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HARVEST INTENSITY AND DELINEATION OF OUTWASH SOILS IN
WISCONSIN

By

Robert P. Richard

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Forest Science

MICHIGAN TECHNOLOGICAL UNIVERSITY

2019

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This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Forest Science.

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Abstract

The whole-tree harvest of an oak forest showed significant decreases to total nitrogen and potassium pools, and the calcium pool showed weaker evidence for significant declines in comparison to the stem-only harvest. Simulated whole-tree harvests in aspen decreased the total number of rotations by a full rotation on nutrient-poor outwash soils (Entic Haplorthods and Typic Udipsamments) by depleting the potassium, calcium, and magnesium pools in 180 years from whole-tree harvest in comparison to 225 years in the stem-only harvest. Nitrogen and phosphorus harvest removals did not compose a large percentage of ecosystem pools. Since harvest removals for some elements exceed the inputs at the current rotation length, inputs to the system should be increased if sustained yields at the current volumes are desired. In comparison to the ecosystem nutrient pools observed in this study, there is textural and management history variation across the landscape that could result in different ecosystem nutrient pool sizes located on the outwash soils.

Soil complexes (Alfic Haplorthods-Entic Haplorthods/Typic Udipsamments) have differing soil properties and are currently partially restricted at the estimated composition of the complex. Habitat type provides a tool to distinguish between the soil types within the soil complexes. Relative elevation in the form of the deviation from mean elevation (DEV) combined with the moisture stress index (MSI) provide a framework to estimate the soil types remotely. DEV performed best for mapping the landforms at the 1300-

meter radius with 10-meter digital elevation models. Landform mapping in the water-worked glacial till context will misclassify coarser textured soils incorporated into the moraine and erosion from the finer textured soils of the moraine to the lower outwash regions. Habitat type will detect the coarser textured soils, and MSI will identify the cases of erosion where trees reside on finer soil textures. The National Cooperative Soil Survey pedon database allowed for the detection of differences in coarse silt between Entic Haplorthods and Typic Udipsamments.

1 Introduction

1.1 Whole-tree harvesting on outwash soils

Whole-tree harvests (WTH) remove an additional proportion of the tree as compared to the stem-only harvest (SOH), which may be a concern for long-term productivity in coarse textured soils (Boyle et al., 1973; Olsson et al., 1996; Silkworth & Grigal, 1982; Sverdrup & Rosen, 1998; Thiffault et al., 2011). WTHs of aspen (*Populus spp.*) remove a larger proportion of Ca and Mg (Boyle et al., 1973), and the recovery years are calculated to be: 48 N, 18 P, 24 K, - Ca, 118 Mg on moraine soil (Silkworth & Grigal, 1982). These impacts were reported on soils with greater fertility than the outwash soils. The outwash soils are composed mainly of sand, and have lower cation release rates, as the cation release rate is related to the aeolian mass present in the outwash soils (Kolka et al., 1996). The lower amounts of cations entering the system implies that the WTH would have greater impacts on the outwash soils. A significant decrease of an additional 54% of the calcium pool was reported after one WTH on an outwash soil in comparison the SOH (Premier, 2015). However, non-significant impacts were later reported for exchangeable Ca in the top 30cm of the outwash soil: 730 K, 420 Ca, 370 Mg kg ha⁻¹ for the SOH and 730 K, 110 Ca, 330 Mg kg ha⁻¹ for the WTH, and may be due to the large standard deviation of the Ca: SOH 620, WTH 320 (Premier et al., 2019). The study also found non-significant impacts from WTH when compared to the SOH across several soil types, but found significant declines to K on one moraine site, and Ca and Mg on another moraine (Premier et al., 2019). These results indicate that there

is a need to relate forest management policy to soils information as different impacts were observed.

The Wisconsin Department of Natural Resources has worked with the Natural Resource Conservation Service (NRCS) to develop WTH guidelines based on soil's putative ability not to supply nutrients lost to WTH: having low clay content (<3%), low cation exchange capacity (<3 meq/liter), drainage class (well-drained or drier), the absence of lamellae, loam, heavier textural layers, carbonates, water table, and not classified as an Alfisol or Mollisol (Bronson et al., 2014). The classification system has led to the identification of morainal-outwash soil complexes that are partially restricted from WTH. Forest managers have reported encountering nutrient rich habitat types as well as productive forests within the soil complex. Additionally, the pedons populating the National Cooperative Soil Survey are limited in number and may not be an adequate representation of the textural variability of the outwash soils. Due to these issues the Wisconsin Department of Natural Resources, Natural Resource Conservation Service (NRCS), and Michigan Technological partnered to better understand the soil complex and document the size of the soil macronutrient pools of the outwash soils.

1.2 Dissertation Overview

The objects of the research were to:

- 1) Delineate soil complexes with restricted and unrestricted status from the practice of the whole-tree harvest
- 2) Establish a nutrient budget model for aspen on outwash soils, while collecting soil pedon information with NRCS soil scientists
- 3) Revisit a whole-tree harvest experiment that occurred on outwash soils after 7.75 years and observe any changes to the macronutrient total pool status

In Chapter 1, *Sites with conflicting regulation status for whole-tree harvesting: scale-appropriate delineation of complexed soils*, I investigate phyto-edaphic and remotely sensed information in regards to delineating soil complexes located throughout northern Wisconsin. The soil complexes are composed of Alfic Haplorthods (moraine) and Entic Haplorthods/Typic Udipsamments (outwash), with the Alfic Haplorthods not restricted from WTH. Habitat type as a single variable best delineates the soil types. A secondary model composed of habitat type, deviation from mean elevation, and moisture stress index is also provided to estimate the location during the off-season with verification necessary when habitat typing is feasible. Through the classification process National Cooperative Soil Survey pedons showed evidence that the restricted soils differ in coarse silt composition and provides another potential factor in podzolization.

In Chapter 2, *Long-term ecosystem nutrient pool status through harvest simulations on sandy outwash soils*, I present a seasonal harvest model for aspen on outwash soils. The goal was to increase the publicly available pedons by sampling with the NRCS, and pair the soils data with tree tissue values in order to simulate harvests through time. The simulated harvests were conventional and whole-tree by the seasonal averages. These harvest types were repeated through time to: 1) compare the effects of the WTH to SOH 2) identify the most favorable season for the WTH. Results indicate that the WTH shortens the total potential rotation lengths by a full rotation at the current input and outputs rates. Seasonal differences were observed but were dwarfed by the scale of the harvest. These results show that the WTH does warrant restriction on the outwash soils and brings into question the definition of sustainable SOHs on the soils since the K, Ca, and Mg pools will be depleted in 225 years of SOH. If SOHs continue, the systems could be expected to function more similarly to a barrens and total yields would be decreased. If the current yields are desired through time, the input terms of K, Ca, and Mg should be increased.

In Chapter 3, *Whole-tree harvest effects on soil macronutrients in an oak dominated system after seven years*, I revisit a harvest intensity experiment in northwestern Wisconsin on the sandy outwash soils. The original research detected significant declines of N, P, K, Ca, and Mg in the woody debris from the WTH in comparison to the SOH, but the differences did not translate to the nutrient modeling, which showed only that P was at risk for depletion across all harvest treatments. After

7.75 years the total pools showed significant decreases from WTH for N and K, and Ca exhibited weak evidence for being significantly lower ($p=0.065$). The key difference in the findings as compared to the harvest impact modeling was the assumption that the woody debris could decompose and be captured in the soil measured at 5 and 20cm with an exchange resin. Here I show that only approximately 10% of the woody debris would have been available according to decomposition models 1.75 years after the harvest.

2 Sites with conflicting regulation status for whole-tree harvesting: scale-appropriate delineation of complexed soils

2.1 Abstract

Whole tree harvesting (WTH) practices are often restricted on soils with intrinsically low soil nutrients. Delineating restricted soil series from non-restricted series presents a challenge for forest practitioners in glaciofluvial parent materials. We investigated a suite of biological and edaphic factors to assess if restricted soil series are functionally distinct from non-restricted soil series in currently restricted soil complexes in the state of Wisconsin. This study tests repeatable methods for soil delineation based on soil forming factors, varying in spatial extent, that are independent of county boundaries or discrepancies across survey units. Habitat type provided the most robust tool to distinguish between the soil types. Habitat type combined with the deviation from mean elevation (DEV) model and the moisture stress index (MSI) provided a framework to estimate the soil types remotely. The 1300m radius DEV performed best in the multivariate model with a 10-m digital elevation model (DEM), and landform effects on the misclassification of different texture types are discussed in the context of moraines vs. outwash plains. Habitat type was able to differentiate the coarser textured soils, and MSI indicated finer soil textures. We recommend using the combined Habitat Type, DEV, and MSI approach when timber sale establishment occurs outside of the growing season.

The material contained in this chapter is in preparation to be submitted to *Journal of Forest Ecology and Management*

Habitat typing can then occur during the growing season to refine the identification of the soil types.

2.2 Keywords

Whole-tree harvesting, habitat type, deviation from mean elevation, podzolization, soil mapping, landform mapping

2.3 Introduction

Unlike a traditional stem-only harvest (SOH), where the bole is harvested down to 10 cm in diameter, a whole-tree harvest (WTH) allows loggers to harvest the entire tree, which consists of branch material less than 10 cm in diameter (Boyle et al., 1973). A disproportionate amount of nutrients are located in the leaves or in the small diameter twigs and branches. Therefore, WTH will export more nutrients from a stand than a traditional stem-only harvest. Wisconsin's forest management guidelines restrict WTH on nutrient-limiting sandy soils due to concerns of sustainability (Bronson et al., 2014). Wisconsin defines nutrient-limiting sandy soils as having clay content ($<3\%$), C.E.C. (<3 meq/liter), drainage class (well-drained or drier), the absence of lamellae, loam, heavier textural layers, carbonates, water table, and not classified as an Alfisol or Mollisol (Bronson et al., 2014). In the state of Wisconsin, the partially restricted soil complexes represent 100,561 hectares (Figure 1). Wisconsin foresters currently use the USDA web soil survey to identify whether the area being harvested is located on the partially restricted soil complexes. The soil complexes are currently restricted from WTH at the

level corresponding to the percent composition of the complex, however, the specific location of the restricted soils is not identifiable.

On regionally nutrient-rich soils associated with sloping areas adjacent to or located on drainageways of ground moraines (Alfic Fragiorthods, Typic Endoaquods) in Wisconsin, the WTH practice was calculated to be repeatable for nine rotations of 30 years before calcium would become a limiting nutrient (Boyle et al., 1973; National Cooperative Soil Survey 2012). Calcium and magnesium were found to not be replaced by inputs when a WTH was conducted on a regionally nutrient rich till soil (Typic Fragiocbrepts) in Minnesota (National Cooperative Soil Survey 2012; Silkworth & Grigal, 1982). Another moraine soil (Inceptic Hapludalfs) in Michigan showed non-significant impacts between the SOH and WTH (National Cooperative Soil Survey 2012; Premer, 2015, Premer et al., 2016). Whereas WTH on aspen stands on a sandy outwash soil (Entic Haplorthods) in Michigan lost approximately 54% more of the extractable Ca after WTH compared to SOH (Premer, 2015). The Wisconsin Department of Natural Resources in collaboration with the Natural Resources Conservation Service have developed guidelines for restricting WTH based on soil productivity, however, water-worked glacial till-outwash soil complexes present a challenge as the outwash is restricted from WTH and the till is not restricted (Bronson et al., 2014). The research highlights the need to identify the locations of the soils within the soil complexes as management activities will have different impacts on the nutrients removed.

The non-restricted (NR) Alfic Haplorthods consociations (Keweenaw, Mancelona, Menominee, Sarona) are typically sandy to sandy loam deposits over loamy till with landform types of drumlins, end moraines, eskers, glacial till, ground moraines, kame moraines, lake plains, outwash plains, and stream terraces (National Cooperative Soil Survey 2012). The restricted (R) Entic Haplorthods and Typic Udipsamments consociations (Sayner, Rubicon, Vilas, Menahga) are coarse sands or sands composed primarily of outwash plains and valley trains, but also of beaches, disintegration moraines, eskers, kames, outwash terraces, outwash areas on moraines, and sand dunes (National Cooperative Soil Survey 2012). The spatially intricate environment from multiple glacial advances and retreats resulted in undifferentiated soils at the mapping scale (<2 ha), and with the technology available at the time of mapping. However, due to the complexity involved in the soil mapping, soil scientists from the Natural Resources Conservation Service (NRCS) have revisited the soil complexes and conducted transect work relating the higher elevations to the Alfic Haplorthods (NR) consociations, and the lower elevations to the Entic Haplorthods (R) and Typic Udipsamments consociations (R) (unpublished communications with NRCS Soil Scientists). In addition to the elevation framework, the soil formation factors: climate, organisms, relief, parent material, and time (Jenny, 1941) should also better delineate soil types on a functional basis relevant to management.

Figure 1. Location of partially restricted soil complexes, consociations, and sampling locations. Artifacts of individual county mapping and remapping efforts are evident.

Climate plays a major role in differentiating restricted soil types, with the main difference between the Entic Haplorthods and Typic Udipsamments being the establishment of the eluvial horizon by the process of podzolization. In the Great Lakes region, factors affecting moisture and acid inputs such as aspect, depth of snowpack, and spring snowmelt pulses influence the podzolization process and have been mapped into podzolization zones (Hunckler & Schaetzl, 1997; Schaetzl & Isard, 1991, 1996; Schaetzl et al., 2015). As such, climate interacts with physiography in determining soil development.

Organisms influence and are influenced by soil properties and development. Plant-soil relationships have a long history of use in forest management decisions such as habitat type and site index (Burger et al., 2002; Carmean et al., 1989). Habitat type has been found to have strong relationships with soil types and has been put forward as a classification system relevant for forest management (Kotar, 1986). The understory communities appear to be fairly stable as they did not show a significant difference between SOH and WTH, although the overall richness, diversity, and evenness did increase after WTH (Premier et al., 2016). Site index values represent the total height of a tree at a base year, which is commonly 50 years in the Great Lakes Region (Carmean, 1975). The site index value reflects a myriad of factors that affect tree growth such as tree genetics, climate, previous management history, and soil properties which influence available water and nutrients (Burger, 1996; Schoenholtz et al., 2000). In addition to site index, the moisture stress index (MSI) has been developed to elucidate plant-soil

relationships with remote sensing of tree canopies (Hunt Jr & Rock, 1989). MSI derived from LANDSAT 5 & 8 has been found to be highly correlated to soil moisture (Welikhe et al., 2017) and may hypothetically aid in the delineation of the soils given textural differences.

Advances in information, technology, and analysis procedures have increased the accuracy of digital soil or landform mapping by including pedological, terrain, and land use-organismal variables (Vincent et al., 2018). In glaciated soils, the deviation from mean elevation model (DEV) $DEV = \frac{Z_0 - \bar{Z}}{\sigma}$ was found to more accurately identify landforms than the topographic position index (TPI) $TPI = Z_0 - \bar{Z}$ (De Reu et al., 2013). The radius of the DEV model is a parameter of the model, and in the glaciated soils radii of 100-2000m were used (De Reu et al., 2013). The water-worked till moraines are intricate environments which can contain inclusions of different textured soils or have experienced erosional events post-deposition. In a similar till-outwash formation known as the Grayling fingers, an investigation found the Kalkaska (Typic Haplorthods) or Rubicon (Entic Haplorthods) series were associated with the side slopes and valleys, and the glacial till with the higher elevations while occasionally incorporating of a sand lens (Schaetzl & Weisenborn, 2004). Similar patterns are expected across the analogous Alfic Haplorthods – Entic Haplorthods/Typic Udipsamments soil complexes. The patterns of elevation were likely used in mapping and visible at the landscape scale as the linear features of the moraines and outwash plains show the direction of glacial retreat (Figure 1). For example, the northeastern pane shows a general north to south pattern for the

landforms. In the southern portion of the northeastern pane, the restricted consociations both dissect the Alfic Haplorthods and are surrounded by them, indicating the complexity of the glaciofluvial environment and the sand lens respectively.

In addition to mapping constraints, the total number of pedons to provide parent material information from the National Cooperative Soil Survey (NCSS) database are limited. In the states of Minnesota, Michigan, and Wisconsin there are currently 40 pedons located within the corresponding consociation map units for the soil series within the complexes, 73 within the same family, and 94 within the same subgroup. Distinctions relevant for soils classification in some circumstances can be extraneous for forest management as the number of forest cover types and habitat types are often much smaller than the number of soil map units (Kotar, 1986). Moreover, series may vary across a forest stand while exhibiting nearly identical textural values. For example, within the Entic Haplorthods, a Vilas is distinguished from a Sayner by the rock percentage being greater than 15%, and a Croswell for having redoximorphic features (National Cooperative Soil Survey 2012). Taken together, the subgroup level of classification appears to be a reasonable approach to guide policy decisions for the soils complexes in the absence of suitable sample sizes. Notwithstanding, we note here that even at this level of classification inconsistencies across soil map units exist, particularly across county boundaries (Figure 1).

The main objective of this study was to provide a functional basis for delineating soil series consociations in WTH-restricted soil complexes. In addition, multiple

methodologies for distinguishing factors of soil formation were explored in relation to the physical properties of WTH-restricted series within the soil complexes. This study tests repeatable methods for soil delineation based on soil forming factors, varying in spatial extent, that are independent of county boundaries or discrepancies across survey units. Together, these activities provide a basis for interpreting where on the landscape WTH-restricted soils within complexes may or may not be functionally different from series without WTH restrictions.

2.4 Materials and Methods

2.4.1 Field

The 2016 study sites were confined to aspen (*Populus* spp.) forests, with an age between 40-55 years as the typical rotation length window (Wisconsin DNR, 2013), and located on the partially restricted soil complex (Figure 1). All 2016 sites were sampled in conjunction with NRCS pedon sampling of the restricted consociation within the complex. Eight sampling points were randomly generated within the intersection of the stand-soil area using the Create Random Points tool in ArcGIS 10.3. A soil core, herbaceous species, and overstory tree information were collected at each sampling point. The soil core was collected with a bucket auger to a depth of 100cm and separated by horizon in a trough by bucket withdrawal (~10 cm resolution). The soil sample was taken across the entire range of the horizon to ensure adequate and unbiased representation. If rocks impeded the bucket auger the process was repeated up to three times, the deepest sample was collected, and missing values were imputed by site. The soil samples were transported to Michigan Technological University (Houghton, MI) and refrigerated before analyses. All herbaceous species were recorded within the vicinity of the sampling point (5m radius) and classified into a habitat type (Burger et al., 2002). The total height, diameter at breast height (DBH), and a tree core were collected from the nearest dominant or codominant tree free of obvious defects and corresponding to the dominant forest type. If the aspen was not available within the local area of the point sampling plot another shade intolerant-mid tolerant species was sampled.

The field-sampling scheme was updated in 2017 to sample across the elevation boundaries of the partially restricted complex, Alfic Haplorthods, and restricted consociations (Figure 2). Eight points per soil type were sampled using 30m DEM centroid locations in an approximate 0.4 ha gridded sampling scheme, which is a finer resolution than the soils were mapped. Incorrect forest inventories, such as aspen not being the primary forest type, at times required deviation from the idealized grid. In these situations, neighboring 30m DEM centroids were sampled with the intent to maximize sample points across the transitional boundaries of the map units. Basal area was recorded by a 10 BAF prism and categorized by aspen and non-aspen.

Figure 2. Field sampling scheme across elevation gradients. The gridded sampling is 0.4 ha and a finer resolution than the soils were mapped.

2.4.2 Lab

Soil samples were dried at 55C° to a constant mass and sieved (no. 10, 0.2 cm mesh) to remove roots, rocks, woody debris, and char. Soil texture was determined using the simplified hydrometer method with 100g of soil and combined with deionized water into 1025 mL suspension tubes with the aggregates displaced by 10 mL sodium hexametaphosphate and dispersed for 5 minutes (Klute et al., 1986). The soil was agitated, and readings were taken at 30 and 60 seconds to determine sand (50 μ m), and 1.5 and 24 hours to determine clay fraction (2 μ m) (Klute et al., 1986).

2.4.3 Data and Modeling

2.4.3.1 Textural Soils Classification from NCSS database

In order to classify the soils collected in the field, decision trees were created from the NCSS database. Soil pedon data was obtained from the NCSS database for all Alfic Haplorthods, Entic Haplorthods, and Typic Udipsamments within Michigan, Minnesota, and Wisconsin. The pedons were intersected with 2018 gSSURGO soil map units, and pedons which still belonged to the appropriate subgroups were selected for analysis resulting in 34 Alfic Haplorthods (NR), 34 Entic Haplorthods (R), and 26 Typic Udipsamments (R). The average texture values from the top 100cm were calculated per pedon.

The recursive partitioning algorithm from the rpart package (Therneau et al., 2018) was used to create decision trees to delineate the texture values (sand, silt, clay) independently. Kernel density estimation (KDE) is a non-parametric estimate of a

probability density function. KDE was used to visualize the distribution of the individual textures and results of the from recursive partitioning algorithm. Repeated cross-validation (k=10, repeats=25) was used to obtain a stable model for small sample sizes (Kuhn & Johnson, 2013). Texture thresholds were determined independently due to the presence of a lamellic horizon present in the Keweenaw series (Alfic Haplorthods) with a width of 0.3-5.1 cm and clay values between 8 and 15 percent (National Cooperative Soil Survey 2012). The Cohen's kappa is a balanced way of representing model accuracy as accounts for random chance of occurrence, with random chance beginning at a value of 0 (Cohen, 1960). The value of 0.3 and above was considered as the baseline for reliable models. The kappa thresholds have been defined as: 0.01-0.2 none to slight, 0.21-0.40 as fair, 0.41-0.60 moderate, 0.61-0.80 as substantial, and 0.81-1.00 almost perfect agreement (Cohen, 1960). The results of the NCSS database classification were then used to label the soils collected in the field.

2.4.3.2 *Predictive Modeling of Field Sampled Soils*

The collected phyto-edaphic information was assembled into a dataset, with specific details provided below. The habitat type variable used the Region 3 classification as the majority of the study sites were within Region 3 and it spans the majority of the northern part of the state. For the study sites located in bordering regions, Region 3 was used as recommended in the Wisconsin habitat type book (Burger et al., 2002). The comparison tables between habitat types were also used to differentiate 1) ATM from PArVAa round-lobbed hepatica (*Hepatica americana*), Baneberries (*Actaea* spp.),

Gooseberries (*Ribes* spp.) and 2) PArVAa from PArV with wild sarsaparilla (*Aralia nudicaulis*) (Burger et al., 2002). The habitat type classifications were coded into a categorical variable according to the Habitat Types by Group and Region matrix in order to rank the habitat types (Appendix Table 2.A.1, Burger et al., 2002). Site index values and tree diameter at breast height (DBH) were scaled to a base year of 50 for the aspen species present (*Populus grandidentata* and *Populus tremuloides*) (Carmean et al., 1989; Teck & Hilt, 1991).

Due to the location of soil types across the state and inherent climatic differences, attempts were made to remove the climatic influences from the variables related to the primary and secondary growth of the aspen. Linear models were developed for the tree productivity metrics based on annual precipitation and growing degree days, and the residuals of the models included in the dataset for future modeling. The tree productivity metrics were also divided by the average growing degree days to estimate growth at 50 years per average growing degree days. The 30-year average of annual growing degree-days above 0° and 10°C were obtained from the USA National Phenology Network (USA National Phenology Network, 2017). Ten-meter DEMs and gSURGGO soil map units were obtained from the USDA NRCS Geospatial Data Gateway. DEV models were calculated for 100-2,000m radii in increments of 100m. All cloud-free and leaf on images from 06/30/2013-09/16/2018 for LANDSAT8 were obtained from USGS Earth Explorer. The LANDSAT8 images were used to calculate monthly averages and overall averages for MSI. When a variable was derived from the same initial dataset the models were run

independently. For example, the site index variable was tested independently without modification, with the residuals of linear models, and by division of the growing degree days. Repeated cross-validation (k=10, repeats=250) was used to find a stable model (Kuhn & Johnson, 2013). As recursive partitioning is prone to overfitting a requirement of a minimum split size of 40 was included.

2.5 Results

2.5.1 NCSS Database Classification

In terms of soils classification from the NCSS pedons, the Alfic Haplorthods (NR) show significant differences from both the Entic Haplorthods (R) and Typic Udipsamments (R) for the total clay, silt, and sand textures (Figure 3, Table 1). The partitions between the groups shows reasonable agreement between the restricted soils (Figure 3, Table 1). Although, the Entic Haplorthods are texturally closer to the Alfic Haplorthods due to a larger silt percentage (Figure 3, Table 1). The total groups are also broken into finer textural size classes, and all groups besides very coarse sand show significant differences between the Alfic Haplorthods and the Entic Haplorthods/Typic Udipsamments (Figure 3, Table 1). The NCSS soil texture values were used to classify the observed textural values from the soil complexes into Entic Haplorthods or Typic Udipsamments by meeting the criteria of: <3.68% clay, <14.43% silt, or >85.33% sand, <3.04% clay, <11.05% silt, or >85.87% sand respectively and in accordance with the sampled map units (Table 1). There is agreement across the soil classification levels for these classification thresholds (Appendix Table 2.A.2).

Textural differences were also detected within the restricted soils. The Entic Haplorthods are significantly different than the Typic Udipsamments for total silt, coarse silt, very fine sand, and medium sand, but only the coarse silt and medium sand provide reliable thresholds for distinguishing the soils (Figure 3, Table 1). The threshold values which separate an Entic Haplorthods from a Typic Udipsamments (both R) are similar to the threshold which distinguishes an Alfic Haplorthods (NR) from an Entic Haplorthods.

Figure 3. Kernel density estimation (KDE) for soil texture by subgroup from National Cooperative Soil Survey pedons. Partitions are presented for significant differences and kappas near or greater than 0.3, represented by vertical lines separating significant peaks. Total clay, silt, and sand percentages were used to classify collected soil samples.

Table 1. Soil texture partitions and Wilcoxon test results for significant differences by subgroup.

Soil Subgroups	Texture	Texture									
		Total Clay	Total Silt	Total Sand	Fine Silt	Coarse Silt	Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Very Coarse Sand
Size (mm)		<0.002	0.002-0.05	0.05-2.0	0.002-0.02	0.02-0.05	0.05-0.10	0.10-0.25	0.25-0.50	0.5-1.0	1.0-2.0
Alfic Partition		>=3.68	>=14.43	<76.7	>=8.39	>=9.90	>=7.83	<22.75	<33.84	<16.55	>=3.23
Haporthods Kappa		0.76	0.74	0.7	0.68	0.79	0.36	0.62	0.64	0.41	0.24
vs Accuracy		0.88	0.87	0.85	0.84	0.9	0.68	0.81	0.82	0.71	0.62
Entic Wilcoxon											
Haporthods p-value		3.37E-13	4.53E-14	2.62E-11	3.96E-10	1.73E-10	5.22E-06	2.14E-06	4.80E-09	1.16E-03	0.23
Alfic Partition		>=3.04	>=11.05	<85.87	>=6.63	>=5.06	>=9.02	<26.71	<34.08	<11.97	>=0.56
Haporthods Kappa		0.57	0.9	0.99	0.86	0.9	0.64	0.32	0.75	0.49	0.04
vs Accuracy		0.79	0.95	0.99	0.93	0.95	0.82	0.69	0.88	0.76	0.55
Typic Wilcoxon											
Udipsanments p-value		1.32E-08	4.99E-11	2.20E-16	9.06E-11	5.51E-11	9.70E-09	3.74E-04	4.72E-10	4.19E-04	0.08
Entic Partition		<1.99	>=11.24	<86.13		>=4.46	>=1.33		<36.68		>2.41
Haporthods Kappa		0.16	0.19	0.21		0.27	0.11		0.34		0.11
vs Accuracy		0.58	0.56	0.57	Con*	0.61	0.61	Con*	0.67	Con*	0.57
Typic Wilcoxon											
Udipsanments p-value		0.32	0.03	0.29	0.09	4.73E-04	3.29E-03	0.37	0.03	0.19	0.06

Con* indicates a conflicting result due to the similarity of the soils and inability of the recursive partitioning to differentiate between the soils.

2.5.2 Model Results

Habitat type as a single variable most strongly predicts the non-restricted soils from the restricted soils from all the models tested (Figure 4). The threshold which separates the soil types is the split between the PArVAa (5) (*Pinus strobus* and *Acer rubrum*) for the restricted soils and AVVb (6) (*Acer saccharum*) for the non-restricted soils. The numbers provided with the habitat type correspond to the (Appendix Table 2.A.1). The bimodal distribution of the restricted habitat types reflects a gap in the categorical variables for Region 3 as compared to the types across the state (Appendix Table 2.A.1).

Figure 4. Kernel density estimation of habitat type by soil type, indicating habitat type is a strong predictor of soil type ($\kappa=0.57$). Recursive partitioning splits the habitat type value between PArVAa and AVVb to delineate the Alfic Haplorthods from the restricted soils, as represented by the vertical dotted line.

The second-best performing model reiterated the importance of habitat type, but also incorporated the DEV model at a radius of 1300 meters and MSI values (Figure 5). The first step of the decision tree splits the data based on habitat type being a higher value than AVVb (6), and secondarily being greater than AVb (8) or less than PArV (3). The decision tree then uses the DEV model to identify the moraine component of the complex by isolating the higher values. Finally, the DEV model and the MSI identifies colluvium at the lower DEV and MSI values. The MSI values resulting in the highest kappa values were the averages from July.

Figure 5. The multivariate decision tree to separate the Alfic Haplorthods from the restricted soils from recursive partitioning (kappa=0.55). Habitat type isolates the tails of the distribution, DEV identifies the upper slopes of the moraine, and DEV-MSI identify lower areas that have eroded from the moraine. Percentages correspond to percent of the dataset.

The multivariate model performed best with the DEV model of a 1300m radius. However, significant differences were not detected until the DEV model was at a radius of 1600m - 2000m (Figure 6). These results highlight the interactions between habitat type and landscape position, as well as demonstrating the general tendency of the Alfic Haplorthods to be located on the moraines and the restricted soils located on outwash landforms as the DEV radius increases.

Figure 6. Kernel density estimations of deviation from mean elevation model by radius sizes derived from (DeReu et al.,2013). The multivariate model to delineate the soil complex performed best at a radius of 1300m, even though it is not significantly different a single variable. * indicates a significant difference was detected in the Wilcoxon test ($\alpha=0.05$).

Productivity metrics used in forest management such as diameter, site index, and total basal area did not perform adequately to separate the soil types (Figure 7). A significant

difference was observed for site index; however, the difference is not large enough to establish a reliable partition.

Figure 7. Kernel density estimations for common productivity metrics by soil type. The commonly used metrics did not provide strong enough relationships to delineate the soils alone or to be included in the multivariate decision tree. Only the site index showed a significant difference between the two soils, but failed to meet the minimum kappa value, which means it cannot be reliably used to create a partition for delineation. This difference is evident as a partition could not be drawn reliably between the two datasets, even though a statistical test can detect that differences exist.

2.6 Discussion

The habitat type classification variable outperforms other models as a single predictor of the restricted and non-restricted soils in the recursive partitioning model. Interestingly productivity metrics such as diameter, basal area, and site index did not provide adequate thresholds to discern between the two soil types (Figure 7). In fact, only site index showed a significant difference ($p\text{-value} = 0.002$) between the soils, though still not presenting an adequate threshold for separation. Although the significant differences were detected between the site index values for the differing soil types, the distributions of the site index values still overlap enough that a reliable partition cannot be established. Aspen are adapted to a variety of soil types and could explain the poor performance of the site index metric in the context of the soil complex, especially if nutrients are shared clonally. Since significant differences were observed between the site index values in the soil complexes, the differences could become more pronounced in the consociations. The efforts made to mitigate the climate effects on the productivity metrics also did not result in better performing models than the habitat type or the combined habitat type, DEV, and MSI models.

When considering selective pressures that species face, a case could be made as to why the habitat type better identifies the soil types than the overstory. The annual or biannual reproduction of the herbaceous species occurs at much faster rate and provides more potential for adaptation to local conditions than the aspen species. The aspen reproduce sexually, but also rely on somatic mutations from clonal reproduction, with

both occurring on the multi-decadal scale. When considering the sum of these reproductive occurrences through time it is clear that the herbaceous species will have reproduced more often and provided more genetic potential for selection forces. Moreover, the use of the life history traits of several species provides a stronger predictive framework than the two aspen species due to an increased sample size.

The multivariate model performed best at a radius of 1300m. All classification models improve when the DEV model radii range from 1300-2000m, which also corresponds to slightly before and where significant differences are detected. The pattern observed by soil scientists of higher elevations corresponding to the Alfic Haplorthods consociations is at times correct, but as can be seen, there are circumstances when the sandier material has been incorporated into the moraines. These findings are similar to the incorporation of the sand lens at higher elevations (Schaetzl & Weisenborn, 2004). A complicating factor in the use of the DEV models is that the current resolution available across the state of Wisconsin is 10 meters. When finer scale DEMs are available the DEV model could be expected to perform better, but still require similar radii to identify the landform patterns to distinguish the moraine from the outwash soils. The glacial processes extend far past Wisconsin and where similar landforms and map units exist this approach can be replicated.

The sesquioxides-organometallic chelate complex theory (Buurman & Reeuwijk, 1984; De Coninck, 1980) and the proto-imogolite theory (Anderson et al., 1982; Farmer, 1982; Farmer et al., 1980) have been proposed to explain the podzolization, as well as a

hybrid of both theories (Jakobsen, 1991; Ugolini & Sletten, 1991; Wang et al., 1986). In order to classify the field collected soils, the NCSS database was used to establish decision trees to classify the soil by texture values. This exercise found reliable decision trees to delineate the Alfic

Haplorthods from the both of the restricted soils, and the restricted soils from each other. The NCSS pedons enabled the detection of the differences between the restricted soils, whereas

previous research relied on SSURGO values populated from NCSS interpretation. The textural differences may help to further explain the nuances of the podzolization process in accordance with the previously identified variables: aspect, snow depth, snowmelt pulsing, and organic matter accumulation (Hunckler & Schaetzl, 1997; Schaetzl & Isard, 1991, 1996; Schaetzl et al., 2015). The connections and feedbacks between forest and soil types have been documented (Mokma & Evans, 2000; Schaetzl, 2002), but the number of connections can be increased as texture appears to be involved in podzolization (Figure 8). For example, higher silt contents provide more exchange sites, while also allowing for greater productivity. The greater productivity could also result in forest types, such as

Figure 8. Factors influencing podzolization for soil and vegetation systems in the Great Lakes region. Adapted from Mokma and Vance (1989), and Schaetzl (2002), while including the contribution of soil texture to the processes.

northern hardwoods, which are less susceptible to wildfires and the accumulation of organic matter. The larger amounts of silt could be expected to delay podzolation due to higher base saturation and water holding capacity, which would both attenuate the vertical movement of acid and counteract the process. However, it may be that the higher amount of silt with larger amounts of nutrients and exchange sites can simply be weathered faster than the sandy texture soils leading to faster soil development when the conditions for podzolation are present. As the outwash soils have had loess deposition of silt which varies spatially this could be the case, particularly as the Typic Udipsamments are exhibiting weaker effects of acidification in the Bw horizon.

2.7 Conclusion

The Alfic Haplorthods-Typic Udipsamments/Entic Haplorthods soils complexes are partially restricted from WTH, and the non-restricted Alfic Haplorthods consociation is best delineated from the restricted complex by habitat type. During the non-growing season, the non-restricted soils can also be identified by relative elevation in the form of the deviation from mean elevation (DEV) model at a radius of 1300 meters combined with the moisture stress index (MSI) from the month of July. Habitat typing can occur later during the growing season to refine the identification of the soil types. Improvements in technology and the availability to obtain finer scaled DEMs will likely also increase the ability of the DEV model to identify the soil types. Due to the topographical differences between the outwash and moraine landforms, finer scaled DEMs may identify the differences slighter before the radii found with 10m DEMs but

could expected to perform well between 1300-2000m. Soil texture information derived from the NCSS pedons allowed for the development of quantitative thresholds to delineate soils within the complex. The NCSS pedons also hints at the role texture is playing in podzolization, most likely through increased productivity, organic matter accumulation, and localized effects on drainage.

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Appendix Table 2.A.1. Habitat Types by Group and Region (Burger et al., 2002) with corresponding indicator variable value.

Habitat Type Group	Region 1	Region 2	Region 3	Region 4	Indicator Variable
Very Dry to Dry	PQGCe	PQG	PQE	PArVAo	1
					2
	Qap	PArV-U	PArV		3
					4
Dry to Dry Mesic	PArVAm	PArVAa-Po	PArVAa	PArVAa-Vb,PArVPo	5
Dry-Mesic		AVCl	AVVb		6
	AVDe	ACl			7
	AAt		AVb	AVb	8
Mesic		ATM	ATM	ATM	9
				AFVb	10
				ATFD	11
		AAs	ATD	ATDH	12
	ACaCi			AFAd	13
			AOCa,AH	AH	14
	ArVRp	ArAbVCo	ArAbVC	ArAbVC	15
Mesic to Wet-Mesic		ArAbSn			16
		AAtRp	TMC,ArAbCo	TMC	17
		ASnMi			18
			ATAtOn	ATAtOn	19
	ASal		ACal,AHI	AHI	20

Appendix Table 2.A.2. Soil thresholds developed on the textures individually and overall by classification level, and results of Wilcoxon tests for significant differences between subgroups by texture. Reported threshold values separate soils for the first reported type.

Soil Texture	Soil Classification Level	Entic Haplorthods vs Alfic Haplorthods		Typic Udipsammments vs Alfic Haplorthods		Entic Haplorthods vs Typic Udipsammments	
		Threshold	Kappa	Threshold	Kappa	Threshold	Kappa
Clay	Subgroup	<3.68	0.76	<3.04	0.57	Conflicting	0.10
	Family	<3.97	0.70	<3.03	0.38	*	
	Series	<3.97	0.73	*		*	
Silt	Subgroup	<14.43	0.74	<11.05	0.90	Conflicting	0.02
	Family	<14.43	0.73	<11.05	0.86	*	
	Series	<14.43	0.51	*		*	
Sand	Subgroup	>=76.70	0.70	>=85.87	0.99	Conflicting	0.08
	Family	>=85.33	0.45	>=85.87	0.99	*	
	Series	>=85.33	0.48	*		*	
All	Subgroup	Silt <14.43	0.65	Sand >=85.87	0.93	Silt >=11.24, Clay <2.19	0.5
	Family	Silt <14.43	0.65	Sand >=85.87	1	Clay <2.19, Silt >=10.09	0.46
	Series	Clay <3.97	0.58	*		*	
Wilcoxon Test p-values	Clay	3.37E-13		1.32E-08		0.11	
	Silt	4.53E-14		4.99E-11		0.03	
	Sand	2.62E-11		2.20E-16		0.29	

* indicates the sample size was inadequate for the recursive partitioning algorithm. Conflicting results were obtained when run on the individual textures of the Entic Haplorthods and the Typic Udipsammments due to their similarities

3 Long-term ecosystem nutrient pool status through harvest simulations on sandy outwash soils

3.1 Abstract

Sandy outwash soils are abundant in the Great Lakes region and compose large amounts of public forestland. The soils have low fertility and are currently restricted from whole-tree harvest (WTH) in some states. To assess the long-term sustainability of WTH on outwash soils, a nutrient budget was constructed from observations in the ecosystem and literature values. The nutrient budget considered a stem-only harvest (SOH) and WTHs seasonally by the average spring, summer, fall, and winter harvest values. The budget showed that WTH shortened the available Ca, K, and Mg by at least full rotation length under all weathering scenarios for the field observed soil textures. Under the minimum and average weathering scenarios the Ca, K, and Mg pools show depletion after 180 years of WTHs and 225 years of SOHs. The maximum weathering rate also shows depletion after 180 years of WTHs for Ca, K, and Mg, and the SOH after 225 years for Ca and 270 for K and Mg. The estimated number of years it would take for the inputs to match the leaching and one harvest output, or recovery years, similarly indicate that both the SOH and WTH exceed inputs at the current rotation length. The recovery years needed to replace outputs lost are estimated to be 292 K, 199 Ca, 101 Mg for the SOH and 373 K, 243 Ca, 128 Mg for the WTH under the maximum weathering rates to

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the soil textures observed in the field. Since textural variation exists in the outwash soils due to the presence of the aeolian cap, non-texturally adjusted weathering rates were also used to calculate recovery years. These rates indicated Ca outputs exceed inputs at the current rotation length, and K and Mg were only sustainable under the maximum weathering rates. The average non-texturally adjusted weathering rate showed recovery years of 140 K, 142 Ca, 63 Mg for the SOH and 178 K, 173 Ca, 80 Mg for the WTH. These recovery years exceed the typical rotation length and indicate that inputs should be increased if sustaining the current production rates is the management goal.

3.2 Keywords

Whole-tree harvesting, nutrient budget, outwash soils, harvest intensity, ecological modeling

3.3 Introduction

Nutrient-poor soils, such as glacial outwash, are abundant throughout the Great Lakes region. The soils compose large percentages of managed public forestlands after being abandoned as the “lands nobody wanted” (Shands, 1991). However, there is still much uncertainty as to exactly how frequently, if at all, intensive harvesting can be done in low-fertility soil without long-term detriment to available nutrient stocks, particularly for calcium and magnesium (Boyle et al., 1973; Silkworth & Grigal, 1982; Sverdrup & Rosen, 1998; Thiffault et al., 2011; Bronson et al., 2014; Premer, 2015; Premer et al., 2019). The shift towards including woody biomaterials in the economy has increased demand for woody biomass yield in forest harvesting practices, which is a concern for the low fertility of the nutrient-poor soils (Bronson et al., 2014). WTH differs from conventional forest harvesting due to the inclusion of smaller woody tissues and branches containing higher concentrations of macro- and micronutrients than bolewood used in dimensional lumber production (Boyle et al., 1973; Alban, 1985; Ruark & Bockheim, 1988), and as such may prove detrimental to long-term forest productivity.

While it is assumed that repeated removals of nutrient-rich tissues could have detrimental effects on long-term soil productivity in coarse textured soils (Thiffault et al., 2011), very few forest nutrient budgets exist to ascertain the effects of timber harvest, and even less is known of long-term effects (Dean et al., 2017). For example, in aspen (*Populus* spp.) dominated forests on more nutrient-rich soils, pools of nitrogen (N), phosphorus (P), and potassium (K) removed in harvest were estimated to be replaced by

inputs, whereas magnesium (Mg) and calcium (Ca) were a concern for depletion (Boyle et al., 1973; Silkworth & Grigal, 1982). Ca was reported as a concern for depletion within 9-30-year rotations (Boyle et al., 1973) and Ca and Mg would not replenish pool size on the 60-year rotation length (Silkworth & Grigal, 1982). Among different forest types, the long-term productivity declines have called into question the iterability of the WTH practice as more base cations were removed than were supplied by weathering and deposition (Olsson et al., 1996; Sverdrup & Rosen, 1998). In operational forestry in the Upper Peninsula of Michigan, the WTH practice approximately halved the available Ca nutrient pool after one rotation in nutrient-poor (Entic Haplorthods) soil (Premer, 2015). Alternatively, more nutrient-rich moraine soil (Inceptic Hapludalfs) experienced non-significant impacts on Ca and Mg from the WTH practice in comparison to SOH and the understory diversity increased (Premer, 2015; Premer et al., 2016, Premer et al., 2019). Site-specific inputs were also demonstrated, where soils named for commonly experiencing groundwater inputs showed a large variance in response to the WTH (Premer, 2015). Groundwater influences have shown their ability to replace the nutrients lost to intensive harvests (Trettin et al., 2011). These results show the importance of understanding the site specific results from differences in inputs terms to the ecosystem from ground water or differences in soil texture and corresponding rates of soil weathering.

Given the long-term productivity concerns and site-specific results, states have begun relating management activity to the soils information available. Both Connecticut

and Wisconsin have incorporated soils map units in WTH management policy (Bronson et al., 2014; Surabian, 2016). Connecticut relies on several soil map unit interpretations to rank the susceptibility of soils to detrimental effects of WTH from Low to High. The variables of interest include drainage class, water capacity, depth to water table, depth to restrictive layer, cation exchange capacity (CEC), soil organic matter (SOM), erodibility, and slope (Surabian, 2016). Wisconsin also relies on soil map unit interpretations and restricts WTH on soils by clay content, CEC, drainage class, absence of lamellae, and carbonates (Bronson et al., 2014). Michigan and Minnesota address long-term productivity by the recommendation to leave residual biomass. Michigan recommends leaving 20-33% of the tops depending on pre-existing volume, and Minnesota recommends leaving 20% of woody-debris (Michigan Department of Natural Resources, 2010; Minnesota Forest Resources Council, 2007). Although state agencies have addressed potentially negative WTH effects on soil productivity through the biomass retention cutoff percentages, site-specific nutrient budgets of elemental inputs and outputs are needed to give a better aim to state policies moving forward.

The goal of this study was to assess the effects of WTHs conducted on the sandy outwash soils by modeling the inputs and outputs to the system through repeated harvests. The secondary objective was to examine seasonal changes in effects of the WTH to determine if there are seasons of operability wherein nutrient removals can be minimized. To meet these objectives, seasonal input-output budget models of forest tissue and soil elemental pools were constructed. The harvest models considered inputs

and outputs on a 45-year rotation length and compared the SOH to winter, spring, summer, and fall WTHs. Each harvest was repeated through time in order to determine the long-term effects of the harvest. Recovery years, defined as how long it would take for inputs to replenish values lost to a harvest and leaching were calculated for comparison with typical rotation lengths at which a specific nutrient is sustainably harvested.

3.4 Methods

3.4.1 Overview

A nutrient budget was constructed for the nutrient-poor soils considering inputs as weathering and deposition, and outputs of soil leaching and harvest removals in comparison to available nutrient pools similar to previous research (Silkworth & Grigal, 1982; Sverdrup & Rosen, 1998). Soil weathering has previously been measured on the sandy outwash soils considered in this study, and the depletion method rates were used for the annual weathering inputs (Kolka et al., 1996). Total deposition was derived from deposition maps (Schwede & Lear, 2014). Soil and tree tissue information was collected across the northern portion of the state of Wisconsin (Figure 1). The nutrient budget considered the SOH and WTH during the winter, spring, summer, or fall, under three regional deposition budgets and three weathering scenarios.

3.4.2 Field Sampling

Soil pedons were sampled cooperatively with the NRCS soil scientists in the summers of 2016 and 2018 following standard procedures, with bulk densities taken in triplicate (Schoeneberger et al., 2012). The 2018 pedons were also sampled for leachate from 150-160cm during the summer (07/12/2018) and resampled by bucket auger from 150-160cm during winter (pre-frost layer, 01/08/2019), and spring (snow-on conditions, 3/12/2019) to capture the seasonal variation of water-soluble nutrients below the rooting depth. The below rooting depth was chosen as previous research has defined the rooting depth of aspen on outwash soils at 150cm (Kolka et al., 1996). The nearest dominant or codominant aspen tree to the soil pit was sampled for nutrient content from 6/18/2018-6/25/2018, and 9/11/2018. Each tree was felled and sampled for a basal cookie, a cookie at diameter at breast height (DBH), bolewood, barkwood, live branch, dead branch, twig, and leaf.

Figure 1. The major nutrient-poor soils (gSSURGO) that are restricted from whole-tree harvest in Wisconsin and state-county managed aspen (WisFIRS). The soil pits were sampled with NRCS soil scientists and the leachate soil pits were resampled seasonally to establish annual leaching rates. Soil map units are Menahga, Plainfield, Rubicon, Sayner, and Vilas, or complexes of two of the map units.

3.4.3 Lab

The soil samples were transported to Michigan Technological University, Houghton, MI. Leachate concentrations were obtained by shaking 20g of field moist soil with 100 mL of deionized water for one hour and filtered through a Whatman 42 filter and a 0.45 μ m filter (Huang & Schoenau, 1996; Kane et al., 2006). The P, K, Ca, and Mg were processed by an Inductively Coupled Plasma Optical Emission Spectrometer ICP-OES and the N was obtained by Shimadzu DOC/TN analyzer. Soil pool values were obtained from the results of the USDA-NRCS NSSC National Soil Survey Laboratory. Extractable Ca, Mg, and K was determined by method 4B1a1a (NH₄OAc and 2 M KCl rinse), N by method 4H2a (dry oxidation), and P by method 4G4 (Burt & Soil Survey Staff, 2014).

The tree tissue samples were transported to the Wisconsin DNR Center, Rhinelander, WI and dried at 55C° to a constant mass. Tissues for N analysis were ground in a ball mill for 5 minutes, equipment cleaned with ethanol between samples, and 5g were analyzed on a Costech 4010 Elemental Analyzer. Tissues for the P, K, Ca, and Mg were ground in a Wiley mill, acid digested by EPA 3052 method, and processed by a Perkin Elmer Optima 7000 DV Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). The DBH cookie was used for the bolewood and barkwood sample. The barkwood was sampled from the outer to inner bark, and bolewood was sampled after the inner bark to the center ring. The branches were sampled with a cross section taken from the center of the branch, with care taken to ensure the cross section

remained intact. The twigs and leaves were sampled in their entirety. Roots were grouped into coarse ($\geq 5\text{mm}$) (Bond-Lamberty et al., 2002) and fine roots ($< 5\text{mm}$) and pooled by horizon type (A-A/E, E-E/A, BHS, BS1, BS2, BS3, BC, C1, C2) to obtain enough volume for nutrient analysis.

3.4.4 Harvest Intensity Simulations

3.4.5 Ecosystem Inputs

Nutrients lost to harvest have the potential to be counteracted by inputs from soil weathering and wet and dry deposition. Soils with low amounts of silt and clay imply small levels of nutrient inputs into the ecosystem as soil texture is highly correlated with cation release rates (Kolka et al., 1996). Soil weathering has been estimated by several methods, and the depletion method is recommended for future use as there is more confidence in the assumptions and it has the least uncertainty (Kolka et al., 1996). The depletion method measured the texture classes of the soils, conducted species elemental analysis by X-ray diffraction, converted to elemental percent, and used multiple regression to calculate depletion (Kolka et al., 1996). The minimum, average, and maximum weathering rates for Ca, Mg, and K from the depletion method and located on the outwash soils (Kolka et al., 1996) were used to create linear regression equations between elemental concentrations and sand percentages, with the exception of the minimum K series which was non-linear and required exponential regression. The weathering rates of outwash soils have been related to the aeolian mass, hence the

equations were necessary adjust the weathering rates from the depletion method for Ca, Mg, and K to the average soil texture observed within the soil pits (Appendix Table 3.A.1). The texturally adjusted minimum, average, and maximum weathering rates were used as inputs into the nutrient budget. The weathering rates from the both the texturally adjusted and non-texturally adjusted outwash soils were used as model parameters to calculate recovery years from a harvest. Since the textural variance has been observed previously on the outwash soils (Kolka et al., 1996) it is most appropriate to treat the weathering rate as a parameter and consider the absolute minimum (floor), averages of the minimum, average, maximum, and absolute maximum (ceiling) weathering rates per element.

Atmospheric deposition is the remaining input into the ecosystem and is comprised of wet and dry deposition. Wet atmospheric deposition has been measured since 1978 and total atmospheric deposition has been estimated since 2000 to present (Schwede & Lear, 2014). The deposition amounts vary spatially, but generally show a pattern of lower deposition in the northeastern part of the state of Wisconsin and higher in the south and southwestern portion within an example 45-year rotation length (Figure 2). Given the differences in deposition amounts, the nutrient model was calculated for three regions. The regions were northeast, northcentral, and northwest corresponding to dominant advancement and retreat patterns from the last glaciation (Teller, 1987). The deposition values for N, K, Mg, and Ca were extracted from the total deposition rasters (Schwede & Lear, 2014) by the sampling points for years 2000-2017, and an average

value per region was calculated per year. The deposition time series were transformed, detrended, and forecasted annually to the end of the rotation length (45 years) using R tseries, TSA, and forecast packages. The augmented Dickey-Fuller test was performed to ensure no unit root existed after transformation and detrending, which would result in a skewed forecast. The total deposition values were best detrended by differencing and log transformation (Appendix Figure 3.A.1- Appendix Table 3.A.2). Most of the time series passed or nearly pass the adjusted dickey fuller test ($\alpha=0.05$), except for the K in the northeast and northcentral areas (Appendix Table 3.A.2). However, across all nutrients there was a spike in the 2017 values which appear to be causing the K time series to fail, since the removal of the 2017 value results in generally white-noise processes (Appendix Figure 3.A.1). Since the transformed K series appeared to be generally white-noise and other transformations also did not pass the dickey fuller tests, the differenced and log transformed values were used to forecast the K time series. The annual observed values from 2000-2017 combined with the forecasted values for one rotation were used for repeated rotations.

Figure 2. Total deposition (Schwede & Lear, 2014) of nutrients across the state of Wisconsin, showing the difference of the nutrients deposited throughout one 45-year rotation. In general, the south and southwestern areas are receiving two to three times the amount in the northeastern area.

3.4.6 Ecosystem Outputs

The losses to the forest ecosystem are leaching and harvest removals and can vary annually in the rotation length of aspen. Leaching rapidly increases after harvest and slows to the undisturbed state after approximately 5-10 years (Silkworth & Grigal, 1982; Wang et al., 1986). In order to approximate this post-harvest effect as a time series, the undisturbed leaching rate must first be provided by the field observed values. The undisturbed leaching rate was established by multiplying the observed seasonal nutrient concentrations by the outflow of a local water balance. The water balance was calculated monthly and was comprised of inflow as precipitation minus evapotranspiration and the storage term of water holding capacity determined from the soil pedons, following similar approaches (Hubbard & Grigal, 1970; Kane et al., 2006). Evapotranspiration was calculated by monthly average temperature and hours of daylight determined by latitude (Thornthwaite & Mather, 1957). The undisturbed leaching values could then be modified by leaching ratios from 1, 2, 5 years post-harvest (Silkworth & Grigal, 1982).

Harvest removals must consider differences between the nutrients removed from the SOH and WTH which is determined by volume of removals by tissue type and nutrient concentrations. The starting forest volume available for harvest removals was calculated by scaling the sampled tissues of the volume per tree to trees per hectare. The sampled tree tissue volumes were normalized to 45 years and scaled allometrically by tissue type; bolewood, bole bark, live branch, leaf, twig (Ruark et al., 1987), dead branch (Perala & Alban, 1994), coarse roots (Bond-Lamberty et al., 2002), and stump, large and

medium roots (Young et al., 1964). The volume per tree was scaled to trees per hectare by the average basal area and site index of aspen stands located within the rotation length window (40-55 years) and on restricted soils in the stocking guide (Brown & Gevorkiantz, 1934). The available forest volume for harvest was then modified by harvest type, with the SOH consisting of the merchantable volume of bolewood and barkwood (Young et al., 1964), and the WTH including 27% more fine woody debris (FWD) and 46% more the coarse woody debris (CWD) (Rittenhouse et al., 2012). The foliar and twig volumes were considered as FWD and the live and dead branch were considered as CWD. The winter WTH was modified as it was found to leave 28% more FWD on site than the remaining WTHs due to increased breakage (Rittenhouse et al., 2012). The volumes by harvest type were then available for the changes in nutrient concentration by season.

The observed tissue concentrations were multiplied by the volume of each individual tree components to provide the amount of macronutrients removed by harvest type. The FWD and CWD concentrations were also modified by the ratios between the seasonal differences. Seasonal differences were determined by the average of the season across the available studies for foliar (leaf +bud) and twig concentrations (Alban, 1985; Gerloff et al., 1964; Henry, 1973; McColl, 1980; Tew, 1970). The seasonal fluctuations and the average across the studies of the seasonal averages are presented for the foliar and twig nutrient values (Appendix Figure 3.A.2-3). Foliar tissues show a spike in N, P, and K during the growing season, whereas Ca and Mg show a peak during the dormant

season (Appendix Figure 3.A.2). Twig nutrient concentrations generally decrease during the growing season and have larger concentrations during the dormant season (Appendix Figure 3.A.3). Note that winter P values are not available, and the twig concentrations are more limited than the foliar, particularly in the winter where only one study presents values.

3.4.7 Nutrient Capital and Modeling Assumptions

The harvest intensity simulations consider losses to the system as leaching and harvest removals, inputs to the system as total deposition and weathering on an annual basis. Five harvest types were considered: SOH, and seasonal WTHs (Winter, Spring, Summer, Fall). The SOH scenario did not include seasonal changes as the branches are left on site. The WTHs required the twig and leaf-bud values to be adjusted to the seasonal averages by the seasonal ratios and sampling time (Alban, 1985; Gerloff et al., 1964; Henry, 1973; McColl, 1980; Tew, 1970) and differences in volume removed (Rittenhouse et al., 2012). The initial soil value is the starting nutrient capital from which the inputs and outputs can be compared annually. The soil pool was classified by soil above 150cm as above the below rooting depth (Kolka et al., 1996). The unharvested volume composed of root and stump values was then combined with the soil values to constitute the nutrient capital post-harvest. The nutrient budget was calculated iteratively on a rotation length of 45 years which is a common rotation length of aspen (Wisconsin DNR, 2013). Each rotation included one harvest year, and the harvests were repeated until the capital pool reached zero or up to 11 rotations (506 years). Although a forest

stand will likely experience different types and seasons of harvest, the goal is to identify differences between the harvest types in order to pursue the most sustainable harvest. Recovery years were calculated by the time it took for the annual outputs and inputs to replace the values lost to one harvest. The average deposition per year across the three modeled locations was used for as the deposition input, and the undisturbed leaching value was used at and after 45 years. The recovery years were calculated for comparison with typical rotations lengths so as to observe the harvesting rate under several weathering scenarios.

3.5 Results

The distribution of the nutrient values of an aspen forest located on the outwash soils show a large proportion of K, Ca, and Mg located within the vegetation pools as compared to the extractable soil pools (Table 1). The N and P vegetation values are small in comparison to the total soil pools (Table 1). The largest locations of nutrients tend to be bolewood, barkwood, leaf, and live branches, and stump combined with large and medium roots across all reported nutrients. Whereas pool sizes within the coarse roots, dead branches, and twigs tend to compose much less of the overall pool of nutrients within the ecosystem.

Table 1. Distribution of nutrient values in an aspen-dominated forest located on nutrient-poor soil types and confidence intervals ($\alpha=0.05$). Average vegetation values are adjusted to 45 years old in the summer season.

	Nutrient (kg ha ⁻¹)				
	N	P	K	Ca	Mg
Leaf	41 ± 8	5 ± 1	23 ± 4	27 ± 7	5 ± 1
Twig	0.92 ± 0.23	0.22 ± 0.05	0.99 ± 0.14	2.14 ± 0.34	0.22 ± 0.05
D.Branch	1.2 ± 0.71	0.15 ± 0.08	0.65 ± 0.45	6.18 ± 4.30	0.39 ± 0.23
L. Branch	34 ± 10	7 ± 2	38 ± 11	136 ± 41	11 ± 3
Barkwood	91 ± 28	13 ± 5	94 ± 40	467 ± 170	24 ± 8
Bolewood	247 ± 209	23 ± 6	109 ± 33	312 ± 158	39 ± 9
Stump + Roots	71 ± 48	8 ± 2	40 ± 15	132 ± 69	13 ± 3
Coarse Roots	0.06 ± 0.01	0.02 ± 0	0.02 ± 0	0.2 ± 0.02	0.02 ± 0.00
Vegetation Total	487 ± 217	57 ± 8	306 ± 55	1083 ± 246	93 ± 13
Soil (0-150cm)	8054 ± 866	2000 ± 301	853 ± 212	2788 ± 460	217 ± 86

Not surprisingly, the WTHs removed a larger portion of all nutrients than the SOH due to more volume being removed (Table 2, Figure 5). The winter season removed the lowest amounts of macronutrients for the WTHs (Table 2). The remaining seasons

have different impacts by element with the spring harvest removing larger amounts of N and K, the summer harvest larger amounts of K and Ca, and the fall harvest removing the largest amount of Ca (Table 2). The P and Mg values do not differ among the WTHs but are larger than the SOH (Table 2). The harvest removals are one or two orders of magnitude larger than the leaching outputs depending on the nutrient, showing the degree to which the harvest removals drive the scenario outputs (Table 2). The inputs do not vary greatly, as the deposition values for K and Mg are similar to the average weathering values across regions, but the Ca deposition values are 1.2-1.5 times larger than weathering values (Table 2). The maximum weathering values are larger than deposition values across all elements (Table 2).

Table 2. Harvest simulations macronutrient inputs and outputs of a single rotation, as well as weathering rates and deposition by region.

Nutrient (kg ha ⁻¹ 45year ⁻¹)		N	P	K	Ca	Mg
Outputs						
<i>Harvest Removals</i>						
SOH	339	36	204	779	63	
WTH - Winter	396	47	248	948	80	
WTH - Spring	440	48	265	940	79	
WTH - Summer	416	49	267	951	80	
WTH - Fall	406	46	254	983	82	
<i>Leaching</i>	4	0.4	24	41	13	
Inputs						
<i>Weathering</i>						
Minimum			5	36	9	
Average			11	69	16	
Maximum			52	126	29	
<i>Deposition</i>						
Northeast	241		9	88	12	
Northcentral	226		9	85	11	
Northwest	268		10	100	12	

When the harvest amounts are compared to the remaining ecosystem nutrients the percentage of removal is equal to or less than five percent of N and P, and between 20-35% of K, Ca, and Mg (Figure 6). In comparison to the SOH, the WTHs remove an additional 5-10% of the ecosystem K, Ca, and Mg, and 1-2% of the N and P, which reflects total and exchangeable pools.

Figure 5. Average macronutrient removal by harvest type and season. The SOH removes a smaller amount than the WTHs, and the winter WTH tends to be lower due to additional breakage. Error bars represent standard error.

Figure 6. Percent of nutrient pools removed by harvest type in comparison to the soil and remaining tree and root tissue values. The large proportion being removed highlights the nutrient-poor status of the soil as the exchangeable K, Ca, and Mg are small in comparison to the harvests.

Although the deposition values vary spatially, the harvest removals drive the trend in the time series models and make the difference non-detectable. Only the time series from the northeastern model are presented under the minimum, average, and maximum weathering scenarios (Figures 7-9). The N and P show differences between the SOH and the WTHs, and the WTHs show differences between seasonal treatments towards the later rotations but are not at risk for depletion throughout the model (Figures 7-9). K WTHs show depletion in four rotations across the minimum, average, and maximum weathering rates with no seasonal differences (Figures 7-9). The K pool under the SOH lasts one rotation longer than the WTHs with the minimum and average weathering rates, but two rotations longer under the maximum weathering rate (Figures 7-9). Calcium is modeled to be depleted within four rotations of WTH and five rotations of SOH under all seasons and weathering rates (Figures 7-9). Mg is modeled to be depleted within three consecutive rotations of WTHs during the fall and four rotations for the remaining seasons under the minimum weathering rate (Figures 7). The Mg pool will be depleted in four WTH rotations under the average and maximum weathering rates, with no differences between the season of WTH (Figures 8). The SOH Mg pool lasts one more rotation longer than the WTHs in the minimum and average weathering rates, but two rotations longer in the maximum weathering rate (Figures 7-9).

Figure 7. Northeastern macronutrient time series by harvest simulation under minimum weathering inputs. WTH manifest seasonal differences in the N pool after many rotations, and between the WTH and SOH. The WTH shows differences in P after multiple rotations compared to the SOH. K, Ca, and Mg show depletion after four rotations of WTH, with the exception of three consecutive fall WTHs depleting the Mg pool. The WTH compared to SOH tends to speed the depletion by a full rotation.

Figure 8. Northeastern macronutrient time series by harvest simulation under average weathering. WTH manifest seasonal differences in the N pool after many rotations, and between the WTH and SOH. The WTH shows differences in P after multiple rotations compared to the SOH. Ca, Mg and K show depletion after four rotations of WTH. The WTH compared to SOH tends to speed the depletion by a full rotation.

Figure 9. Northeastern macronutrient time series by harvest simulation under maximum weathering rates. WTH manifest seasonal differences in the N pool after many rotations, and between the WTH and SOH. The WTH shows differences in P after multiple rotations compared to the SOH. Ca, Mg and K show depletion after four rotations of WTH, with the exception of five sequential winter WTHs of K. The WTH compared to SOH speeds the depletion of the Ca pool by a full rotation, or two rotations for the K and Mg pools.

In addition to the time series, the recovery years also show the harvest outputs are greater than inputs to the outwash system at the current rotation length under all scenarios besides K and Mg in the ceiling and maximum values (Table 3). The Ca recovery years exceed the average rotation length by a factor of two under the ceiling weathering values on the non-texturally adjusted soils (Kolka et al., 1996), which shows that the Ca removed from the system is not occurring at a sustainable rate by both the SOH and average WTH. When the weathering rates are adjusted to textures observed in the field the recovery years increase greatly and indicate non-sustainable removal rates (Table 3).

Table 3. Recovery time in years for weathering and deposition inputs to replace outputs of a single harvest and leaching by harvest type. The number of recovery years demonstrates that the inputs do not replace outputs at current rotation lengths, besides K and Mg in the non-texturally adjusted ceiling and average of the maximum weathering rates. * indicates the weathering rates and deposition do not exceed the outputs meaning the harvest is not replaced.

Weathering Type	Rate	SOH			WTH		
		K	Ca	Mg	K	Ca	Mg
Outwash Soils (Kolka et al.,1996)	Ceiling	31	82	28	39	101	36
	Avg. of Maximums	54	110	43	69	135	54
	Avg. of Averages	140	142	63	178	173	80
	Avg. of Minimums	*	186	90	*	228	114
	Floor	*	449	280	*	549	357
Texturally Adjusted to Observed	Maximum	292	199	101	373	243	128
	Average	*	293	183	*	359	233
	Minimum	*	403	335	*	494	426

3.6 Discussion

The annual inputs to the system over a 45-year period do not replace the amount of nutrients lost to harvest and are particularly concerning for the K, Ca, and Mg pools. Multiple WTHs on the nutrient poor soils would likely deplete the Ca, Mg, and K pools after four rotations if the average weathering rate is assumed. The SOH shows Ca, Mg, and K depletion after five rotations if the average weathering rate is assumed. The minimal impacts to the long-term productivity N has been modeled previously on the sandy, nutrient-poor soils (Wang et al., 2014). Ca and Mg pools have long been reported as a potential concern of WTHs in aspen stands (Boyle et al., 1973; Silkworth & Grigal, 1982) and especially on coarse textured soils (Thiffault et al., 2011). The decrease in total rotation lengths from WTH has previously been reported on in analogous systems in Sweden, where base cations were also suspected to shorten the total rotations by 1-2 rotations (Sverdrup & Rosen, 1998).

The leaching values from the water budget approach are much more conservative than have been previously reported on regional soils 4 N 0.4 P, 24 K, 41 Ca, 13 Mg (kg ha⁻¹ 45year⁻¹). For example, when leaching rates are imputed from post-harvest to the undisturbed rates on a 45 year rotation the sandy soil leaching values are 138 N, 85 P, 170 K, 344 Ca, 353 Mg (kg ha⁻¹ 45year⁻¹)(Wilhelm et al., 2013), and 18 N, 25 P, 131 K, 1424 Ca, 604 Mg (kg ha⁻¹ 45year⁻¹) on a gravelly sandy loam (Silkworth & Grigal, 1982). The leaching values measured on the sandy soils would most closely represent the values that could be expected, however, the values were measured at 60cm and likely still plant

available as the below rooting depth for aspen has been defined as 150cm (Kolka et al., 1996). Moreover, the leaching values on the sandy soil compose a large percentage of the soil pool: 182% N, 17% P, 49% K, 14% Ca, and 55% Mg (Wilhelm et al., 2013). The sandy loam leaching values better approximate the below rooting depth but contain much higher silt (30%) and clay (5%) values (Silkworth & Grigal, 1982) than the soils examined in this study. Given the depth, large percentages, and often higher leaching rates for the loamy textured soils, the sandy soil leaching values are likely an overestimate to values leaving the system.

The harvest simulations can be compared to the effects of the WTH in the same outwash soils, wherein a significant decrease in soil pool size of Ca by 54% after one rotation was observed (Premer, 2015). The northeastern model in Wisconsin best represents the conditions that could be expected in the study as it occurred adjacently in the Upper Peninsula of Michigan. The northeastern model in this study only reaches a similar difference for the percentage of loss between the SOH and WTH for Ca after the third rotation. The difference between the simulated and measured harvests could have many potential explanations, such as differences between stand history, logging crews and equipment relating to volume removed in WTH, silt composition differences and depletion status, or the timeframe of the sampling. The study showing decreases of soil Ca by 54% after one WTH sampled five stands on the Rubicon soil, two WTH and three SOHs, along a chronosequence of approximately 8, 15, 19, 27, and 30 years (Premer,

2015). The sampling design could have captured differences in the post-harvest nutrient pool status given sampling across the primary stages of aspen regeneration.

However, the largest complication with the outwash soils is the considerable textural variation, with important consequences for the weathering rates (Kolka et al., 1996 ; Appendix Table 3.A.1). The mass of the aeolian loess cap is highly correlated with cation release rates across outwash soils, with combined clay and silt values ranging from (10-24%) and the average cation release rates from the depletion methods reporting ranges of: K 3.5-0.7; Ca 6.9-1.3; Mg 1.7-0.4 (kg ha⁻¹ yr⁻¹) (Kolka et al., 1996). Whereas the combined silt + clay values in this study ranged from 6-11 percent. The differences between the silt + clay percentages may not have been detectable with field observations of the pedon but could result in different weathering rates. The weathering rates are particularly important in the shallow aeolian horizons of these soils, and some may have reached a stable weathering rate after the Ca and Mg bearing minerals have been depleted whereas some may still be weathering to that stage (Kolka, 1993; Kolka et al., 1996). Pedons were observed in the field to confirm soil characteristics, but textural analysis and values were not reported (Premier, 2015). The exchangeable values reported in the top 30cm are SOH (730 K, 420 Ca, 370 Mg kg ha⁻¹) and WTH (730 K, 110 Ca, 330 Mg kg ha⁻¹) and significant differences were not reported (Premier et al., 2019). The large standard deviation values reported for Ca (SOH 620, WTH 320) (Premier et al., 2019), provides some evidence that the silt and clay variation may be complicating the results.

Whatever the cause for the underestimation of the harvest models in comparison to observed Ca results (Premer, 2015), the harvest simulations call into question the practice of continual forest harvests on the sandy outwash soils in the absence of increasing the input terms of Ca, Mg, and K. Although efforts have been made to parametrize the weathering rates to account for the textural variation, there is always the possibility of intensively managed forests being further along in the harvest rotation models or having lower starting soil pool values than the average field observed soil values (833 K, 2788 Ca, 217 Mg kg ha⁻¹). For instance, if the 30cm values soil values from the observed WTH and SOH are extrapolated to 150cm the average exchangeable soil nutrients would be SOH (3650 K, 2100 Ca, 1850 Mg kg ha⁻¹) and WTH (3650 K, 550 Ca, 1650 Mg kg ha⁻¹) (Premer et al., 2019). This extrapolation would overestimate the values as in the soil the A-B horizons are being applied through to the depth of the C horizon but is necessary for comparison. The average Ca value reported after the WTH has important consequences because the next harvest removal, regardless of the type, has the potential to deplete the Ca. The harvest removal values (SOH: 339 N, 36 P, 204 K, 779 Ca, 63 Mg; WTH Average: 414 N, 48 P, 208 K, 955 Ca, 80 Mg kg ha⁻¹) appear to be very consistent with previously reported aspen harvest values (454 N, 43 P, 355 K, 1034 Ca, 95 Mg kg ha⁻¹) (Silkworth & Grigal, 1982). These results indicate that some outwash soils may be more at risk for negative harvest impacts depending on the management history and weathering status of the aeolian mass.

It is important to remember many of the soils exist now as publicly owned forest lands from not being agriculturally productive and the “lands nobody wanted” (Shands, 1991). The low fertility of the sandy soils in combination with the modeled outputs exceeding inputs at the current rotation length indicates that future yields could be diminished if the soil becomes depleted. The impacts from the increased removal of nutrients necessary for plant growth should manifest in decreased productivity when a single nutrient reaches the limiting level (for example, Liebig, 1840). Differences in forest productivity were not observed after one WTH rotation, even though the pools were halved on the coarse textured soil (Premer, 2015; Premer et al., 2016). These results indicate that after one WTH rotation the Ca and Mg have not become limiting to the aspen which is adapted to the nutrient-poor soils. The harvest simulation models indicate that Ca, Mg, and K are likely to become limiting after the fourth WTH or fifth SOH from the current nutrient pool status and input terms. If such a point were reached, for example after 225 years of intensive harvesting with no increases to the input terms, the ecosystem could be expected to convert to pine or oak savannahs and function more similarly to pine or oak barrens. If the cations became limiting, the yields could be expected to decrease and reduce the harvest output terms sequentially.

If the barrens system is not desired and the management goal is production forestry the input terms of Ca, Mg, and K should be increased to mitigate the harvest removals. A possible solution to the removal of base cations is the application of wood ash which is common on similar soils in Scandinavia (Reid & Watmough, 2014).

Increased productivity has been observed in temperate forests after wood ash application and has been recommended in acidic soils with established forests where Ca, Mg, and K are deficient (Augusto et al., 2008). Wood ash applications do have the drawback of containing heavy metals (Augusto et al., 2008). The management goals and financial constraints will dictate these management options.

3.7 Conclusion

Harvest simulations show that increasing the harvest intensity from SOH to WTH of aspen on nutrient-poor soils leads to shortening the available nutrients by one full rotation length for Ca, Mg, and K. N and P were less impacted since the percent removed in each harvest is generally small in comparison to the residual tissues and soil pools. The harvest simulation models also call into question the sustainability of the SOH practice on the nutrient poor soils if the input terms are not increased. The seasonal differences between the WTH removals were diminished by the scale of the harvest in comparison to the remaining pools and didn't have time to manifest before depletion. This means that although there are seasonal differences, the harvest removals under the current rotation lengths (e.g., 45 years) are the major force dictating the direction of harvest models since the removals are large in comparison to remaining pools. In fact, only the fall WTH showed a difference in the number of rotations possible for K under the maximum weathering rates in comparison to other seasonal WTHs. These findings are similar to previous studies on different soil types and give credence to the policy decision to restrict

the WTH of aspen on the nutrient-poor outwash soils. The large portion of base cations located within the vegetative pool and removed during the harvest implies that inputs by weathering and deposition cannot keep pace within the sandy, nutrient-poor soils in northern Wisconsin. The harvest removals show depletion of the Ca, Mg, and K during the fourth WTH or fifth SOH, in which case the system is likely to convert to pine-oak savannahs or barrens. Wood ash is a potential solution to replace the base cations if production forestry is the desired management goal.

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Appendix Table 3.A.1. Soil texture within the top 150cm comparing observed soil pedons to outwash soils used to calculate weathering rates. The named soils which show larger clay and silt percentages are derived from Kolka et al, 1996.

Plot ID	Clay (%)	Silt (%)	Sand (%)
P4475 C78 S11	1.3	8.2	90.5
P4475 C61 S1	2.7	8.5	88.8
P4475 C19 S6	1.0	8.2	90.8
P1900 C56 S1	1.3	7.0	91.7
P4475 C47 S2	1.4	9.1	89.5
P1900 C17 S8	0.8	5.0	94.2
P6476 C257 S11	1.7	7.9	90.4
P3800 C337 S2	1.9	7.2	90.9
P5800 C94 S10	1.4	4.5	94.1
P6600 C58 S16	2.5	4.3	93.2
P3800 C55 S2	1.8	6.5	91.7
P6476 C79 S1	2.2	8.1	89.7
P4475 C19 S6	1.7	6.2	92.0
P4475 C8 S2	1.8	6.4	91.8
Cloquet	7.5	16.7	75.8
Omega	5.7	8.9	85.3
Solon Springs	7.2	3.3	89.5

Appendix Figure 3.A.1. Time series of total deposition time series for regional harvest model inputs after differencing and log transformation. When excluding the large spike in the 2017 values, seen as the second from right value due to differencing, the processes appear to generally be white-noise.

Appendix Table 3.A.2. Augmented Dickey-Fuller unit root test p-values indicating most processes are white-noise ($\alpha=0.05$) after differencing and log transformation. All K values fail the test, however, when excluding the 2017 values the processes appear to be white-noise.

Region	N	K	Ca	Mg
Northeast	0.05	0.48	0.01	0.01
Northcentral	0.02	0.41	0.02	0.01
Northwest	0.05	0.06	0.07	0.03

Appendix Figure 3.A.2. Seasonal foliar macro-nutrient concentrations by day of the year observed in aspen, as well as the average of the seasonal averages across studies (Derived from Alban, 1985; Gerloff et al., 1964; Henry, 1973; McColl, 1980; Tew, 1970.) N, P, and K show increases during the growing season while decreasing during the dormant season, with Ca and Mg showing the opposite pattern. Trembling aspen (*Populus tremuloides*) is represented by POTR and bigtooth aspen (*Populus grandidentata*) is represented by POGR.

Appendix Figure 3.A.3. Seasonal twig macro-nutrient concentrations by day of the year observed in aspen, as well as the average of the seasonal averages across studies (Derived from Alban, 1985; Gerloff et al., 1964; Henry, 1973; McColl, 1980; Tew, 1970.) The macro-nutrients all show increases during the dormant season while decreasing during the growing season. Trembling aspen (*Populus tremuloides*) is represented by POTR and bigtooth aspen (*Populus grandidentata*) is represented by POGR.

4 Whole-tree harvest effects on soil macronutrients in an oak dominated system after seven years

4.1 Abstract

Revisiting a whole-tree harvest (WTH) and stem-only harvest (SOH) experiment showed significant decreases ($\alpha=0.05$) in the total N and K pools from WTH. Total Ca was nearly significantly decreased by the WTH ($p=0.065$) in comparison to the SOH. The woody debris was significantly decreased from the WTH across all macronutrients measured (N, P, K, Ca, Mg). The differences in the woody debris were initially detected but did not influence the nutrient budget (Wilhelm et al., 2013). The nutrient budget relied on the assumption that the woody debris was rapidly available through mineralization within 1.75 years post-harvest as the only inputs to the budget were soil measurements captured with an exchange resin at 5 and 20cm and atmospheric deposition. Revisiting the sites at 7.75 years post-harvest allowed for the detection of the differences in total N and K pool sizes due to the differences in harvest intensity.

4.2 Keywords

Whole-tree harvesting, nutrient budget, outwash soils, harvest intensity, ecological modeling

The material contained in this chapter is in preparation to be submitted to *Journal of Forest Ecology and Management*

4.3 Introduction

The lasting effects of a whole-tree harvest (WTH) and stem-only harvest (SOH) on soil fertility have generally indicated an increased loss of base cations, particularly for coarse textured soils (Boyle et al., 1973; Olsson et al., 1996; Silkworth & Grigal, 1982; Sverdrup & Rosen, 1998; Thiffault et al., 2011). However, variation among studies is large, and the net effects of harvesting for sustained soil fertility are not universal (Premier et al., 2019; cf. Bowd et al., 2019). In a recent study in an oak (*Quercus* spp.) dominated system located in sandy soil, only phosphorus (P) was modeled to have a net depletion across all harvest treatments, whereas the nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg) were found to be accumulating (Wilhelm et al., 2013). However, differences in woody residues were detected between treatments, with $23,400 \pm 6070 \text{ kg ha}^{-1}$ in the SOH and $11,100 \pm 2,220 \text{ kg ha}^{-1}$ in the WTH (Wilhelm et al., 2013). Although the woody residues may show impacts of the harvest, the nutrient budget findings are contradictory to previous research on similarly sandy outwash soils where the WTH practice on aspen (*Populus* spp.) forest halved the available Ca pool (Premier, 2015), and on more nutrient rich loams which showed the loss of Ca and Mg (Boyle et al., 1973; Silkworth & Grigal, 1982). More recently, on a sandy loam moraine soil impacts on Ca and Mg from WTH were minimal, and the understory diversity increased (Premier, 2015; Premier et al., 2016). The differences in results highlight the complexity faced by forest scientists and managers when attempting to determine the lasting effects of removing more volume from a forest.

The complexity of determining the WTH impacts stems not only from variation in harvest species and soil types across studies, but also from the differences in the modelling approaches, nutrient pool definitions, and post-harvest sampling timeframe. In one instance where P was modeled to have a net depletion across harvest treatments, coarse textured soils were sampled immediately after the harvest and up to 1.75 years after harvest (Wilhelm et al., 2013). In contrast, finer textured soils were sampled 1, 2, 5 years following harvest and determined Ca and Mg would be limiting with successive harvests (Boyle et al., 1973; Silkworth & Grigal, 1982). The finer textured soils also provide much higher weathering rates of Ca and Mg (Kolka et al., 1996). Therefore, if Ca and Mg have reported losses due to WTH, it follows that the coarse textured soil would exaggerate the effect, since the supply of Ca and Mg is much less. Moreover, these studies varied in their definitions of nutrient input pools over time (Boyle et al., 1973; Silkworth & Grigal, 1982; Wilhelm et al., 2013). Revisiting these harvested sites over time, evaluating changes in soil nutrient pools in a consistent manner, would elucidate potential lasting differences in WTH effects on soil fertility. The purpose of this study was to revisit the SOH and WTH harvest intensity experiments initiated by Wilhelm and others (2011), assessing changes in available nutrient pools six years after the initial assessment. The prior study did detect significant differences in the woody debris by harvest type, and modeling efforts showed that P was the only element depleted in the soil (Wilhelm et al., 2013). However, these assessments were informed by inputs defined as mineralization combined with weathering and atmospheric deposition in a time frame that may have not allowed for the decomposition of the woody debris to manifest as an

input to the mineralization and weathering pool. Therefore, we revisited these same harvest trials, accounting for a longer time frame allowing for further decomposition of the woody debris. We hypothesized: significant differences between WTH and SOH would be observed in the 1) woody debris pools and 2) total pools 7.75 years after the harvest.

4.4 Methods

Initial Treatments

The harvest intensity treatments were first carried out between November and December of 2009 on the oak dominated stands in the Governor Knowles State Forest, as previously described by Wilhelm, 2011. The harvest intensity treatments were designed to represent a conventional harvest (biomass $\leq$ 4in./10cm left on site), a slightly intensified harvest (biomass $\leq$ 2in./5cm left on site), a whole tree harvest (all biomass removed), and an unharvested reference site. Ecosystem nutrient values, including deposition through precipitation, living tissues in the herbaceous, shrub, and overstory species, woody debris, soil pools, and leachate, were collected during the growing seasons of 2010 and 2011 (Wilhelm et al., 2013). Soil mineralization and weathering was assessed at 5cm and 20cm depth by mixed-bed exchange resin (Wilhelm et al., 2013). The woody debris were categorized as coarse woody debris (CWD) with a minimum total length of 0.9 m and greater than 2.54 cm diameter, and fine woody debris (FWD) defined

as less than 2.54cm diameter (Wilhelm et al., 2013). The forest litter or forest floor pool was defined as any non-woody decaying organic matter including fruits, leaves, organisms or scat decayed beyond recognition up to the mineral soil (Wilhelm et al., 2013). A nutrient budget was constructed which consisted of the inputs of precipitation and mineralization combined with weathering, and outputs as leaching and biomass retention (Wilhelm et al., 2013). The study design focused on the volume of woody residue being removed as the treatment, with significant differences detected between the SOH with $23,400 \pm 6070 \text{ kg ha}^{-1}$ and $11,100 \pm 2,220 \text{ kg ha}^{-1}$ in the WTH (Wilhelm et al., 2013).

Site Re-measurements and Nutrient Analyses

Three of the sites from the original study were subsequently harvested, and therefore were not included in this study. The three harvested sites not available for resampling were located on Typic Udipsamments, and the two sites that were available for resampling were located on Entic Haplorthods. The N and P soil values did not show significant differences between the soil types, but the K, Ca, and Mg were significantly lower for the Entic Haplorthods (Wilhelm, 2011).

The two unharvested sites of the original study sites, Sunrise and Trade River, were resampled in August of 2017. The two sites contained the intact SOH and WTH treatments and were sampled for soil cores, forest litter, and fine woody debris at 8m from the plot center in the cardinal directions (n=8) similar to the original study (Wilhelm

et al., 2013). Soil cores were taken from 0-8 and 8-60cm with a 1-inch diameter AMS soil probe similar to the original study (Wilhelm et al., 2013). Forest floor litter was sampled with a 0.25m² frame and all woody debris was sampled in 1m² frame. A soil pit was dug in the center of the experimental plot and was described and sampled following standard procedures (Schoeneberger et al., 2012). Bulk density samples were taken in duplicate by horizon in the soil pit with a bulk density core or a 1-inch diameter AMS soil probe. Soil probe values were scaled to kg ha⁻¹ by the bulk densities from the soil pits with a weighted average by depth corresponding to the 0-8 and 8-60cm probe. The Wilcoxon signed-rank test was used for all statistics ($\alpha = 0.05$).

Vegetation was dried at 55°C until a constant weight was obtained. Vegetation was transported to Marshfield lab for acid digestion by ICP-OES on a Perkin Elmer 8000 ICP. Soils were transported to Michigan Technological University and were dried at 55°C to a constant mass and sieved (no. 10, 0.2-cm mesh) to remove roots, rocks, woody debris, and char. K, Ca, and Mg were obtained by shaking 5g of soil in 20mL of 1M NH₄OAc for 20 minutes, filtered by Whatman 42 filter paper, and analyzed by ICP-OES using a Perkin Elmer Optima 7000DV. Available phosphorus was determined spectrophotometrically with the ascorbic acid method (Bray & Kurtz, 1945; Menage & Pridmore, 1973). Nitrogen was determined with 33.33g of soil into 100mL 1M KCl, shaken for 20 minutes, filtered through Whatman 42 filter paper, and analyzed by QuikChem 8000 instrument by Lachat with nitrate by QuikChem Method 12-107-04-1-F and ammonium by QuikChem Method 12-107-06-1-B (Lachat Instruments, 1998).

4.5 Results

The total nutrient pools consisting of the soil 0-60cm, forest litter, and woody debris, show significant reductions in N and K in the WTH compared with SOH (Figure 1, Table 1). The woody debris showed significant differences between the SOH and WTH across all elements measured (Figure 2a, Table 1). Litter pools only showed a significant difference for Mg, with the WTH being larger than the conventional harvest (Figure 2b, Table 1). No significant differences were detected between harvests within the soil pools (Figure 2c, Table 1). The volume of woody debris shows significant decreases in the WTH as compared to the SOH, but the forest floor shows no difference in volume between treatments (Figure 3).

Figure 1. Total nutrient pools by harvest type with error bars representing standard error. Significant differences are detected for N and K, but not P, Ca and Mg by the Wilcoxon signed-rank test ($\alpha = 0.05$). Note that Ca does appear to be significantly different, but the Wilcoxon test returns a non-significant result ($p=0.065$). * indicates a significant difference.

Table 1. Average kilograms per hectare and confidence intervals ($\alpha = 0.05$). Wilcoxon signed-rank test p-values by nutrient pool and element, showing significant differences across all elements for woody debris, litter Mg, and N and K for the total pools ($\alpha = 0.05$).

Nut. Pool	Type	N	P	K	Ca	Mg
Woody Debris	SOH	66a $\pm$ 27	3a $\pm$ 1	11a $\pm$ 5	114a $\pm$ 48	6a $\pm$ 3
	WTH	9b $\pm$ 9	0b $\pm$ 0	1b $\pm$ 1	9b $\pm$ 8	1b $\pm$ 1
	p val.	0.0011	0.0039	0.0027	0.0002	0.0063
Forest Litter	SOH	17a $\pm$ 4	1a $\pm$ 0	1a $\pm$ 0	18a $\pm$ 6	2a $\pm$ 0
	WTH	21a $\pm$ 5	1a $\pm$ 0	2a $\pm$ 1	18a $\pm$ 5	3b $\pm$ 1
	p val.	0.3282	0.1719	0.2345	0.7984	0.03792
Soil	SOH	98a $\pm$ 15	93a $\pm$ 31	167a $\pm$ 29	1052a $\pm$ 220	175a $\pm$ 34
	WTH	88a $\pm$ 26	106a $\pm$ 14	135a $\pm$ 13	806a $\pm$ 198	169a $\pm$ 48
	p val.	0.1949	0.5737	0.1605	0.1304	0.9591
Total	SOH	180a $\pm$ 41	97a $\pm$ 30	180a $\pm$ 33	1185a $\pm$ 241	183a $\pm$ 33
	WTH	118b $\pm$ 26	108a $\pm$ 14	138b $\pm$ 12	834b $\pm$ 201	172a $\pm$ 48
	p val.	0.0281	0.6454	0.0499	0.0650	0.8785

Figure 2. Specific nutrient pools by harvest type with error bars representing standard error showing **a)** significant differences for N, P, K, Ca, Mg in the woody debris pool, **b)** Mg in the litter pool, and **c)** no significant differences in the soil by the Wilcoxon test ($\alpha = 0.05$). * indicates a significant difference.

Figure 3. Woody debris and forest floor organic matter volume comparing the SOH and WTH 7.75 years after harvest. The woody debris shows the WTH is significantly lower than the SOH. The forest floor values do not show significant differences between treatments. * indicates a significant difference.

4.6 Discussion

The difference between a WTH and a SOH should be evident in the woody-debris immediately after the harvest, and as the debris begins to decompose the effect could be seen moving into the forest floor and soil pools. Since the distribution and amounts of woody debris were directly affected by harvest intensity, it is not surprising that the stocks of all elements investigated experienced significant declines within the woody debris pool from the WTH. The difference in woody debris did not translate into the forest litter, as only Mg was significantly different between treatments, in this case with the WTH being the larger pool. The volume of the forest litter pool is not significantly different between treatments, which means the decaying organic matter is more Mg rich in the WTH. The magnitude of difference between the forest floor volume at 1.75 years (SOH 20,000, WTH 22,000 kg ha⁻¹) as compared to 7.75 years (SOH 949, WTH 897 kg ha⁻¹) post-harvest indicates increased decomposition of the forest floor across both treatments. Increased decomposition of the total forest floor volume is likely to occur because the amplitude of temperature is increased due to the removal of the overstory, which is also no longer providing leaf litter inputs.

The original study design focused on the volume of woody residue being removed as the treatment, with significant differences detected between the SOH with $30,600 \pm 6,540$ kg ha⁻¹ and $11,100 \pm 2,220$ kg ha⁻¹ in the WTH (Wilhelm et al., 2013). The significant differences were also detected by debris type with the CWD reported as 19,000 kg ha⁻¹ in the SOH and 1,400 kg ha⁻¹ in the WTH, and the FWD was 14,000 kg

ha^{-1} in the SOH and $9,000 \text{ kg ha}^{-1}$ in the WTH (Rathsack, 2011). The differences in gross volume also translated to significant differences across the macronutrients observed in the CWD as the SOH contained 24 N, 20 P, 152 K, 68 Ca, 30 Mg (kg ha^{-1}) and the WTH 1 N, 1 P, 13 K, 5 Ca, 2 Mg (kg ha^{-1}) (Rathsack, 2011). FWD debris values were 70 N, 5 P, 20 K, 135 Ca, 9 Mg (kg ha^{-1}) in the SOH and 40 N, 3 P, 10 K, 67 Ca, 5 Mg (kg ha^{-1}) in the WTH (Rathsack, 2011). Significant differences in the FWD were not reported in the original research (Rathsack, 2011), but t-tests from the reported mean, standard deviation, and degrees of freedom between the WTH and SOH show significant differences across all elements. The total volume of woody residue is much lower, particularly for the SOH, at 7.75 years ($9,772 \text{ SOH}$, $1,785 \text{ WTH kg ha}^{-1}$) than what was observed up to 1.75 ($30,600 \text{ SOH}$, $11,300 \text{ WTH kg ha}^{-1}$) years post-harvest. The comparison is not ideal as the preharvest values are derived across all study sites and the post-harvest values are only derived from the two available for resampling. Since significant differences were observed between the soil types (Wilhelm, 2011), it is possible that productivity differences exist and could translate to differences in woody debris. However, the ratios of the woody debris volume between the WTH and SOH should be consistent across the two soil types even if differences in the total amount existed. The WTH woody debris volume showed a change of -84% in the WTH and the SOH -68%, which appears to be fairly consistent given the larger size of debris left after the SOH.

The decomposition of the woody debris and forest floor did not result in significant differences between WTH and SOH within the soil pools of the

macronutrients measured 7.75 years after harvest. The soil Ca does appear to be trending towards a significant reduction in the WTH vs. SOH (Figure 2c, Ca Wilcoxon test $p = 0.06$; t-test $p = 0.045$). Since the SOH has more woody debris remaining for decomposition than the WTH it is likely that Ca will be significantly different in the future given leaching losses and fewer inputs. Since all elements significantly differed in the amount of woody debris available for decomposition this could potentially be the situation for all elements, but comparison with the total pools would give the best indication of future nutrient status. The total pools indicate significant declines in the WTH N and K pools, and potentially Ca as compared to the SOH. Regionally, and in the same family of soils, the available Ca was decreased by 54% due to WTH in an aspen stand after one rotation (Premier, 2015). This study found a difference loss of 22% Ca when comparing WTH to SOH. Previously Ca and Mg pools have been identified as potentially at risk of removal by WTH in aspen stands (Boyle et al., 1973; Silkworth & Grigal, 1982). Differences in the chemical composition of the overstory species present may explain why we did not see changes in Mg stocks, as the oak has approximately 53 kg ha⁻¹ less in the total tree than the average aspen value (Pastor & Bockheim, 1984; Perala & Alban, 1982; Wilhelm et al., 2013).

The soil pool values across all macronutrients are smaller (SOH 98 N, 93 P, 167 K, 1052 Ca, 175 Mg; WTH 88 N, 106 P, 135 K, 806 Ca, 169 Mg kg ha⁻¹) at 7.75 years than previously observed in the control at 1.75 years (73 N, 388 P, 295 K, 1900 Ca, 517 Mg kg ha⁻¹). The previous study collected bulk densities by soil corers in the soil pit and

by soil probe. The soil probes appear to have been used to scale the soil nutrients to kg ha⁻¹ (Rathsack, 2011). The soil probe bulk density calculations are provided within the soil pool for comparison (SOH 175 N, 134 P, 273 K, 1839 Ca, 285 Mg; WTH 137 N, 159 P, 205 K, 1203 Ca, 245 Mg). The soil pit bulk density values are plausibly more accurate and should be considered as the observed values. Small-diameter cores have been shown to introduce bias concerning the rock content and bulk density of the soil (Jurgensen et al., 2017). Given that both of the sampling methods rely on the core method, the total depth of sampling must be considered in terms of the amount of bias. Less bias is introduced in a bulk density soil corer horizontally at the soil pit face with a maximum sampling depth of 0-5cm, versus 0-8 and 8-52cm vertically.

When comparing the soil pools to other regional studies on more nutrient rich soils the values appear to be reasonably smaller given the inherent differences in the soil and different depths of sampling. Most soils are sampled at a depth less than 60cm. For a comparison, we extrapolated those values to 60cm, which is likely an overestimation of the values. The similar in texture sandy soil was sampled to 30cm and reported values after one SOH of (1,460 K, 840 Ca, 740 Mg) and (1,460 K, 220 Ca, 660 Mg) when extrapolated to 60cm (Premer et al., 2019). In comparison to the values observed in this study the K values are substantially lower, Ca substantially higher, and Mg fairly similar. In comparison with National Soil Information System (NASIS) pedon values sampled on Entic Haplorthods in northern Wisconsin the values observed in the study fall between the minimum (173 K, 567 Ca, 52 Mg kg ha⁻¹) and average values (417 K, 1656 Ca, 138

Mg kg ha⁻¹) from the weighted average up to 60cm. The maximum values (714 K, 3063 Ca, 249 Mg kg ha⁻¹) from the NASIS up to 60cm are also reported for comparison. On a loamy fine sand underlain by clay at 85cm and sampled to a depth of 61cm the exchangeable pools projected to 60cm in kg ha⁻¹ were slightly larger (N 2429 (total N), P 138, K 326, Ca 2899, Mg 388 (Perala & Alban, 1982). Similarly, in a sandy loam with a fragipan at 30cm and sampled to 30cm the exchangeable pools projected to 60cm were also slightly larger (N 6,440 (total N), P 203, K 282, Ca 1,680, Mg 236 kg ha⁻¹)(Pastor & Bockheim, 1984). Although the values observed in the study are somewhat low, they are not unreasonably low as they fall within the lower bounds of NASIS pedons and other reported values.

The differences in the woody residue 1.75 years post-harvest did not translate into differences in the nutrient budget models (Wilhelm et al., 2013). However, the magnitude of the difference of the elements in the woody debris between treatments suggests differences should exist in the nutrient budget. For example, the difference between the SOH and WTH for the average combined woody debris pools (N 53, P 21, K 149, Ca 131, Mg 32 kg ha⁻¹ yr⁻¹) is much greater than reported 1.75 year average accumulation or depletion rates (SOH 7 N, -0.02 P, 12 K, 5 Ca, 2 Mg kg ha⁻¹ yr⁻¹) and WTH (13 N, -0.015 P, 14 K, 16 Ca, 3 Mg kg ha⁻¹ yr⁻¹). The differences between woody debris by treatment are generally an order of magnitude larger than the estimated 1.75 years accumulation or depletion values (Wilhelm et al., 2013). Implicit in the input terms of the nutrient model is the assumption that the treatment variable, woody harvest residues, are immediately

and completely available within 0.5-1.75 years for mineralization and captured by a resin at 5cm and 20cm depth in the soil. The timeframe could explain why significant differences between the SOH and WTH were detected in the woody debris pools 1.75 years after harvest, but not in the nutrient budgets of the original study. The lag decomposition model equation for white oak (*Quercus alba*) FWD with diameters of 1-8 cm shows that at 1.75 years an estimated maximum volume decomposed would be 8-10% for FWD located on the soil surface and 0-11% for FWD suspended above the soil (Fasth et al., 2011). The decomposition model was developed in North Carolina and given the larger mean annual temperature it is likely an overestimate to what could be expected in northern Wisconsin. Therefore, the mineralization assay in the original study (Wilhelm et al., 2013) would have only had the potential to capture at maximum approximately 10% of the decomposition of the FWD. The definitions of terms used for the modeling of the initial observations (≤ 1.75 years) capture past management history, rather than differences between a SOH and a WTH. The decomposition models show that observations at 7.75 years will allow the FWD to have decomposed approximately 91-93% for FWD located on the soil surface and 60-86% for FWD suspended above the soil surface (Fasth et al., 2011).

There are two notable complications with the harvest model (Wilhelm et al., 2013), dealing with the size of atmospheric deposition and leaching. The deposition values reported in the original study from the growing season are generally larger than combined annual wet and dry deposition estimated from the National Atmospheric

Deposition Program (NADP) values for the same years (Appendix Table 4.A.1) (Schwede & Lear, 2014; Wilhelm et al., 2013). Calcium in particular is notable, as it is reported as 19 times higher than total deposition estimated by Schwede & Lear (2014). The N values reported in Wilhelm's study are almost twice the estimated values in 2010, but nearly equal in 2011, whereas the Mg values are 2-3 times larger (Appendix Table 4.A.1). The P values are one third of that estimated in 2010, but slightly larger in 2011 (Appendix Table 4.A.1). The underestimation of P deposition in year 2010 would mitigate the losses and change the status from depletion to accumulation. However, the 2011 P budget would still be considered in the depletion status with the updated deposition values. The leaching values were measured at 60cm, and likely still plant available. If the original leaching values are imputed from the first harvest years until the undisturbed forest values at 80 years the total lost during one rotation to leaching is (N 243, P 148, K 299, Ca 610, Mg 630 kg ha⁻¹). In proportion the imputed leaching values up to 80 years are 321% N, 29% P, 85% K, 25% Ca, 98% Mg of the observed soils pool in the original study and are likely an overestimation. Regardless of the complexities involved in modeling forest harvests and the necessity to rely on various assumptions and definitions, the reassessment of the experimental site after 7.5 years allowed for the direct measurement of the nutrient pools. Re-sampling the nutrient pools indicates significant declines the N and K pools.

4.7 Conclusion

Significant decreases in the total nutrient pool were detected for N and K when comparing a WTH to a SOH after 7.75 years in an oak dominated system. Ca is also near to being significantly lower in the WTH ($p=0.065$) and may not have been detected in the low sample size due to subsequent re-harvesting of the original experimental field sites. Although initial findings from 1.75 years after the harvest documented differences in woody debris between treatments, those values were not included directly in the nutrient budget model as the debris was assumed to be captured in the pool measuring mineralization and weathering. Decomposition models show that only approximately 10% of the woody debris would be decomposed within the first 1.75 years after harvest (Fasth et al., 2011). Revisiting the site at 7.75 years allowed for the detection of the total nutrient pool differences for N and K. The WTH has significantly less nutrients available in woody debris pools across all elements. The Ca is nearly significantly lower and could be a concern as previous research indicated that Ca is negatively impacted by WTH on coarse textured soils (Thiffault et al., 2011). The research also highlights the importance of the overstory species being harvested as Mg was not impacted in the oak context as it has been in aspen (Boyle et al., 1973; Silkworth & Grigal, 1982).

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Appendix Table 4.A.1. Average deposition values in kg ha⁻¹ for the years of 2010-2011 on the harvest intensity study site in northern Wisconsin. The values reported in the Wilhelm study generally overestimate the values in comparison to Schwede & Lear.

Year	Study	N	P	K	Ca	Mg
2010	Wilhelm et al. 2013	9.40	0.07	2.65	7.50	0.57
	Schwede & Lear, 2014	5.05	0.21	-	1.92	0.25
	W/SL	1.86	0.34	-	3.90	2.26
2011	Wilhelm et al. 2013	4.16	0.24	16.90	34.10	0.81
	Schwede & Lear, 2014	4.60	0.20	-	1.78	0.24
	W/SL	0.90	1.21	-	19.20	3.42

5 Conclusion

The whole-tree harvest removals of aspen have been shown to decrease the available potassium, calcium, magnesium pools to 180 years from 225 years in the SOH at the current input and output rates. The calcium harvest outputs exceed the typical rotation length for the soil textures observed in the field under all weathering rates. Potassium and magnesium would be sustainably harvested under the maximum weathering rates of the non-texturally adjusted soils (Kolka et al., 1996), but calcium is still overharvested. The major limitation of the outwash soils fertility is the large amount of sand and smaller cation release rates (Kolka et al., 1996). The major source of cations in the outwash soils is derived from the aeolian mass and when that source is depleted the remaining particles will weather at a stable rate (Kolka et al., 1996). If harvests were to continue to a point that yields were impacted, the system could function like a barrens and harvest removals could be decreased. If the harvest removals are the desired management goal the input terms to the budget should be increased. Wood-ash has long been reported as a potential solution to cation depletion in coarse textured and acidic soils (Augusto et al., 2008). Future research could focus on identifying the age of the aspen in which the greatest return on investment is identified for applying the woodash. Since the coarse textured soils are susceptible to leaching losses it is appropriate to identify the age in which the aspen can take the most advantage of the increased cation availability.

The harvest intensity experiment showed significant declines in total nitrogen and potassium pools after one WTH in comparison to the SOH. Calcium showed weaker

evidence for significant declines from the WTH ($p=0.065$), and the phosphorus and magnesium were not significantly different. These findings have begun to capture the signal of the original experiment. The original experiment identified the significant differences in woody debris between the SOH and WTH but resulted in phosphorus being depleting across harvest types. After 7.75 years of decomposition we detected significant differences in nitrogen and potassium from the WTH on a sandy outwash soil.

Textural partitions were created from the NCSS pedon database for the soils in the partially restricted soil complex which was best delineated by habitat type. These findings correspond to the development of the original classification system which found strong relationships between soils and herbaceous species (Kotar, 1986). The division in habitat type was found between white pine and sugar maple as the terminal species in the climax community. The second-best performing model provides a means to identify the location remotely using the deviation from mean elevation and moisture stress index values. The deviation from mean elevation detects the underlying topographic relationships between the moraine and outwash soils, and potential erosion events with the non-restricted soil at lower deviation from mean elevation values and confirmed by trees less stressed for moisture in the index. Habitat type information can be used for confirmation when available. Future research could use finer DEMs to ask the same question from the data labels obtained in this study. We expect the radius of the relative elevation to be somewhere near the 1300-2000m radii found herein, since the underlying topographic relationships between the moraine and outwash will not change.