Impacts of woody biomass harvesting on saproxylic communities, nutrient availability, and productivity in aspen ecosystems

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EXECUTIVE SUMMARY

Although woody biomass represents a clean, renewable energy source, concerns have been raised regarding the ecological impacts of increased woody biomass extraction from Minnesota's forests. In particular, the Biomass Guideline Committee appointed by the Minnesota Forest Resources Council (MFRC) recently identified several key knowledge gaps regarding the impacts of biomass harvesting on critical ecosystem components, including deadwood dependent organisms, native plant communities, and nutrient availability. Understanding these impacts, as well as potential site-level management practices for protecting these ecosystem components are crucial for developing biomass harvesting guidelines that ensure the ecological sustainability of Minnesota's forests.

This report will cover:

1). The implementation of a large-scale, silvicultural experiment that was established in the winter of 2010 to assess the ecological impacts of different levels of woody biomass harvesting and evaluate the importance of site-level legacies (green trees and harvest residues) in maintaining the resiliency and sustainability of these systems. This project has provided the needed framework and baseline data to look at the role of fine and coarse woody debris and green trees in maintaining native biodiversity and ecosystem productivity in aspen-dominated ecosystems.

2). The progress of subsequent publications based on this research effort.

KEY FINDINGS and PRELIMINARY RESULTS

This research addressed the following objectives related to the immediate and long-term ecological impacts of biomass harvesting and the roles biological legacies play in mitigating these impacts in aspen systems:

1. **Impacts of biomass harvesting on fungal and saproxylic animal communities, forest regeneration and productivity, nutrient availability, and carbon**

Biodiversity of saproxylic fungal communities

- A total of 2 358 polyporoid fungi occurrences, representing 86 unique species, were recorded on 16 host tree species.
- Aspen-dominated forests support a species-rich community of polyporoid fungi, including potentially rare species. Three species (*Funalia trogii*, *Pycnoporellus fulgens*, and *Skeletocutis chrysella*) have red-listed status in northern Europe as rare or threatened species. One additional species, *Rigidoporus crocatus*, is potentially rare in North America.
- Tree species (*Betula papyrifera* and *Acer spicatum*) were the most influential deadwood host influencing polyporoid species occurrence. However, the presence of small diameter substrates (branches) and decay class were also important in structuring the polyporoid species community.
    - Overall, there were very few occurrences of polyporoid fungi on large diameter or well-decayed substrates, which have been shown to be an important substrate for rare polyporoid species in northern Europe.

Biodiversity of saproxylic amphibian and vertebrate animals

Presence of small mammals and amphibians was related to harvested conditions versus slash levels:

- Negative harvest effects: wood frog, short-tailed shrew
- Positive harvest effects: American toad in clearcuts, , shrew species (*Sorex* spp.), meadow vole at Melrude site.
- Long-term monitoring will critical for assessing role of slash and leave-trees in affecting these populations over time

Productivity – Medium term impacts on tree regeneration and soils –results from a Long term Site Productivity Study

Evaluation of three LTSP experiments for medium-term impacts of biofuels harvests on forest site productivity suggest slash removal impacts vary by soil type. Over all, results indicate that the impacts of biomass harvests are persistent even after 15 years and may influence the sustainability and resilience of aspen-dominated forest communities in the future, particularly on less productive sites.

- +/neutral on clay and loam soils
- Negative on sandy soils

2. **The influence of site-level management factors on the resiliency and sustainability of forest ecosystems. To what extent does retention of green tree legacies and harvesting residues (slash) ameliorate the impacts of biomass harvesting? Specifically how did residual trees and residues influence future status of nutrient pools?**

Green tree and slash retention impacts on carbon and nutrient stocks

- Slash-retention had a significant effect on post-harvest biomass and carbon stocks within total ecosystem components and woody debris.
- Green-tree retention and the interaction between these two factors did not have a significant effect on post-harvest biomass, carbon, and nitrogen stocks within total ecosystem components and woody debris.
- High levels of post-harvest FWD biomass existed regardless of slash retention treatment.
- The soil pool generally represented the largest proportion of C and N on site.
- The forest floor and root stocks represented the largest pools of N within biomass (i.e., excluding soil).
- In terms of nutrients, it is possible that the mineral soil may contain large enough stocks of C and N to mitigate any effect of harvest on future productivity. However, the relatively large pools of nutrients in FWD, forest floor, and roots suggest that removing or disturbing these pools could potentially impact future site productivity.
- Maintaining pools of FWD, forest floor, and roots could possibly lessen the impact of intensive biomass harvesting on site nutrient stores and subsequently on future site productivity.

Fate of green - tree retention

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Section I. MFRC Biomass Project

STUDY DESIGN and METHODS

Sites and treatment layout

Study sites were located in St. Louis County, Minnesota, U.S.A. near the towns of Independence, Minnesota (47° 0' N, -92° 24' W); Melrude, Minnesota (47° 15' N, -92° 19' W); south of Orr, Minnesota (48° 1' N, -92° 59' W); and north of Orr, Minnesota (48° 9' N, -92° 59' W) and were named Independence (IND), Melrude (MEL), Pelican Lake (PL), and Lost River (LR), respectively. Elevations at these four sites ranged from 395 – 428 m with slopes between 0 – 8%. Soils generally consisted of loams derived from till. Soils at IND consisted of stony to very stony loams and sandy loams while soils at MEL, PL, and LR were silt loams and loams. The climate of the study area is continental with a mean temperature of -16°C in January and 26°C in July. Mean annual precipitation ranges between 660 – 710

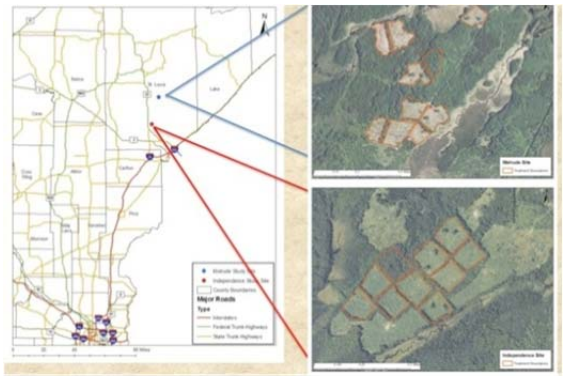


Figure 1. Study location and layout

mm, about 75% of which occurs between the months of May and October.

Stands were mesic and generally hardwood dominated, most notably by *P. tremuloides*. Other prevalent hardwoods included *Betula papyrifera*, *Acer rubrum*, and *Fraxinus nigra*. In addition, commonly occurring softwoods included *Abies balsamea*, *Picea mariana*, and *Picea glauca* with occasional *Thuja occidentalis* and *Pinus strobus*. The stands originated from clearcutting and ranged in age from 55 to 68 years. In addition, a few scattered trees were removed from MEL in 1999 following a windthrow event. Site index for all four sites ranges from 22 to 24 m at 50 years for *P. tremuloides*.

Sites of approximately 40.5 ha each were selected for harvest. Harvest treatments were organized in a randomized complete block design and replicated across four blocks (IND, MEL, PL, and LR).

Treatments were designed to examine the effects of two factors, slash-retention and green-tree retention, each comprised of three levels including 0%, 20%, and 100% slash retention and no, dispersed, and aggregate green-tree retention. Dispersed green-trees were prescribed with a density of approximately 15 – 30 trees/ha and 21 m spacing across designated stands. For aggregate green-tree retention, two roughly square or rectangular clumps with area approximately 0.1 ha each were located within designated stands. Dispersed and aggregate green-tree retention and 20% slash retention were all based on recommendations within the Minnesota biomass harvesting guidelines (MFRC, 2007) and were included in this study to examine their impacts on post-harvest stand conditions. Each block was setup in a 3X3 fully factorial design plus an unharvested control resulting in ten stands per block, each approximately 4.1 ha in area. Slash-retention of 20% and dispersed and aggregate tree retention were based on current biomass harvesting guidelines from the Minnesota Forest Resources Council (MFRC 2007). Each treatment area is a minimum of 4-hectares and harvests were implemented over the winter of 2010 (February).

1. Impacts of biomass harvesting on fungal and saproxylic animal communities and forest productivity

Fungi - Site selection and sampling

Four sites (IND, MEL, LR and PL) in northern Minnesota were sampled for wood-inhabiting polyporoid fungi during late September and early October in 2009 and 2010. The sampling scheme consisted of thirty 400 m^2 circular plots (radius = ~11.3 m) distributed across each of the four sites, resulting in 120 total plots sampled. All fine and coarse woody debris (FWD and CWD, respectively), along with standing trees (living or dead, to a height of two meters) within each 400 m^2 plots were non-destructively inventoried for polyporoid fruiting bodies during late September and October of 2009 or 2010. All substrates with a diameter ≥ 1 cm were sampled regardless of length. When a fruiting body was encountered, the following characteristics were recorded: fungal species (when known; see below for unknowns), substrate type (branch, log, suspended log, snag, stump, and living tree), substrate species, diameter class (1- <5, 5- <10, 10- <15, 15- <20, 20- <25, and >25 cm), and decay class (following the five-class system of Maser *et al.* [1979]). Dead fruiting bodies were also inventoried, unless their state of degradation precluded identification. Inventories were conducted during early fall to ensure detection of those species producing annual fruiting bodies. This sampling detail and intensity is comparable to similar studies in Scandinavia (see Junninen & Komonen 2011). Sampling was carried out by three people, together working until all polyporoid fungi occurring on substrates with a diameter ≥1 cm were sampled per plot, which on average took 30 minutes.

Polyporoid species identification

For fungal species not easily identified in the field, a sample of the fruiting body was collected and dried before being returned to the laboratory. Samples were identified by either microscopic analysis of morphological features or DNA sequencing of the internal transcribed spacer (ITS) or nuclear large subunit (nLSU) regions. In addition, voucher specimens of some common polyporoid species were also collected to generate reference sequence data. All DNA extractions, PCR, and sequencing protocols were carried out as described in Lindner & Banik (2009). The Basic Local Alignment Search Tool (BLAST) was used to search for similar sequences in GenBank (Altschul et al. 1997) to identify unknown isolates, using a 97% similarity threshold for species-level identifications. For isolates that could not be matched to known species in GenBank, molecular operational taxonomic units (MOTUs) were designated using the program jMOTU (https://nematodes.org/bioinformatics/jMOTU/). The jMOTU program uses the Needleman-Wunch megablast search algorithm to align sequences, then user-defined parameters to designate MOTUs. Within jMOTU, the minimum sequence length used for analysis was set at 300 base pairs (bp) to eliminate short sequences, and MOTUs were designated at 3% sequence divergence. Because of intraspecific variation and the large number of indels present within the ITS region, a low BLAST identity filter was set at 90%, and the default sequence alignment overlap (60% of the minimum sequence length) was used.

Once unknown isolates were grouped into MOTUs, phylogenetic analyses were performed using sequences representing the most closely related species for comparison, as determined from the original BLAST search. Sequences were aligned with MAFFT v. 6 using the FFT-INS-i option (Katoh *et al.* 2005), and phylogenetic reconstruction of ITS and partial nLSU sequences was performed in MEGA v. 5 (Tamura *et al.* 2011) using methods described in Brazee *et al.* (2011). The use of molecular diagnostics greatly increased our accuracy in identifying both rare species and common species exhibiting high phenotypic plasticity. The use of morphological features alone would likely have resulted in a reduced number of uncommon and rare species identified. Polyporoid nomenclature was based on Index Fungorum (www.indexfungorum.org) with exceptions, and collected specimens have been preserved in the USDA Forest Service, Center for Forest Mycology Research (CFMR) herbarium.

Fungi data analyses

One of our primary objectives was to characterize the polyporoid species community, including the sources of variation, found within aspen-dominated forest systems. Therefore, we conducted a non-metric multidimensional scaling (NMS) ordination in PC-ORD v. 6.0 (McCune & Mefford 2011), using the Sørensen distance measure and random starting coordinates. Two frequency matrices were used for

analysis, with the primary matrix composed of polyporoid species (columns; $N = 57$) by plots (rows; $N = 120$) while the secondary matrix was composed of deadwood variables (columns; $N = 27$) by plots. To down-weight the influence of very abundant polyporoid species, a general relativization by column totals was used to transform the polyporoid species matrix. In addition, polyporoid species with less than three occurrences (29/86 species) were excluded from the analysis. The percent variance explained in the distance matrix was calculated using the Sørensen measure, and the two axes with the highest increment R^2 were selected to best describe the data. To determine the significance of the deadwood variables and polyporoid species that were structuring the NMS axes, bivariate correlations using Kendall's tau-b were performed in SPSS 16.0 (SPSS Inc., Chicago, IL), with a sequential Bonferroni correction set at $P = 0.05$ (Holm 1979).

To further assess the relatedness of the polyporoid communities by plot, we carried out an analysis of nestedness using the equations developed by Brualdi and Sanderson (1999) and Jonsson (2001). A determination of nestedness would indicate that uncommon polyporoid species are more likely to be found in species-rich plots, an important consideration for conservation efforts. In PC-ORD, the Nestedness6 application was run using all 86 species from 120 plots with 1,000 randomizations. If the observed nestedness (N_a) equals zero, then nestedness equals the random expectations from a null population. A negative value indicates the population is more strongly nested, while a positive value indicates the population is more weakly nested compared to a random sample.

To determine how polyporoid species richness changed by each of the four deadwood variables (substrate, substrate type, diameter class, and decay class); we generated species accumulation curves (SACs) using rarefaction equations developed by Sanders (1968) and modified by Hurlbert (1971). SACs were generated in R (www.R-project.org) and details regarding the equations used have been described previously in Lindner *et al.* (2006). For substrate species, we generated curves with and without *Populus tremuloides*, so that we could better interpret the curves of the less abundant, non-aspen hosts.

In order to determine how similar the polyporoid communities were by each of the four deadwood variables, a presence/absence matrix of polyporoid species (rows; $N = 86$) by deadwood variables (columns; $N = 26$) was created. The Sørensen similarity index, for which joint absences are excluded from consideration and matches are double weighted, was used to create the distance matrices. The Sørensen measure was also performed in SPSS.

Amphibian and small mammal sampling

Environmental variables

Harvest type (i.e., harvest vs. control) and green tree reserve type (i.e., none, dispersed, clumped) for each of the 10 plots at a given site were recorded at the beginning of the study. Green tree reserves followed Minnesota Forest Resources Counsel guidelines for dispersed (6-12 per acre) and clumped (two 0.25 acre clumps per treatment) reserve type. Several additional metrics were recorded during every visit to each sampling location: start time, temperature (i.e., soil surface and soil at 15 cm), soil moisture, and survey method (drift fence vs. visual search). Soil surface temperatures were recorded using an Extech IR Thermometer & Humidity Meter (Model: RH101) and soil temperature at 15 cm was recorded using an analog soil thermometer. Volumetric water content (i.e., soil moisture) was recorded with a Field Scout Soil Moisture Probe (Model: TDR 200). Daily high and low air temperatures and daily totals of precipitation were acquired from a local weather station located within 15km of each site (47.16539° N, 92.41526° W; Station 211840).

The volume of CWD was estimated for each of the 10 plots per site using the formula:

$$V = (\pi^2 \times \sum d^2 \div 8L) \times 10000$$

where V is the volume (m^2 / ha), d is the diameter of CWD (m), and L is the transect length (m) (adapted from: Van Wagner, 1968). We estimated the volume of CWD on each of the 10 plots at each site. Measurements were taken at four random locations (same locations as each of the two drift fence arrays and time- and area-constrained quadrats), each with a transect length of approximately 45m (i.e. 180m per plot) using four Y-shaped transects consisting of three 15m wings. CWD debris was defined as woody materials ≥ 5cm in diameter and ≥ 10cm in length.

Vertebrate sampling

Sampling occurred on nine experimentally manipulated plots and an untreated control at each of the southern two study sites IND and MEL (for this section referred hereafter as "Site-1" and "Site-2") There are a variety of accepted standard techniques for sampling amphibian and small mammal species including but not limited to box-traps (e.g., Sherman Traps), snap-traps, and pitfall traps (with and without drift-fence arrays), visual encounter surveys, and cover board arrays (Heyer et al., 1994; Wilson et al., 1996). All nine plots and the control were sampled using drift-fence arrays for small mammals; with both drift-fence arrays and time- and area-constrained searches for amphibians. Each drift-fence array and time- and area-constrained search quadrat area were randomly placed at least 15m from the

edge of the treatments to minimize edge effects, and at least 50 m from each, other using ArcView (v.9.0; ESRI) with the third party Hawth's Analysis Tools extension. Sampling for amphibians and small mammals occurred during three discrete occasions from mid-June to mid-August 2010, consisting of 8, 10, and 9 consecutive days respectively. Approximately 14 days separated each of the three sampling periods.

After capture, small mammals were identified to species, and if alive, a single mark was placed on the underside of the tail for small mammals or near to facilitate the quick and easy identification of previously marked individuals. Amphibian species were marked using a marking system corresponding to the sampling period in which they were captured, allowing groups of individuals marked during each of the three sampling periods to be distinguished from each other (Fig. 2). Individuals also received a plot-specific toe-mark, allowing the detection of between-treatment movements. Recaptured individuals found during subsequent sampling periods were given an additional mark in the location corresponding to the sampling period in which it was recaptured. At the end of the 2010 field season individuals had up to three sampling period-specific marks and a single plot-specific mark corresponding to their original capture location. Both amphibians and small mammals were marked using visual implant elastomer (hereafter VIE; Northwest Marine Technology, Inc.; see: Nauwelaerts et al., 2000), after which they were released approximately 15m from the site of capture. Using VIE to mark amphibians is an accepted technique that has a significantly higher mark retention rate when compared to standard toe clipping practices (Davis and Ovaska, 2001). At least one study has observed individual salamanders (*Eurycea spelaea*) with visible VIE marks ≥ three years post injection (Dante Fenolio, Atlanta Botanical Garden, pers. comm.).

Figure 2. Visual implant elastomer (VIE)

Incidental visually encountered amphibian species not previously captured in drift fence arrays or time- and area-constrained searches were noted and included in treatment and site-level species richness estimates, but were not marked, and were excluded from all other analyses. Aural data for anuran were excluded from all comparisons and analyses.

Time- and area- constrained searches - Heyer et al. (1994) recommended that searches be conducted within 8m x 8m quadrats, allowing for easier comparison between studies. Following this recommendation, two 8m x 8m quadrats were randomly placed in each survey plot. Six time- and area-constrained searches were performed in each plot, two per plot per sampling period. These searches

consisted of 20 person-minutes of searching per quadrat for a total of 120 person-minutes per plot per year. Low-impact visual searches (i.e., replacing objects to original positions) were conducted within each quadrat to allow for repeated sampling. Quadrats were typically sampled before 1200 hours or during preferred weather conditions (e.g., overcast skies, light rain, and/or cool temperatures) to maximize the probability that amphibians would be above-ground.

Drift fence arrays - Drift fence arrays were constructed using 90cm wide silt fencing, which was partially buried so that approximately 75cm was above ground. An array consisted of three wings, each approximately 7m long and spaced 120° from each other, with dark blue 19L buckets for the pitfall traps (Fig. 3; see: Gibbons and Semlitsch, 1981; Crawford and Kurta, 2000). These larger diameter pitfall traps have been shown to be more effective than the smaller diameter pitfall traps typically used in amphibian studies (Friend et al., 1989). Pitfalls were filled with approximately 2-4cm of water, and a flat rock and/or sponge to protect amphibians from desiccation and reduce the possibility of small mammal escapes. Each plot was sampled using two drift fence arrays that were opened during each of three sampling periods. Pitfall traps were checked every other day due to the large size of sites, number of pitfall traps installed, and personnel limitations. Buckets were closed with secure fitting lids when not in use.

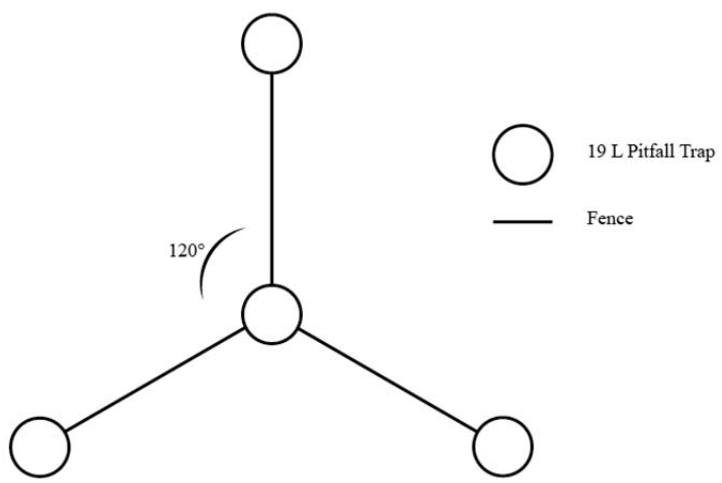


Figure 3. Conceptual diagram depicting the drift-fence array

Amphibian and Small Mammal Data Analyses

Given the high mortality rates associated with small mammal pitfall trapping and relatively low sample sizes for many of the amphibian and small mammal species encountered, the initial capture data (i.e., excluding recaptures) from drift-fence captures was used as an index of amphibian and small mammal relative abundance (Menkens and Anderson, 1988). Index of body condition for the two species of amphibian with ≥ 50 captures were developed using "gape width" (Rogers, 2009) and mass to compare the effects of harvest on body condition during the study (methods reviewed in: Schulte-Hostedde et al., 2005). Time- and area-constrained search encounters and incidental observations were included for site-level comparisons (e.g., site-level species richness comparisons), but excluded from analyses used to

model the response of captures vs. treatment effects and covariates. Shrew species (*Sorex* spp.) captured in drift fence arrays were pooled for regression analyses because of difficulties in identification and to allow easier comparison to studies using higher taxonomic rankings for analyses (e.g., soricids).

Using the software package R (v 2.14, 2011), the distribution (i.e., normal, Poisson, or negative binomial) of the individual species daily count data was investigated. These initial investigations indicated that data were both over-dispersed and contained excess zeros. Because of this, and partially due to the difficult nature of running generalized linear mixed models following a negative binomial distribution in R, capture data were aggregated across days into the 3-decrete sampling periods outlined in the survey methods. This greatly reduced the zero-inflation present in these data (Tu, 2002), and these aggregated data more closely followed a Poisson distribution. Several *a priori* models were tested for each of the amphibian and small mammal species (or species groups) with sample size ≥ 50 (Appendix B, Table 1) using generalized linear mixed models (GLMMs) in R with the 'lme4' package (Bates et al., 2011). Full models considered several fixed effects as well as a single random effect of "Plot" to better account for between plot variability and repeated measures (Appendix B, Table 2). All models included either "Harvest" (i.e. harvested vs. un-harvested control) or "Treatment" (i.e., green tree retention level vs. un-harvested control) as fixed effect parameter(s) because of the important biological and experimental relevance (i.e., all models include a 'Harvest' parameter regardless of statistical support or a 'Treatment' parameter when supported by AIC). The Akaike information criterion (AIC; Burnham and Anderson, 2002) was used to evaluate model support as it corrected for small sample sizes (i.e., AIC_c). The unsupported fixed-effect parameters were removed one by one until either all-remaining parameters were supported statistically and/or until models were penalized via an increase in AIC_c. All models, especially those within 2 ΔAIC of the top-performing model, were examined for uninformative parameters and these models were dismissed in favor of simpler and better-supported (i.e., lower AIC_c) models (Arnold 2010).

Tree regeneration and soil productivity (Long Term Soil Productivity)

The USDA Forest Service established the Long-Term Soil Productivity (LTSP) study in the early 1990's to examine effects of organic matter removal (slash retention) and compaction on productivity in a variety of forest ecosystems (Powers et al. 2005). The LTSP network covers a broad expanse of conditions and ecosystem types, including affiliated sites in Canada. The study investigates two primary factors, each with three levels. Organic matter removal treatments included bole only harvest (MBH), total tree harvest (TTH), and total tree harvest plus forest floor removal (FFR). Compaction treatments consisted of no additional compaction (C1), moderate compaction (C2), and heavy compaction (C3). We focused on three installations of the LTSP study within aspen forests in Minnesota in Michigan (Table 1).

While designed and implemented nearly two decades ago, the LTSP study provides information relevant to objective 1 of this research report. Two of the organic matter removal harvests, bole only harvest and total tree harvest, created conditions comparable to the extreme slash retention treatments recently implemented in the portion of this research funded in part by the MFRC (all slash retained and all slash removed, respectively). Data from three installations of the larger LTSP study provide the opportunity to examine how above-ground biomass production varies in response to extreme slash retention treatments in aspen-dominated forests of the upper Lakes States region (Figure 4). Additionally, while aspen dominates the canopy at all three sites, the soil texture, climate, and composition of non-aspen species differ among sites (Table 1). So, we were able to assess and compare medium-term impacts of total tree and bole only harvest in aspen-dominated forests with clay, loamy, and sandy soils 15 years following treatment.

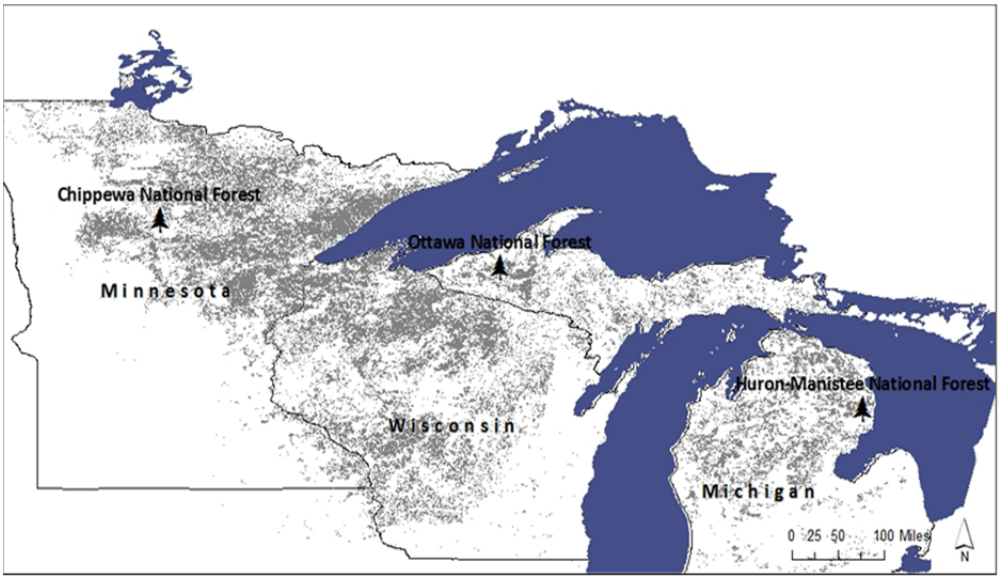


Figure 4. Study site locations for the LTSP study

Table 1. Characteristics of the Long-term Soil Productivity (LTSP) study sites within the Lake States region

Location	Elevation (m)	Precipitation (cm/yr)	Soil origin	Soil texture	Site index (m)[a]
Chippewa National Forest (MN)	410	64	loess/till	loamy	23
Ottawa National Forest (MI)	350	77	lacustrine clay	clay	17
Huron-Manistee National Forest (MI)	240	75	outwash sand	sandy	19

[a] Corresponds to trembling aspen (*Populus tremuloides*) at each site at base age of 50 years.

Field Methods and Analysis

The two factors, organic matter removal and compaction, were crossed using a factorial design resulting in nine different treatments per site (Figure 5). Each treatment was applied to 50 m X 50 m treatment plots and replicated three times at each site. Within each treatment plot, 40 m X 40 m sampling plots were established for measuring density, volume, composition, and biomass of woody and herbaceous regeneration. Data used in this analysis were collected 5, 10, and 15 years post-harvest.

Errors in implementation at the Ottawa site resulted in an unbalanced treatment design. Rather than having three replicates of each treatment as at the other sites, the moderate-compaction total tree harvest (C2/TTH) was applied to five plots, the moderate compaction bole only harvest (C2/MBH) was applied to two plots, and the heavy compaction/bole only harvest treatment (C3/MBH) was applied to only one plot.

This analysis includes data from three different LTSP sites each containing three replicates of each factorial combination (treatment) measured repeatedly over time. Accordingly, mixed-model repeated-measures analysis of variance (ANOVA) was performed using SAS software to examine medium-term treatment effects on productivity (SAS institute, 2008). Each site was analyzed separately. Type III sums of squares was used to account for the unbalanced design resulting from treatment implementation errors at the Ottawa National Forest LTSP installation.

Soil Compaction	Organic Matter Removal: Merchantable Bole Harvest (MBH)	Total Tree Harvest (TTH)	Forest Floor Removal (FFR)
Light (C1)	C1 X MBH	C1 X TTH	C1 X FFR
Moderate (C2)	C2 X MBH	C2 X TTH	C2 X FFR
Heavy (C3)	C3 X MBH	C3 X MBH	C3 X FFR

Figure 5. Treatment design (3x3 factorial) for LTSP study 1

2. Harvesting residues and green tree legacy impacts on carbon and nutrient stocks

Carbon and Nutrient Sampling

This portion of the study examined the effects of slash retention and green-tree retention following biomass harvesting on site carbon and nutrient stocks. Specifically, harvest treatments including slash-retention levels of 0%, 20%, and 100% crossed with no, dispersed, and aggregate green-tree retention were applied at the four sites. The objectives of this study were to determine the changes in biomass and nutrient stocks within these harvested sites by analyzing empirical data from pre- and post-harvest field measurements for the various biomass harvesting scenarios applied on site. Moreover, were interested in determining how residual trees and residues might influence future status of nutrient pools.

Prior to harvest, six permanent, circular plots with area 0.04 ha were located within each stand for repeated measurements and sampling (Fig. 7). Each plot was randomly located within one of six approximately equal areas of the stand. Plots were selected such that basal area of aspen (*Populus tremuloides*) was determined to be >40% by sighting stems through a wedge prism. In addition, plot centers were located >20 m from stand boundaries, clump boundaries, all other plots, and wetlands; >10m from any roads or trails; and with no man-made cuttings or large man-made debris within plot boundaries. Plots within stands prescribed with aggregate green-tree retention were setup roughly within the middle of the retained clump and plot boundaries were within clump boundaries.

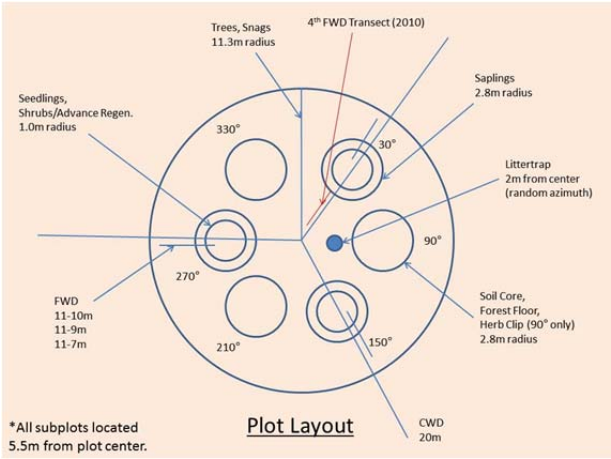


Figure 7. Carbon and nutrients plot layout

Field-methods

Measurements and sampling of a number of forest components were conducted in order to best capture the effects of each treatment on biomass, C, and N pools within stands. These forest components included large woody stems (trees), smaller woody stems (saplings and woody shrubs/advance regeneration), litterfall (for nutrient analyses), fine woody debris (FWD), coarse woody debris (CWD), herbaceous vegetation, forest floor material, mineral soil, fine roots, and coarse roots (for nutrient analyses). Each of these components were measured both pre- and post-harvest during the summers of 2009 and 2010.

Woody vegetation

Diameter at breast height (DBH) was measured and recorded for all large woody stems (trees) ≥10 cm DBH within the full area of each main plot. In addition, species, living or dead status, and snag height were recorded for each tree. Smaller woody stems (saplings, shrubs/advance regeneration) were measured within three circular subplots located at azimuths of 30°, 150°, and 270° with centers located 5.5 m from main plot center. Subplots for saplings were 25 m^2 in area while subplots for shrubs/advance regeneration were 3.14 m^2 in area. Saplings included all woody stems ≥2.5 cm and <10 cm DBH. Measurements for saplings included DBH, species, living or dead status, and snag height. Shrubs/advance regeneration comprised all woody stems >15 cm height and <2.5 cm DBH. Measurements for shrubs/advance regeneration included species and stem diameter at 15 cm height. In addition, dead shrubs/advance regeneration were measured within the same sampling area as live stems except only at azimuth 270° within each plot. Diameter at 15 cm height was the only metric recorded for dead shrubs/advance regeneration.

Downed woody debris (CWD & FWD)

Sampling for both downed CWD and FWD was based on the line-intercept method as described by Brown (1974). CWD included all logs >7.5 cm in diameter and was measured along 20 m transects originating from plot center at azimuths of 30°, 150°, and 270°. Measurements included species and decay class based on a 5-class system of decay as described by Sollins (1982). Following harvest, manipulations to the levels of woody debris on plots designated with no slash retention and not within aggregate clumps were conducted at all sites to better reflect the prescribed level of retention. Specifically, slash from trees felled during harvest that were >7.5 cm in diameter, as measured at the base of each branch, and within a 20 m radius of plot center were moved outside the 20 m radius and, therefore, were not tallied for analyses.

Smaller diameter FWD was tallied within three size classes (≤0.6 cm, >0.6 cm to ≤2.5 cm, and >2.5 cm to ≤7.5 cm) along 1 m, 2 m, and 4 m transects, respectively, all located along the three larger CWD transects. A fourth FWD sampling transect was added to the larger 20 m transect located along the 30° azimuth for post-harvest measurements in order to better capture variability within FWD. In summary, for measuring FWD, three sampling transects existed pre-harvest and four sampling transects existed post-harvest where a sampling transect consisted of one set of 1 m, 2 m, and 4 m transects.

Herbaceous vegetation, Forest floor, Mineral soil, & Roots

Samples of litter-fall, herbaceous vegetation, forest floor, mineral soil, and fine roots were also collected for quantifying the size of these pools and for further laboratory analysis of nutrient concentrations within the materials. Litter-fall was collected at each plot in 45 cm diameter circular litter-traps with centers located 2 m from plot center at a random azimuth. Litter-traps were placed in the field before leaf-out in the spring and were collected following leaf-off in autumn of each sampling year. Samples of herbaceous vegetation, forest floor, and soil were taken from within subplots with centers located 5.5 m from main plot center. Herbaceous vegetation was clipped and collected within a 15 cm diameter ring at an azimuth of 90° within each plot. Forest floor was sampled within a 15 cm diameter plastic ring in subplots located at azimuths of 90°, 210°, and 330°. Depth of forest floor material was recorded within the plastic ring prior to removal. Forest floor included all dead material to the surface of the mineral soil and excluded any woody debris. Mineral soil cores of 6.35 cm diameter and 20 cm depth were collected at 90°, 210°, and 330° within the same sampling area as forest floor. Soil samples were divided into two classifications by depth for further analyses (0 to 5 cm, 5 to 20 cm depth). Fine roots with diameter ≤5 mm at the large end and coarse roots with diameter >5 mm were removed from soil samples dried and weighed.

Biomass Calculations

Oven-dry biomass estimates of both living trees and saplings were calculated using allometric biomass equations based on DBH from Jenkins et al. (2003). Equations were specific to hardwoods and softwoods and were further specific to wood type. In addition to calculating total biomass for each tree or sapling, ratios of each tree component provided by Jenkins et al. (2003) were used to calculate biomass estimates of the specific components of each tree. Oven-dry biomass estimates of dead trees and saplings were calculated using the same equations from Jenkins et al. (2003). However, these dead stems were assumed to have no foliage and so this component was excluded from all biomass estimates of dead stems. In order to calculate stem biomass of snags, stems were assumed to be a paraboloid and volume was calculated by an equation from Duvall (1997) using DBH and snag height. Estimates of snag bark biomass were not included in estimates of total snag biomass since snag biomass was derived from the volume of a paraboloid with no means of including bark. In order to derive mass of each dead tree and sapling, specific gravities of wood from Harmon et al. (2008) were converted to density and multiplied by the calculated volume to determine mass of each dead stem. Coarse roots of dead stems were calculated from Jenkins et al. (2003) and were added to stem biomass estimates to create estimates of total snag biomass. Since no decay states were recorded for dead stems, all densities were assumed to be within decay class 1 as defined by Harmon et al. (2008). Thus, estimates of dead tree and sapling biomass are

likely overestimates of actual biomass, even with bark excluded from snag biomass, as stems are not exactly paraboloids in volume and were likely further decayed than was assumed. To account for coarse roots following harvest despite the removal of stems during harvest, all pre-harvest coarse root stocks were assumed to exist post-harvest. Therefore, post-harvest coarse root stocks are equal to pre-harvest coarse root stocks.

Stocks of biomass within total post-harvest woody debris were split into five size classes for analysis within each size class. Specifically, FWD was divided into the three size classes as measured in the field (≤0.6 cm, >0.6 cm to ≤2.5 cm, and >2.5 cm to ≤7.5 cm) representing 1-, 10-, and 100-hr burning times, respectively. These size classes have been referred to as FWD-S, FWD-M, and FWD-L, for the small, medium, and large size classes of FWD, respectively. In addition, CWD was divided into two size classes, un-merchantable (CWD-U, >7.5 cm to <22.5 cm) and merchantable (CWD-M, ≥22.5 cm) sizes representing stems that were too small to be sawlogs (i.e., minimum pulpwood diameters) and those of sawlog size, respectively.

Oven-dry biomass estimates for shrubs/advance regeneration were calculated using allometric biomass equations from Perala & Alban (1993) based on diameter at 15 cm height. Allometric equations were specific to species with the exception of dead stems which had a single allometric equation specifically for all dead material. Equations were specific to components of shrubs/advance regeneration including foliage, stems, and roots. Combining estimates of foliage and stems of these components resulted in total biomass for each particular shrub/advance regeneration stem measured. Roots of shrubs/advance regeneration were accounted for in fine root stocks as described below.

Estimates of CWD and FWD biomass were calculated using equations for volume from Brown (1974) and densities derived from Harmon et al. (2008). Volume estimates were multiplied by densities to obtain mass estimates. Estimations of mass for herbaceous vegetation, forest floor, and mineral soil were calculated by dividing oven-dry mass measurements from the laboratory and sampling area as measured in the field and then scaled to the appropriate level (Mg/ha or kg/ha).

Nutrient Analyses and Calculations

Nutrient analyses were conducted on a number of sampled components in order to better assess the impacts of each treatment on post-harvest carbon and nitrogen pools. Specifically, litter-fall, herbaceous vegetation, forest floor material, coarse and fine roots, and mineral soil were all analyzed for percent total carbon and nitrogen. These values were then used to determine the total amount of carbon and nitrogen within each respective pool (i.e., foliage, herbaceous vegetation, forest floor material, coarse

and fine roots, and mineral soil) of the harvested stands. All values utilized for calculating pre- and post-harvest carbon and nitrogen amounts were from samples collected pre-harvest. The exception to this was mineral soil which was from both pre-harvest and post-harvest samples and was used to calculate the corresponding pre-harvest or post-harvest nutrient total. All samples analyzed for nutrient concentrations were dried at a temperature of 65 – 75°C until a constant mass was reached and were then ground and homogenized in Wiley mills. Percent total carbon and nitrogen was determined by use of a LECO Truspec CHN Macro analyzer (LECO Corporation, St. Joseph, Michigan).

Nutrient concentrations of FWD and CWD were obtained from a separate study conducted within the same harvest sites and surrounding forests of this study. Nutrient concentrations for woody debris were determined by sampling material from *Abies balsamea*, *Acer rubrum*, *Betula papyrifera*, *Fraxinus nigra*, and *Populus tremuloides*. In addition, these species were sampled across a range of decay classes for both FWD and CWD. Nutrient concentrations were used to calculate nutrient totals for FWD and CWD and were applied to specific decay classes.

A total of 240 litter-fall samples were collected with one sample representing one plot. Nutrient values from each plot were used to calculate total nutrients in foliage from that plot. A total of 240 herbaceous vegetation samples were collected, one from each plot, and were homogenized by stand. Therefore, nutrient totals for each stand were calculated using the homogenized herbaceous vegetation nutrient concentrations from each respective stand. A total of 720 forest floor samples were collected across all four sites. Three sub-samples were collected within a plot and homogenized to represent that single plot resulting in 240 total, homogenized forest floor samples. Forest floor nutrient concentrations from each plot were used to calculate nutrient totals for material from that plot. A total of 720 mineral soil samples were collected, split by depth (0 to 5 cm, 5 to 20 cm), and homogenized in a similar fashion as forest floor samples for each depth. Finally, roots were removed from soil samples and divided by size to represent coarse roots (>5 mm diameter) and fine roots (2 to ≤5 mm diameter). As with soils, root samples were homogenized by plot (240 total homogenized root samples) within each size class and nutrient concentrations determined for calculating nutrient totals for each root size class within a given plot.

Biomass Statistical Analyses

Analysis of covariance (ANCOVA) was used to determine the effects of slash-retention and green-tree retention on post-harvest biomass, C, N, Ca, K, and P stocks using PROC MIXED in SAS (SAS Institute, Inc). Initial ANCOVA analyses of these factors indicated no significant effect from green-tree retention therefore we focused exclusively on slash retention effects. Subsequently, the fixed

effect within the model included slash retention and the random effect was slash retention nested within site. In all cases, the covariate was the pre-harvest value of the dependent variable (post-harvest values) and served as a control to further explain variation in post-harvest data. Diagnostics were conducted to examine whether data met the assumptions of ANCOVA, specifically, normally distributed residuals and homogeneous variances. When these assumptions were violated, data were transformed using mathematical functions commonly used for data transformations, including natural logarithm, square root, and inverse. These transformations were first tested on the dependent variable alone and when data still violated the assumptions both the dependent variable and the covariate were transformed and tested. In some cases, data still did not meet the necessary assumptions for these tests after applying these transformations and, thus, rank transformations were applied (Conover & Iman, 1982). The rank transformed data met the assumptions of ANCOVA and allowed for the use of common post-hoc pairwise comparisons on the ranked data, specifically, the Tukey-Kramer method.

Once initial diagnostics were complete, the effect of the covariate was tested in order to determine its relevance in explaining variation in the dependent variable. This testing included evaluating the estimates of the slopes for each treatment group in the model. Specifically, the data were examined for significant differences in the estimates of the slopes for each group and whether a common slope for all groups was significantly different from zero. If a common slope different from zero was appropriate then the covariate was included in the model to account for any pre-harvest variation in the dependent variable. If a common slope for all groups was not different from zero the covariate was dropped and analysis of variance (ANOVA) was conducted instead. When ANOVA was applied, diagnostics testing for normality of residuals and homogeneity of variances was conducted with appropriate mathematical or rank transformations (Conover & Iman 1981) applied as necessary. The Tukey-Kramer method was employed to find significant differences between the slash retention treatments for both ANCOVA and ANOVA. The unharvested control was not included in analyses but is presented alongside the analyzed data as a reference for visual comparison. All significance testing was at $\alpha = 0.05$ level and all data is presented in non-transformed format and prior to being adjusted for the covariate in cases in which ANCOVA was used.

Green Tree Retention

While the current MFRC guidelines suggest retention levels for these legacies, a formal evaluation of how these guidelines affect patterns of biodiversity, nutrient availability, carbon storage, and forest productivity has not been conducted. In addition, a basic, functional understanding of how green trees and woody debris contribute to maintaining biodiversity and ecosystem function within managed aspen ecosystems is needed for informing the ongoing review of site-level management

recommendations. Moreover, an assessment of how the amount and spatial patterns of legacies affect resilience and sustainability will be central to future refinement of woody biomass and general forest harvesting guidelines. Tree mortality within clumped and dispersed treatments was recorded for each of the four study sites post-harvest. Over time the fate of residual trees will be assessed and patterns related to arrangement of residual trees.

RESULTS and DISCUSSION

1. Impacts of biomass harvesting on fungal and saproxylic animal communities

Fungi

Polyporoid species identification and occurrence

From 120 plots, 2358 occurrences of polyporoid fungi were recorded, representing 86 unique species from 16 host tree species (Appendix A, Table 1). Most fruiting bodies could be identified to species in the field (2088/2358; 89%), while the remainder (270/2358; 11%) required collection for morphological and molecular analyses. From the 270 collections, 230 ITS and 11 nLSU sequences were generated, with GenBank accession numbers listed in Table 1. Of the 230 ITS sequences, 224 met the minimum sequence length threshold of 300 bp set in jMOTU. The mean sequence length was 634 bp with a range of 394 to 771 bp, and a 60% minimum sequence overlap value of 238 bp. Although 86 unique taxa were identified, 22 could not be accurately assigned a species epithet based on microscopic characters and ITS/nLSU sequences (Appendix A, Table 1).

Using the polyporoid species list generated in this study along with the results from a previous study in nearby Wisconsin and Michigan (Lindner *et al.* 2006), we generated an informal red-list of rare and/or threatened polyporoid species for the U.S. Lake States (Appendix A, Table 1). *Populus tremuloides* supported 62 species of polyporoid fungi from 1705 observations (Appendix A, Table 1). The next most abundant host was *Betula papyrifera*, which supported 24 species from 296 observations (Appendix A, Table 1). Eight polyporoid species (*Trichaptum biforme*, *Bjerkandera adusta*, *Trametes hirsuta*, *Phellinus tremulae*, *Fomes fomentarius*, *Irpex lacteus*, *Fomitopsis ochracea* and *Antrodia serialis*; listed in decreasing abundance) made up 1573/2358 (67%) of all observations. Meanwhile, 45 species were encountered five times or less, and 18 species were encountered only once (Appendix A, Table 1). When only the polyporoid fungi that occurred on aspen ≥95% of the time are considered, 31 species were present (Appendix A, Table 1). Of those, 24 species (77%) occurred on aspen deadwood pieces with mean diameters in the three smallest diameter classes (1– <15 cm), and no species were recorded on aspen deadwood with a mean diameter in the largest class (>25 cm; Appendix A, Table 1).

The mean diameter of aspen substrates supporting these 24 polyporoid species was 7.2 cm (*SD* = 3.4; *N* = 441), while the remaining seven species found primarily on aspen were found on substrates with a mean diameter of 19.8 cm (*SD* = 2.2; *N* = 574).

Polyporoid community analysis

A three-axis NMS solution (final stress = 20.01; final instability < 0.00001; $P = 0.004$) best described the data set (cumulative $R^2 = 0.71$). Fourteen quantitative deadwood variables were significantly correlated with NMS axes one and two, which explained 30 and 22% of the variation, respectively. For axis 1, small diameter deadwood was determined to be the variable with the strongest tau-b coefficient (diameter class I: $\tau = 0.427$; $P < 0.001$; Figure 7 and Appendix A, Table 2). The correlations with axis 1 indicate that plots in the positive segment of this axis contained higher levels of diameter class I deadwood, and a greater abundance of *Antrodia serialis*, *Antrodiella* sp. 1, *Datronia scutellata*, *Fomitopsis ochracea*, *Junghunia nitidia*, *Polyporus brumalis*, and *Stromatoscypha fimbriata* (Figure 7 and Appendix A, Table 2). Meanwhile, plots in the negative section of this axis had higher levels of *Bjerkandera adusta* and *Trichaptum biforme* (Figure 7 and Appendix A, Table 2). While several deadwood variables were significantly correlated to axis 2, they explained less of the overall variation and are not presented in the NMS diagram (Figure 7 and Appendix A, Table 2). In addition, 17 polyporoid species were found to be significantly correlated to both axes, with tau-b correlation coefficients ranging from -0.400 to 0.431 (Appendix A, Table 2). Yet overall, there were no tau-b coefficients that exceeded ±0.5 for any of the deadwood variables or polyporoid fungi. Results of the nestedness analysis ($N_a = -1.14$) were not significantly different than expected under the null hypothesis ($P = 0.13$ from a *t*-distribution and $P = 0.14$ from null matrices).

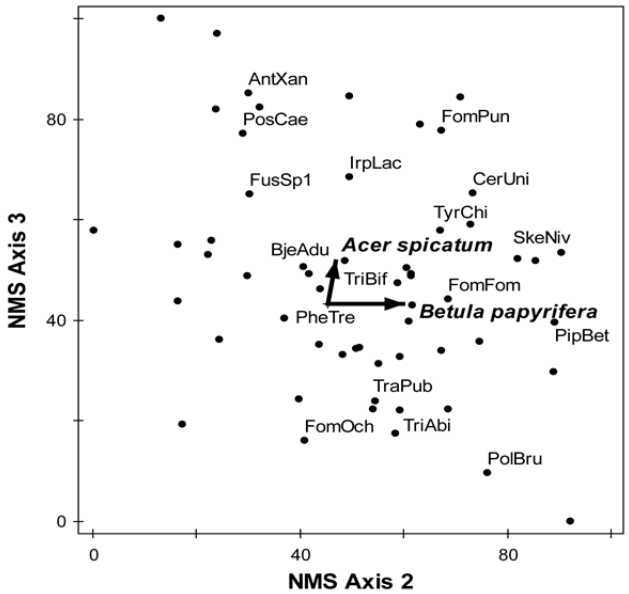


Figure 7. Non-metric scaling (NMS) summarizing the variation explained for polyporoid fungi significantly correlated to the axes. Polyporoid fungi not significantly related to the axes have no abbreviation shown. The length of the

Species accumulation curves of polyporoid species occurrence by each of the deadwood characteristics are presented in Figure 8. The SAC using substrate species illustrated that presence of non-aspen hosts are important for polyporoid species richness, especially *Abies balsamea*, *Acer* spp., and *Betula alleghaniensis* (Fig 8; the SAC using all substrate species is not shown). SACs using additional deadwood variables demonstrated that small diameter substrates were important for polyporoid species richness compared to larger diameter classes and well-decayed substrates supported a higher diversity of polyporoid species compared to fresher decay classes (Figure 8).

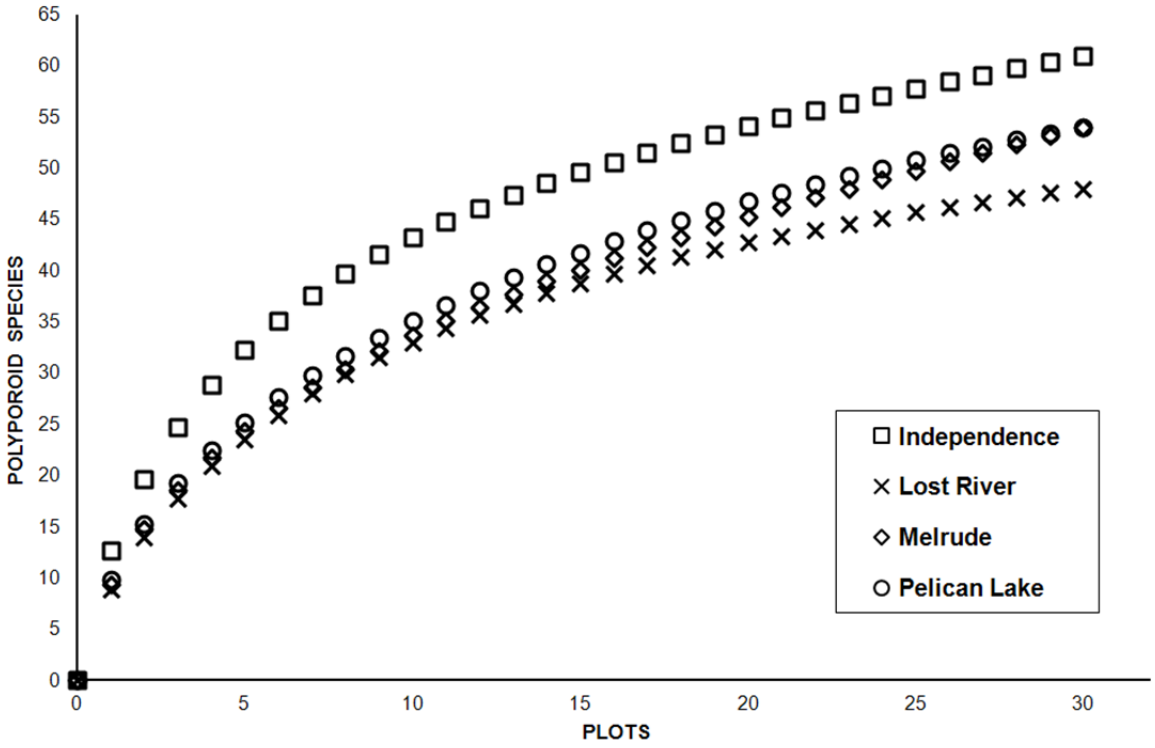


Figure 8. Species accumulation curves of polyporoid species at four aspen-dominated sites in northern Minnesota, USA.

Similarity of polyporoid communities

The Sørensen similarity index showed that the composition of polyporoid species varied by each deadwood variable (diameter class, decay class, substrate type, and host species), but differences by host were most pronounced (Appendix A, Table 3). The mean similarity (percentage of shared polyporoid species using presence/absence) by host was only 28%, and the host with the highest similarity to aspen was *B. papyrifera*, at 37% (Appendix A, Table 3). Diameter classes I (1- <5 cm) and II (6- <10 cm)

supported nearly identical numbers of polyporoid species, 53 and 51 respectively, but were only 70% similar to one another (Appendix A, Table 3).

Summary

The aspen forest type in Minnesota supports a diverse assemblage of polyporoid species, including potentially rare and/or threatened species. Currently, no red list exists for North American fungi, and studies documenting the community structure of polyporoid fungi are nearly nonexistent. However, our informal red list based on the results of this study and a previous study in nearby Wisconsin and Michigan (Lindner *et al.* 2006), shows that four polyporoid species encountered in Minnesota aspen forests (*Funalia trogii*, *Pycnoporellus fulgens*, *Rigidoporus crocatus*, and *Skeletocutis chrysella*) should be considered rare and/or threatened in the Lake States region. Two of these three species were found at multiple sites, suggesting that while rare, they are potentially widespread across the aspen forest type in the Lake States.

Also clear from these results is that small diameter substrates were the most significant driver of polyporoid species composition. Management plans aimed at maintaining or increasing polyporoid species richness should seek to promote or retain these substrates. In addition, the substrate species diversity was an important variable in the composition of polyporoid species community. Future management efforts should focus on retaining or promoting advanced regeneration of non-aspen species to increase levels of host diversity. Future research on this subject should target larger diameter, well-decayed aspen substrates to determine if rare or threatened polyporoid fungi require these substrates. It is important to take into consideration that the typical rotation for managed aspen forests in the Lake States is relatively short (40 to 60 years), creating a challenge for forest managers to maintain both large-diameter trees and well-decayed CWD while still achieving management objectives aimed at maximizing economic returns or product yields. However, given these findings, management of these ecosystems for biomass should include provisions for the retention of a diversity of fine and coarse woody debris substrate sizes and a variety of woody species to ensure the maintenance of these critical components of biodiversity within managed landscapes.

Amphibian and small mammals

Environmental Variables

The volume of CWD in plots ranged from 52.9 – 143.9 m^3 / ha (mean = 97.1 m^3 / ha; n = 18 plots) for harvested plots and 42.4 – 69.0 m^3 / ha (mean = 55.7 m^3 / ha; n = 2 plots) for control plots. CWD volumes did not differ among experimental sites (Fig. 9). Soil moisture levels were elevated in harvested plots at Site-1 by about 14% but little effect of harvest on soil moisture levels was detected at Site-2 (Figure 9). At Site-1, elevated soil moisture levels in the harvested plots remained elevated during the course of the study (Figure 10). Soil temperature at 15cm below the surface was elevated in harvested plots at both sites but differences lacked significance.

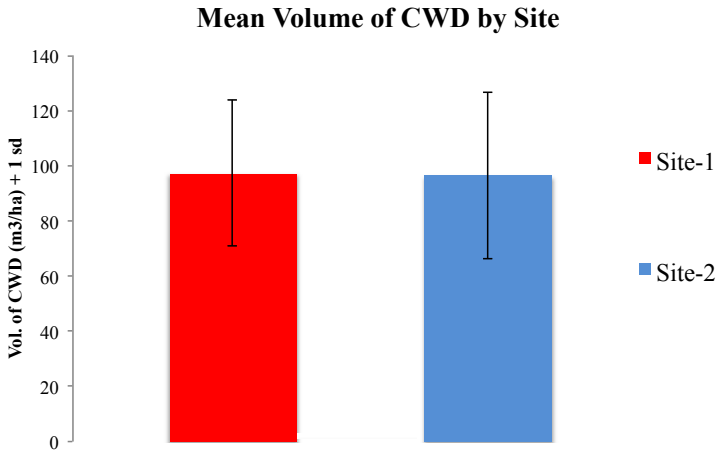


Figure 9. - Comparison of mean volume (m^3 / ha) of coarse woody debris (CWD) showing that the overall mean volume did not differ by site.

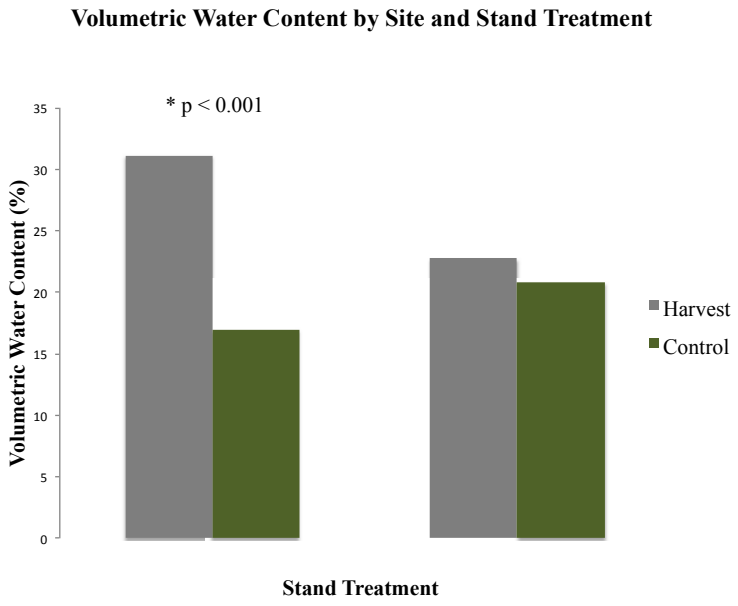


Figure 10. - Volumetric water content between stand treatments (i.e., Harvest vs. Control) by site. Statistical significance determined using Welch's t-test accounting for unequal variances.

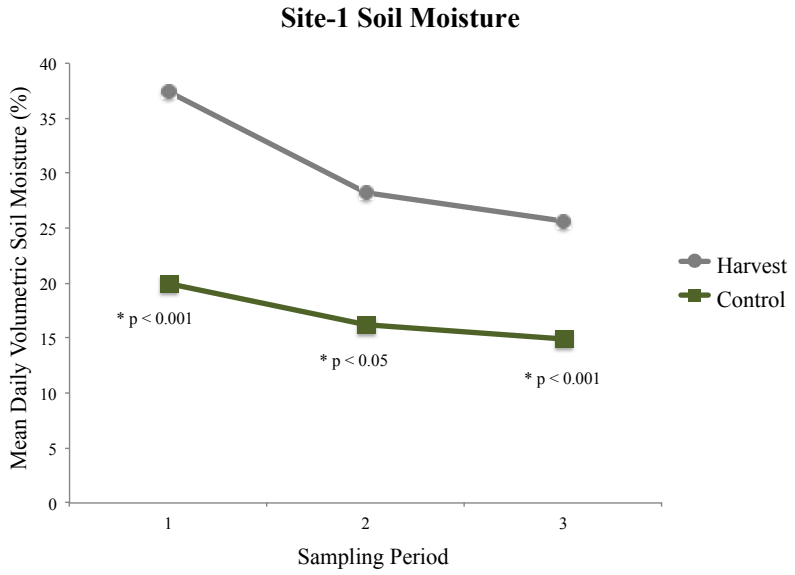


Figure 11 - Volumetric water content between stand treatments (i.e., Harvest vs. Control) at Site-1. Statistical significance determined using Welch's t-test accounting for unequal variances.

Time- and area- constrained searches - Time- and area-constrained visual encounter 15 captures representing five species of amphibian during 40 person-hours of searching (Appendix B, Table 3). Red-backed salamanders (*Plethodon cinereus*) were the most commonly encountered amphibian species during VES surveys (n=6, 40.0%) followed by American toads (*Anaxyrus americanus*; n=4, 26.6%). Time- and area-constrained visual encounter surveys out-performed drift-fence arrays with regard to *P. cinereus* and *Pseudacris crucifer* capture success but performed poorly for other amphibian species. *Pseudacris crucifer* was the only species of amphibian detected using VES surveys that was not detected using drift-fence arrays.

Drift fence arrays - During a single season of trapping, 3,067 captures (including recaptures) of 18 species of amphibian and small mammal resulted from 540 array-nights per site (Appendix B,Table 4). *Sorex* spp. were the most frequently encountered small mammals, comprising approximately 42.2% of all small mammal captures. *Microtus pennsylvanicus* and *Myodes gapperi* comprised approximately 31.5% and 13.4% of all small mammal captures, respectively. *Anaxyrus americanus* and *Lithobates sylvaticus* comprised approximately 82.9% and 13.2% of all amphibians captured, respectively. Recaptures for both groups were low with only 37 recaptured amphibians and 32 recaptured small mammals. Of the 37 recaptured amphibians, 36 (97.3%) were *A. americanus*, and a single *L. sylvatus* (2.7%). Small mammal recaptures included several species: *M. pennsylvanicus* (n=17; 53.1%), *Sorex* spp. (n=7; 21.9%), *M. gapperi* (n=3; 9.4%), and *Zapus hudsonicus* (n=3; 9.4%). *Blarina brevicauda* and *Peromyscus maniculatus* were each recaptured on a single occasion (n=1; 3.1%).

Capture associations - Using top-ranked model(s), we identified variables that best explained the relative-abundance of individual species or species groups during the course of this study. Only two species of amphibian (*A. americanus* and *L. sylvaticus*) were captured with sufficient frequency to model capture associations. Both amphibian species showed a negative initial effect of harvest on abundance, although this initial harvest effect for *A. americanus* was weak and not supported statistically (Appendix B, Tables 5-6; Figures. 12-13). However, there were significant positive clearcut (i.e., Treatment-2) by period interactions for periods-2 and -3 indicating that *A. americanus* captures increased significantly in clearcut plots. Additionally, there were near significant decreases in *A. americanus* abundance through time in the un-harvested control plots as well as in harvested plots with dispersed green tree reserves by sampling period-3 (i.e., Treatment-3 * Period-3 interaction).

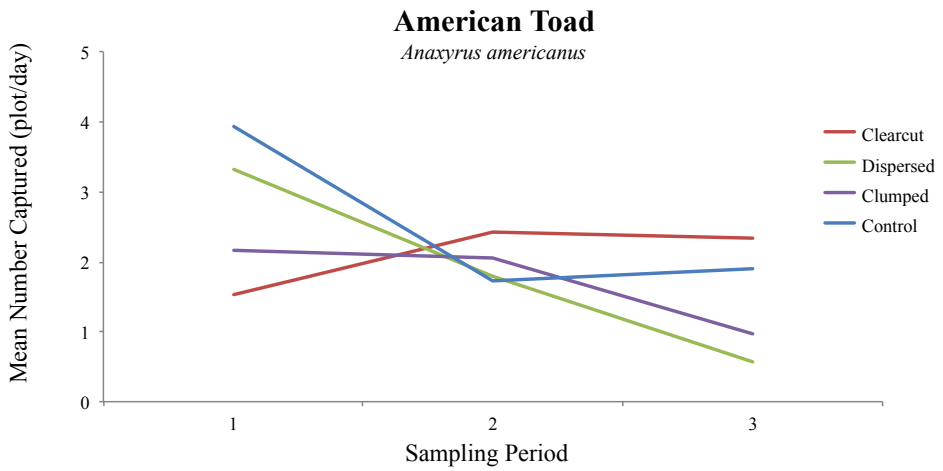
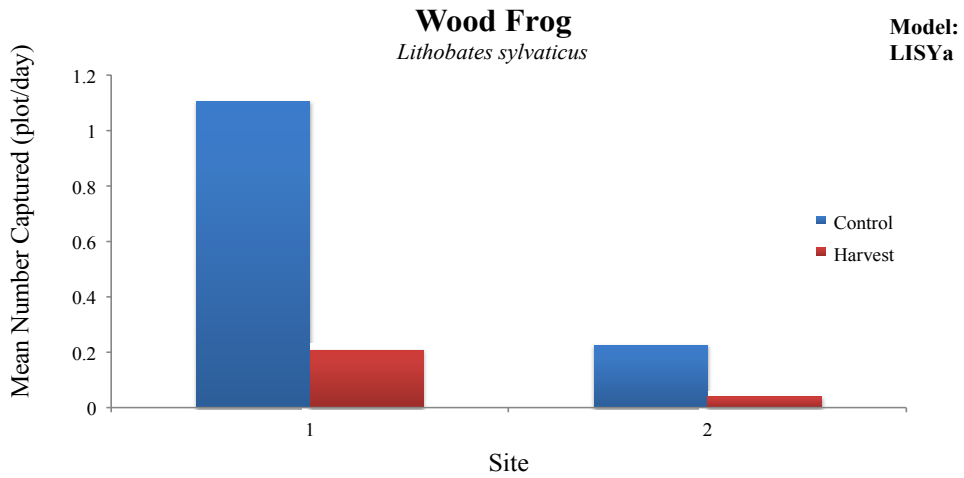


Figure 12 - Mean number of *A. americanus* captured per plot per day by treatment in Saint Louis County, Minnesota, 2010. Precipitation is held constant at overall daily mean (2.58 mm).



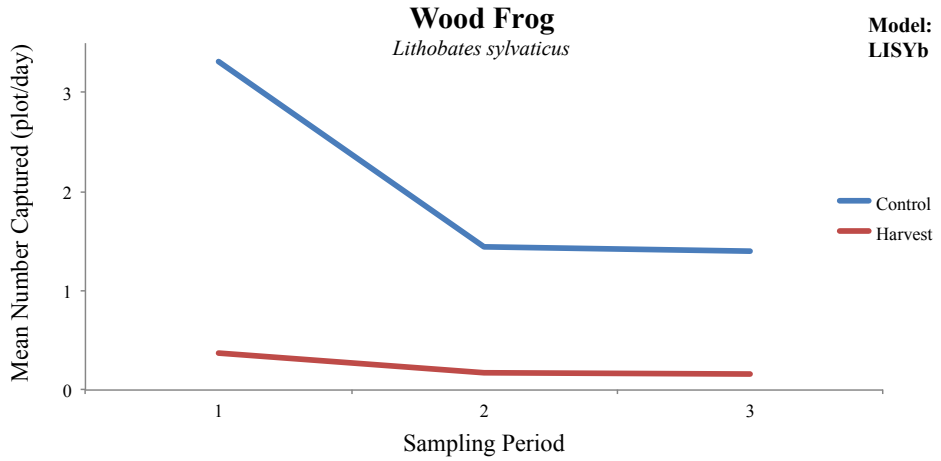


Figure 13 - Mean number of *L. sylvaticus* captured per plot per day by treatment in Saint Louis County, Minnesota, 2010. Top figure depicts output from model LISYa with below-ground soil temperature is held constant at overall daily mean (17.81 °C). Bottom figure depicts output from model LISYb. Bottom figure excludes Site-2 data, however Site-2 showed similar temporal effects but with fewer overall captures.

Six small mammal species, or species groups (e.g., *Sorex* spp.), were captured with enough frequency to model capture associations. The initial response to harvest varied by species and included positive, negative and neutral effects. The top-ranked model for *M. pennsylvanicus* included a significant positive effect of harvest at Site-2 but no effect of harvest was detected at Site-1 (Appendix B, Table 7; Fig. 14). Captures of *M. pennsylvanicus* significantly increased through time in both harvested and non-harvested plots across both sites. Similarly, the top-ranked model for *M. gapperi* lacked support for an initial effect of harvest. However there was weak support for a positive harvest by period-2 interaction ($p = 0.08$; Appendix, Table 8; Figure 15). However, this model included a significant parameter for mean minimum daily temperature as well as a marginally significant parameter for mean daily by-plot belowground soil temperature ($p = 0.07$). Two equally competitive models ranked highest for *B. brevicauda* (Appendix B, Table 9; Figure 16). The first, and slightly more complex, model included a negative initial effect for harvest across all the three levels of green tree retention types as well as a marginally significant positive effect of volume of CWD. The model also indicated a positive temporal effect across all treatments and controls. The second model included a negative response to harvest (regardless of green tree reserve type) as well as a positive temporal effect (i.e., positive effect through time). However, this positive temporal effect increased in parallel between harvested and non-harvest plots through time. Two equally competitive models ranked highest for *P. maniculatus* as well (Appendix B, Table 10; Figure 17). The first, and slightly more complex, model included positive non-significant initial response to harvest ($p = 0.487$) as well as weak non-significant interactions between harvest and periods-2 and -3, though the inclusion of these interaction terms were supported by AIC. Relative abundance for *P. maniculatus* seemed to be influenced more heavily by abiotic conditions (i.e., mean minimum daily temperature and mean daily precipitation) than by timber harvest. Again, two equally competitive models ranked highest for *Z. hudsonius* (Appendix B, Table 11; Figure 18). Both models showed a positive response to harvest; however the effect of harvest lacked significance in both models. Both models included a weak negative significant effect of CWD volume. The top-ranked model for *Sorex* spp. was by far the most complex of the species analyzed (Appendix B, Table 12; Figure 19). The top-ranked model included positive initial responses to harvest that included all the three levels of green tree reserves ('Treatments'). Significant positive interactions between experimental treatments by Periods-2 and -3 were supported. Sorex captures were positively correlated with mean daily precipitation. In addition, Sorex captures were positively correlated with below-ground soil temperature on un-harvested plots while negatively correlated in harvested plots.

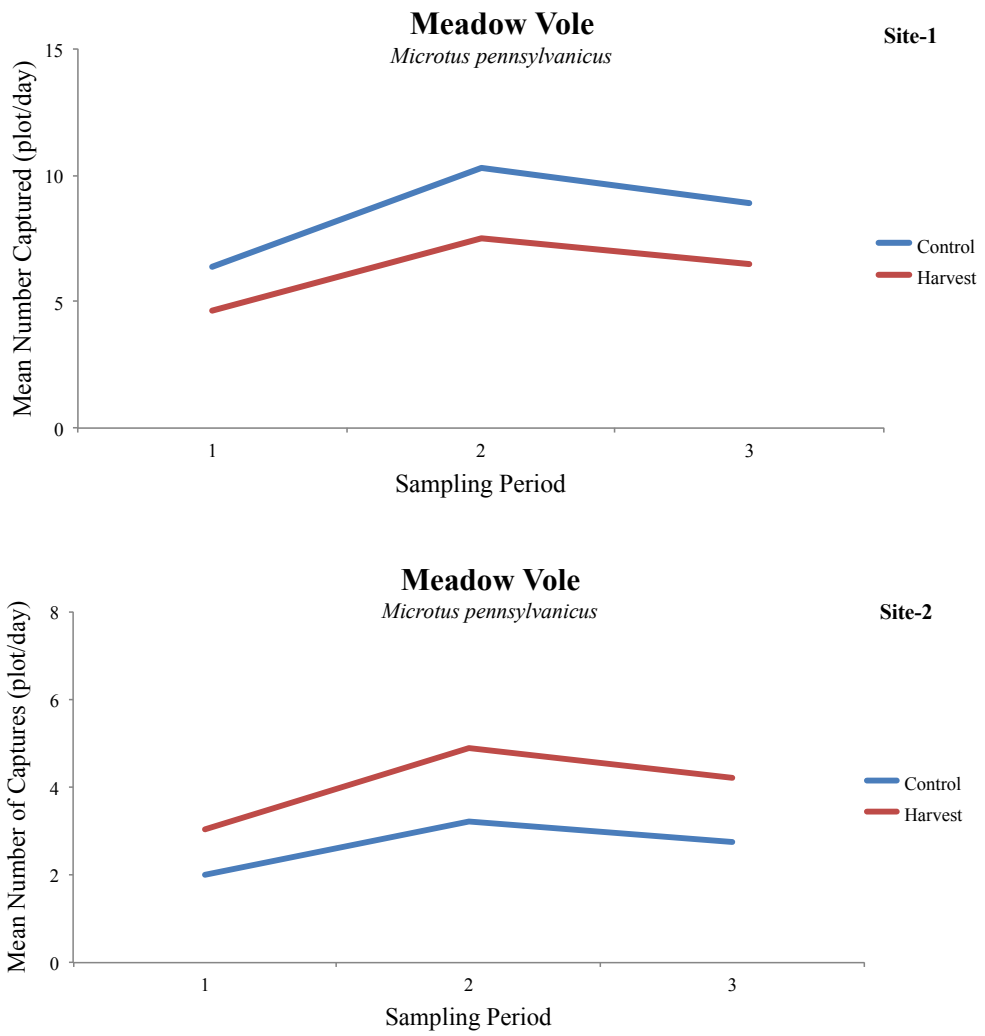


Figure 14 - Mean number of *M. pennsylvanicus* captured per plot per day by treatment in Saint Louis County, Minnesota, 2010. Top figure depicts output from Site-1, while bottom figure depicts output from Site-2.

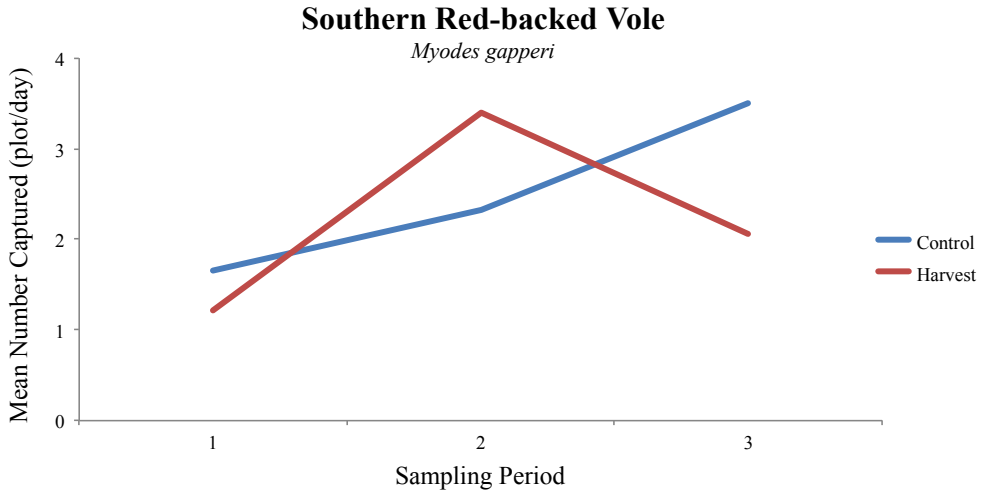
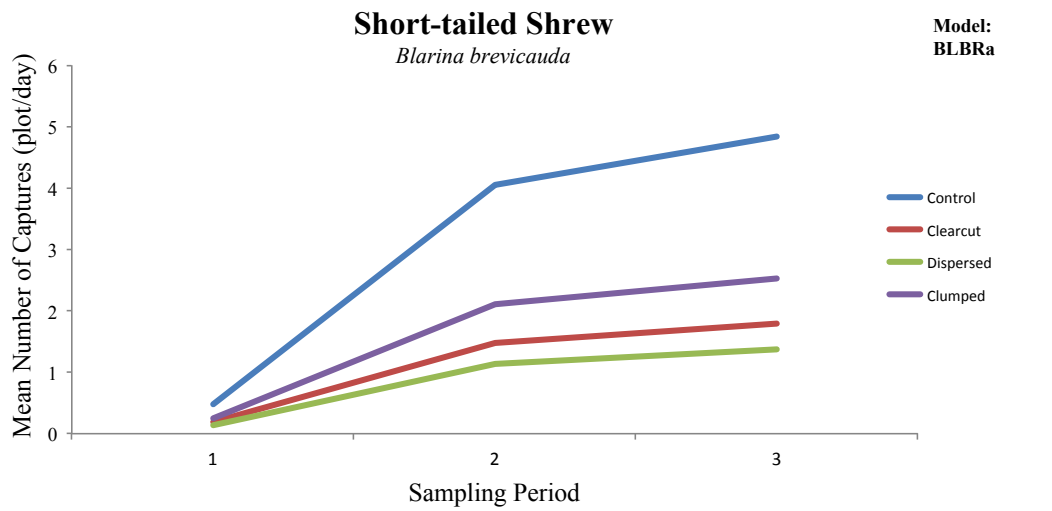


Figure 15 - Mean number of M. gapperi captured per plot per day by treatment in Saint Louis County, Minnesota, 2010. Site-level differences were not supported in model. Minimum air temperature and below-ground soil temperature are held constant at overall daily mean (13.61 °C and 17.81 °C respectively).



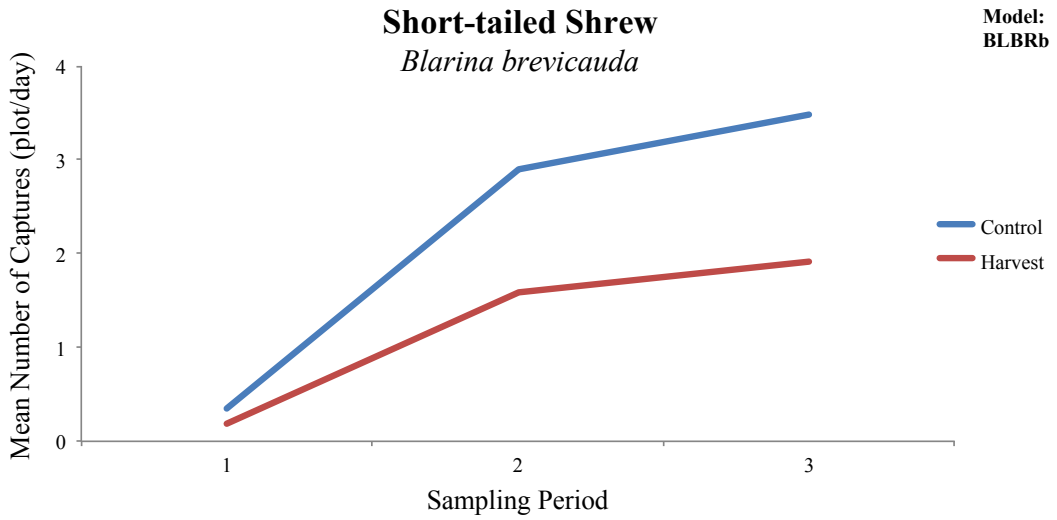
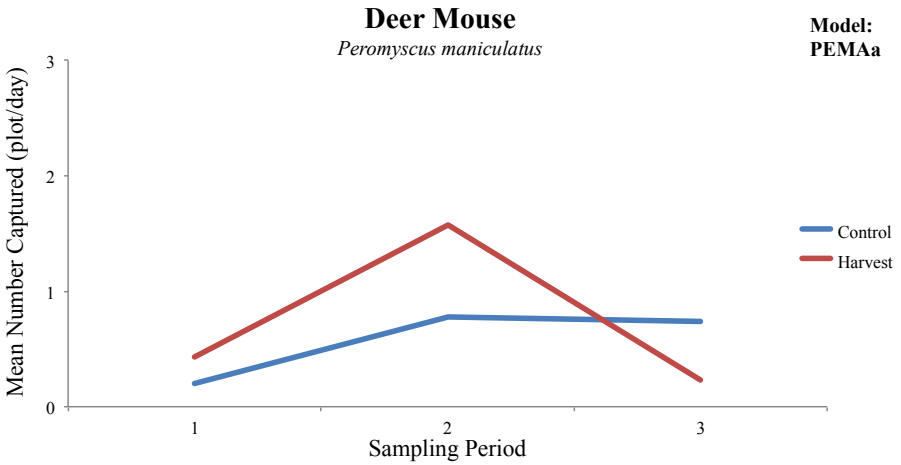


Figure 16 - Mean number of *B. brevicauda* captured per plot per day by treatment in Saint Louis County, Minnesota, 2010. Top figure depicts output from model BLBRa with volume of CWD is held constant at overall mean (96.90 m^3 / ha). Bottom figure depicts output from model BLBRb. Both figures exclude Site-2 data, however Site-2 showed similar temporal effects but with fewer overall captures.



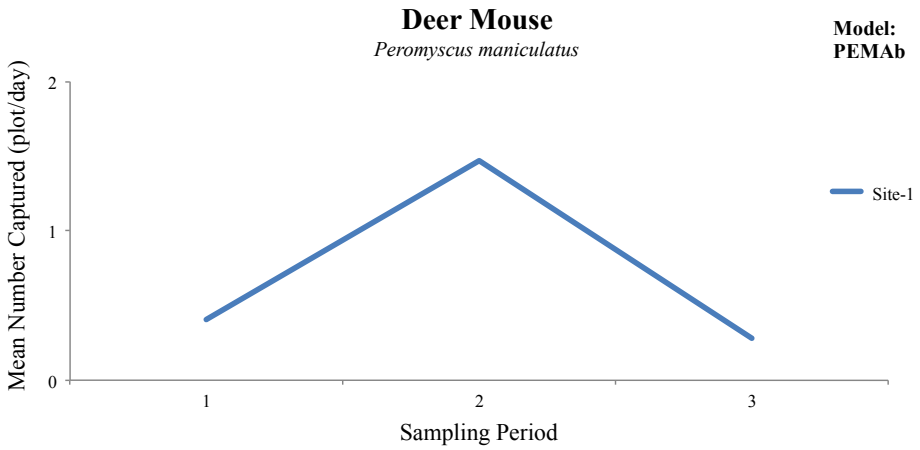


Figure 17 - Mean number of *P. maniculatus* captured per plot per day in Saint Louis County, Minnesota, 2010. Top figure depicts output from model PEMAa, while bottom figure depicts output from model PEMAb. Bottom figure excludes Site-2 data, however Site-2 showed similar temporal effects but with fewer overall captures. Model PEMAb displays a single line representing no statistical support for differences between harvest and control. For both models, minimum air temperature and precipitation are held constant at overall daily mean (13.61 °C and 2.58 mm respectively).

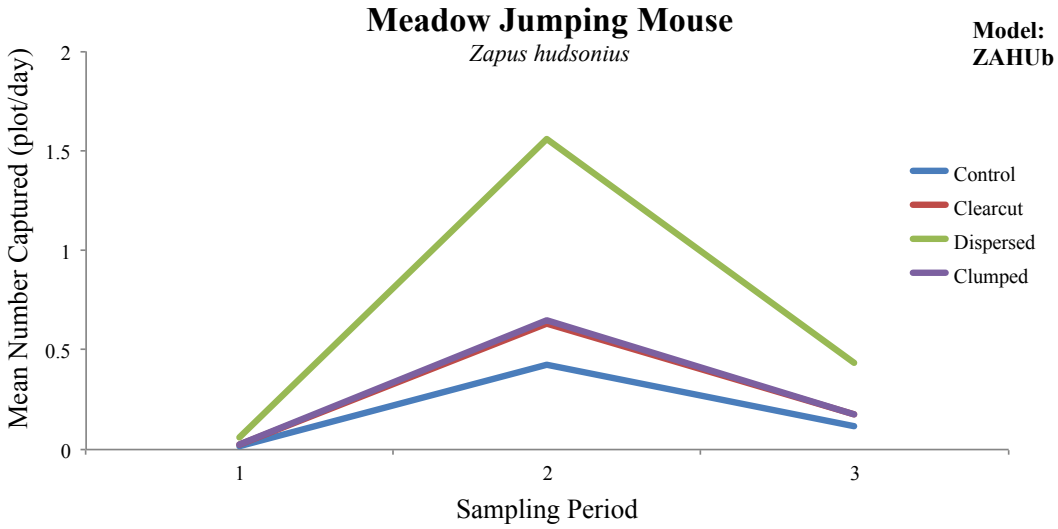


Figure 18 - Mean number of *Z. hudsonius* captured per plot per day by treatment in Saint Louis County, Minnesota, 2010. Top figure depicts output from model ZAHUa while the bottom figure depicts output from model ZAHUb. Volume of CWD is held constant at overall mean (96.90 m^3 / ha) for both.

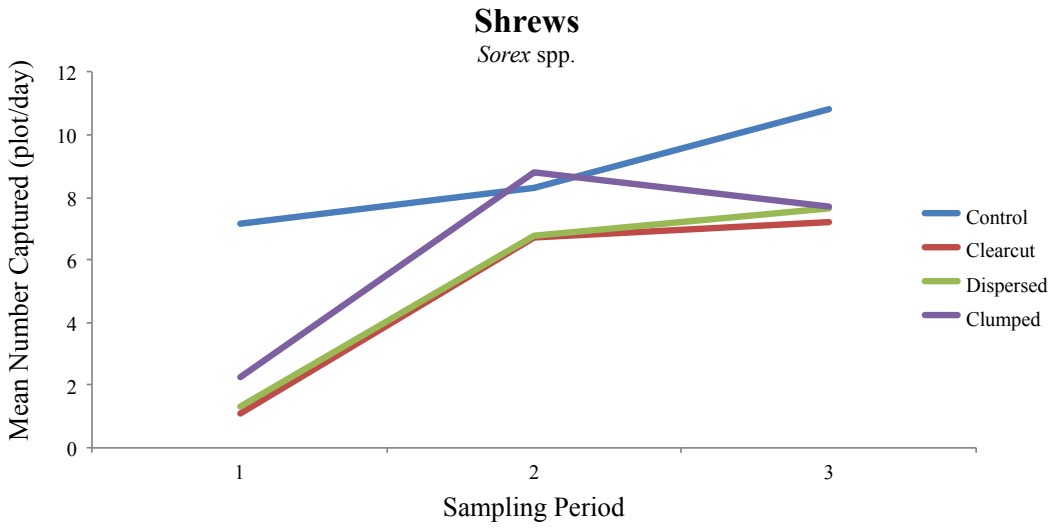


Figure 19 - Mean number of *Sorex* spp. captured per plot per day by treatment in Saint Louis County, Minnesota, 2010. Volume of CWD is held constant at overall mean (96.90 m^3 / ha) for both. Precipitation is held constant at overall daily mean (2.58 mm). Below-ground soil temperature held constant at harvest-level mean by sampling period due to model complexity to allow for better visualization of response (Sampling Period-1, control plots = 14.6 °C, harvested plots = 16.9 °C; Sampling Period-2, control plots = 16.7 °C, harvested plots = 19.0 °C; Sampling Period-3, control plots = 17.4 °C, harvested plots = 19.4 °C).

Effects on amphibian body condition - Using simple linear models in R (v2.14, 2011), the effects of harvest (regardless of green tree reserve type) and harvest with respect to green tree reserve type as well as the interaction of these parameters through time (i.e., by sampling periods) on amphibian body condition (BC) for both *A. americanus* and *L. sylvaticus* (i.e., the two amphibian species with sample sizes of ≥ 50) were compared.

For *A. americanus*, the best model had a non-significant harvest effect ($p = 0.17$) as well as a non-significant positive temporal effect ($p = 0.14$) regardless of the presence of green tree reserves. For *L. sylvaticus*, the best model had a non-significant harvest effect ($p = 0.61$) but a significant positive temporal effect on BC ($p < 0.05$). While it is reasonable to suspect an increase in BC through time, interpretation is cautioned due to small sample size during sampling Period-3.

Summary

The use of woody materials, especially CWD obtained during timber harvest, as a supplementary feedstock for coal-fired power plants has generated concerns regarding the ecological impact and sustainability of these practices in relation to wildlife and other ecosystem services. Evidence for an initial response to timber and CWD harvest for several species of amphibian and small mammals are presented above. The three hypotheses of interest (i.e., change in survival, change in immigration or emigration or change in above-ground activity patterns) are addressed, and provide evidence for species-specific

responses to harvest within and between taxonomic groups. While the retention of CWD appears irrelevant for many of the species in the study, we should be cautious about our conclusions. The volume of CWD retained on-site will likely play an important role with regard to re-colonization of species that emigrated from the harvested areas as well as the carrying capacity of the system going forward. As CWD begins to decay, it will likely provide refugia for individuals moving through the harvested, possibly counter-acting the effects of changes in soil moisture and temperature.

In an effort to increase sustainability, the dispersal abilities for species of conservation interest should be considered before harvest. Changes in the over-all area of harvest, green tree reserve type, edge effects and barriers to dispersal will likely influence the effect of timber and CWD harvest on the persistence of small vertebrate species. In addition, the impact of future climate change may influence species' ability to respond to disturbance in these forested systems, especially for species presently living near the edge of their physiological tolerances (e.g., species living at the edge of their range).

LTSP – Medium term impact results

As expected, organic matter removal treatments significantly affected above-ground woody biomass production over 15 years at all sites (Table 2) but effects differed among sites. Results on clay soils suggest that removing the forest floor in addition to all slash can reduce productivity as expected, but leaving all slash on site may inhibit regeneration of woody vegetation, particularly of tree species (Figure 3, Table 2). Similarly, leaving all slash on site reduced productivity on loamy soils (Figure 20, Table 2). In contrast, biomass production at the sandy site consistently declined with increasing organic matter removal at the time of harvest (Figure 20, Table 2). Leaving slash on site following harvest had a beneficial effect on biomass production. In Scandinavian forests where soil nutrients were expected to be limiting, removing slash from thinning treatments showed results consistent with our findings on sandy soils (Helmisaari et al. 2011).

The effects of compaction treatments also significantly affected above-ground woody production at all sites (Table 2), but differed depending on soil texture. Results on clay and loamy soils suggest that biomass production decreases with increasing compaction with all treatments differing significantly (Figure 21, Table 2). These results are consistent with other findings that indicate tree species, particularly aspen, are sensitive to the decrease in water-holding capacity and oxygen availability that can occur with compaction of fine-textured soils (Greacen and Sands 1980, Bates 1993, Powers 1999). At the sandy site, however, greater compaction led to greater over all biomass production, though only the

extreme treatments differed significantly (Figure 21, Table 2). It is possible that compaction of the sandy soils improved growing conditions by decreasing macro-pore space and increasing water-holding capacity as has been observed in other studies with coarse-textured soils (Greacen and Sands 1980, Powers 1999).

Table 2. ANOVA results for treatment effects on above-ground woody biomass production over 15 years following harvest. Abbreviations are as follows: OMR = organic matter removal, CPT = compaction. Significant effects are in bold type. P-values reported for pairwise comparisons are Tukey-adjusted.

Site	Source	df	F	P	Pairwise comparisons
Ottawa NF (clay)	OMR	2	6.65	**0.0027**	TTH>FFR, MBH (p=0.0062, p=0.0182)
	CPT	2	4.95	**0.0108**	C1 > C3 (p=0.0086)
	TIME	2	112.3	**<0.0001**	
	OMR*CPT	4	4.2	**0.0052**	
	CPT*TIME	4	0.56	0.693	
	OMR*TIME	4	0.03	0.9976	
	OMR*CPT*TIME	6	0.81	0.6003	
Huron NF (sandy)	OMR	2	7.59	**0.001**	MBH > TTH, FFR (p=0.0479, 0.0007)
	CPT	2	4.34	**0.0167**	C1 > C2 (p=0.012)
	TIME	2	76.38	**<0.0001**	
	OMR*CPT	4	2.5	**0.05**	
Chippewa NF (loamy)	OMR	2	5.48	**0.0068**	FFR, TTH > MBH (p=0.044, 0.007)
	CPT	2	70.11	**<0.0001**	C1 > C2 > C3 (p<0.0001, p<0.0001, p=0.0003)
	TIME	2	32.84	**<0.0001**	
	OMR*CPT	4	3.65	**0.0105**	
	CPT*TIME	4	0.22	0.9266	
	OMR*TIME	4	1.44	0.2348	
	OMR*CPT*TIME	6	0.23	0.9827	

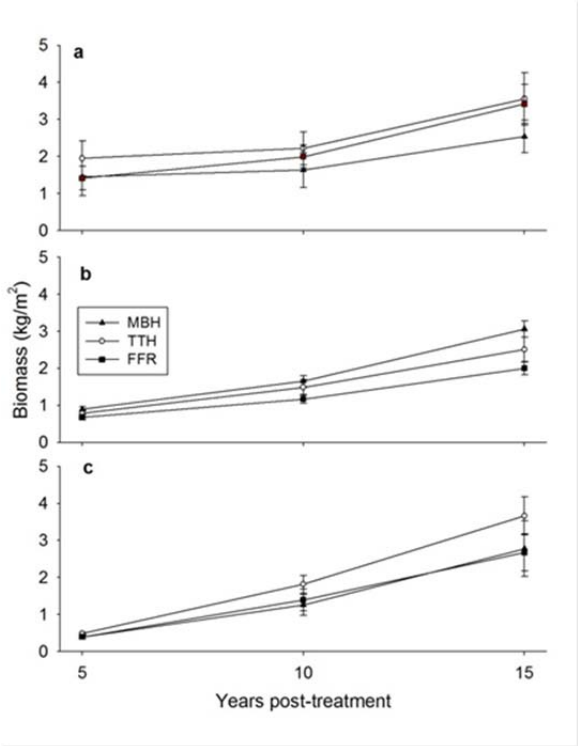


Figure 20 - Effects of organic matter removal on above-ground woody biomass production over time. Abbreviations are as follows: MBH = bole only harvest, TTH = total tree harvest, FFR = total tree harvest plus forest floor removal. Significant differences among individual treatments only are presented for each site. a) Chippewa National Forest (loamy soils) b) Huron-Manistee National Forest (sandy soils), c) Ottawa National Forest (clay soils).

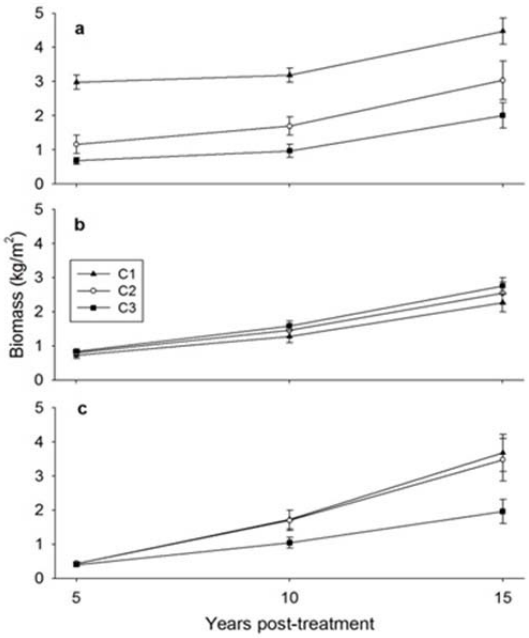


Figure 21 - Effects of compaction on above-ground woody biomass production over time. Treatments are labeled as follows: C1 = no additional compaction, C2 = moderate compaction, C3 = heavy compaction. a) Chippewa National Forest (loamy soils); b) Huron-Manistee National Forest (sandy soils); c) Ottawa National Forest (clay soils).

Summary

The findings relate to the LTSP sites are preliminary and not presented in complete form. Therefore, we urge caution in applying them before analysis has been finalized. Over all, results indicate that the impacts of biomass harvests are persistent even after 15 years and may influence the sustainability and resilience of aspen-dominated forest communities in the future, particularly on less productive sites. This confirms the importance of understanding the implications of different management actions particularly as they relate to biomass harvests. These findings also suggest that it may be appropriate to incorporate into guidelines recommendations that are specific to particular soil textures and forest types.

2. Harvesting residues and green tree legacy impacts on carbon and nutrient stocks

Carbon and Nutrients

Biomass & Carbon

Slash retention significantly affected total post-harvest biomass stocks ($F = 3.53$, $p = 0.0410$) and total post-harvest C stocks without soil pools included ($F = 4.19$, $p = 0.0241$). Slash retention had a marginally significant effect on C stocks with soil pools included ($F = 3.29$, $p = 0.0504$). Carbon stocks were roughly half the magnitude of biomass stocks (Table 3a, b). More specifically, for stocks of biomass, C with soil, and C without soil, 'all-slash retained' treatments were significantly higher than 'no-slash retained', whereas '20%-slash retained' treatments were not significantly different from 'no-slash retained' and 'all-slash retained' treatments (Table 3b). The unharvested control was not statistically analyzed but is presented for visual comparison to individual treatments. When compared to the unharvested control, there were substantial reductions in stocks of biomass and C in overstory vegetation across all treatments, directly related to harvest removals (Table 1a). In addition, stocks of FWD and CWD biomass and C were substantially greater in all treatments than in the unharvested control reflecting influence from the prescribed slash retention levels (Table 3b). Stocks of C within the soil were far greater than any other pool of C within the forest ecosystem in all treatments and the unharvested control (Table 3b).

Nitrogen

Slash retention did not significantly affect stocks of N both with ($F = 1.10$, $p = 0.3451$) and without soil ($F = 0.89$, $p = 0.4187$) and the levels of slash retention did not differ significantly from each other. Stocks of N within the soil were by far the greatest in magnitude among all pools of N (Table 3b). In fact, N stocks within the soil pool alone were an order-of-magnitude greater than all other pools of N combined (Table 3b). Nitrogen in standing trees and saplings was very low (Table 3a) and the unharvested control was lower in total N than two of the three slash retention treatments both with and without soil (Table 3b). Specifically, '20% slash retained' and 'all slash retained' treatments were greater than the unharvested control (Table 3b) in total N stocks. Excluding soil, N stocks in pools of forest floor and coarse roots were dramatically greater than any other pool of N (Table 3b & Table 3a, respectively). For all slash retention treatments, stocks of N in forest floor were greater in magnitude than coarse roots. Other pools with relatively high levels of N included understory vegetation, particularly herbaceous material, and FWD.

Table 3a. Post-harvest ecosystem biomass in Mg/ha, C in Mg/ha, and N in kg/ha by ecosystem component and slash retention treatment. Table shows means and standard errors that have not been adjusted for the respective covariates.

Treatment	Overstory Vegetation					Understory Vegetation			
Slash	**Live Trees**	**Dead Trees**	**Live Saplings**	**Dead Saplings**	**Coarse Roots (2009)**	**Live Shrubs**	**Dead Shrubs**	**Herbs**	**Fine Roots (to 20 cm)**
Biomass									
Control	121.48 (7.48)	11.49 (1.57)	4.44 (1.23)	0.76 (0.13)	32.84 (1.73)	0.74 (0.24)	0.21 (0.13)	1.02 (0.05)	1.87 (0.22)
None Retained	1.73 (0.40)	0.19 (0.11)	0.10 (0.04)	0.01 (0.00)	29.67 (2.22)	1.13 (0.15)	0.20 (0.05)	1.88 (0.22)	2.35 (0.34)
20% Retained	1.67 (0.35)	0.17 (0.03)	0.03 (0.01)	-	32.87 (1.70)	1.23 (0.19)	0.08 (0.03)	1.90 (0.21)	1.99 (0.06)
All Retained	3.07 (0.98)	0.08 (0.05)	0.06 (0.03)	0.01 (0.01)	30.85 (2.78)	1.24 (0.15)	0.16 (0.05)	1.69 (0.26)	1.74 (0.15)
Carbon									
Control	59.70 (3.69)	5.65 (0.77)	2.20 (0.62)	0.38 (0.06)	15.27 (0.81)	0.60 (0.22)	0.11 (0.07)	0.44 (0.02)	0.87 (0.11)
None Retained	0.85 (0.19)	0.09 (0.05)	0.05 (0.02)	-	13.45 (1.01)	0.62 (0.07)	0.10 (0.03)	0.83 (0.10)	1.06 (0.16)
20% Retained	0.82 (0.17)	0.08 (0.01)	0.02 (0.01)	-	14.85 (0.70)	0.66 (0.11)	0.04 (0.02)	0.84 (0.09)	0.90 (0.02)
All Retained	1.49 (0.47)	0.04 (0.02)	0.03 (0.02)	-	13.85 (1.25)	0.66 (0.08)	0.08 (0.02)	0.74 (0.11)	0.78 (0.08)
Nitrogen									
Control	86.69 (6.01)	2.58 (0.18)	9.43 (3.53)	1.04 (0.17)	238.97 (25.10)	5.78 (1.98)	0.38 (0.24)	16.62 (1.51)	14.01 (1.14)
None Retained	1.37 (0.35)	0.03 (0.01)	0.21 (0.10)	0.01 (0.00)	221.69 (20.51)	9.15 (1.26)	0.36 (0.10)	33.68 (4.47)	18.52 (3.28)
20% Retained	1.42 (0.35)	0.03 (0.00)	0.07 (0.03)	-	265.92 (24.25)	10.25 (1.78)	0.14 (0.05)	35.73 (5.88)	17.42 (1.44)
All Retained	2.32 (0.67)	0.02 (0.01)	0.12 (0.04)	0.01 (0.01)	238.76 (27.43)	9.84 (1.26)	0.28 (0.09)	31.22 (4.24)	14.15 (1.14)

Table 3b. Post-harvest ecosystem biomass in Mg/ha, C in Mg/ha, and N in kg/ha by ecosystem component and slash retention treatment. "Total" column contains the sum of all components from Table 2a and Table 2b. Values in the same column with similar letters are not significantly different (p>0.05) based on ANCOVA results. Table shows means and standard errors that have not been adjusted for the respective covariates. However, letters indicating statistical significance are based on adjusted values derived from ANCOVA results.

Treatment	Woody Debris			Mineral Soil		Total	
Slash	FWD	CWD	Forest Floor	0-5 cm	5-20 cm	w/o Soil	w/Soil
Biomass							
Control	6.85 (1.60)	12.56 (2.58)	26.94 (2.48)	-	-	221.19 (8.53)	-
None Retained	18.18 (1.46)	22.04 (2.06)	30.69 (1.45)	-	-	108.18 (5.04)[a]	-
20% Retained	24.42 (2.24)	26.13 (4.21)	33.34 (5.17)	-	-	123.84 (6.61)[ab]	-
All Retained	27.93 (3.93)	31.84 (4.72)	32.54 (5.14)	-	-	131.20 (6.51)[b]	-
Carbon							
Control	3.50 (0.82)	6.07 (1.26)	10.97 (1.70)	25.51 (2.67)	31.37 (5.43)	105.75 (4.17)	162.64 (6.43)
None Retained	9.29 (0.75)	10.72 (1.01)	12.14 (0.87)	23.91 (1.82)	32.10 (3.36)	49.20 (2.20)[a]	105.20 (6.18)[a]
20% Retained	12.48 (1.14)	12.72 (2.03)	13.95 (2.34)	26.93 (2.87)	33.04 (2.91)	57.36 (3.05)[ab]	117.34 (3.83)[ab]
All Retained	14.27 (2.01)	15.55 (2.30)	13.24 (2.29)	25.41 (1.31)	30.55 (3.91)	60.75 (3.14)[b]	116.72 (2.41)[b]
Nitrogen							
Control	13.33 (3.12)	13.31 (2.59)	385.46 (74.58)	1730.61 (80.51)	2081.87 (156.52)	787.60 (62.04)	4600.08 (245.91)
None Retained	35.41 (2.84)	17.53 (6.54)	373.08 (51.41)	1453.39 (101.34)	1955.48 (164.82)	711.02 (53.91)[a]	4119.89 (278.23)[a]
20% Retained	47.55 (4.36)	14.24 (3.08)	449.63 (117.67)	1810.47 (216.67)	2083.77 (209.99)	842.41 (95.73)[a]	4736.65 (404.82)[a]
All Retained	54.38 (7.66)	10.34 (2.92)	431.96 (94.85)	1733.49 (179.67)	2167.21 (368.30)	793.41 (75.99)[a]	4694.11 (490.09)[a]

Woody Debris (FWD & CWD) Biomass & Nutrients

Other Nutrients (N, Ca, K, P)

Analyses of N stocks in total post-harvest woody debris indicated that slash retention did not have a significant effect on total post-harvest N stocks ($F = 0.28$, $p = 0.7580$) in woody debris and no significant differences existed between each level of slash retention (Figure 22c). When looking at the magnitude of N stocks in FWD and CWD within the total post-harvest woody debris pool, FWD was substantially greater than CWD across all slash retention treatments (Figure 22c).

In addition to the major elements contained within biomass (C and N), stocks of Ca, K, and P were also analyzed in total post-harvest woody debris. Results showed that slash retention had a significant effect ($F = 9.72$, $p = 0.0005$) on Ca stocks in total post-harvest woody debris. Comparisons of each slash retention level showed that 'all slash retained' treatments were significantly greater than 'no slash retained' treatments (Figure 22d). Also, the Ca stocks in '20% slash retained' treatments were similar to both 'no slash retained' and 'all slash retained' treatments (Figure 22d). Similar magnitudes of Ca stocks were evident in the FWD and CWD pools within each slash retention treatment post-harvest (Figure 22d).

As with Ca, slash retention had a significant effect on stocks of K ($F = 14.84$, $p < 0.0001$) in total post-harvest woody debris. Specifically, each slash retention treatment was significantly different than all other treatments (Figure 22e). Stocks of K in 'all slash retained' treatments were significantly greater than 'no slash retained' and '20% slash retained' treatments (Figure 22e). 'No slash retained' treatments had significantly lower stocks of K than '20% slash retained' and 'all slash retained' treatments (Figure 22e). Finally, '20% slash retained' treatments had significantly greater stocks of K than 'no slash retained' treatments but significantly lower stocks than 'all slash retained' treatments (Figure 22e). Also, stocks of K within FWD and CWD pools were relatively similar in magnitude (Figure 22e).

Slash retention had a significant effect on stocks of P in total post-harvest woody debris ($F = 6.88$, $p = 0.0033$). Specifically, 'all slash retained' treatments had significantly greater stocks of P than 'no slash retained' treatments while '20% slash retained' treatments were similar to both 'no slash retained' and 'all slash retained' treatments (Figure 22f). Similar to N in woody debris, stocks of P in FWD were substantially greater in magnitude than in CWD within slash retention treatments (Figure 22f). Within CWD, stocks of P generally appeared to be equivalent across each treatment if only slightly greater in treatments with higher slash retention levels (Figure 22f).

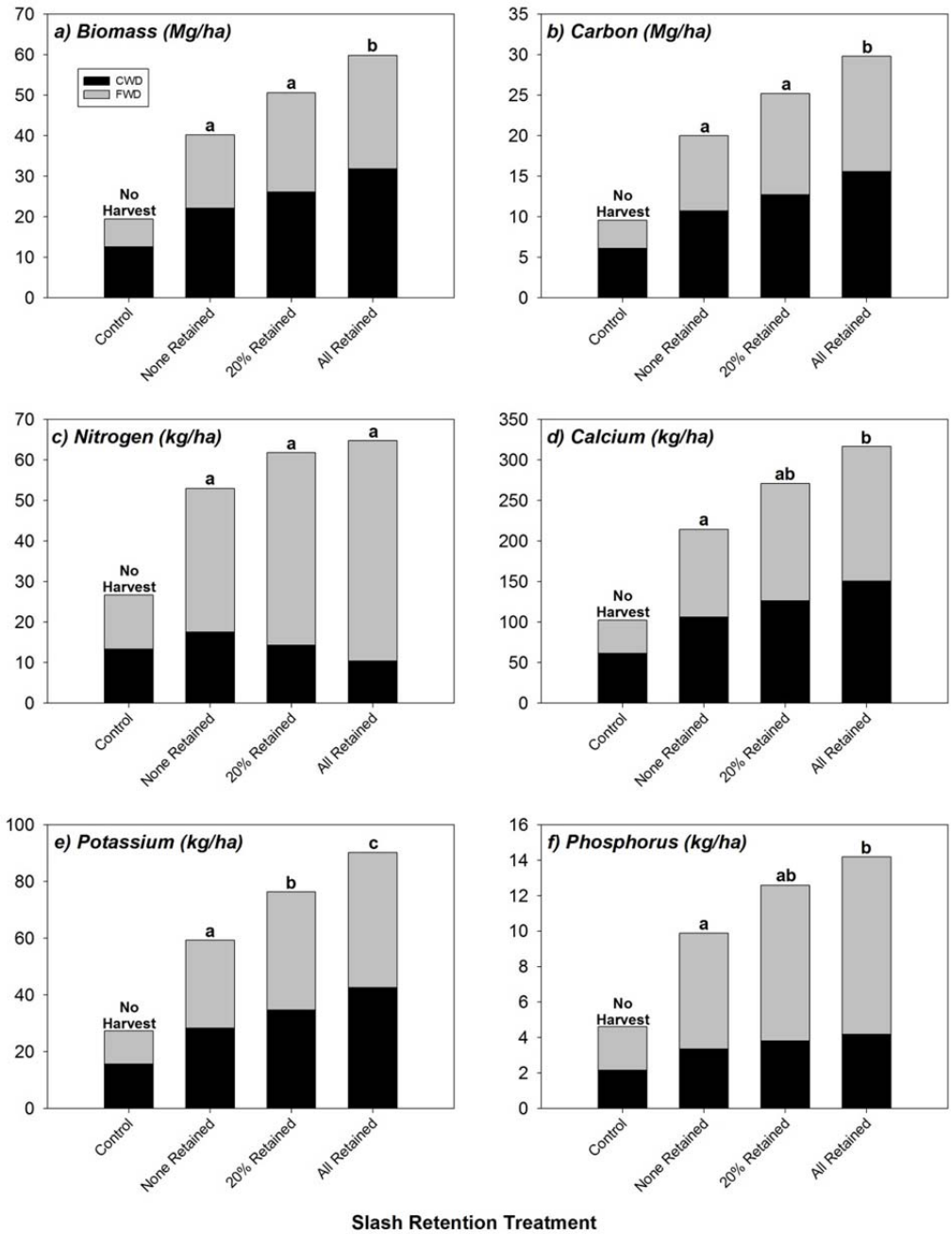


Figure 22a-f - Total post-harvest woody debris a) biomass in Mg/ha, b) C in Mg/ha, c) N in kg/ha, d) Ca in kg/ha, e) K in kg/ha, and f) P in kg/ha by FWD and CWD and slash retention treatment. Within each graph, bars with similar letters are not significantly different (p > 0.05) based on Tukey-Kramer comparisons from ANCOVA results. Figures show means and standard errors that have not been adjusted for the respective covariates however letters indicating statistical significance are based on adjusted values derived from ANCOVA results.

Woody Debris Biomass by Size & Treatment

Slash retention had a significant effect on most size classes of woody debris biomass, specifically FWD-M ($F = 3.75$, $p = 0.0341$), FWD-L ($F = 7.16$, $p = 0.0026$), and CWD-U ($F = 4.45$, $p = 0.0198$). Slash retention did not significantly affect biomass stocks in FWD-S ($F = 0.45$, $p = 0.6394$) and CWD-M ($F = 0.76$, $p = 0.4749$). More specifically, for FWD-M and CWD-U, 'all slash retained' treatments had significantly greater stocks of biomass than 'no slash retained' treatments while '20% slash retained' treatments were similar to both (Figure 23). For FWD-L, both '20% slash retained' and 'all slash retained' treatments were similar and had significantly greater stocks of biomass than 'no slash retained' treatments (Figure 23). The smallest and largest size class groupings, FWD-S and CWD-M, did not significantly differ between each level of slash retention (Figure 23). As with all other results, the unharvested control was not statistically analyzed but is presented for visual comparison to individual treatments. Within each size class, the magnitude of biomass stocks within slash retention treatments were substantially greater than stocks in the unharvested control, most notably for FWD-M, FWD-L, and CWD-U.

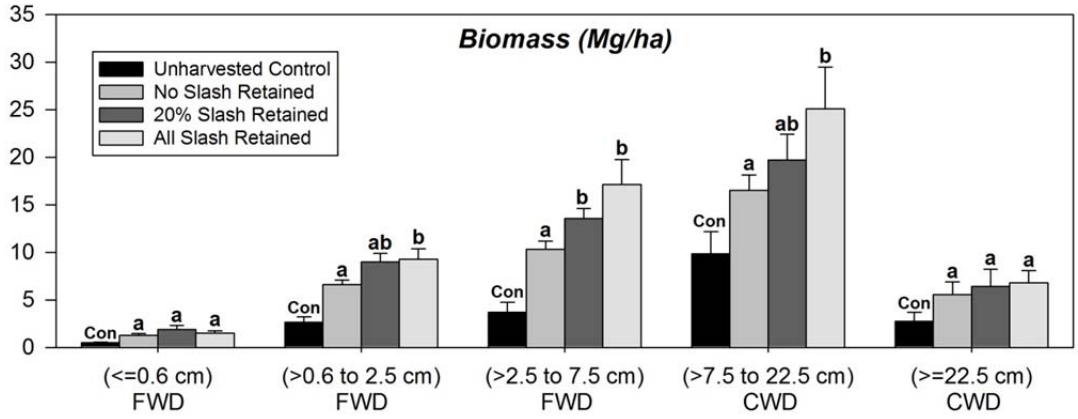


Figure 23 - Total post-harvest woody debris biomass in Mg/ha by size class and slash retention treatment. Bars within the same size class with similar letters are not significantly different ($p > 0.05$) based on Tukey-Kramer comparisons from ANCOVA or ANOVA results, depending on which analysis was most appropriate. The unharvested control (Con) was not included in statistical analyses. Where ANCOVA was applied, figures show means and standard errors that have not been adjusted for the respective covariates however letters indicating statistical significance are based on adjusted values derived from ANCOVA results.

Summary

Results of this study indicated that slash retention had a significant effect on post-harvest biomass and nutrient stocks, whereas there was no effect from green-tree retention immediately post-harvest. For slash retention levels, significant differences existed between 'no slash retained' and 'all slash retained' treatments. The level of '20% slash retained', as recommended in Minnesota biomass harvesting guidelines, was variable and did not represent a distinct level of slash retention different from 'no slash retained' and 'all slash retained' treatments. Regardless of slash retention level, large stocks of FWD biomass existed post-harvest and represented large pools of C, N, Ca, K, and P. Unsurprisingly, biomass and C showed nearly identical trends in amount and statistical significance across pools. No significant differences were observed in post-harvest total ecosystem N stocks between harvested stands.

Given the high levels of slash retained within all slash retention levels, it seems difficult to retain a specific amount of slash on site following harvest or to identify an ideal level for retention in these systems. Particularly, the high levels of incidental breakage during winter harvest in *Populus tremuloides*-dominated systems provide large inputs of nutrient-rich FWD regardless of prescribed slash retention levels. Therefore, retaining some level of FWD as well as forest floor and roots would possibly lessen negative impacts of intensive biomass harvesting on site nutrient stores and subsequently on future site productivity. Further research is necessary to understand the impacts of these high levels of slash on regenerating plants and their importance as a source of habitat. In addition, more detailed analyses of larger CWD material will provide key information on the effects of slash retention level on CWD as a source of habitat within freshly harvested stands. Finally, continued monitoring of the harvested sites will provide crucial information on future site productivity as well as the prevalence and persistence of current and future woody debris inputs, specifically from retained green-trees.

Fate of green trees by site and slash retention treatments among dispersed, clumped

Figure 24 - Dispersed treatment - Proportion of residual trees blown down in each slash treatment after 1 yr.

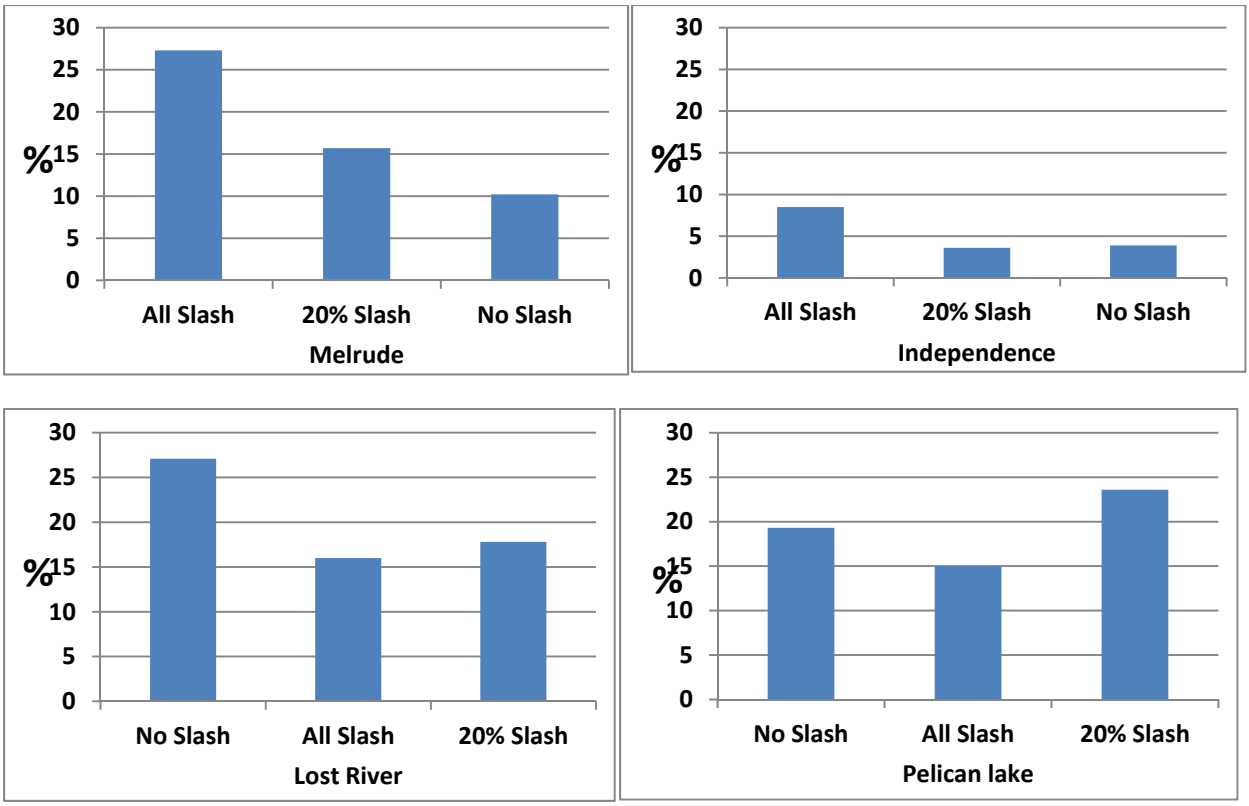


Figure 25 - Mean number of residual trees averaged by site after 1 yr. in dispersed stands. Each site represents three dispersed residual stands.

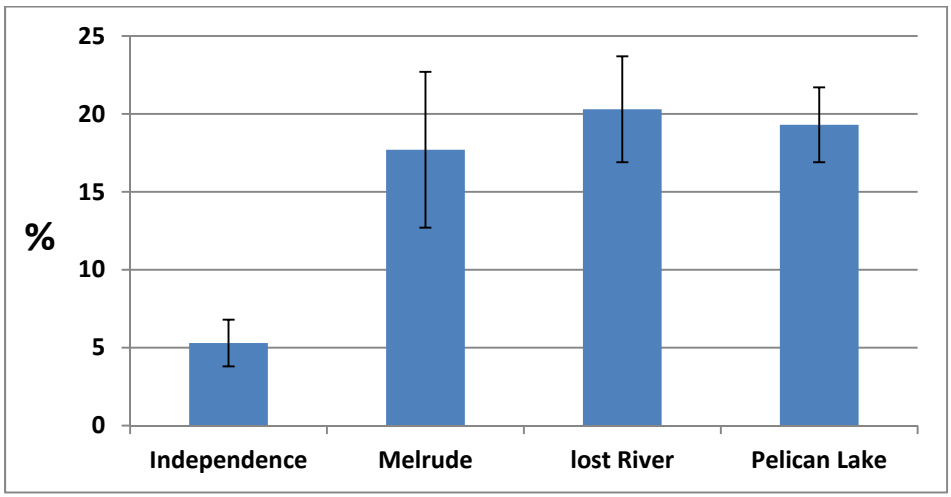


Figure 26 - Clumped treatment - Proportion of residual trees blown down in each slash treatment (n=2) after 1 yr. Each slash treatment represents two residual clumps.

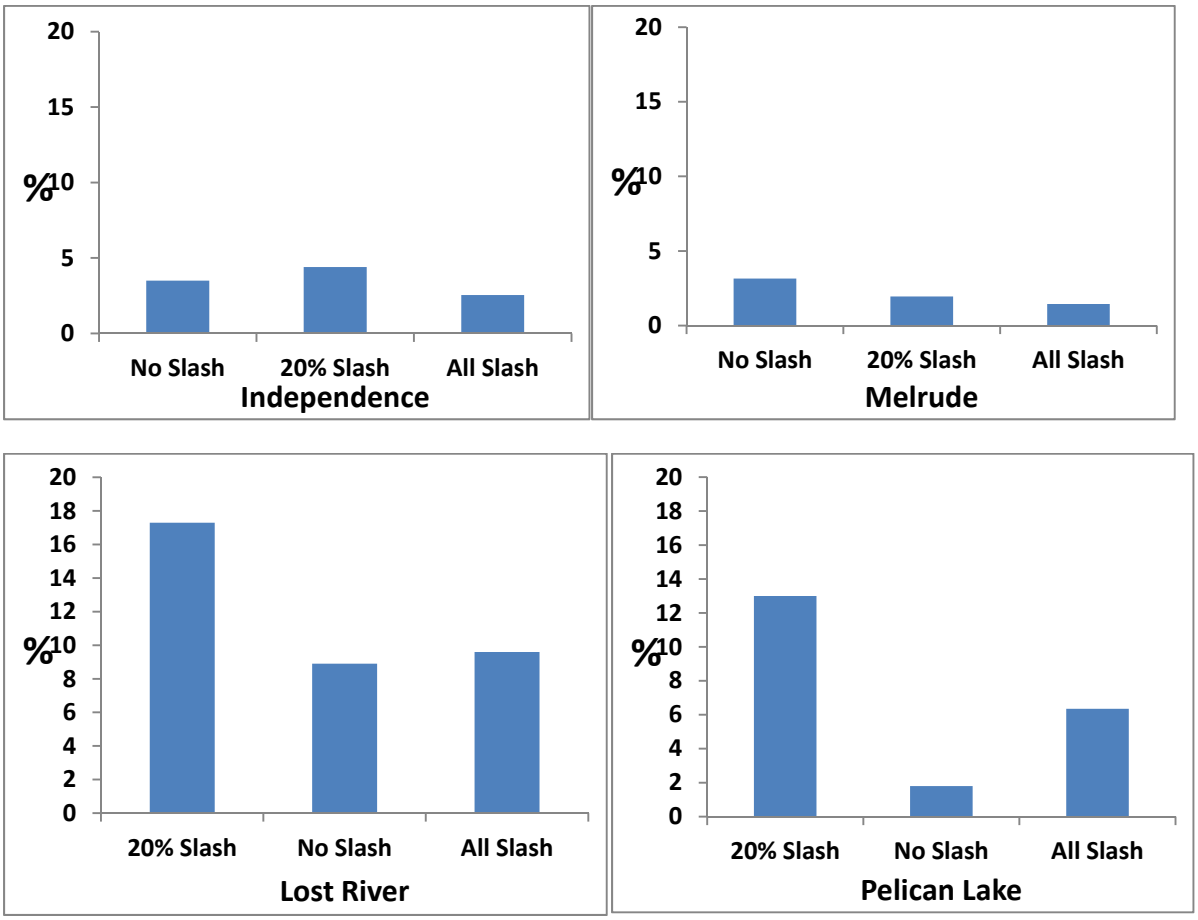
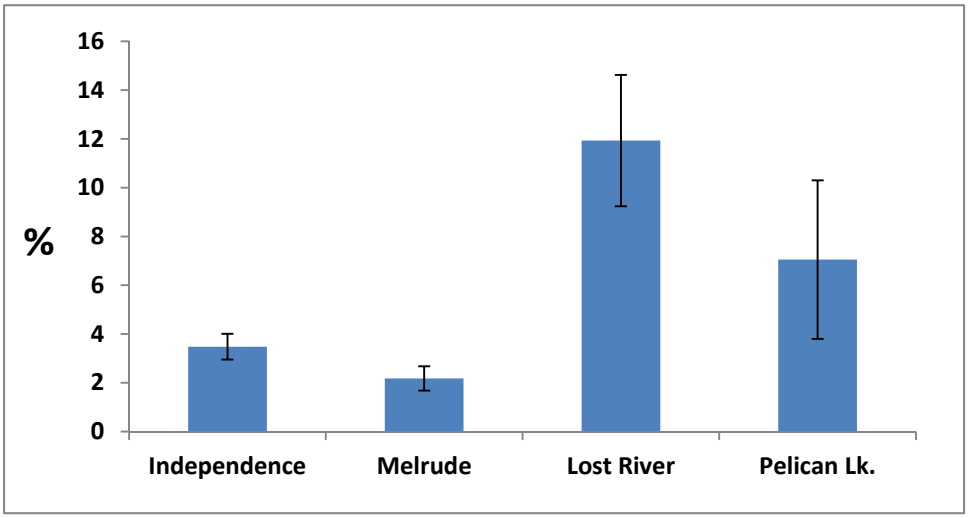


Figure 27 - Percent of original residual clumps blown down after 1yr. Each site represents six residual clumps.



Section I. - MFRC Biomass Project

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Appendix A – Section I. Fungi Tables

Table 1. Polyporoid species, observations, and host characteristics.

			Substrate Diameter		Host								
Polyporoid Species	Abrev.	Obs.	Mean	SD	ABBA	Acer	ACSP	Alnus	BEAL	BEPA	POTR	UNKH	Other
Antrodia serialis **(A)**	AntSer	59	10.6	7	1	0	0	0	0	0	49	9	0
Antrodia xantha **(A)**	AntXan	11	14.2	6	0	0	0	0	0	0	10	1	0
Antrodiella romellii	AntRom	4	8.5	4	2	0	0	0	0	0	1	1	0
Antrodiella semisupina **(A)**	AntSem	7	8.1	8	0	0	0	0	0	0	5	2	0
Antrodiella sp. 1	AntSp1	32	6.4	5	0	1	0	0	1	0	27	3	0
Antrodiella sp. 2 **(A)**		2	6.5	2	0	0	0	0	0	0	2	0	0
Antrodiella sp. 3 **(A)**		1	14.0	—	0	0	0	0	0	0	1	0	0
Bjerkandera adusta **(A)**	BjeAdu	311	17.5	7	0	0	0	0	0	9	300	1	1
Cerenna unicolor	CerUni	23	15.3	9	0	13	2	0	0	4	3	0	1
Ceriporia purpurea **(A)**		1	5.0	—	0	0	0	0	0	0	1	0	0
Ceriporia sp. 1 **(A)**		1	18.0	—	0	0	0	0	0	0	1	0	0
Ceriporiopsis aneirina **(A)**	CeiAne	37	6.0	4	0	0	0	0	0	0	35	2	0
Ceriporiopsis pannocincta	CeiPan	10	18.5	7	0	1	0	0	0	0	8	0	1
Ceriporiopsis sp. 1		1	14.0	—	1	0	0	0	0	0	0	0	0
Ceriporiopsis sp. 2 **(A)**	CeiSp2	5	9.2	6	0	0	0	0	0	0	4	1	0
Ceriporiopsis subvermispora **(A)**		1	20.0	—	0	0	0	0	0	0	1	0	0
Daedaleopsis confragosa	DaeCon	9	8.8	11	0	0	0	0	1	3	0	3	2
Datronia scutellata	DatScu	19	2.1	1	0	0	0	4	0	0	12	3	0
Elmerina sp. 1		1	25.0	—	0	0	0	0	0	0	1	0	0
Fomes fomentarius	FomFom	150	18.7	9	0	0	0	0	1	107	40	0	2

Fomitiporia punctata	FomPun	20	5.1	4	0	1	15	0	0	0	2	2	0
Fomitopsis cajanderi		2	22.5	4	0	0	0	0	0	0	1	0	1
Fomitopsis ochracea **(A)**	FomOch	84	21.6	9	0	0	0	0	0	0	84	0	0
Fomitopsis pinicola	FomPin	14	17.1	10	2	1	0	0	0	8	0	1	2
Funalia trogii **(RL) (A)**	FunTro	3	17.7	6	0	0	0	0	0	0	3	0	0
Fuscoporia ferrea	FusFer	16	4.1	2	0	3	3	1	0	0	6	3	0
Fuscoporia ferruginosa **(A)**	FusFeu	9	4.4	1	0	0	0	0	0	0	7	2	0
Fuscoporia gilva		1	4.0	—	0	0	0	1	0	0	0	0	0
Fuscoporia sp. 1	FusSp1	22	11.1	10	3	1	0	0	0	0	11	7	0
Ganoderma applanatum	GanApp	5	26.2	9	0	0	0	0	0	1	4	0	0
Gloeophyllum carbonarium		1	45.0	—	0	0	0	0	0	0	0	0	1
Gloeophyllum sepiarium		2	13.5	13	1	0	0	0	0	0	0	1	0
Gloeoporus dichrous	GloDic	10	13.6	7	0	1	0	0	0	1	8	0	0
Gloeoporus sp. 1		2	4.0	0	0	0	0	0	0	0	0	2	0
Inonotus obliquus	InoObl	4	10.8	3	0	0	0	0	2	2	0	0	0
Irpex lacteus	IrpLac	106	3.7	3	0	24	29	11	0	1	34	7	0
Ischnoderma resinosa	IscRes	8	17.8	8	0	0	0	0	1	5	0	2	0
Junghuhnia nitida **(A)**	JunNit	42	5.8	5	0	0	1	0	0	0	31	10	0
Lenzites betulina	LenBet	6	7.5	6	0	0	0	0	0	6	0	0	0
Mensularia radiata	MenRad	3	3.3	1	0	0	2	0	0	0	0	1	0
Oxyporus corticola	OxyCor	4	10.3	5	0	1	0	0	0	0	2	1	0
Oxyporus populinus	OxyPop	5	24.2	7	0	3	0	0	0	0	0	0	2
Oxyporus sp. 1 **(A)**		1	6.0	—	0	0	0	0	0	0	1	0	0
Perenniporia medula-panis		2	8.0	8	0	0	0	0	0	0	1	1	0
Perenniporia sp. 1 **(A)**		2	5.5	2	0	0	0	1	0	0	1	0	0
Perenniporia subacida	PerSub	3	17.7	3	1	0	0	0	0	1	1	0	0
Phaeolus schweinitzii		1	35.0	—	1	0	0	0	0	0	0	0	0
Phellinus conchatus		1	4.0	—	0	1	0	0	0	0	0	0	0
Phellinus igniarius s.l.	PheIgn	30	13.5	8	0	0	0	0	4	21	1	1	3
Phellinus laevigatus	PheLae	3	13.3	14	0	0	0	0	1	2	0	0	0
Phellinus sp. 1 **(A)**	PheSp1	1	11.0	—	0	0	0	0	0	0	1	0	0

Phellinus tremulae **(A)**	PheTre	173	23.6	11	0	0	0	0	0	0	172	1	0
Piptoporus betulinus	PipBet	40	10.6	7	0	0	0	0	0	38	0	0	2
Polyporus alveolaris	PolAlv	3	2.7	1	0	0	1	0	0	0	2	0	0
Polyporus arcularis **(A)**	PolArc	6	3.3	1	0	0	0	0	0	0	5	1	0
Polyporus brumalis	PolBru	14	3.4	2	0	0	0	5	0	2	5	2	0
Polyporus varius	PolVar	3	4.7	5	0	0	0	0	0	2	1	0	0
Porodaedalea chrysoloma		1	22.0	—	0	0	0	0	0	0	0	0	1
Postia caesia **(A)**	PosCae	20	5.6	4	0	0	0	0	0	0	13	7	0
Postia lactea **(A)**		2	8.0	0	0	0	0	0	0	0	1	1	0
Postia sericeomollis	PosSer	3	40.0	9	0	0	0	0	0	0	0	0	3
Postia sp. 1 **(A)**		2	4.0	0	0	0	0	0	0	0	2	0	0
Postia sp. 2	PosSp2	18	16.1	7	3	0	0	0	0	0	13	1	1
Postia subcaesia **(A)**	PosSub	11	3.7	1	0	0	0	0	0	0	10	1	0
Pycnoporellus fulgens **(RL)**		1	5.0	—	0	0	0	0	1	0	0	0	0
Rigidoporus crocatus	RigCro	3	33.3	3	1	0	0	0	0	1	0	0	1
Schizopora c.f. *radula*	SchRad	25	8.4	8	0	1	0	0	0	1	21	2	0
Schizopora sp. 1		2	20.0	17	0	1	0	0	0	0	1	0	0
Schizopora sp. 2 **(A)**		1	20.0	—	0	0	0	0	0	0	1	0	0
Schizopora sp. 3		1	25.0	—	1	0	0	0	0	0	0	0	0
Skeletocutis amorpha		1	10.0	—	1	0	0	0	0	0	0	0	0
Skeletocutis chrysella **(RL)** **(A)**	SkeChr	10	10.7	8	0	0	0	0	0	0	10	0	0
Skeletocutis nivea	SkeNiv	15	4.4	5	0	0	1	1	0	1	10	1	1
Skeletocutis sp. 1 **(A)**	SkeSp1	3	2.2	1	0	0	0	0	0	0	2	1	0
Skeletocutis sp. 2 **(A)**		1	4.0	—	0	0	0	0	0	0	1	0	0
Stromatoscypha fimbriata	StrFim	38	9.6	8	0	0	0	0	0	2	29	7	0
Trametes hirsuta **(A)**	TraHir	201	9.6	6	0	1	0	1	0	0	199	0	0
Trametes ochracea **(A)**	TraOch	5	11.6	5	0	0	0	0	0	0	5	0	0
Trametes pubescens	TraPub	47	7.5	7	0	0	0	14	0	25	5	3	0
Trametes versicolor	TraVer	6	10.2	7	0	1	1	0	0	0	4	0	0
Trechispora mollusca	TreMol	33	6.1	3	3	0	0	1	0	0	25	4	0

Trechispora sp. 1		2	9.0	1	2	0	0	0	0	0	0	0	0
Trechispora sp. 2 **(A)**		2	3.5	1	0	0	0	0	0	0	2	0	0
Trichaptum abietinum	TriAbi	31	12.1	7	30	0	0	0	0	0	0	0	1
Trichaptum biforme	TriBif	489	11.2	7	1	3	1	0	0	51	430	1	2
Tyromyces chioneus	TyrChi	47	8.0	7	0	0	1	2	0	2	36	5	1
Total		2358	12.7	9	54	63	57	42	12	296	1705	105	24

(A): a polyporoid species was present on aspen ≥95% of the time (excluding unknown hardwood; (RL): a species has red-list status in northern Europe.

Abbrev.: Polyporoid species without abbreviations had less than three occurrences and were excluded from the NMS analysis.

Host: ABBA = *Abies balsamea*, Acer = *Acer* spp., ACSP = *Acer spicatum*, Alnus = *Alnus* spp, BEAL = *Betula alleghaniensis*, BEPA = *Betula papyrifera*, POTR = *Populus tremuloides*, UNKH = unknown hardwood, and Other (*Betula* spp., *Fraxinus nigra*, *Picea glauca*, *Pinus strobus*, *Salix* spp., unknown, and unknown conifer).

Table 2. Kendall's Tau-b correlation coefficients from the second and third axes and quantitative variables (polyporoid species and deadwood characteristics). Significance values were determined using a sequential Bonferroni correction at p = 0.05 and are coded as: *p < 0.01; **p < 0.001; ns = non-significant. 1

Variables	NMS 2	NMS 3
Polyporoid Species		
Antrodia xantha	-0.232*	ns
Bjerkandera adusta	-0.362**	ns
Cerrena unicolor	ns	0.239*
Fomes fomentarius	0.258*	0.493**
Fomitiporia punctata	ns	0.304**
Fomitopsis ochracea	0.374**	-0.314**
Fuscoporia sp. 1	-0.250*	ns
Irpex lacteus	-0.354**	0.283**
Phellinus tremulae	ns	-0.284**
Piptoporus betulinus	0.279**	0.381**
Polyporus brumalis	0.289**	ns
Postia caesia	-0.331**	ns
Skeletocutis nivea	ns	0.239*
Trametes pubescens	0.267**	ns
Trichaptum abietinum	0.267**	ns
Trichaptum biforme	-0.222*	ns
Tyromyces chioneus	ns	0.317**
Deadwood Characteristics		
Diameter Class 1 (1-5 cm)	ns	0.258**
Diameter Class 2 (6-10 cm)	ns	0.270**
Diameter Class 6 (>26 cm)	ns	-0.240**
Decay Class 2	ns	0.240**
Substrate Type (Tree)	ns	-0.259**
Substrate (*Acer spicatum*)	-0.234*	0.281**
Substrate (*Betula papyrifera*)	0.245**	0.338**

Table 3. Sørensen similarity values for polyporoid species (presence or absence) by deadwood variables (decay class, substrate type, diameter class, and host species).

	Decay Class			
Deadwood Variables[a]	I	II	III	IV
I (17)	—			
II (69)	0.40	—		
III (61)	0.33	0.74	—	
IV (6)	0.17	0.08	0.12	—

	Substrate Type					
	Branch	Log	Suspended Log	Snag	Stump	Tree
Branch (48)	—					
Log (72)	0.65	—				
Suspended log (22)	0.55	0.44	—			
Snag (26)	0.52	0.48	0.63	—		
Stump (24)	0.48	0.43	0.57	0.60	—	
Tree (6)	0.11	0.13	0.21	0.25	0.33	—

	Diameter Class (cm)					
	1- <5	5- <10	10- <15	15- <20	20- <25	>25
1- <5 cm (53)	—					
5- <10 cm (51)	0.70	—				
10- <15 cm (44)	0.66	0.75	—			
15- <20 cm (33)	0.54	0.64	0.74	—		
20- <25 cm (36)	0.57	0.62	0.67	0.70	—	
>25 cm (35)	0.48	0.60	0.57	0.58	0.67	—

	Host[b]								
	ABBA	Acer	ACSP	Alnus	BEAL	BEPA	POTR	UNKH	Other
ABBA (16)	—								
Acer (17)	0.18	—							

ACSP (11)	0.07	0.43	—						
Alnus (11)	0.07	0.21	0.36	—					
BEAL (8)	0	0.08	0	0	—				
BEPA (24)	0.20	0.29	0.29	0.29	0.38	—			
POTR (62)	0.18	0.35	0.27	0.27	0.09	0.37	—		
UNKH (39)	0.29	0.32	0.32	0.32	0.17	0.41	0.65	—	
Other (19)	0.29	0.28	0.27	0.13	0.22	0.51	0.25	0.28	—

[a]Numbers in parenthesis beside each deadwood variable code refers to the number of unique polyporoid species unique to that category.
[b]Host taxa codes: ABBA = *Abies balsamea*, Acer = *Acer* spp., ACSP = *Acer spicatum*, Alnus = *Alnus* spp, BEAL = *Betula alleghaniensis*, BEPA = *Betula papyrifera*, POTR = *Populus tremuloides*, UNKH = unknown hardwood, and Other = *Betula* spp., *Fraxinus nigra*, *Picea glauca*, *Pinus strobus*, *Salix* spp., unknown, and unknown conifer.

Appendix B Section I – Amphibian and Small Mammal Tables

Table 1. List of amphibian and small mammal species with samples sizes ≥ 50 (excluding recaptures) captured in drift-fences during this study in Saint Louis County, Minnesota, 2010.

Common Name	Scientific Name	Site		Sample Size
		1	2	n =
American Toad	*Anaxyrus americanus*	X	X	298
Wood Frog	*Lithobates sylvaticus*	X	X	52
Short-tailed Shrew	*Blarina brevicauda*	X	X	169
Meadow Vole	*Microtus pennsylvanicus*	X	X	822
Southern Red-backed Vole	*Myodes gapperi*	X	X	353
Deer Mouse	*Peromyscus maniculatus*	X	X	77
Arctic Shrew	*Sorex arcticus*	X	X	
Masked / Pygmy Shrew	*Sorex cinereus/hoyi*	X	X	1117*
Water Shrew	*Sorex palustris*	X	X	
Meadow Jumping Mouse	*Zapus hudsonius*	X	X	73
Total				2961

* Number includes 59 unidentified *Sorex* specimens. *Sorex* spp. pooled in models.

Table 2. Parameter definitions and abbreviations used in models

Name	Type	Levels	Model Abbr.	Description
Harvest	Factor	2	Harvest-#	Control plots are represented by '1' and harvested plots are respresented by '2'.
Treatment	Factor	4	Treatment-#	Control plots are represented by 'Treatment-1', clearcuts by 'Treatment-2', harvest with dispersed green tree reserves by 'Treatment-3' and harvest with clumped green tree reserves by 'Treatment-4'.
Coarse Woody Debris	Continuous	-	CWD	Volume of downed coarse woody debris (m3/ha).
Sampling Period	Factor	3	Period-#	Three discrete sampling periods.
Site	Factor	2	Site-#	Represents both sites sampled.
Precipitation	Continuous	-	Precip.	Mean daily rainfall totals (mm).
Soil Temperature	Continuous	-	Temp-Soil	Mean soil temperature at 15cm below the soil surface (C°).
Air Temperature	Continuous	-	Temp-Min.	Mean daily minimum air temperature (C°).
Soil Moisture	Continuous	-	Soil-Moist.	Volumetric water content (%).
Plot	Factor	10	Plot	Experimental plots recieving a treatment (see above definiation of treatment).

Table 3. List of amphibians captured during visual encounter surveys (VES), Saint Louis County, Minnesota, 2010.

Common Name	Scientific Name	Site		Sample Size
		1	2	n =
Blue-spotted Salamander	*Ambystoma laterale*	X		1
Red-backed Salamander	*Plethodon cinereus*	X		6
American Toad	*Anaxyrus americanus*	X	X	4
Wood Frog	*Lithobates sylvaticus*	X	X	2
Spring Peeper	*Pseudacris crucifer*		X	2
Total				15

Table 4. List of amphibian and small mammal species captured by drift array sampling method during this study in Saint Louis County, Minnesota, 2010.

Common Name	Scientific Name	Site		Survey Method	
		1	2	VES	Drift Fence
Blue-spotted Salamander	*Ambystoma laterale*	X	X	X	X
Red-backed Salamander	*Plethodon cinereus*	X		X	X
American Toad	*Anaxyrus americanus*	X	X	X	X
Green Frog	*Lithobates clamitans*	X	X		X
Northern Leopard Frog	*Lithobates pipiens*		X		X
Mink Frog	*Lithobates septentrionalis*		X		X
Wood Frog	*Lithobates sylvaticus*	X	X	X	X
Spring Peeper	*Pseudacris crucifer*		X	X	
Boreal Chorus Frog	*Pseudacris maculata*	X			X
Short-tailed Shrew	*Blarina brevicauda*	X	X		X
Star-nosed Mole	*Condylura cristata*	X	X		X
Meadow Vole	*Microtus pennsylvanicus*	X	X		X
Southern Red-backed Vole	*Myodes gapperi*	X	X		X
Deer Mouse	*Peromyscus maniculatus*	X	X		X
Arctic Shrew	*Sorex arcticus*	X	X		X
Masked / Pygmy Shrew	*Sorex cinereus/hoyi*	X	X		X
Water Shrew	*Sorex palustris*	X	X		X
Red Squirrel	*Tamiasciurus hudsonicus*	X			X
Meadow Jumping Mouse	*Zapus hudsonius*	X	X		X

Table 5. Regression associations from the top-ranked model for *Anaxyrus americanus* captured in drift-fence arrays in Saint Louis County, Minnesota, 2010.

Species	Model	Explanatory Variables	Estimate	SE	Z-Value	P > |z|	
A. americanus	ANAM	Intercept	1.600	0.434	3.68	< 0.001	*
		Treatment-2	-0.925	0.532	-1.74	0.082	*
		Treatment-3	-0.423	0.518	-0.82	0.414	
		Treatment-4	-0.803	0.519	-1.55	0.122	
		Precip.	-0.233	0.114	-2.04	0.042	*
		Period-2	-0.825	0.466	-1.77	0.077	*
		Period-3	-0.724	0.477	-1.52	0.129	
		Treatment-2 * Period-2	1.290	0.553	2.33	0.020	*
		Treatment-3 * Period-2	0.207	0.516	0.40	0.688	
		Treatment-4 * Period-2	0.772	0.526	1.47	0.142	
		Treatment-2 * Period-3	1.153	0.566	2.04	0.041	*
		Treatment-3 * Period-3	-1.045	0.591	-1.77	0.077	*
		Treatment-4 * Period-3	-0.076	0.573	-0.13	0.894	
		Treatment-2 * Precip.	-0.022	0.135	-0.17	0.869	
		Treatment-3 * Precip.	0.257	0.135	1.90	0.057	*
		Treatment-4 * Precip.	0.208	0.134	1.55	0.120	

* Statistical signficance at $\alpha < 0.1$

Table 6. Regression associations from the top-ranked models for *Lithobates sylvaticus* captured in drift-fence arrays in Saint Louis County, Minnesota, 2010.

Species	Model	Explanatory Variables	Estimate	SE	Z-Value	P > |z|	
L. sylvaticus	LISYa	Intercept	5.337	1.727	3.09	0.002	*
		Harvest	-1.583	0.775	-2.04	0.041	*
		Soil-Temp	-0.294	0.101	-2.91	0.004	*
		Site-2	-1.658	0.628	-2.64	0.008	*
	LISYb	Intercept	1.199	0.679	1.77	0.077	*
		Harvest	-2.168	0.696	-3.11	0.002	*
		Period-2	-0.828	0.344	-2.41	0.016	*
		Period-3	-0.862	0.353	-2.44	0.015	*
		Site-2	-1.602	0.602	-2.66	0.008	*

* Statistical signficance at $\alpha < 0.1$

Table 7. Regression associations from the top-ranked model for *Microtus pennsylvanicus* captured in drift-fence arrays in Saint Louis County, Minnesota, 2010.

Species	Model	Explanatory Variables	Estimate	SE	Z-Value	P > |z|	
M. pennsylvanicus	MIPE	Intercept	1.853	0.228	8.12	< 0.001	*
		Harvest-2	-0.318	0.232	-1.37	0.172	
		Period-2	0.476	0.090	5.29	< 0.001	*
		Period-3	0.330	0.093	3.54	< 0.001	*
		Site-2	-1.165	0.359	-3.24	0.001	*
		Harvest-2 * Site-2	0.738	0.377	1.96	0.050	*

* Statistical signficance at $\alpha < 0.1$

Table 8. Regression associations from the top-ranked model for *M. gapperi* captured in drift-fence arrays in Saint Louis County, Minnesota, 2010.

Species	Model	Explanatory Variables	Estimate	SE	Z-Value	P > |z|	
M. gapperi	MYGA	Intercept	15.128	3.954	3.83	< 0.001	*
		Harvest-2	-0.309	0.377	-0.82	0.413	
		Temp-Min	-0.865	0.264	-3.28	0.001	*
		Temp-Soil	-0.160	0.088	-1.83	0.068	*
		Period-2	0.342	0.474	0.72	0.471	
		Period-3	0.754	0.426	1.77	0.077	*
		Harvest-2 * Period-2	0.693	0.396	1.75	0.080	*
		Harvest-2 * Period-3	-0.220	0.343	-0.64	0.523	

* Statistical signficance at $\alpha < 0.1$

Table 9. Regression associations from the top-ranked models for *B. brevicauda*. captured in drift-fence arrays in Saint Louis County, Minnesota, 2010.

Species	Model	Explanatory Variables	Estimate	SE	Z-Value	P > |z|	
B. brevicauda	BLBRa	Intercept	-1.460	0.450	-3.25	0.001	*
		Treatment-2	-0.999	0.312	-3.20	0.001	*
		Treatment-3	-1.266	0.360	-3.51	< 0.001	*
		Treatment-4	-0.655	0.286	-2.29	0.022	*
		CWD	0.007	0.004	1.83	0.067	*
		Period-2	2.141	0.372	5.76	< 0.001	*
		Period-3	2.324	0.370	6.29	< 0.001	*
		Site-2	-0.564	0.160	-3.51	< 0.001	*
	BLBRb	Intercept	-1.077	0.425	-2.54	0.011	*
		Harvest-2	-0.599	0.252	-2.38	0.018	*
		Period-2	2.141	0.374	5.73	< 0.001	*
		Period-3	2.324	0.372	6.26	< 0.001	*
		Site-2	-0.553	0.182	-3.04	0.002	*

* Statistical signficance at $\alpha < 0.1$

Table 10. Regression associations from the top-ranked models for *P. maniculatus* captured in drift-fence arrays in Saint Louis County, Minnesota, 2010.

Species	Model	Explanatory Variables	Estimate	SE	Z-Value	P > |z|	
P. maniculatus	PEMAa	Intercept	19.955	8.789	2.27	0.023	*
		Harvest-2	0.754	1.084	0.70	0.487	
		Temp-Min	-1.622	0.653	-2.49	0.013	*
		Precip.	0.201	0.105	1.91	0.056	*
		Period-2	1.346	1.324	1.02	0.310	
		Period-3	1.307	1.183	1.10	0.270	
		Site-2	-0.845	0.376	-2.25	0.025	*
		Harvest * Period-2	-0.048	1.297	0.04	0.970	
		Harvest * Period-3	-1.923	1.204	-1.60	0.110	
	PEMAb	Intercept	20.404	8.709	2.34	0.019	*
		Harvest-2	0.003	0.497	0.01	0.996	
		Temp-Min	-1.605	0.652	-2.46	0.014	*
		Precip.	0.210	0.104	2.01	0.045	*
		Period-2	1.287	0.516	2.50	0.013	*
		Period-3	-0.371	0.458	-0.81	0.418	
		Site-2	-0.867	0.385	-2.25	0.024	*

* Statistical signficance at $\alpha < 0.1$

Table 11. Regression associations from the top-ranked models for *Z. hudsonius* captured in drift-fence arrays in Saint Louis County, Minnesota, 2010.

Species	Model	Explanatory Variables	Estimate	SE	Z-Value	P > |z|	
Z. hudsonius	ZAHUa	Intercept	-2.449	0.993	-2.47	0.014	*
		Harvest	0.393	0.676	0.58	0.561	
		CWD	-0.014	0.008	-1.77	0.077	*
		Period-2	3.235	0.731	4.42	< 0.001	*
		Period-3	1.964	0.765	2.57	0.010	*
	ZAHUb	Intercept	-2.034	0.998	-2.04	0.041	*
		Treatment-2	0.404	0.707	0.57	0.568	
		Treatment-3	1.304	0.790	1.65	0.099	*
		Treatment-4	0.422	0.678	0.62	0.534	
		CWD	-0.021	0.009	-2.49	0.013	*
		Period-2	3.235	0.731	4.43	< 0.001	*
		Period-3	1.964	0.768	2.57	0.102	

* Statistical signficance at $\alpha < 0.1$

Table 12. Regression associations from the top-ranked model for *Sorex* spp. captured in drift-fence arrays in Saint Louis County, Minnesota, 2010.

Species	Model	Explanatory Variables	Estimate	SE	Z-Value	P > |z|	
Sorex spp.	SOREX	Intercept	-15.094	7.828	-1.93	0.054	*
		Treatment-2	13.178	8.051	1.64	0.102	*
		Treatment-3	19.925	8.114	2.46	0.014	*
		Treatment-4	17.885	7.965	2.25	0.025	*
		Precipiation	0.083	0.020	4.17	< 0.001	*
		Period-2	-2.272	1.253	-1.81	0.070	*
		Period-3	-2.817	1.747	-1.61	0.107	
		Site-2	0.318	0.069	4.63	< 0.001	*
		Temp-Soil	1.154	0.551	2.09	0.036	*
		Treatment-2 * Period-2	3.880	1.309	2.96	0.003	*
		Treatment-3 * Period-2	4.521	1.296	3.49	< 0.001	*
		Treatment-4 * Period-2	3.903	1.286	3.03	0.0024	*
		Treatment-2 * Period-3	4.449	1.798	2.47	0.0131	*
		Treatment-3 * Period-3	5.303	1.795	2.95	0.0031	*
		Treatment-4 * Period-3	4.369	1.777	2.46	0.0139	*
		Treatment-2 * Temp-Soil	-1.048	0.564	-1.86	0.063	*
		Treatment-3 * Temp-Soil	-1.437	0.566	-2.54	0.0111	*
		Treatment-4 * Temp-Soil	-1.283	0.560	-2.29	0.0218	*

* Statistical signficance at $\alpha < 0.1$

Section II. Publications in preparation

IN PRESS

Brazee, Nicholas J., Daniel L. Lindner, Shawn Fraver, Anthony W.D'Amato, and Amy M. Milo. *In Press*. Wood-inhabiting, polyporoid fungi in aspen-dominated forests managed for biomass in the U.S. Lake States. *Fungal Ecology*.

Abstract

To better understand the potential long-term effects of biomass harvesting on biodiversity, the polyporoid fungi community was characterized from 120 plots at four aspen-dominated forests in Minnesota. Four deadwood variables (substrate species, substrate type, decay class, and diameter class) were recorded for each polyporoid species occurrence. A total of 2358 polyporoid occurrences, representing 86 species, were recorded on 16 tree species. Eight species (*Trichaptum biforme*, *Bjerkandera adusta*, *Trametes hirsuta*, *Phellinus tremulae*, *Fomes fomentarius*, *Irpex lacteus*, *Fomitopsis ochracea* and *Antrodia serialis*) made up 67% of occurrences. Four polyporoid species (*Funalia trogii*, *Pycnoporellus fulgens*, *Rigidoporus crocatus* and *Skeletocutis chrysella*) are potentially rare and/or threatened in the Lake States. Similarity indices and non-metric multidimensional scaling demonstrated that diameter class was the most important deadwood variable influencing polyporoid species occurrence. Aspen-dominated systems show great potential for biomass production, but these forests also support a species-rich community of polyporoid fungi, including potentially rare species.

Keywords: ecosystem indicators; non-metric multidimensional scaling; Minnesota; molecular operational taxonomic units; Polyporaceae; woody feedstocks.

IN PREPARATION FOR PUBLICATION

Initial Response of Amphibian and Small Mammal Species to Timber and Coarse Woody Debris Harvest in Mixed Hardwood Forests of northern Minnesota

Christopher E. Smith - MS Thesis

Recently, there has been growing public awareness of both the finite nature and the ecological effects of using fossil fuels to generate energy. This public awareness has created an increased interest in renewable bioenergy resources, especially those produced within a nation's own borders. In light of this fact, I addressed whether the relative abundance and body condition of amphibians and small mammals varied predictably across forest plots that differ in the amount of woody biomass removal using drift-fence arrays and visual encounter surveys. Results varied between species. However, only two species (*Blarina brevicauda* and *Lithobates sylvaticus*) showed a clear negative response to harvest. These data showed that the initial effect of harvest, or harvest and green tree reserve type, appear to be important predictors for many of the amphibian and small mammal species studied. To ensure forest sustainability, further study during stand maturation will be necessary to better ascertain the long-term effects of coarse woody debris harvest on amphibian and small mammal species.

Nutrient concentrations in coarse and fine woody debris in Populus tremuloides-dominated forests, northern Minnesota, U.S.A.

Paul Klockow MS Thesis

Abstract

Recent forest harvesting practices, specifically harvesting woody biomass as a source of bioenergy feedstock, may remove more woody debris from a site than does conventional harvesting. Because woody debris plays a key role in maintaining ecosystem nutrient stores following disturbance, understanding woody debris nutrient dynamics is necessary to assess the long-term nutrient consequences of altered harvesting practices and disturbance regimes. Nutrient concentrations of various sizes, decay classes, and species of woody debris were characterized within Populus tremuloides-dominated forests of northern Minnesota, U.S.A. Nutrient concentrations were significantly affected by decay state and generally increased as decay progressed. Concentrations of N, Mn, Al, Fe, and Zn in coarse woody debris (> 7.5 cm diameter) increased between one and three orders-of-magnitude while K decreased by an order-of-magnitude with progressing decay. Fine woody debris ($\leq$ 7.5 cm diameter) had higher nutrient concentrations than coarse woody debris for all nutrients except Na and Mn, and nutrient concentrations varied among species. These results underscore the complexity of nutrient dynamics within woody debris in forested ecosystems and suggest that retaining fine woody debris at harvest can provide a potentially important source of nutrients following intensive removals of biomass feedstocks.

Impacts of post-harvest slash and live-tree retention on biomass and nutrient stocks in *Populus tremuloides*-dominated forests, northern Minnesota, U.S.A.

Paul Klockow MS Thesis

Abstract

Globally, there is widespread interest in using forest-derived biomass as a source of bioenergy. While conventional timber harvesting generally removes only merchantable tree boles, harvesting biomass feedstock can remove all forms of biomass (i.e., trees down through to forest floor material) resulting in a greater loss of biomass, nutrients, and habitat from a site. To investigate the potential impacts of this practice, this study examined the initial impacts (pre- and post-harvest) of various levels of slash and live-tree retention on biomass and nutrient stocks in Populus tremuloides-dominated forests of northern Minnesota. Treatments examined included 0%, 20%, and 100% slash retention with no, dispersed, and aggregate tree retention.

Slash retention was the primary factor affecting immediate post-harvest biomass and nutrient stocks within total ecosystem and woody debris pools. High levels of biomass and nutrients in harvest slash were observed in all treatments compared to the unharvested control. Typically, 100% slash retained treatments contained significantly greater biomass and nutrient stocks than no slash retained treatments. Stocks of biomass and nutrients within the 20% slash retained treatment, a slash retention level recommended by Minnesota's biomass harvesting guidelines, were generally similar to both no slash retained and 100% slash retained treatments. When split into additional size classes, biomass in smaller-diameter slash material (typically between 2.5 cm and 22.5 cm in diameter) tended to dominate the woody debris pool regardless of slash retention level. Trends among these size classes were generally similar to those in the total woody debris pool where 100% slash retained treatments contained significantly greater amounts of biomass than no slash retained treatments and 20% slash retained treatments were similar to both no slash and 100% slash retained treatments.

Given the high stocks of smaller diameter slash material retained on these sites, the results of this study highlight the high level of breakage during winter harvest operations in P. tremuloides forests regardless of prescribed slash retention levels. In addition, the high stocks of nutrients within this smaller slash material underscores the importance of deliberate retention of fine woody debris as a source of nutrients following harvests of biomass feedstocks.

Immediate and long term changes to vascular plant diversity and composition due to biofuel harvests.

Miranda Curzon Ph.D. thesis in progress

As a complement to this project, additional ongoing funding from the USDA/DOE is enabling the assessment of three LTSP installations to look at the medium-term impacts of biofuels harvests on site productivity in aspen-dominated forests with loamy, sandy, and clay soils. Data that describe soil nutrient and carbon stores, aboveground productivity, biomass production, and nutrient and carbon cycling rates have been collected at five year intervals for 15 years following harvest.