5.7	3.1
Bs ₁	2.0	29.2	0.07	811.1	19.4	53.4	17.1	37.2	3.1	8.9
Bs ₂	1.4	24.7	0.05	875.9	9.7	24.6	13.9	21.6	1.6	3.9
Total		73.8		2514.9		123.7		83.2		18.4

^aExchangeable cations in the mineral soil

^b(SD)

Table 3.5: Percent of nutrients stored above-ground (excluding stump) in four jack pine stands in the Hiawatha National Forest

Stand	N ^a		Ca ^b		K ^b		Mg ^b	
	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%
Stand 1								
Above-ground ^c	231.2	8.7	146.1	50.0	97.3	47.4	29.3	50.0
Below-ground ^d	2435.9	91.3	146.3	50.0	107.8	52.5	29.3	50.0
Total	2667.1		292.4		205.1		58.6	
Stand 2								
Above-ground	164.7	5.5	141.1	50.1	73.5	39.9	22.6	41.2
Below-ground	2842.2	94.5	140.3	49.9	110.5	60.1	32.2	58.7
Total	3006.9		281.4		184.0		54.8	
Stand 3								
Above-ground	157.5	7.8	118.0	58.5	69.0	34.8	21.5	51.8
Below-ground	1864.9	92.2	83.7	41.5	129.2	65.2	20.0	48.2
Total	2022.4		201.7		198.2		41.5	
Stand 4								
Above-ground	157.8	5.9	110.2	45.0	68.2	43.2	21.6	50.8
Below-ground	2527.2	94.1	134.9	55.0	89.8	56.8	20.9	49.2
Total	2685.0		245.1		158.0		42.5	

^aTotal N

^bExchangeable cations in the mineral soil

^cIncludes bole, limbs, and foliage

^dIncludes, stump, coarse roots, total N and cations in FF, total N and exchangeable cations in top 30 cm of mineral soil

A nutrient budget for a 65-year-old jack pine stand regenerating after various degrees of harvest intensity was constructed using values of mean annual accumulation over the period 0-20 years, 20-30 years, and 30-65 years estimated by Foster and Morrison (1976). Available N was estimated as a percentage of total N based on values of total and available N determined by Foster and Morrison (1976). In all harvest scenarios, the amount of total N left on site is more than what would be needed during the first 65 years of stand growth, but very large deficits occur when available N is considered (Table 3.6). CH of stands 1, 2, and 4 will leave enough cations on site for the regenerating stand while all CH scenarios in stand 3 will result in Ca deficits. Ca deficits will also occur following total stand WTH of all stands, with especially large Ca deficits occurring following all WTH scenarios in stand 3. Leaving hardwood species as retention during harvest has a large influence in the amount of nutrients left on-site in stand 2 due to the high amount of Ca found in the branches and roots of quaking aspen.

Table 3.6: Nutrient budget for four jack pine stands in the Hiawatha National Forest

	Sum Left On Site After Harvest (kg/ha)					Amount needed for jack pine (ages 1-65) ^a (kg/ha)				Difference (kg/ha)				
	Total N	Avail. N ^b	Ca ^f	K ^f	Mg ^f	N	Ca	K	Mg	Total N	Avail. N	Ca	K	Mg
Stand 1														
CH	2589	19	211	166	44	207	155	106	27	2382	-188	56	60	17
WTH	2440	17	150	110	30	207	155	106	27	2233	-190	-5	4	3
Stand 2														
Jack pine ^c														
CH	2963	21	234	162	47	207	155	106	27	2756	-186	79	56	20
WTH	2875	21	198	129	38	207	155	106	27	2668	-186	43	23	11
Total Stand ^e														
CH	2956	21	218	157	45	207	155	106	27	2749	-186	63	51	18
WTH	2850	20	148	115	34	207	155	106	27	2643	-187	-7	9	7
Stand 3														
Jack pine ^c														
CH	1974	14	150	174	33	207	155	106	27	1767	-193	-5	68	6
WTH	1894	14	117	145	26	207	155	106	27	1687	-193	-38	39	-1
Jack pine/Red pine ^d														
CH	1970	14	145	172	32	207	155	106	27	1763	-193	-10	66	5
WTH	1877	13	105	137	23	207	155	106	27	1670	-194	-50	31	-4
Total Stand ^e														
CH	1967	14	136	170	32	207	155	106	27	1760	-193	-19	64	5
WTH	1871	13	90	133	22	207	155	106	27	1664	-194	-65	27	-5
Stand 4														
Jack pine ^c														
CH	2635	19	192	133	33	207	155	106	27	2428	-188	37	27	6
WTH	2561	18	162	106	26	207	155	106	27	2354	-189	7	0.4	-1
Jack pine/Red pine ^d														
CH	2623	19	179	127	31	207	155	106	27	2416	-188	24	21	4
WTH	2529	18	136	91	21	207	155	106	27	2322	-189	-19	-15	-6

^aAdapted from Foster and Morrison (1976)^bEstimated as percentage of total N based on total and available N values from Foster and Morrison (1976)^cAssumes jack pine harvest only; all other species left as retention trees^dAssumes jack pine and red pine harvest; hardwoods left as retention trees^eAssumes all trees are harvested; no retention^fTotal in FF, exchangeable in mineral soil

4. DISCUSSION

4.1 Stand biomass and nutrients

Estimated total aboveground biomass and nutrients in these four jack pine sites are comparable to published values for jack pine stands of similar age (Table A.1). The measured height of dominant trees in each plot was compared to the estimated height of those same trees in order to determine the reliability of the allometric height estimators. This showed that allometric estimators tended to overestimate height. Care was taken to locate allometric estimators developed in similar site and soil conditions as the study sites. However, Perala and Alban (1993) biomass equations were developed from stands growing on Grafton sand (Coarse-loamy, mixed, mesic Entic Haplorthod), Redby loamy fine sand (Mixed, frigid Aquic Udipsamment), and Kalkaska sand (Sandy, isotic, frigid Typic Haplorthod), all of which exhibit properties of sites more productive than Rubicon soil. Grafton and Redby sands are characterized by finer, loamy texture while Kalkaska sand is associated with organic matter accumulation in a Bhs horizon and ortstein columns (USDA NRCS 2006a, 2006b, 2010). The slightly finer texture of Grafton and Redby sands will likely retain more organic matter and water than the very coarse textured Rubicon (Bot and Benites 2005). Deeper organic matter accumulation in Kalkaska sand will serve as a source of nutrients as well as aiding in preventing nutrient loss by increasing cation exchange capacity (Bot and Benites 2005). Differences in productivity can also be seen in differences in cation exchange capacity (CEC) among the soil. Rubicon sand has a CEC of just 2.6 cmol/kg (USDA NRCS 2009b), while Redby and Kalkaska sands have CECs of 3.8 and 160 cmol/kg, respectively (USDA NRCS 2009b). The higher CEC of these soils will help the soil retain cations necessary for plant growth. Differences in soil properties among the study sites and those where biomass estimators were developed, as well as the overestimated height, may lead to inaccurate estimations. However, considering that the total biomass of these stands is comparable to the literature, I feel that the biomass estimation is still within a reasonable source of error.

The method used to estimate CWD nutrient content could also result in an overestimation as nutrient concentration will change as the wood decomposes. However, the wood volume and decay class will be reflected in the nutrient estimation as these factors were used to determine CWD weight. Furthermore, I feel that this method reduces uncertainty associated with using published values as differences with age and amount of CWD have been eliminated.

Soil C and N values in the study sites are comparable with values found by Perala and Alban (1982), while exchangeable Ca, K, and Mg in the study sites are lower (Table A.3). Lower exchangeable cations in the study sites may be due to differences in productivity and soil texture in the study sites and that of published literature.

4.2 Harvest Impacts on Nutrient Pools

WTH of these jack pine stands will leave much more total N than what is needed by the next rotation. However, only a small portion of the total soil N in jack pine stands is available for tree uptake as Foster and Morrison (1976) found just 29 kg/ha available N in a total N pool of 4,057 kg/ha in the organic and mineral soil under a 30-year-old jack pine stand in Ontario. All harvest scenarios will create very large deficits of available N.

WTH will result in large Ca deficits and smaller K and Mg deficits. Ca deficits are especially large in stand 3 and following total stand harvest of stand 4. Total stand WTH of stand 4 will also result in large K deficits. However, retaining red pine during WTH of stand 4 does not increase the nutrient retention so much that a nutrient deficiency would not be of serious concern. Leaving hardwoods as retention during WTH of stand 2 does considerably increase the nutrient pool left on-site following WTH, but since many of these nutrients would be sequestered in the living tissues of the hardwood trees, nutrient availability for the subsequent rotation may still be a concern.

Soil nutrients are most likely to show the sharpest change during the first years following harvest (Knoepp and Swank 1997). Ground vegetation can play a large role in nutrient retention (Crow et al. 1991), but since forest harvest results in large-scale disturbance (Grigal 2000), re-vegetation may not occur right away. This could be especially detrimental to these sites as coarse-texture and low mineral soil OM may make them more susceptible to leaching loss. Furthermore, removing slash during WTH can increase the temperature and moisture of the soil by increased energy absorption (Hornbeck 1970, Kubin and Kemppainen 1991, Keenan and Kimmins 1993) and decreased transpiration (Keenan and Kimmins 1993). Soil temperature and moisture are two main factors controlling decomposition rates (Berg and McClaugherty 2003), and increasing these variables has been shown to increase soil microbe activity (Swift et al. 1979, Jurgensen et al. 1997) and subsequent decomposition rates. Evidence suggests that leaching losses of nutrients increases immediately after harvest, regardless of intensity (Mann et al. 1988), and greater decomposition and decreased vegetation to uptake newly available nutrients immediately following WTH could potentially increase leaching losses.

Leaching loss of soil nutrients following timber harvest is likely on these coarse-textured Rubicon soils, as the OM content of the mineral soil is very low, and increased OM decomposition could cause proportionally large losses. Since OM accounts for large percentages in mineral soil cation exchange capacity (CEC) (Brady and Weil 2008), this could also have severe negative implications for cation retention. Furthermore, loss of OM in the mineral soil could increase the infiltration rate of water (Brady and Weil 2008), which, along with the low inherent CEC of Rubicon soil (USDA NCSS 2011), could potentially lead to large leaching losses of cations. Beyond leaching losses, a reduction in mineral soil OM content could considerably increase the infiltration rate of water while decreasing the AWHC (Brady and Weil 2008). This could have serious negative implications for the future productivity of stands growing on these coarse-textured soils than nutrient removal as soil physical properties have been shown to play a larger role than nutrient availability in jack pine productivity (Pawluk and Arneman 1961).

Over time, atmospheric deposition and mineral weathering will help the soil recover from nutrient losses, but annual inputs are small, and it could take many years for a substantial amount of nutrients to be added. During the years 2000-2009, total deposition added an average of 13 kg/ha/year available N, 0.2 kg/ha/year Ca and K, and 0.1 kg/ha/year Mg in the Upper Peninsula of Michigan (NADP 2011). Using these estimates, deposition will add 845 kg/ha N, 13 kg/ha Ca, 13 kg/ha K, and 6.5 kg/ha Mg during the first 65 years of growth. This will supply enough N to correct any N losses of available N following harvest, but the amount of cations added is far less than what will be needed by the regenerating stand.

Chemical weathering is the most important natural source of cations (Anderson 1988, Waring and Running 2007, Farve and Napper 2009), but it is unlikely that this will release enough cations for the next rotation. Johnson et al. (1968) estimated that 8.0 kg/ha/year Ca, 0.1 kg/ha/year K, and 1.8 kg/ha/year Mg are released through weathering of a medium to coarse textured till soil in New Hampshire. Using these weathering rates, enough Ca and Mg would be released from minerals during the first 65 years of stand growth to replace cation losses following WTH. However, weathering rates are highly linked to the chemical and physical properties of the soil's parent material (Anderson 1988), and it is likely that weathering in Rubicon sand will be much lower. The quartz-dominated sand in these soils lacks rocks and minerals containing plant nutrients (Brady and Weil 2008), so the potential nutrient contribution by chemical weathering will likely be very small. High water infiltration rates in the Rubicon soil would also limit the amount of time during which chemical weathering can take place (Anderson 1988).

Due to the possibility of large leaching losses, low soil nutrient reserves, and low cation input via deposition, all scenarios of WTH should be avoided on these and similar sites. With the exception of Ca in stand 3, CH will leave enough cations for the next rotation, but atmospheric deposition will not add enough cations to the surplus to support a subsequent stand. In the HNF, jack pine is typically left as retention at a density of approximately 2 m²/ha (Jean Perkins, personal communication). Increasing this density will help retain more nutrients, and could also help sustain the productivity of the soil resource. Hardwood species and red pine should also be left, as the presence of hardwoods in a conifer forest can increase the cycling of base cations (Prescott 2002). Furthermore, leaving live vegetation on-site may help to reduce the amount of nutrients lost through leaching, as the living trees will be able to take up newly available nutrients. While these nutrients will be sequestered in vegetative tissues, they will eventually be returned to the soil in litter rather than leached below the rooting zone. Retaining slash on-site could help regulate the soil temperature and reduce the possibility of increased OM decomposition (Hornbeck 1970, Kubin and Kemppainen 1991, Keenan and Kimmins 1993). The slash will also contain immobilized nutrients that will become available slowly during decomposition. This may help to reduce the amount of nutrients lost through leaching, but in order for CH to continue without creating productivity declines for future stands, hardwood species and red pine should be left behind. The amount of jack pine left as retention should also be increased, and rapid regeneration of jack pine, whether through planting or natural regeneration, should be encouraged in order to increase vegetative nutrient uptake.

5. CONCLUSION

The results of this study show the above- and below-ground biomass and nutrient pools in four jack pine stands in the Hiawatha National Forest. Each stand varied in age and species composition, but the amount of variation in biomass and nutrient content was relatively small. The results also indicate that CH will probably leave enough cations on-site for the next rotation, with the exception of Ca in stand 3, but the cation surplus will be small and the addition of cations through atmospheric deposition will not add enough for the second rotation. WTH will likely result in Ca deficits in all stands, but this is more severe in stands 3 and 4. WTH may also result in smaller deficits of K and Mg. Where deficits do not occur, the surplus is so small that weathering and atmospheric deposition will not replenish the pool for the second rotation following WTH. Furthermore, the potential for increased decomposition and increased leaching loss may further increase nutrient loss. Due to these reasons, WTH should be avoided on these

sites. Still, more work needs to be conducted in order to determine exactly how severe WTH could be to these sites. Tissue samples should be collected to obtain exact above-ground nutrient contents. Leaching losses following CH should be measured, and the soil should also be analyzed for available N and total mineral soil cations. These pieces of information would help strengthen the argument that WTH should be avoided on these sites in order to preserve the soil resource.

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APPENDIX A

Table A.1: Total above-ground biomass (ton/ha) and nutrient (kg/ha) accumulation for jack pine

Age	Biomass (ton/ha)	Nitrogen (kg/ha)	Potassium (kg/ha)	Calcium (kg/ha)	Magnesium (kg/ha)	Location/Source
30	99.21	195	94.7	126.4	19.8	Ontario, Morrison (1973)
30	63.43	113.2	55.7	76.3	11.8	Ontario, Morrison (1973)
30	88.5	184.8	89	116.9	18.4	Ontario, Morrison (1973)
30	61	119	57.9	77.4	12.1	Ontario, Morrison (1973)
32	129	263	60	173	32.9	Upper MI, Alban (1988)
32	84	229	90	156	32.3	Lower MI, Alban (1988)
34	116	228	99	130	29.7	Upper MI, Alban (1988)
35	80	196	77	117	21.8	Lower MI, Alban (1988)
36	52	139	49	90	12.1	Lower MI, Alban (1988)
37	60.61	No Data	No Data	No Data	No Data	New Brunswick, Maclean and Wein (1976)
37	59.07	No Data	No Data	No Data	No Data	New Brunswick, Maclean and Wein (1976)
38	58.91	No Data	No Data	No Data	No Data	New Brunswick, Maclean and Wein (1976)
40	65.26	No Data	No Data	No Data	No Data	New Brunswick, Maclean and Wein (1976)
44	59.29	No Data	No Data	No Data	No Data	New Brunswick, Maclean and Wein (1976)
49	67.42	No Data	No Data	No Data	No Data	New Brunswick, Maclean and Wein (1976)
57	66.77	No Data	No Data	No Data	No Data	New Brunswick, Maclean and Wein (1976)
65	105.78	161.1	81	115.6	17.5	Ontario, Morrison (1973)
65	53.99	84.9	42.5	60.2	9.2	Ontario, Morrison (1973)
65	76.05	121.2	60.6	85.5	13	Ontario, Morrison (1973)
65	43.64	71.3	35.5	49.8	7.6	Ontario, Morrison (1973)

Table A.2: Distribution of biomass (ton/ha) and nutrients (kg/ha) in jack pine

Age	Biomass (ton/ha)	Nitrogen (kg/ha)	Potassium (kg/ha)	Calcium (kg/ha)	Magnesium (kg/ha)	Location/Source
----- Foliage -----						
30	n/a	55.8	17.3	16.0	3.1	Ontario, Foster and Morrison (1976) Minnesota, Perala & Alban (1982); Alban et al. (1978) Minnesota, Perala & Alban (1982) Minnesota, Green & Grigal (1980) Minnesota, Green & Grigal (1980)
39	5.5	65	20	20	5.6	
41	4.9	64	26	15	5	
>50*	18.01	106	32	57	12	
>50*	30.92	189	68	113	20	
----- Branches -----						
30		47.8	22.8	31.7	4.4	Ontario, Foster and Morrison (1976) Minnesota, Perala & Alban (1982) Minnesota, Alban et al. (1978) Minnesota, Perala & Alban (1982)
39	24	78	26	52	10.1	
40	23.4	76	25	51	9.9	
41	12.2	39	19	27	5.8	
----- Total Stem -----						
30		48.8	34.0	51.4	8.1	Ontario, Foster and Morrison (1976) Minnesota, Perala & Alban (1982) Minnesota, Alban et al. (1978) Minnesota, Perala & Alban (1982) Minnesota, Green & Grigal (1980) Minnesota, Green & Grigal (1980)
39	121.7	121	53	131	22.7	
40	118.4	118	52	128	22.2	
41	111.5	93	54	126	22.3	
>50	65.92	92	23	81	15	
>50	118	121	59	145	28	
----- Stump+Root -----						
39	29	38	23	43	8	Minnesota, Perala & Alban (1982) Minnesota, Alban et al. (1978) Minnesota, Perala & Alban (1982)
40	28	37	22	42	8	
41	17	20	14	38	5	
----- Total Aboveground -----						
Range	43.64- 105.78	71.3-263	35.5-101	49.8-178	7.6-32.9	Alban (1988), Maclean & Wein (1976), Morrison (1973)

Table A.3: Soil nutrient content under jack pine (Perala and Alban 1982)

Depth	Organic Matter ton/ha	Total N	Available K	Available Ca	Available Mg
		-----kg/ha-----			
<i>Loam:</i>					
Forest Floor	33	700	68	770	81
0-10 cm	48	1731	94	2080	134
10-25 cm	14	640	98	1029	83
25-30 cm ^a	2	116	40	315	48
Total	97	3187	300	4194	346
<i>Sand:</i>					
Forest Floor	25	468	37	375	50
0-10 cm	44	1382	99	1496	138
10-25 cm	24	666	107	977	131
25-30 cm ^a	3	123	32	209	31
Total	96	2639	275	3030	350

^aExtrapolated from 25-36 cm

APPENDIX B

Table B.1: Equations used to estimate biomass (From Perala and Alban 1993)

Species	Jack pine	Red pine	Red maple	Quaking aspen	Red Oak	Pin Cherry
Height	$6.117 \cdot \text{DBH}^{\wedge} 0.3579$	$2.921 \cdot \text{DBH}^{\wedge} 0.5213$	$4.183 \cdot \text{DBH}^{\wedge} 0.4558$	$2.391 \cdot \text{DBH}^{\wedge} 0.5296$	$3.707 \cdot \text{DBH}^{\wedge} 0.4932$	$2.313 \cdot \text{DBH}^{\wedge} 0.562$
Foliage	$0.0008988 \cdot \text{DBH}^{\wedge} 2.903$	$0.0006622 \cdot \text{DBH}^{\wedge} 3.122$	$0.01913 \cdot \text{DBH}^{\wedge} 1.867$	$0.00274 \cdot \text{DBH}^{\wedge} 2.275$	$0.04801 \cdot \text{DBH}^{\wedge} 1.455$	$0.02979 \cdot \text{DBH}^{\wedge} 2.582 \cdot \text{H}^{\wedge} 0.913$
Live Limb	$0.002956 \cdot \text{DBH}^{\wedge} 2.830$	$0.03118 \cdot \text{DBH}^{\wedge} 4.098 \cdot \text{H}^{\wedge} 2.271$	$0.1072 \cdot \text{DBH}^{\wedge} 2.841 \cdot \text{H}^{\wedge} 0.104$	$0.06059 \cdot \text{DBH}^{\wedge} 3.806 \cdot \text{H}^{\wedge} 2.033$	$0.01684 \cdot \text{DBH}^{\wedge} 2.514$	$0.04189 \cdot \text{DBH}^{\wedge} 3.54 \cdot \text{H}^{\wedge} 1.58$
Dead Limb	$0.2391 \cdot \text{DBH}^{\wedge} 2.943 \cdot \text{H}^{\wedge} 1.769$	$0.0005819 \cdot \text{DBH}^{\wedge} 2.714$	$0.00338 \cdot \text{DBH}^{\wedge} 2.337$	$0.001631 \cdot \text{DBH}^{\wedge} 3.33 \cdot \text{H}^{\wedge} 1.552$	$0.000478 \cdot \text{DBH}^{\wedge} 3.125$	$0.009592 \cdot \text{DBH}^{\wedge} 2.224$
Bole Bark	$0.0157 \cdot \text{DBH}^{\wedge} 1.775 \cdot \text{H}^{\wedge} 0.3952$	$0.01408 \cdot \text{DBH}^{\wedge} 2.09$	$0.02102 \cdot \text{DBH}^{\wedge} 2.191$	$0.005244 \cdot \text{DBH}^{\wedge} 1.855 \cdot \text{H}^{\wedge} 0.8777$	$0.004408 \cdot \text{DBH}^{\wedge} 2.047 \cdot \text{H}^{\wedge} 0.8264$	$0.03156 \cdot \text{DBH}^{\wedge} 1.846 \cdot \text{H}^{\wedge} 0.666$
Bole Wood	$0.01395 \cdot \text{DBH}^{\wedge} 1.709 \cdot \text{H}^{\wedge} 1.327$	$0.02137 \cdot \text{DBH}^{\wedge} 1.809 \cdot \text{H}^{\wedge} 1.037$	$0.02347 \cdot \text{DBH}^{\wedge} 1.888 \cdot \text{H}^{\wedge} 0.9912$	$0.01516 \cdot \text{DBH}^{\wedge} 2.053 \cdot \text{H}^{\wedge} 0.8777$	$0.02635 \cdot \text{DBH}^{\wedge} 1.88 \cdot \text{H}^{\wedge} 0.979$	$0.02869 \cdot \text{DBH}^{\wedge} 1.886 \cdot \text{H}^{\wedge} 0.9768$
Stump+ Root	$0.09178 \cdot \text{DBH}^{\wedge} 2.498 \cdot \text{H}^{\wedge} 0.6471$	$0.09178 \cdot \text{DBH}^{\wedge} 2.498 \cdot \text{H}^{\wedge} 0.6471$	$0.09178 \cdot \text{DBH}^{\wedge} 2.498 \cdot \text{H}^{\wedge} 0.6471$	$0.09178 \cdot \text{DBH}^{\wedge} 2.498 \cdot \text{H}^{\wedge} 0.6471$	$0.09178 \cdot \text{DBH}^{\wedge} 2.498 \cdot \text{H}^{\wedge} 0.6471$	$0.09178 \cdot \text{DBH}^{\wedge} 2.498 \cdot \text{H}^{\wedge} 0.6471$

DBH: Diameter at breast height (cm)

H: Height (m)

Table B.2: Equations used to estimate CWD weight and C (Woodall and Williams 2005)

Weight (kg/ha)	$[(\pi/2L) \cdot (V/I_i) \cdot f] \cdot (1000 \cdot G)$
Mg C	$[(\pi/2L) \cdot (V/I_i) \cdot f] \cdot (0.521 \cdot G)$

L=Total length of the transect

I_i = Length of individual CWD piece (m)

V = Volume of individual piece (m^3)

f = Conversion factor ($10,000 \text{ m}^2/\text{ha}$)

G= Specific gravity (Decay class 1 & 2: 0.40, 3 & 4: 0.30)

Table B.3: Nutrient concentrations used to estimated stand nutrient content

Species	N (%)	Ca (%)	K (%)	Mg (%)
Jack pine ^a				
Foliage	1.280	0.335	0.402	0.081
Live Limb	0.436	0.206	0.228	0.054
Dead Limb	0.236	0.172	0.025	0.022
Bole Bark	0.301	0.439	0.110	0.042
Bole Wood	0.079	0.071	0.043	0.016
Red pine ^a				
Foliage	0.977	0.306	0.407	0.094
Live Limb	0.332	0.328	0.191	0.061
Dead Limb	0.196	0.315	0.027	0.033
Bole Bark	0.293	0.483	0.129	0.058
Bole Wood	0.086	0.083	0.045	0.019
Red maple ^b				
Foliage	1.847	1.203	0.990	0.173
Limbs	0.440	1.157	0.343	0.050
Bole Bark	0.452	3.290	0.247	0.050
Bole Wood	0.070	0.210	0.180	0.030
Quaking aspen ^b				
Foliage	2.210	1.307	0.730	0.267
Limbs	0.630	1.843	0.383	0.143
Bole Bark	0.368	1.450	0.280	0.088
Bole Wood	0.060	0.160	0.070	0.020
Red oak ^b				
Foliage	2.167	0.967	0.883	0.137
Limbs	0.447	1.140	0.213	0.077
Bole Bark	0.362	3.348	0.122	0.030
Bole Wood	0.140	0.040	0.080	0.000
Pin cherry ^c				
Foliage	2.632	0.709	1.108	0.297
Live Limb	0.351	0.416	0.162	0.044
Dead Limb	0.211	0.263	0.045	0.026
Bole (Bark+Wood)	0.18	0.201	0.090	0.018

^aAlban (1988)

^bRutkowski and Stottlemyer (1993)

^cMarks (1974)