Public Service Commission of Wisconsin
& The Statewide Energy Efficiency and Renewables Administration

Environmental and Economic Research and Development Program

Final Report
March 2010

Impacts of Biomass Removal on Carbon and Nutrient Pools in Wisconsin Northern Hardwood Forests: Establishment of a Long-Term Study

Prepared by:
David J. Mladenoff, Jodi A. Forrester, Jason Schatz
Department of Forest and Wildlife Ecology
University of Wisconsin - Madison

focus on energy[sm]
The power is within you.

Executive Summary

Background

A better understanding of the environmental impacts of harvesting forest biomass has become a priority because of the recent emphasis on renewable, alternative energy sources. Though removing additional biomass from our forests may reduce the use of fossil fuels, improve aesthetic appearance and stimulate job creation, there may be detrimental impacts on the forest ecosystem. Woody debris is a critical structural and functional component of forests, yet its influence on fundamental questions like carbon exchange and storage remain poorly understood. *Our overall research question is: how will the removal of all biomass during single tree to small group selection harvests alter carbon and nutrient storage in forest soils over the long-term?* Understanding how forest management affects longer term storage and turnover rates of soil nutrients is critical to evaluate the sustainability of possible management alternatives for biomass energy production – especially in the context of increasing atmospheric CO_2 and deposition of anthropogenic nitrogen.

Research Objective

This study focuses on the effects of biomass harvest and removal on key nutrients in Wisconsin northern hardwood forests, including nitrogen, phosphorus, calcium, and potassium. Our objectives were to (1) measure above- and belowground nutrient pools in a second-growth northern hardwood forest and (2) predict how intensive utilization and removal of aboveground biomass will alter the belowground nutrient status.

Methods

We have established baseline conditions of soil nutrient status in long-term permanent plots where woody debris levels have been augmented or left unaltered following single-tree to small group selection harvests. To estimate the site nutrients removed during harvests, we analyzed tree components for site and species specific nutrient concentrations. We used fine-scale sampling near woody debris of varied decay stages to assess if belowground nutrient storage may be altered over time following woody debris removal.

Results and Conclusions

The majority of the forest's nutrient capital is contained in the living aboveground biomass as opposed to the woody debris or forest floor strata. The experimental group selection cuts removed approximately 4-5% of total aboveground N, K and Ca pools. Where the harvested wood was left in place following cutting, the woody debris nutrient pool increased to over four times the reference conditions. The largest pool of N is in the mineral soil and was not observed to differ between experimental treatments after two years.

The nutrient content of the forest floor appeared higher near woody debris of any type. Potassium in the forest floor was significantly greater beneath coarse and fine woody debris than at greater distances away from the debris. Soil nutrient pools beneath debris were similar to those estimated away from debris with few exceptions.

These results establish the initial conditions of the forest before and immediately following forest harvest. Repeated sampling in future years will allow us to study the impacts of intensive harvests to evaluate the sustainability of this management practice.

Table of Contents

Tables and Figures

Introduction

Forests and Renewable Energy

Traditional management for wood fiber, is now being augmented with demands for more intensive harvest for bioenergy use. Therefore it is even more important that research close information gaps in knowledge about forest ecosystem sustainability (Landsberg and Gower 1997, Volk et al. 2004). Growth in use of wood as a renewable bioenergy source is occurring worldwide. In Finland energy production from the utilization of forest residues increased 22-fold between 1995 and 2003 and in Sweden production raised fivefold between 2002 and 2005 (Walmsley et al. 2009). A clear understanding of the role of woody debris, both fine and coarse, in the sustainability of forest ecosystems is unquestionably important as both short-rotation forestry and intensive utilization of forest biomass could greatly reduce these components from forested ecosystems (Hart 1999).

Sustainable forest management activities must at a minimum maintain soil productivity. Site productivity has been found to decrease in response to management treatments that reduce soil porosity and/or remove organic matter (Stone 2002). Several decades ago an international network of cooperators established the Long-Term Soil Productivity (LTSP) study that was designed to assess how soil porosity and organic matter content influence soil processes that control forest productivity and sustainability (Powers et al. 2004). Experimental sites were located across major forest types and soil groups throughout the United States and Canada. Organic matter treatments included 3 levels: bole removed, whole tree harvesting, and total surface organic matter removal (WTH plus forest floor). After five years, the Lakes States aspen LTSP sand locations in MN and MI reported that stand diameter, height and biomass were negatively related to the intensity of organic matter removal, suggesting a potential decline in productivity with repeated total tree harvesting on sand soils (Stone 2002). These treatment differences were not significant on the fine-textured soil sites. Additionally sites in MN and MI had the slowest recovery from compaction rates, supporting the importance of timing of forest management activities in the area (Powers et al. 2005).

An affiliate study established on contrasting soil types of medium-quality in northwestern WI reported that aspen growth on plots where organic matter had been removed 12 years earlier, lagged behind those where only live boles were harvested but the differences were not significant at that time (Bockheim et al. 2005). Few treatment-related differences in soil and chemical properties were found 2 years post-treatment on either the loamy sand or clay-loam sites. Twelve years after treatment, aspen growth was higher on the loamy sand site than the clay-loam, though patterns are attributed to differences in deer herbivory and insect outbreaks rather than soil quality (Bockheim et al. 2005).

Whole tree harvest was found to remove up to 3-4 times larger quantities of N, P and K in tree biomass and lead to greater competition with tree natural regeneration than conventional bole-only harvesting in a study comparing second rotation Sitka spruce stands in North Wales over two decades post-harvest (Walmsley et al. 2009). The removal of the fine woody debris led to a reduction in concentrations of soluble cations such as K, Na, and Ca in the surface organic soil horizon, but not soil organic matter. Calcium concentrations increased in the lower mineral soil horizon – a change they speculate could be attributable to differences in rooting depths between the harvest types. The implications of vertical displacements of cations such as this are important since this could lead to long-term tree nutrition deficiencies. The second-rotation trees already appeared to be influenced by whole-tree removal, with significantly reduced diameters and moderately reduced heights and basal areas. Also, in northern Wisconsin, work from our previous collaborative old-growth study showed evidence for Ca depletion even without harvesting, likely due to acidic atmospheric deposition (Bockheim and Crowley 2002). These studies indicate that slash retention may or may not have long-term implications and the initial nutrient status of the site may greatly influence the impacts of removing additional forest materials.

Background

Woody debris is a critical component of forest ecosystems since it retains essential nutrients, stores water, contributes to soil development, and provides habitat for bacteria, insects, fungi, plants, and animals. Coarse woody debris (CWD) influences the maintenance of species diversity, soil nutrient cycling, and global carbon dynamics, yet despite its importance, its influence on fundamental questions like carbon exchange and storage remain poorly understood and a major source of uncertainty (Harmon et al. 1986, Yatskov et al. 2003, Suchanek et al. 2004).

Like CWD, canopy gaps are a structural characteristic more common to mature forests that affect biogeochemical cycles, productivity, and biodiversity of forest stands (Clebsch and Busing 1989, Dahir and Lorimer 1996, Scheller and Mladenoff 2002, Latty et al. 2006). Canopy openings are created both through natural tree mortality or forest harvesting. The microclimate often differs within these forest gaps and from surrounding intact canopy areas, with air and soil temperature, soil moisture and solar radiation generally increasing after canopy disturbance (Collins and Pickett 1987, Denslow and Spies 1990, Gray et al. 2002). Decay rates of woody debris are related to microbial activity, air temperature, moisture availability and substrate quality (Edmonds et al. 1986, Harmon et al. 1995); several of which may be altered following canopy removal. If decomposition is occurring at a different rate within canopy openings, the potentially faster reduction of this pool is important since these increased rates could eventually affect the stand woody debris pool and the carbon and nutrient balance of the ecosystem.

Whole tree harvesting affects canopy architecture while removing potentially significant quantities of nutrients contained in CWD and fine woody debris (FWD). While FWD comprises a small proportion of total forest biomass, many components such as leaves and cambium contain disproportionate quantities of nutrients compared to bole wood (Powers et al. 2005). Of the potentially limiting nutrients, calcium appears most subject to long term depletions (Mann et al. 1988, Federer et al. 1989). Nutrient budget models suggest that whole tree harvesting could remove enough nutrients for long term productivity to decline, though evidence from the field as mentioned previously, has been generally unclear due to a lack of long term studies and inability to clearly separate harvesting practices from other treatments and conditions (Janowiak and Webster 2010). Our experimental design allows clear comparisons to be made between various wood removal and addition treatments.

Flambeau Experiment

The study here described was part of the Flambeau Experiment, a study begun in 1994 as a collaboration between the Wisconsin Department of Natural Resources and UW-Madison. The precursor observational phase of the Flambeau Experimental noted two major changes in forest structure resulting from harvest. First, old-growth forests contain more and larger (by about 70%) fallen timber and snags than second-growth stands. Second, individual gaps in the canopy are twice as big in old-growth stands. Based on these observational studies, the Flambeau Experiment seeks to experimentally modify forest management in order to allow second-growth stands to more rapidly develop the structural features of old-growth stands.

Experimental treatments within the Flambeau Experiment include:

1) canopy gap creation (cut and remove wood)
2) woody debris (WD) addition
3) canopy gap creation + WD addition
4) mechanical (harvesting equipment pass through)
5) fenced (deer exclusion) + canopy gap creation
6) fenced
7) control (no manipulation)

The study described in this report uses a subset of treatments from the Flambeau Experiment (for full suite of treatments see text box above) **to assess the effects of biomass harvest and removal on carbon and key nutrients in Wisconsin forests, including nitrogen, calcium, and potassium.** Our objectives are to (1) measure above- and belowground nutrient pools in a second-growth northern hardwood forest and (2) predict how intensive utilization and removal of aboveground biomass will alter the belowground nutrient status. This work will establish baseline conditions of soil nutrient status in long-term permanent plots where woody debris levels have been augmented or left unaltered following single-tree to small group selection harvests.

Figure 1. Location map of Flambeau River state Forest in northern Wisconsin, USA.

Site Description

The Flambeau Experiment is located within the Flambeau River State Forest, an over-36,500 ha property located in north central Wisconsin, USA (Fig. 1). The 300 ha study site is located within the southernmost portion of the Flambeau State Forest, and the Wisconsin Department of Natural Resources has committed to hosting the experiment for 50 years. After two years of intensive site evaluation, the Flambeau Experiment site was selected as representative of the composition and age class structure of sugar maple (*Acer saccharum*) dominated northern hardwood forests, which cover 5.3 million acres and constitute the most abundant forest type in Wisconsin.

Soils on the site are predominantly well-drained silt loams (glossudalfs) of the Magnor and Freeon series overlaying dense glacial till. January and July air temperatures (2005-2008) average -10 and 20º C, respectively with mean annual precipitation of 570 mm. The median length of the growing season is 105 days (1971-2000; Midwest Regional Climate Center). Annual precipitation for 2007-2008 was 618 mm and 530 mm, respectively based on a rain gauge in the center of the research area.

The stand is largely an even-aged, second-growth mature forest with most stems originating between 1920-1940s. The overstory is dominated by sugar maple (*Acer saccharum*), American basswood (*Tilia americana*) and white ash (*Fraxinus americana*), with lesser components of black ash (*Fraxinus nigra*), bitternut hickory (*Carya cordiformis*) and eastern hemlock (*Tsuga canadensis*) (Table 1).

Table 1. Structure and composition of trees >10 cm diameter at breast height of the study area in Flambeau River State Forest (n=35, 80m x 80m plots).

Species	Density (stem/ha)			Basal area (m^2/ha)		
	Mean		S.E.	Mean		S.E.
Sugar maple (*Acer saccharum*)	287.72	±	8.35	16.34	±	0.59
American basswood (*Tilia americana*)	51.43	±	4.59	4.62	±	0.40
Ash (*Fraxinus spp.*)	45.40	±	5.75	4.33	±	0.52
Bitternut Hickory (*Carya cordiformis*)	23.66	±	5.40	1.19	±	0.27
Eastern hophornbeam (*Ostrya virginiana*)	18.04	±	4.98	0.25	±	0.07
Red oak (*Quercus rubra*)	4.91	±	1.14	0.66	±	0.17
Yellow birch (*Betula alleghaniensis*)	5.54	±	1.20	0.49	±	0.13
Red maple (*Acer rubrum*)	7.01	±	3.35	0.36	±	0.16
Cherry (*Prunus spp.*)	3.75	±	1.82	0.38	±	0.22
Eastern hemlock (*Tsuga canadensis*)	2.50	±	0.64	0.29	±	0.08
Trembling aspen (*Populus tremuloides*)	3.13	±	2.46	0.17	±	0.11
Elm (*Ulmus spp.*)	2.37	±	0.57	0.07	±	0.02
Butternut (*Juglans cinerea*)	0.76	±	0.31	0.07	±	0.03
All species	456.38	±	13.34	29.25	±	0.49

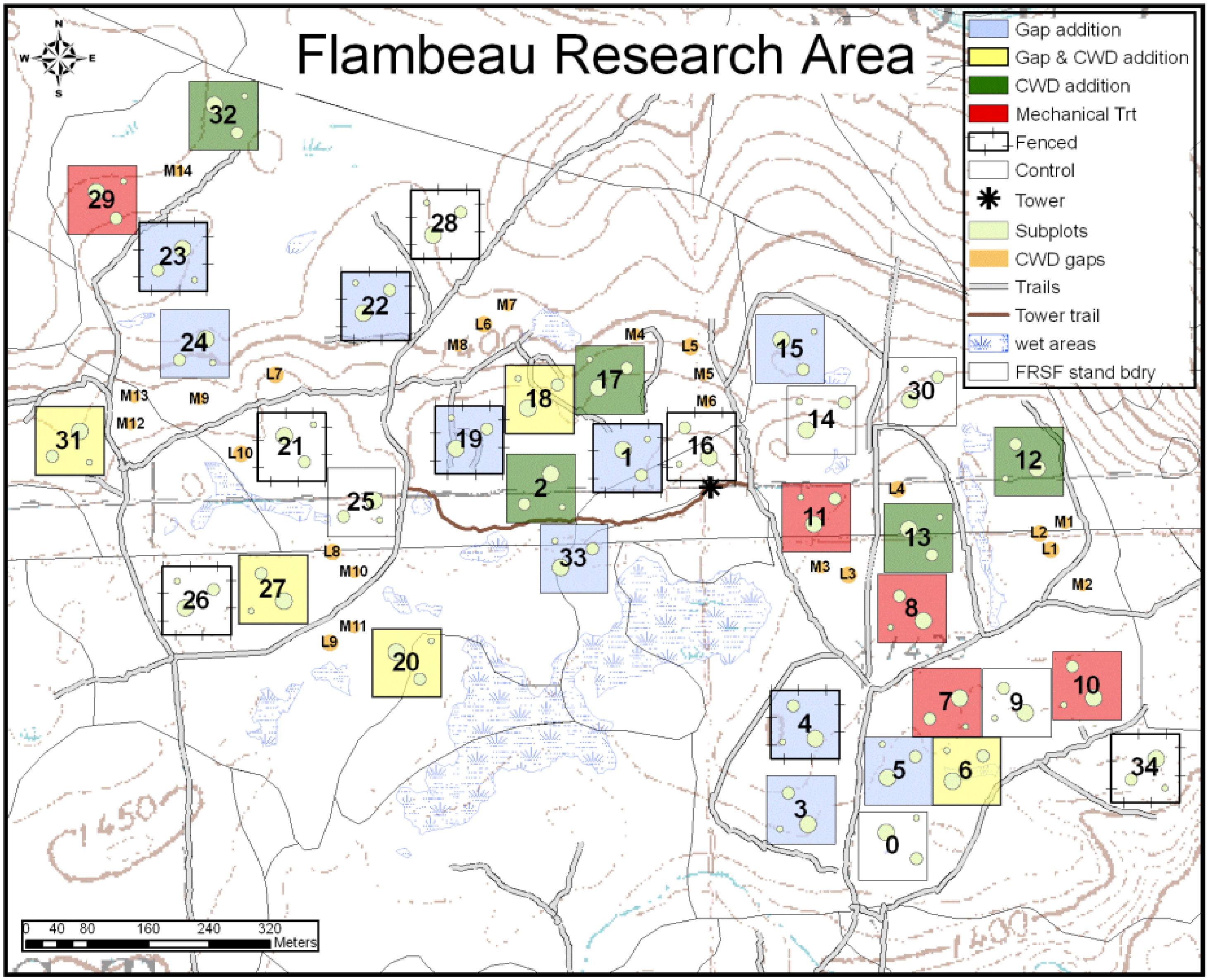

Figure 2. Site map of study area in Flambeau River State Forest, northern Wisconsin, USA.

Study Design

Treatments including canopy gap creation, woody debris addition, the combination of wood and gap additions, and a series of controls to isolate the influence of logging machinery and white-tailed deer (*Odocoileus virginianus*) were randomly assigned to thirty-five 80m x 80m (0.64 ha) permanent plots for a total of five replicates of seven treatments (Fig. 2). Harvesting and coarse woody debris addition treatments were carried out in late January 2007 with a Ponsse Ergo harvester and Ponsse Buffalo forwarder (both low-impact rubber-tired logging equipment) under frozen ground conditions and snow cover. Canopy openings were 50 m^2, 200 m^2, and 380 m^2 for the small, medium, and large subplots, respectively. The large subplot size was selected to represent the maximum gap size typical of old-growth northern hardwood forests in the region, with medium and small representing a range of smaller gaps. The amount of CWD added to each plot varied based on pre-existing amounts, but each plot was augmented up to that expected in typical old-growth northern hardwood stands of the region (28.7 Mg ha^{-1}; Goodburn and Lorimer 1998). All CWD that was added was freshly cut to be of uniform decay class. The relative amount of CWD and cut stumps following the various gap creation and CWD addition treatments can be seen in Figure 3. In August of 2007 the perimeters of five gap treatment and five control plots (entire 0.64 ha main plots) were fenced to exclude deer.

The experiment was set up as a split plot design with gap size (subplots) nested within the seven whole plot treatments. Subplots were further divided into gap, transition, and buffer zones, within which permanent vegetation quadrats were established. In all plots, sixteen 2m x 2m vegetation quadrats were established in each large and medium subplot, and ten 2m x 2m quadrats were established in each small subplot. Quadrats were located in the middle of each subplot zone at cardinal and sub-cardinal compass directions with respect to the subplot centers (Fig. 4).

The experimental design included three blocks to account for the natural heterogeneity of pre-treatment plant species composition throughout the research area. The presence of hemlock and ash species described the most variation between plots. The presence of hemlock influences soil carbon and nitrogen dynamics (Campbell and Gower 2000). Therefore the three blocks designated prior to treatment were: (1) maple-hemlock, (2) maple-ash, and (3) maple. The third block included plots where several other species at the site were more abundant, including bitternut hickory, American basswood, red and white elm (*Ulmus rubra*) and *U. americana*. Treatments were randomly assigned to plots within each block.

Pre-treatment baseline data was collected annually from 2004-2006 and post-treatment data was collected annually from 2007-2009.

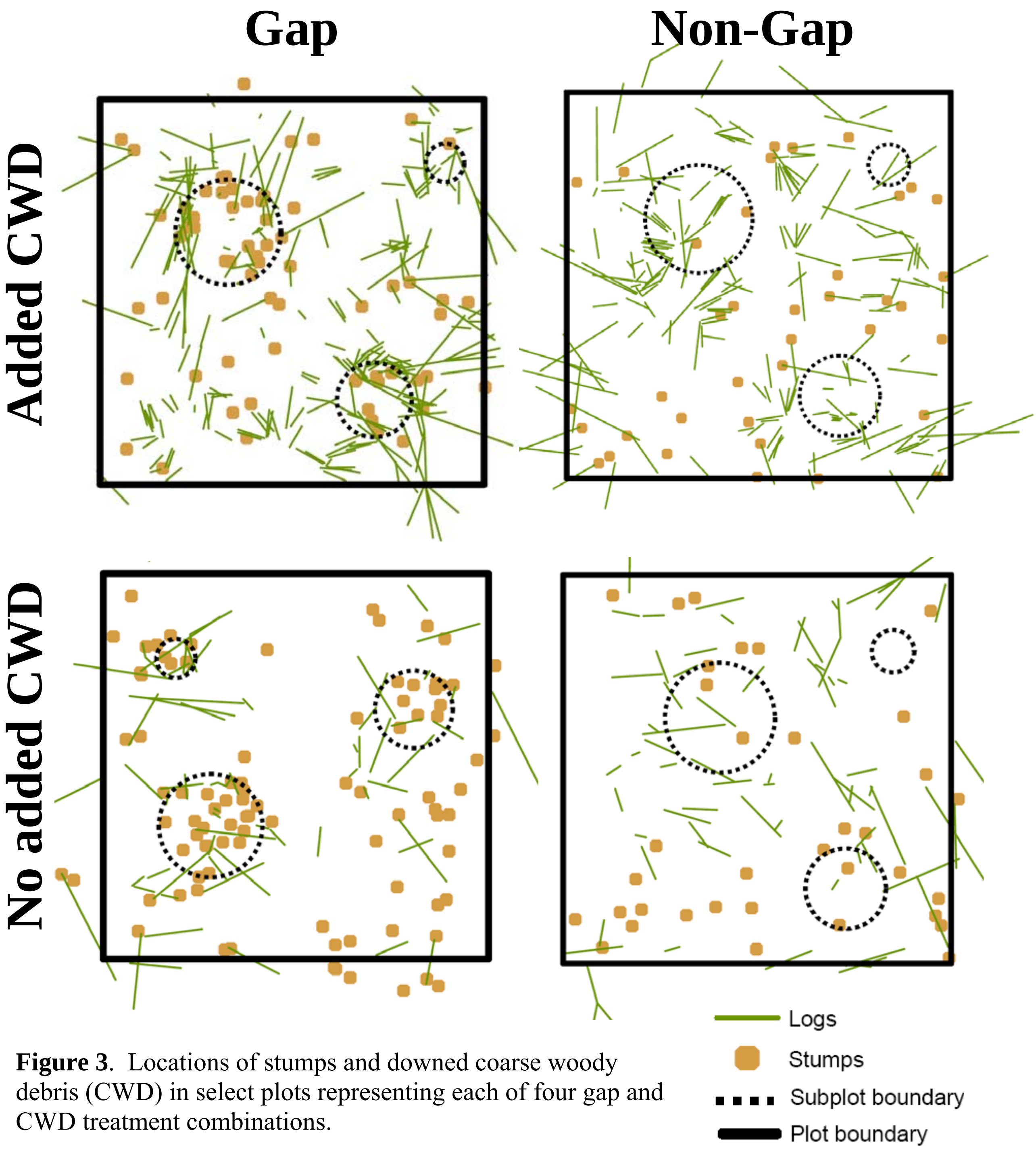

Figure 3. Locations of stumps and downed coarse woody debris (CWD) in select plots representing each of four gap and CWD treatment combinations.

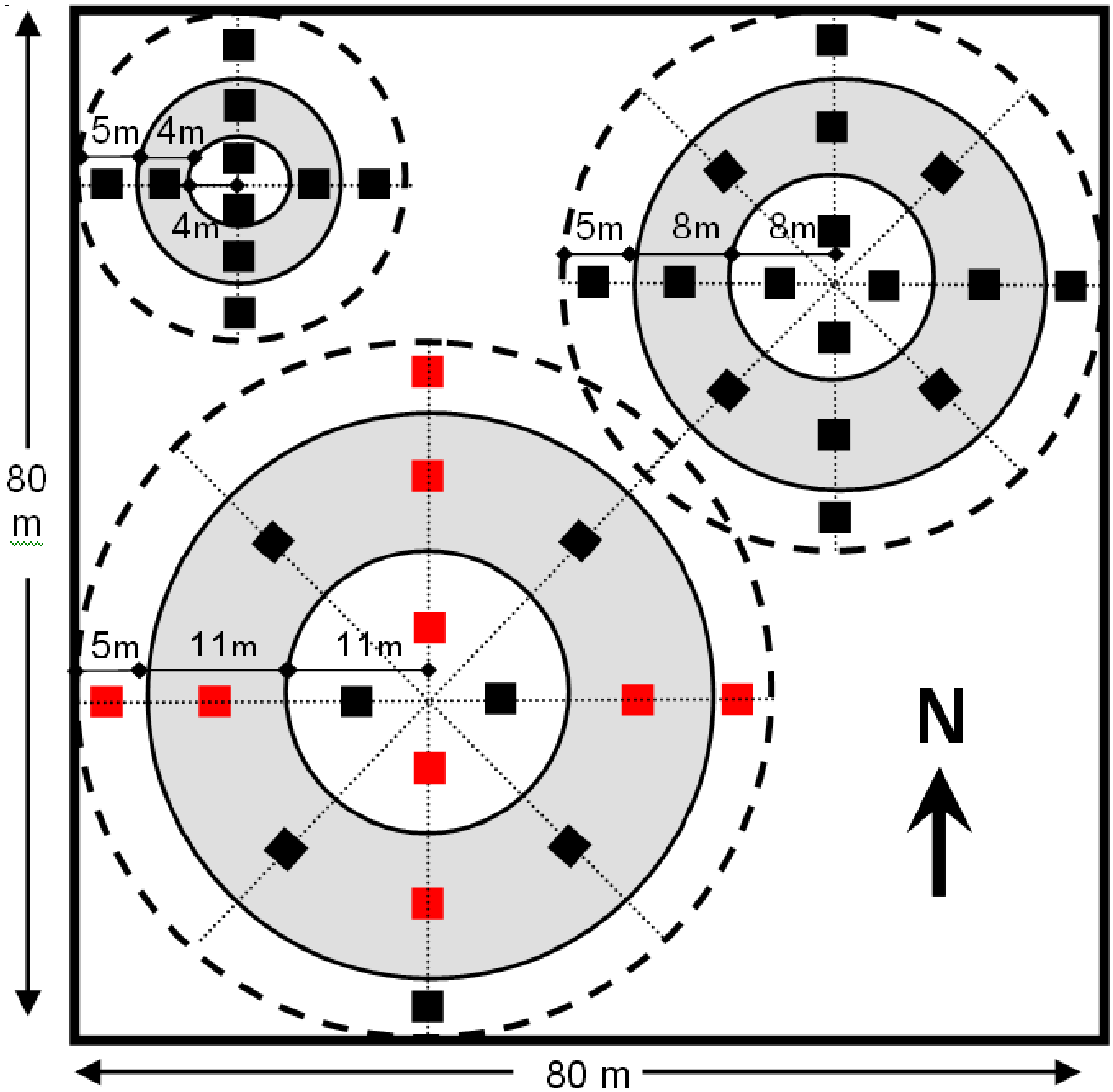

Figure 4. Detail of existing subplot and 4-m^{2}quadrat sampling design within 80m x 80m treatment plots. The central gap zones of subplots have radii of 4, 8 and 11 m which coincide with range of gap treatments. The gap/closed canopy transition zones are 4, 8 and 11 m in width, respectively. The outer buffer (closed canopy) zones are 5 m wide for all subplots. In gap treatments, added gaps coincide with central gap zones, while CWD treatments are equally distributed across subplots. Solid squares depict 2m x 2m quadrats used for understory vegetation, microclimate monitoring, etc. Red squares indicate quadrats with continuous microclimate monitoring at the seven existing sub-canopy datalogger stations.

Methods

Tree Inventory

In Fall 2005, all trees (stems≥10 cm DBH) within the whole plots were identified by species and numbered with an aluminum tag, which provides a permanent reference point for annual DBH measurements. Snags were defined as standing dead trees >1.5 m in height at an angle >45° to horizontal. Snags were also tagged, measured at breast height, assigned a decay class (Table 2) and measured for height with a clinometer and distance tape. On each live tree, DBH, percent live crown (2006) and canopy class (dominant, codominant, intermediate, suppressed) were recorded. In the fall of subsequent years, the DBH of all tagged trees was remeasured, and all ingrowth (stems that reached 10 cm DBH in preceding year) were tagged and measured. All trees were mapped in 2008 and 2009 using compasses and measuring tapes or laser rangefinders.

Table 2. Snag decay classes used in tree and sapling inventories. In assigning decay classes, branching characteristics took precedence over all other characteristics.

Decay Class	Characteristics
1	**all fine branches present**; normally pointed top, all bark remaining, sound sapwood, hard heartwood;
2	**no fine branches**, normally few large branches, usually broken top with main bole unbroken;
3	**all or most coarse branch stubs present**, but not branches, usually broken top with main bole unbroken;
4	**few branch stubs**, usually broken top with main bole unbroken;
5	**no branch stubs**, usually broken top with main bole unbroken;
6	**broken main bole**, no branch stubs;
7	**decomposed**, no branch stubs, broken main bole;
8	**fallen**, no branch stubs, broken main bole;
9	**stump**.

Sapling Inventory

Saplings were defined as all live and dead trees 0.5 < 10 cm DBH, >1.4 m tall and standing at an angle greater than 45° to the horizontal. In 2005 and 2006, all saplings were surveyed and tagged in the gap and transition zones, measured at DBH with calipers and categorized into one of five DBH classes; 0.5-0.9 cm, 1-2.4 cm, 2.5-4.9 cm, 5.0-7.4 cm and 7.5-9.9 cm. Starting in 2007, DBH was measured to the nearest 0.1 cm with metal calipers. Sapling heights were measured using either a height pole (to the nearest 0.01 m) or a clinometer and distance tape and recorded from 2005 – 2008.

Coarse Down Woody Debris Inventory

In 2004 and 2006 (large subplots only) and 2008 (all subplots in Table 3), coarse woody debris (CWD) and fine woody debris (FWD) were inventoried in all plots. Both CWD and FWD consist of fallen, dead material that is at an angle of less than 45° from horizontal (i.e. no snags).

CWD included stumps <1.5 m in height and logs >1.5 m in length. CWD >10 cm in diameter was measured in the gap zone of all subplots, while CWD >20 cm in diameter was measured in the gap and transition zones of all subplots and the buffer zone of the large subplots. Stumps of >20 cm basal diameter were also measured in the above zones. Species, decay class (Table 4), diameter at three locations (large, middle and small end), hollow area and length were recorded for each piece of CWD encountered. Decay classes were assigned based on attributes of bark and soundness of wood (Goodburn and Lorimer 1998). All CWD was permanently tagged for future monitoring.

FWD consisted of woody debris >25 cm in length with diameters from 2-4 cm (Class 2) or 4-10 cm (Class 4). FWD was inventoried in fixed area, nested quadrats at various compass directions from subplot centers. Each quadrat consisted of a 2m x 2m area in which Class 4 FWD was inventoried (Table 2) and a nested 1m x 1m plot in which Class 2 FWD was inventoried. For each piece of FWD, length, diameter (calipers to nearest 0.1 cm), decay class (sound, intermediate, rotten) and species were recorded.

In 2009, all stumps and CWD measured and tagged in the CWD inventories were mapped using a Lasertech TruPulse 360B rangefinder and an HP iPAQ PDA using ArcPad 7.0. Mapping consisted of shooting a single point for each stump and one point for each end of logs (including branches and forks whose basal diameters exceeded the 10 cm or 20 cm limit for a given subplot zone; see Table 2). In addition, all stumps and other CWD >20 cm in diameter were mapped and measured in all remaining areas of the plots (e.g. all areas not listed in Table 3). Measurements included orientation, length, diameter, and decay class (Table 4) for each piece of previously unmeasured CWD.

Table 3. Summary of location and fixed area sampling of woody debris inventory procedures. An ‘x’ indicates that CWD sampling occurred in a given subplot. A number indicates the number of FDWD quadrats located in a given subplot.

Diameter Class	Zone	Subplot			Sampling Method/Extent
		Large	Medium	Small	
CWD-20 >20 cm	Gap Transition Buffer	x x x	x x --	x x --	Entire zones of all subplots
CWD-10 10<20 cm	Gap	x	x	x	Entire zones of all subplots
FDWD-4 4<10 cm	Gap Transition	4 8	4 8	2 4	2m x 2m quadrats †
FDWD-2 2<4 cm	Gap Transition	4 8	4 8	2 4	1m x 1m quadrats nested in the 2m x 2m FDWD-4 quadrats †

† In gap zone of medium and large subplots, FWD quadrats were located at 45°, 135°, 225°, and 315° from subplot center; in small gap zone at 90° and 270°. In transition zone of large and medium subplots, quadrats were located at 22.5°, 67.5°, 112.5°, 157.5°, 202.5°, 247.5°, 292.5°, and 337.5° from subplot center; in small transition zone at 45°, 135°, 225°, and 315°. All quadrats were located in middle of each zone.

Table 4. Coarse down woody debris (CWD) decay classes.

Coarse Down Woody Debris (CDWD) Decay Classes:

(modified from Goodburn and Lorimer, 1998; Harmon et al., 1986; Idol et al., 2001; Pyle and Brown, 1998; Sollins, 1982; Tyrell and Crow, 1994)

Character	Class 1	Class 2	Class 3	Class 4	Class 5
Bark	Intact, tight	Mostly intact, some slippage	Mostly absent	Absent	Absent
Structural Integrity	Sound, clear or slightly stained wood	Sapwood rotting	Heartwood sound, outer decay obvious	Heartwood rotten, some outer xylem missing, cleaves into large chunks	Heartwood rotten, collapsed debris, little structural integrity, > 85 % powder wood
Branches	Fine twigs present	No fine twigs, but larger twigs present	Larger branches present	Branch stubs present	Absent
Cross Section	Round	Round	Round	Oval or somewhat flattened	Often flattened, maybe some rounding
Metal Rod (0.5 cm dia.) Penetration	< 0.5 cm	0.5 cm-1/2 dia.	More than 1/2 dia., but less than 1 dia.	Full dia.	Full dia.
Primary Surface Substrate	Sound bark	Hard wood, decayed bark	Soft wood, wet wood compresses but springs back	Very spongy, powder wood	Loosely aggregated powder wood

Tissue Collection

In 2008 leaf, branch, bole and bark tissue samples were collected from live individuals of the common tree species in order to estimate the aboveground nutrient pools of N, P, K, Ca, Mg, S and C. Samples were collected outside the permanent experimental plots in order to avoid alteration of plot biomass and productivity. In order to eliminate variability due to differences in tree size, samples were collected from trees with DBH of 30-45 cm, except for *Ostrya virginiana*, for which 12-25 cm DBH individuals were selected. Samples were collected from three individuals of each species.

Leaf and branch samples were collected from the mid-canopy by shooting branches from the canopy with a shotgun. A minimum of 50 leaves were collected from each tree. Bark samples were collected from each tree by cutting and scraping bark from two 5x20 cm vertical sections at breast height. Bole samples consisted of two 15 cm cores taken 90° from one another (laterally) at breast height; all bark was removed from cores before processing.

Samples were dried at 70° C to constant mass, ground with a Wiley Mill and sent to Brookside Laboratories, Inc. (New Knoxville, OH) for nutrient analysis.

Forest Floor and Mineral Soil

In the fall of 2008, mineral soil and forest floor samples were collected in order to measure their nutrient content. In the control, wood addition, gap and wood addition and gap addition plots, forest floor and mineral soil samples were collected one meter north of: the north and south vegetation quadrats in each small subplot; the north, east and south quadrats in each medium subplot; and the north, east, south and west quadrats in each large subplot (Fig. 4). In each location, forest floor samples were collected by slicing all forest floor materials along the inside edge of a 33 cm diameter PVC sampling frame. Samples were dried at 70° C to constant mass and weighed to ±0.001 g. Dried samples were ground to pass a fine screen (20 mesh/cm).

After forest floor samples were removed from the soil surface, mineral soil samples were collected from the same locations. Soil samples were collected with a 5 cm diameter hammer driven corer. At each location, one core was taken to a depth of 15 cm. Samples were dried at air temperature to constant mass and weighed to ±0.001 g. Soil samples were sieved and ground using a mortar and pestle. Organic content was determined by weight-loss-on-ashing for 18 hours at 550˚C in a muffle furnace. A subsample of each ground forest floor and mineral soil sample was sent to Brookside Laboratories, Inc. (New Knoxville, OH) for analysis of element concentrations. Total C and N were analyzed on separate subsamples using an Elementar varioMacro CHN analyzer.

Fine-scale Sampling Near Woody Debris: Soil Characteristics

To account for effects of CWD and FWD on soil nutrient status, fine scale sampling of soil and forest floor materials were conducted in the wood addition (n=5) and gap and wood addition (n=5) treatments in the fall of 2008. In the gap zone of each large subplot, three replicates of each of five debris classes (DC) were selected: DC I (s) FWD, decayed (r) FWD; DC I CWD; DC II/III CWD; and DC IV/V CWD (Table 4).

At each of the 15 replicates in each plot, forest floor and mineral soil samples were collected in three locations: directly adjacent to (CWD) or under (FWD) the

CWD/FWD; 0.5 meters from the CWD/FWD; and two meters from the CWD/FWD. Sampling points at 0.5 meters and two meters from replicates were located away from other woody debris in order to prevent interference from unaccounted-for debris.

Forest floor samples consisted of all organic material <2 cm in diameter within a 15 cm diameter area. Samples were collected by slicing all forest floor materials along the inside edge of a 15 cm diameter PVC sampling frame. Mineral soil samples were collected from within the same sampling points used to collect forest floor materials. Using a 53 cm long push probed, four cores of the top 15 cm of mineral soil were collected from within each frame location and composited in the field. The forest floor and soil samples were processed as described in the previous methodological section.

Tissue samples from the debris were collected using either an increment borer or saw, depending on the decay state. Samples were dried at 70° C and ground with a Wiley Mill. A subsample was sent to Brookside Laboratories, Inc. (New Knoxville, OH) for nutrient analysis. Another subsample was analyzed for total C and N using an Elementar varioMacro CHN analyzer.

Analyses

Species-specific allometric equations were used to calculate stem, branch and bark biomass for each tree and sapling (Jenkins et al. 2004). Allometric equations were selected from the literature based on geographic proximity to our study site and having appropriate range of diameters for the particular species because these are the two most important factors influencing biomass estimates (Gower et al. 1996). Because we were unable to locate an equation for butternut (*Juglans cinerea*) we substituted the bitternut hickory equation due to similarities in structure.

The volume (V) of woody debris pieces was calculated using Newton's formula:

$$V=(L/6)*(A_b+4A_m+A_u)$$

where L represents piece length, A_b the cross-sectional area at the base, A_m the cross sectional area at the longitudinal midpoint, and A_u the cross-sectional area at the upper end of the piece. Volume was converted to biomass using wood density estimates based on samples from the site (presented in Fraver et al. 2007).

Organic content, bulk density, coarse fragments, and horizon thickness were used to estimate total soil mass. All component nutrient pools were calculated by multiplying nutrient concentrations by biomass.

Fine-scale Sampling Near Woody Debris

We used a mixed effects procedure (PROC MIXED) to determine differences in forest floor and soil nutrient pools between debris types and distances from debris. Fixed effects were species gradient (block), treatment, debris type and distance. Random effects included plot by the interaction of block and treatment, plot by the interaction of block, treatment, and type, and plot by the interaction of block, treatment, type and distance. Statistical analyses were conducted with SAS version 9.1 software (SAS Institute Inc 2003, Cary, NC).

Results and Discussion

Total Aboveground Biomass

Aboveground biomass of living trees >10cm DBH before the experimental treatments were applied ranged from 208-215 Mg ha^{-1} in 2006. Two seasons following treatment (2008), aboveground biomass increased to 223 and 218 in the control and wood addition treatments and decreased to 206 and 201 in the gap addition and gap and wood addition treatments, respectively (Fig. 5).

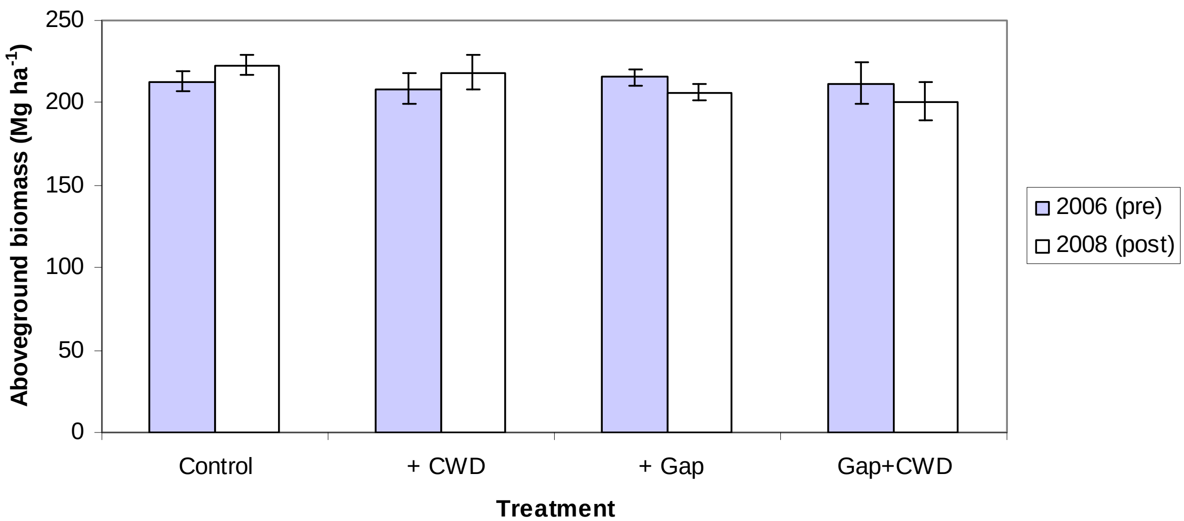

Figure 5. Tree aboveground biomass in permanent plots in the Flambeau River State Forest in fall 2006 and 2008. Trees were harvested from gap treatments in January 2007.

These estimates are comparable to several other studies of northern hardwood forests, whose aboveground biomass estimates ranged from 190 Mg/ha (Fahey et al. 2005) to 267 Mg/ha (Rutkowski and Stotlemyer 1993), with several intermediate estimates (Yanai 1998, Arthur et al. 2001, Fisk et al. 2002). Two recent studies of approximately 80-100 year old unmanaged second growth northern hardwood forests in New Hampshire (Goodale and Aber 2001) and northern Michigan (Crow et al. 2002) estimated aboveground biomasses of 192 and 201.7 Mg/ha, respectively.

Biomass Components

Living trees comprised 94% of total aboveground biomass. The remaining components of aboveground organic matter were coarse woody debris (2.1%), saplings (1.6%), snags (1.3%) and fine woody debris (1.1%; Fig. 6). The species composition of the aboveground pools, but especially the living tree component will influence the organic matter and nutrient distribution among the plots.

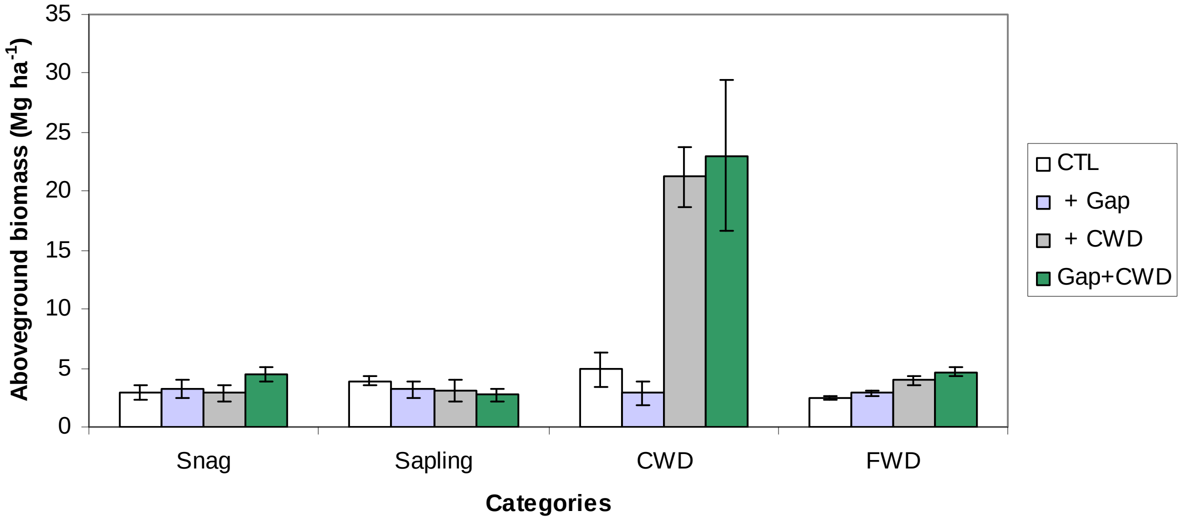

Figure 6. Aboveground biomass by component in permanent plots in fall 2008.

Living Tissue Nutrient Content

As expected, nutrients were at the highest concentration within the leaves and bark of the trees, and lower within the branches and bole wood (Table 5). Species differed in their nutrient composition, with American basswood having the highest concentration of nearly all macronutrients in the leaves. Quaking aspen had the highest concentrations of macronutrients in the branches. Sugar maple was among the highest in macronutrients in the bole wood and bark.

Table 5. Mean nutrient concentrations (% wt) of plant tissues. Means include samples collected from the Flambeau River State Forest in September 2008. Standard errors are in parentheses.

	N	P	K	Ca	Mg	S	C
Leaves							
Acer saccharum	1.74 (0.09)	0.16 (0.02)	0.81 (0.06)	1.71 (0.07)	0.27 (0.02)	0.14 (0)	45.16 (0.09)
Betula alleghaniensis	2.14 (0.3)	0.23 (0.02)	1.11 (0.08)	1.66 (0.15)	0.35 (0.02)	0.12 (0.01)	46.10 (0.6)
Carya cordiformis	2.00 (0.21)	0.19 (0.02)	0.81 (0.04)	1.76 (0.11)	0.32 (0.01)	0.14 (0.01)	44.19 (0.4)
Fraxinus americana	0.89 (0.06)	0.20 (0.02)	0.84 (0.08)	1.96 (0.09)	0.38 (0.03)	0.15 (0.02)	43.93 (0.2)
Fraxinus nigra	1.17 (0.14)	0.16 (0.01)	0.91 (0.12)	1.89 (0.08)	0.34 (0.05)	0.14 (0)	44.90 (0.45)
Ostrya virginiana	1.86 (0.13)	0.18 (0.01)	0.88 (0.1)	2.62 (0.8)	0.33 (0.05)	0.13 (0.01)	44.11 (0.71)
Populus tremuloides	2.21 (0.04)	0.21 (0.01)	0.78 (0.11)	1.48 (0.12)	0.20 (0.01)	0.16 (0.01)	49.35 (0.26)
Quercus rubra	2.09 (0.14)	0.20 (0.02)	0.8 (0.09)	0.92 (0.01)	0.20 (0.03)	0.13 (0.02)	47.55 (0.39)
Tilia americana	2.03 (0.06)	0.22 (0.02)	1.14 (0.23)	3.15 (0.23)	0.51 (0)	0.16 (0)	43.52 (0.75)
Tsuga canadensis	1.64 (0.04)	0.17 (0.01)	0.57 (0.03)	0.57 (0.06)	0.12 (0.02)	0.11 (0)	50.45 (0.18)
Branches							
Acer saccharum	0.32 (0.04)	0.04 (0)	0.20 (0.04)	1.22 (0.18)	0.05 (0.01)	0.04 (0)	46.96 (0.11)
Betula alleghaniensis	0.59 (0.01)	0.07 (0)	0.15 (0.01)	0.78 (0.11)	0.07 (0)	0.04 (0)	48.79 (0.07)
Carya cordiformis	0.50 (0.06)	0.05 (0.01)	0.22 (0.05)	1.11 (0.11)	0.10 (0.03)	0.05 (0)	46.45 (0.09)
Fraxinus americana	0.56 (0.06)	0.06 (0.01)	0.20 (0.06)	0.87 (0.14)	0.08 (0)	0.06 (0)	47.34 (0.61)
Fraxinus nigra	0.61 (0.04)	0.06 (0)	0.42 (0.02)	0.83 (0.13)	0.07 (0)	0.05 (0)	47.52 (0.24)
Ostrya virginiana	0.42 (0.02)	0.04 (0)	0.11 (0.01)	0.71 (0.1)	0.05 (0)	0.04 (0)	47.21 (0.2)
Populus tremuloides	0.71 (0.05)	0.09 (0.01)	0.38 (0.02)	1.55 (0.11)	0.13 (0.01)	0.05 (0)	48.98 (0.18)
Quercus rubra	0.38 (0.05)	0.03 (0)	0.14 (0)	0.79 (0.14)	0.05 (0.01)	0.03 (0)	46.90 (0.2)
Tilia americana	0.57 (0.03)	0.08 (0)	0.36 (0.03)	0.88 (0.06)	0.12 (0.01)	0.06 (0)	46.77 (0.09)
Tsuga canadensis	0.23 (0.02)	0.03 (0)	0.10 (0)	0.36 (0.01)	0.03 (0)	0.02 (0)	49.69 (0.05)

Table 5 (cont.)

	N	P	K	Ca	Mg	S	C
Bole							
Acer saccharum	0.13 (0.05)	0.01 (0)	0.12 (0.08)	0.26 (0.14)	0.02 (0.01)	0.01 (0)	47.46 (0.1)
Betula alleghaniensis	0.09 (0.02)	0 (0)	0.06 (0.02)	0.1 (0.02)	0.01 (0)	0 (0)	47.77 (0.15)
Carya cordiformis	0.11 (0.01)	0 (0)	0.12 (0.02)	0.22 (0.02)	0.06 (0)	0.01 (0)	47.45 (0.25)
Fraxinus americana	0.12 (0)	0 (0)	0.09 (0.01)	0.09 (0.02)	0.02 (0)	0.02 (0)	48.20 (0.22)
Fraxinus nigra	0.10 (0.01)	0 (0)	0.25 (0.02)	0.17 (0.02)	0.02 (0)	0 (0)	46.84 (0.13)
Ostrya virginiana	0.12 (0.01)	0 (0)	0.08 (0.03)	0.24 (0.01)	0.03 (0)	0.01 (0)	48.04 (0.26)
Populus tremuloides	0.06 (0.01)	0 (0)	0.06 (0)	0.21 (0.05)	0.02 (0)	0 (0)	47.60 (0.12)
Quercus rubra	0.06 (0.01)	0 (0)	0.06 (0.01)	0.05 (0.03)	0 (0)	0 (0)	47.57 (0.05)
Tilia americana	0.12 (0.02)	0.02 (0)	0.10 (0.01)	0.22 (0.02)	0.03 (0)	0.02 (0)	47.23 (0.33)
Tsuga canadensis	0.10 (0.01)	0.02 (0)	0.10 (0.02)	0.12 (0.02)	0.02 (0)	0 (0)	49.73 (0.12)
Bark							
Acer saccharum	1.03 (0.08)	0.05 (0.01)	0.23 (0.09)	3.2 (0.26)	0.19 (0.02)	0.08 (0.01)	49.82 (0.13)
Betula alleghaniensis	0.72 (0.03)	0.04 (0)	0.08 (0)	0.73 (0.16)	0.05 (0.01)	0.05 (0)	57.35 (0.6)
Carya cordiformis	0.57 (0.06)	0.04 (0)	0.15 (0.02)	3.01 (0.09)	0.12 (0)	0.05 (0)	46.77 (1.13)
Fraxinus americana	0.59 (0.09)	0.04 (0.01)	0.13 (0.01)	2.93 (0.27)	0.19 (0.03)	0.08 (0.01)	48.10 (0.82)
Fraxinus nigra	0.47 (0.01)	0.04 (0)	0.61 (0.01)	2.52 (0.36)	0.09 (0.01)	0.06 (0)	47.67 (0.58)
Ostrya virginiana	0.75 (0.05)	0.04 (0)	0.18 (0.04)	3.78 (0.05)	0.07 (0.01)	0.07 (0)	45.69 (0.34)
Populus tremuloides	0.32 (0.04)	0.02 (0)	0.19 (0.04)	1.48 (0.08)	0.07 (0.01)	0.03 (0)	51.55 (0.25)
Quercus rubra	0.45 (0.03)	0.02 (0)	0.09 (0.01)	2.79 (0.26)	0.04 (0.01)	0.04 (0)	50.53 (0.87)
Tilia americana	0.67 (0)	0.05 (0)	0.12 (0.02)	2.19 (0.09)	0.10 (0)	0.07 (0)	48.16 (0.12)
Tsuga canadensis	0.33 (0.02)	0.02 (0)	0.03 (0)	0.52 (0.01)	0.02 (0)	0.03 (0)	54.41 (0.3)

Woody Debris Nutrient Concentration

Nutrient concentrations were higher in fine woody debris than an average of all coarse woody debris (downed debris 10+ cm in diameter). Yet, if coarse woody debris is differentiated by decay stage, fine woody debris is similar in macronutrient concentrations to the most highly decayed coarse woody debris (decay classes IV/V)(Table 6). Concentrations of N, P, Ca, Mg and S increased with decay, while K decreased. These results are similar to patterns observed previously and could be related to increased nutrient input from throughfall or litterfall, fungal or root colonization, or loss of organic matter (Arthur et al. 1993, Harmon et al. 1987). The C:N ratio of CWD decreased from decay class I to V (174, 122, and 66 for DC I, II/III, and IV/V, respectively), but was similar between FWD decay classes (76 for both classes).

Table 6. Mean nutrient concentrations (% wt) of downed woody debris tissues. Means include samples collected from the Flambeau River State Forest in September 2008. Standard errors are in parentheses.

Debris Category	N	P	K	Ca	Mg	S
CWD – I	0.28 (0.04)	0.02 (0)	0.10 (0.01)	0.47 (0.10)	0.04 (0.01)	0.02 (0)
CWD – II/III	0.40 (0.04)	0.02 (0)	0.12 (0.02)	0.46 (0.10)	0.05 (0.01)	0.03 (0)
CWD – IV/V	0.74 (0.06)	0.04 (0.01)	0.08 (0.01)	0.82 (0.16)	0.09 (0.01)	0.06 (0.01)
FWD – Solid	0.63 (0.04)	0.05 (0)	0.12 (0.01)	0.98 (0.04)	0.06 (0)	0.05 (0)
FWD - Rotten	0.63 (0.06)	0.04 (0.01)	0.09 (0.01)	1.09 (0.14)	0.06 (0.01)	0.05 (0.01)

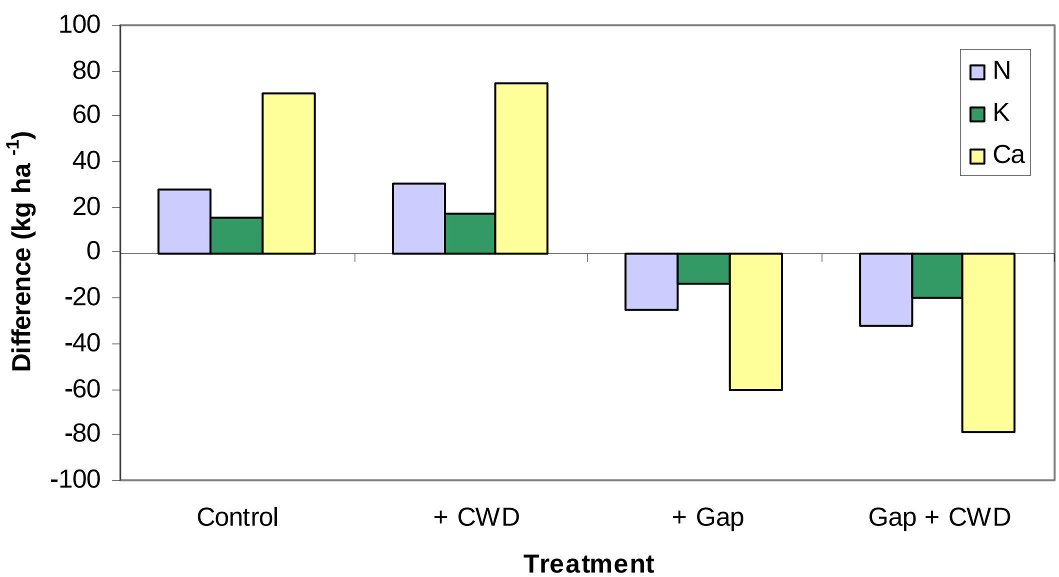

Figure 7. Difference between 2006 and 2008 nutrient content in living vegetation among treatments

Nutrient Pools

The experimental gap treatment, akin to whole-tree removal, removed approximately 4-5% of total N, K and Ca from the plots (Table 7). The amount of nutrients removed in the gap treatment approximates the annual increase measured in the control treatment (Fig. 7). In gap and wood addition treatments the nutrient pool did not decrease, because the nutrients within the trees were reallocated to the woody debris pools. Our wood addition treatments caused a more than four-fold increase in the woody debris biomass and nutrient pool within this component of the forest (Table 8).

The nutrient pool in the forest floor was lower than that contained in the vegetation components (Table 9). The largest pool of all macronutrients is in the mineral soil (Table 9). In only two years following treatment, we did not observe differences in the bulk density and mineral soil nutrient pools between treatments.

Table 7. Total nutrient (kg ha^{-1}) and carbon (Mg ha^{-1}) content of the trees (>10 cm DBH) before treatment (2006) and following experimental treatments (2008)

Year	Treatment	N	K	Ca	C
2006	Control	572.8 (68.2)	322.5 (37.7)	1430.6 (165.6)	102.5 (11.8)
	+ Gap	646.2 (25.4)	354.5 (12.5)	1593.6 (54.6)	115.8 (3.8)
	Gap+CWD	641.8 (50.4)	367.7 (16.7)	1609.9 (101.4)	114.2 (7.0)
	+ CWD	625.2 (31.8)	354.4 (12)	1504.2 (59.9)	112.1 (5.0)
2008	Control	600.2 (71.6)	338 (39.5)	1500.9 (173.6)	107.3 (12.3)
	+ Gap	620.7 (25.3)	340.9 (11.8)	1533.2 (55)	111.2 (3.7)
	Gap+CWD	609.4 (46.6)	348.3 (15.8)	1531.4 (94.8)	108.6 (6.5)
	+ CWD	655.3 (34.5)	371.7 (13.4)	1578.7 (64.7)	117.4 (5.5)

Table 8. Biomass and nutrient content (kg ha^{-1}) of the woody debris pool in 2008

Size class	Treatment	Biomass (Mg/ha)	C (Mg/ha)	N	P	K	Ca	Mg	S
CWD	Control	4.9	2.4	22.6	1.3	4.8	27.6	2.8	1.9
	+ Gap	2.9	1.4	13.2	0.8	2.8	16.1	1.7	1.1
	Gap+CWD	23	11.2	105.8	6	22.4	129	13.3	9
	+ CWD	21.2	10.3	97.4	5.5	20.6	118.8	12.2	8.3
FWD	Control	2.5	1.2	15.9	1.1	2.7	26.2	1.6	1.3
	+ Gap	2.9	1.4	18.1	1.2	3.1	29.7	1.8	1.5
	Gap+CWD	4.7	2.3	29.4	2	5	48.4	2.9	2.4
	+ CWD	4	1.9	25	1.7	4.2	41.2	2.5	2.1

Table 9. Mineral pools (kg ha^{-1}) in forest floor and upper 15 cm of mineral soil in the Flambeau River State Forest. Standard errors are in parentheses. Estimates are means from 5 permanent plots sampled in fall 2008, following experimental treatments implemented in January 2007.

	Treatment	**C** (Mg ha^{-1})	**N**	**P**	**K**	**Ca**	**Mg**	**S**	
Floor	Control	2.82 (0.22)	77.6 (17.3)	6.4 (1.1)	17.9 (1.6)	140.8 (17.4)	14.8 (1.6)	7.2 (1.4)	
	+ CWD	2.36 (0.27)	53.3 (7.4)	4.2 (0.5)	13.7 (0.8)	99.3 (11.5)	11.1 (1)	5 (0.6)	
	+ Gap	2.82 (0.29)	70.1 (11.1)	5.1 (0.7)	13.5 (1.6)	127.7 (18.6)	12.5 (1.6)	6.2 (1)	
	Gap + CWD	3.31 (0.59)	118.5 (32.4)	8.1 (2.2)	17.6 (2.5)	171 (37.8)	15.4 (3)	10.7 (2.9)	
									BD
Min soil	Control	43.3 (2.34)	3865.7 (184.5)	25.3 (2.7)	98.2 (6.5)	1641.4 (107.3)	176.3 (7.6)	15.7 (0.6)	0.86 (0.02)
	+ CWD	40.7 (1.67)	3550.6 (149.4)	20.6 (4.2)	86.3 (3.9)	1157.6 (101.3)	145.2 (6.4)	16.1 (0.6)	0.87 (0.02)
	+ Gap	42.1 (2.99)	3682.7 (252.1)	19.5 (2)	92.2 (5.4)	1520.1 (102.8)	180.5 (10.7)	15.7 (0.5)	0.88 (0.02)
	Gap + CWD	38.7 (1.79)	3520.1 (141.9)	24.5 (2.5)	102 (5.5)	1642.9 (96.6)	176 (8.5)	15.5 (0.7)	0.86 (0.03)

Basic comparisons of our aboveground biomass nutrient pools can be made with other studies of northern hardwood forests with comparable standing biomass to ours. For Ca, our Ca pools of 1431-1610 kg/ha (Table 7) are on the high end of typical estimates, though several studies of hardwood forests have found comparable values ranging from 1290 to 1463 kg/ha (e.g. Federer et al. 1989, Trettin et al. 1999, Adams et al. 2000). Aboveground biomass K pools at other sites appear to be comparable to ours, with Federer et al. (1989) reporting 160 kg/ha and Rutkowski and Sottlemyer (1993) reporting 440 kg/ha compared to our pools of approximately 323-372 kg/ha (Table 7). Several studies of northern forests have reported aboveground biomass N pools from 459 to 578 kg/ha (Rutkowski and Stottlemyer 1993, Yanai 1998, Friedland and Miller 1999, Arthur et al. 2001, Fisk et al. 2002). Nitrogen pools at the Flambeau Experiment ranged from 572-655 kg/ha, putting our site at the high end of reported values for northern forest sites.

It is difficult to make direct cross-study comparisons of forest floor nutrient pools, because studies vary in their inclusion of leaf litterfall, woody materials of various diameters, live and dead roots, and other forest floor constituents. In general, however, our forest floor nutrient pools were small compared to those reported by other studies (e.g. Federer et al. 1989, Rutkowski and Stottlemyer 1993). One likely explanation is that our site lacks a prominent A-horizon; most of our forest floor mass consists of hardwood leaf litterfall that turns over relatively quickly and does not accumulate in large quantities.

It is also difficult to compare soil nutrient pools between studies, because studies differ in the depth to which they sample mineral soil as well as the nutrients they measure. However, some basic comparisons of select nutrients can be made with studies that measured those elements at comparable soil depths in forest ecosystems. In a second growth northern hardwood forest in New Hampshire, Goodale and Aber (2001) found approximately 38 Mg/ha of carbon and 1700 kg/ha of nitrogen in the top 10 cm of soil. In a mature hardwood forest in South Carolina, Richter et al. (2000) found that the mineral soil from 0-15 cm contained 23.8 Mg/ha of carbon and 1068 kg/ha of nitrogen. At Hubbard Brook Experimental Forest in New Hampshire, Fahey et al. (2005) reported 31.7 Mg C/ha in the top 10 cm of soil and another 26 Mg/ha at the 10-20 cm depth. Our estimates of 38.7-43.3 Mg C/ha and 3520-3866 Mg N/ha in the top 15 cm of soil (Table 9) are comparable to these values. However, as with our aboveground biomass nitrogen pools, our mineral soil nitrogen pools are somewhat higher than many other studies, suggesting that our site is relatively nitrogen rich.

Fine-scale Sampling Near Woody Debris

We hypothesized that nutrients would be concentrated directly beneath woody debris and that these hotspots/pools would diminish with distance from the log. There was no debris type by distance interactions in the fall sampling conducted in a subset of the plots. In the floor, N, P, and Ca differed significantly between the types of debris (p=0.0139, 0.0105, and 0.0251, respectively). Floor nutrient pools were greatest near decayed FWD (FR in Fig 8) and lowest near the most decayed CWD (C5). Pools near any of the debris types were consistently higher than the mean nutrient pools estimated in the control plots. Potassium did not differ by debris type, but was significantly greater directly beneath the debris than at further distances (distance effect, p=0.0021)(Fig. 9).

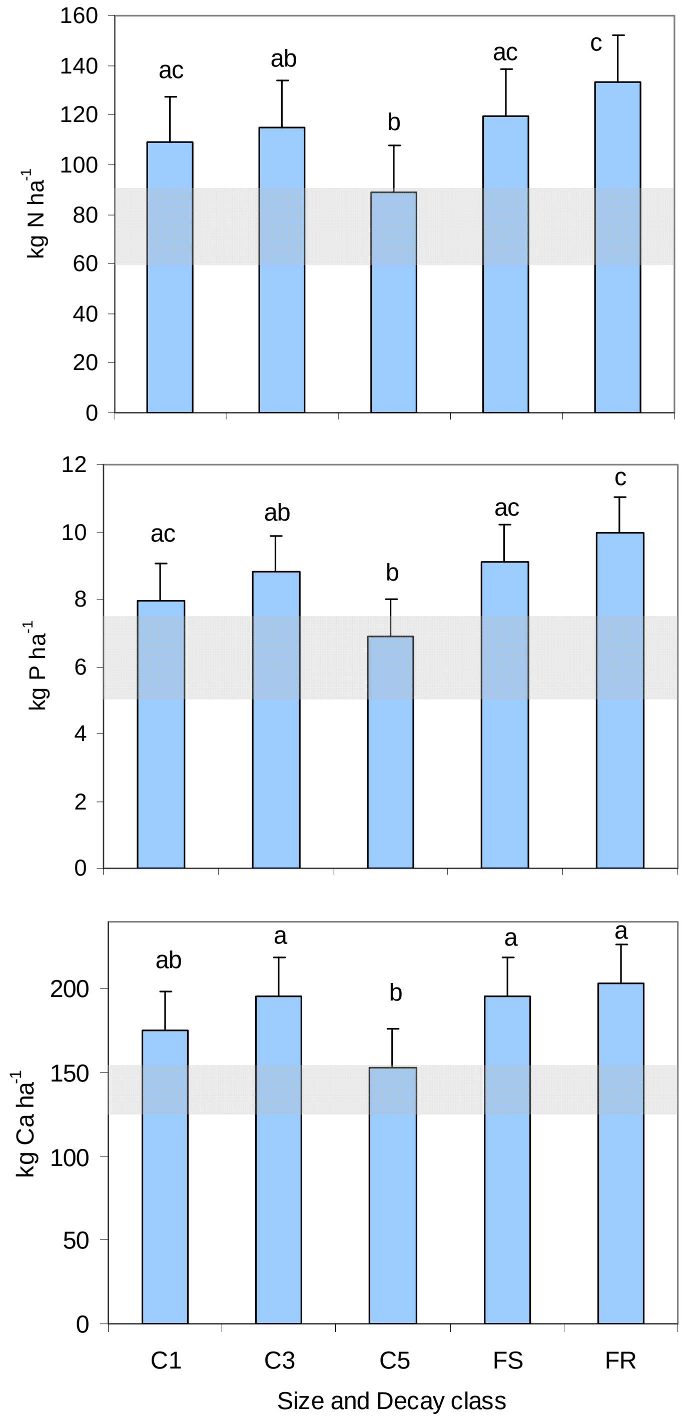

Figure 8. Forest floor nutrient pools near coarse and fine woody debris classes of different decay stages. The gray band depicts the estimated range for the mean pool in control treatment.

Soil nutrient pools (to 15 cm depth) beneath debris were similar to those estimated for our control treatment and there were few differences between soils near debris. Nitrogen varied between treatments, debris type and distance (p=0.0456)(Fig. 10). Differences in P varied by ecological block, treatment, debris type and distance from debris (p=0.0037). Significant differences in P between distances from debris were more common for CWD in the most advanced stages of decay (DC 3-5). These few differences are not displayed because the results do not exhibit a consistent pattern as to whether P levels are higher or lower beneath or away from debris. Calcium pools differed significantly between blocks and treatments, but not by debris types or distance. We found no differences in K soil pool.

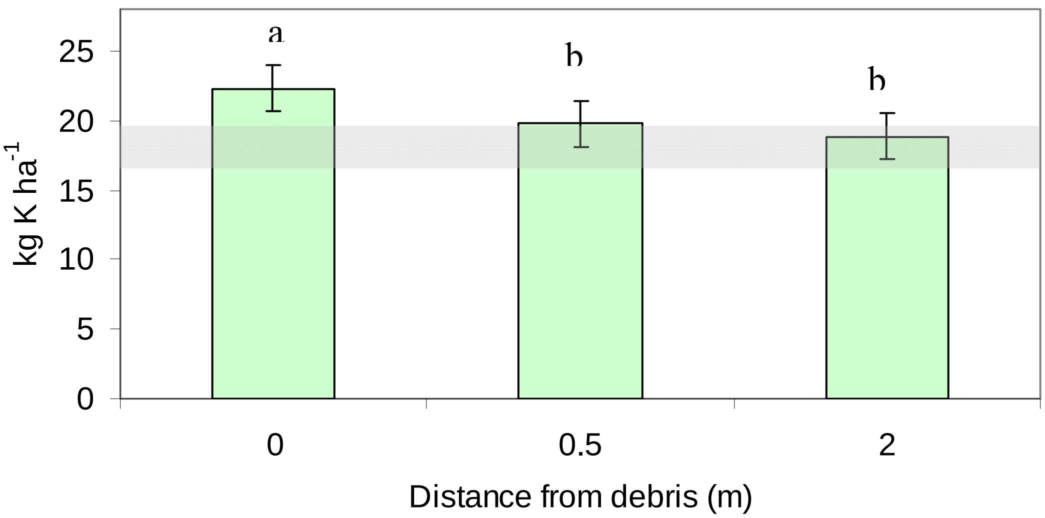

Figure 9. Differences in forest floor nutrient pools immediately under (0m) and away from downed woody debris. The gray horizontal band encloses the estimated range for K pool in control treatment.

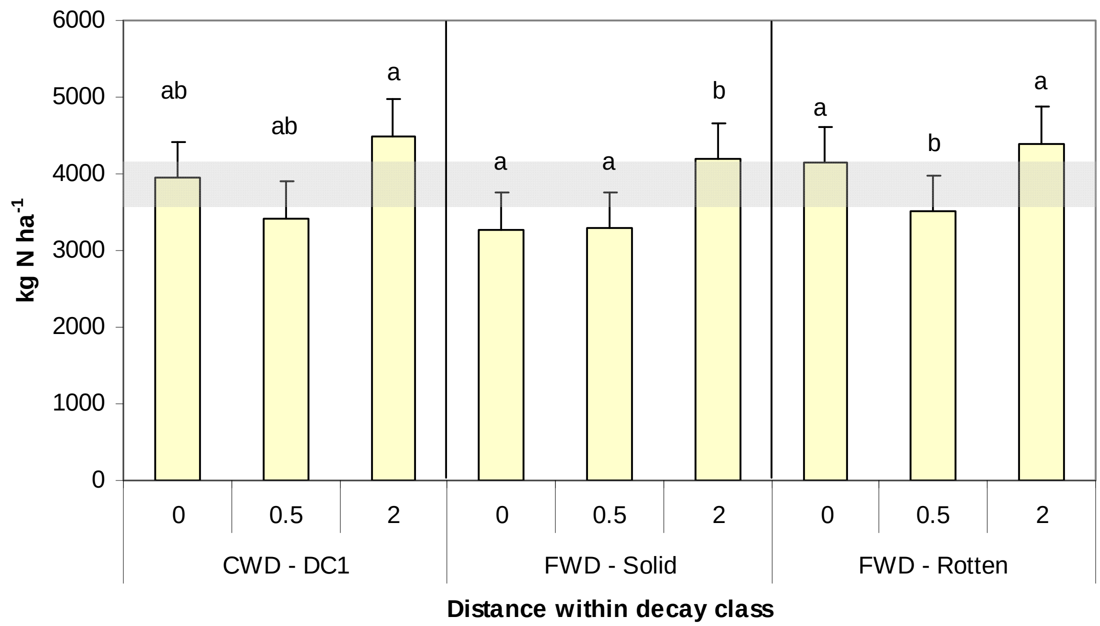

Figure 10. Differences in soil nutrient pools under (0m) and away woody debris. The gray horizontal band encloses the estimated range for the N pool in control plots.

Conclusion

This study reports biomass and nutrient removals from experimental treatments akin to whole-tree harvests and juxtaposes this with a treatment in which harvested wood is left in place to augment the woody debris pool. We have documented baseline conditions of the above and belowground nutrient pools and with time and repeated samplings will be able to evaluate the impacts of intensive removal in a nutrient rich northern hardwood second-growth forest.

Future Directions

Our research on forest carbon and nutrient stocks and cycles will continue as part of a U.S. Department of Energy funded initiative to generate accurate, regional-scale estimates of the environmental sustainability of feedstock harvests and the region's capacity to produce forest-derive biofuel feedstocks. This study will use environmental and ecological field measurements across a unique regional network of existing base-funded, large-scale manipulative experiments across the northern forested portions of Michigan, Wisconsin, and Minnesota, including the Flambeau experiment (Fig. 11, to achieve four interrelated objectives:

1) Assess the impacts of forest-derived biofuel production on environmental sustainability and site productivity within common forest types of the northern Lake States region by directly measuring the short- and medium-term ecosystem response to biofuel harvests

2) Estimate the maximum sustainable yield of forest-derived biofuel feedstocks by modeling the long-term impacts of increased biofuel harvesting on forest productivity
3) Quantify the physical availability and potential supply of biofuel feedstocks throughout the region by integrating measures of forest abundance across ownership types with social, economic, and environmental factors
4) Estimate the total amount of fossil fuel emissions that could be sustainably offset by biofuel feedstocks in the northern Lake States by conducting life cycle analyses that build upon the results from Objectives 1-3

Fieldwork in support of these objectives will begin in Spring 2010.

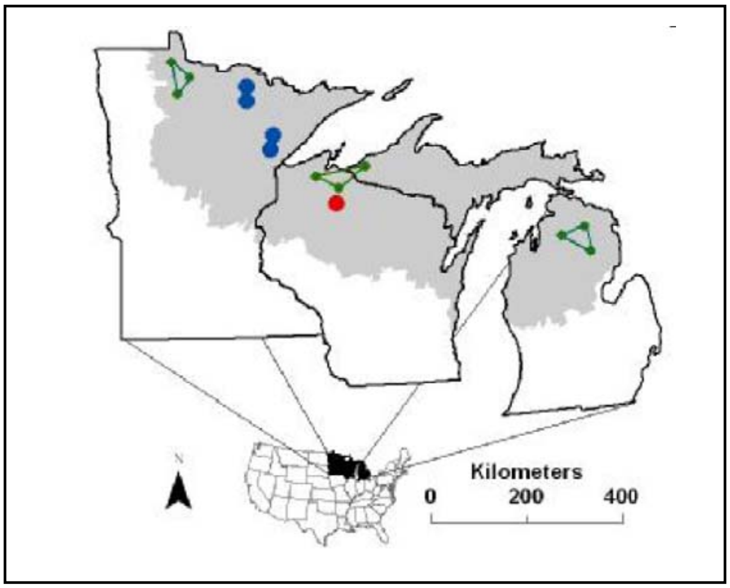

Figure 11. Focal region and intensive study sites for assessment of forest-derived biofuel feedstock production and utilization. The forested portion of the northern Lake State is shown in gray; replicated short-term harvesting experiments in aspen and northern hardwood forests are shown in blue and red dots, respectively, and replicated 15+ year ongoing manipulations are shown in green.

Literature Cited

Arthur, M.A., L.M. Tritton, and T.J. Fahey. 1993. Dead bole mass and nutrients remaining 23 years after clear-felling of a northern hardwood forest. Canadian Journal of Forest Research 23: 1298-1305.

Adams, M.B., J.A. Burger, A.B. Jenkins, L. Zelazny. 2000. Impact of harvesting and atmospheric pollution on nutrient depletion of eastern US hardwood forests. Forest Ecology and Management 138: 301-319.

Arthur, M.A., S.P. Hamburg, T.G. Siccama. 2001. Validating allometric estimates of aboveground living biomass and nutrient contents of a northern hardwood forest. Canadian Journal of Forest Research 31:11-17.

Bockheim, J.G., and S.E. Crowley. 2002. Ion cycling in hemlock-northern hardwood forests of the southern Lake Superior region: A preliminary study. Journal of Environmental Quality 31:1623-1629.

Bockheim, J.G., H. Park, and J. Gallagher. 2005. Genotypic variation and recovery of Populus tremuloides from biomass removal and compaction in northern Wisconsin, USA. Canadian Journal of Forest Research 35: 221-228.

Clebsch, E.E.C. and R.T. Busing. 1998. Secondary succession, gap dynamics and community structure in a Southern Appalachian Cove Forest. Ecology 70:728-735.

Collins, B.S. and S.T.A. Pickett. 1987. Influence of canopy opening on the environment and herb layer in a northern hardwoods forest. Vegetatio 70:3-10.

Crow, T.R., D.S. Buckley, E.A. Nauertz, and J.C. Zasada. 2002. Effects of management on the composition and structure of northern hardwood forests in upper Michigan. Forest Science 48(1): 129-145.

Dahir, S.E. and C.G. Lorimer. 1996. Variation in canopy gap formation among developmental stages of northern hardwood stands. Canadian Journal of Forest Research 26:1875-1892.

Denslow, J.S. and T. Spies. 1990. Canopy gaps in forest ecosystems: an introduction. Canadian Journal of Forest Research 20:619.

Edmonds, R.L., D.J. Vogt, D.H. Snadberg, and C.H. Driver. 1986. Decomposition of Douglas-fir and red alder wood in clear-cutting. Canadian Journal of Forest Research 16:822-831.

Fahey, T.J., T.G. Siccama, C.T. Driscoll, G.E. Likens, J. Campbell, C.E. Johnson, J.J. Battles, J.D. Aber, J.J. Cole, M.C. Fisk, P.M. Groffman, S.P. Hamburg, R.T. Holmes, P.A. Schwarz, and R.D. Yanai. 2005. The biogeochemistry of carbon at Hubbard Brook. Biogeochemistry 75: 109-176.

Federer, C.A., J.W. Hornbeck, L.M. Tritton, C.W. Martin, R.S. Pierce, and C.T. Smith. 1989. Long-term depletion of calcium and other nutrients in eastern US forests. Environmental Management 13(5): 593-601.

Fisk, M.C., D.R. Zak, and T.R. Crow. 2002. Nitrogen storage and cycling in old- and second-growth northern hardwood forests. Ecology 83(1): 73-87.

Friedland, A.J. 1999. Major-element cycling in a high-elevation Adirondack forest: patterns and changes, 1986-1996. Ecological Applications 9(3): 958-967.

Goodale, C.L. and J.D. Aber. 2001. The long-term effects of land-use history on nitrogen cycling in northern hardwood forests. Ecological Applications 11(1): 253-267.

Gray AN, Spies TA, Easter MJ. 2002. Microclimatic and soil moisture responses to gap formation in costal Douglas-Fir forests. Canadian Journal of Forest Research 32: 332-343.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, Jr., and K.W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302.

Harmon, M. E., K. Cromack Jr., and B. G. Smith. 1987. Coarse woody debris in mixed-conifer forests, Sequoia National Park, California. Canadian Journal of Forest Research 17: 1265-1272.

Harmon M.E., D.F. Whigham, J. Sexton, and I. Olmsted. 1995. Decomposition and mass of woody detritus in the dry tropical forests of the north-eastern Yucatan Peninsula, Mexico. Biotropica 27:305-316.

Hart, S.C. 1999. Nitrogen transformations in fallen tree boles and mineral soil of an old-growth forest. Ecology 80:1385-1394.

Janowiak, M.K. and C.R. Webster. 2010. Promoting ecological sustainability in woody biomass harvesting. Journal of Forestry 108(1): 16-23.

Landsberg, J.J. and S.T. Gower. 1997. Applications of physiological ecology to forest management. Academic Press, New York. 354 p.

Latty, E.F., S.M. Werner, D.J. Mladenoff, K.F. Raffa, and T.A. Sickley. 2006. Response of ground beetle (Carabidae) assemblages to logging history in northern hardwood-hemlock forests. Forest Ecology and Management 222:335-347.

Mann, L.K., D.W. Johnson, D.C. West, D.W. Cole, J.W. Hornbeck, C.W. Martin, H. Rierkerk, C.T. Smith, W.T. Swank, L.M. Tritton, and D.H. Vanlear. 1988. Effects of whole-tree and stem-only clearcutting on post-harvest hydrologic losses, nutrient capital, and regrowth. Forest Science 34(2): 412-428.

Powers, R.F., D.A. Scott, F.G. Sanchez, R.A. Voldseth, D. Page-Dumroese, J.D. Elioff, and D.M. Stone. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. Forest Ecology and Management 220: 31-50.

Rutkowski, D.R. and R. Stottlemyer. 1993. Composition, biomass, and nutrient distribution in mature northern hardwood and boreal forest stands, Michigan. American Midland Naturalist 130(1): 13-30.

Scheller, RM and D.J. Mladenoff 2002. Species diversity, composition, and spatial patterning of understory plants in old-growth and managed northern hardwood forests. Ecological Applications 12:1329-1343.

Suchanek T.H., H.A.Mooney, J.F. Franklin, H. Gucinski, and S.L. Ustin. 2004. Carbon dynamics of an old-growth forest. Ecosystems 7:421-426.

Stone, D.M. 2002. Lake States aspen productivity following soil compaction and organic matter removal pp.59-67. In: Parker, S. and S.S. Hummel, eds. Beyond 2001: A silvicultural odyssey to sustaining terrestrial and aquatic ecosystems. PNW-GTR-546.

Trettin, C.C., D.W. Johnson, and D.E. Todd, Jr. 1999. Forest nutrient and carbon pools at Walker Branch Watershed: changes during a 21-year period. Soil Science Society of America Journal 63: 1436-1448.

Volk, T.A. T. Verwijst, P.J. Tharakan, and L.P. Abrahamson. 2004. Growing energy: assessing the sustainability of willow short-rotation woody crops. Frontiers in Ecology and the Environment. 2: 411-418.

Walmsley, J.D., D.L. Jones, B. Reynolds, M.H. Price, and J.R. Healey. 2009. Whole tree harvesting can reduce second rotation forest productivity. Forest Ecology and Management 257: 1104-1111.

Yanai, R.D. 1998. The effect of whole-tree harvest on phosphorous cycling in a northern hardwood forest. Forest Ecology and Management 104: 281-295.

Yatskov, M., M.E. Harmon, and O.N. Krankina. 2003. A chronosequence of wood decomposition in the boreal forests of Russia. Canadian Journal of Forest Research 33:1211-1226.

Appendix A. Geographic coordinates

Table A1. Decay class, plot/subplot location, and UTM coordinates of coarse woody debris (CWD) and fine woody debris (FWD) semi-permanent sampling points.

Plot	Subplot	CWD/FWD	Decay Class	Replicate	X-coordinate (UTM)	Y-coordinate (UTM)
2	L	CWD	I	1	672670.8	5054785.7
2	L	CWD	I	2	672660.9	5054790.1
2	M	CWD	I	3	672631.5	5054745.7
2	L	CWD	II/III	1	672660.1	5054787.5
2	L	CWD	II/III	2	672654.9	5054791.7
2	L	CWD	II/III	3	672654.0	5054792.8
2	L	CWD	IV/V	1	672666.3	5054790.8
2	L	CWD	IV/V	2	672661.7	5054796.3
2	L	CWD	IV/V	3	672666.5	5054798.1
2	M	FWD	s	1	672620.7	5054743.8
2	M	FWD	s	2	672619.2	5054747.9
2	M	FWD	s	3	672626.2	5054747.9
2	L	FWD	r	1	672657.4	5054790.8
2	L	FWD	r	2	672665.3	5054778.9
2	L	FWD	r	3	672656.8	5054784.2
6	L	CWD	I	1	673192.4	5054367.6
6	M	CWD	I	2	673223.7	5054422.5
6	L	CWD	I	3	673181.7	5054387.1
6	L	CWD	II/III	1	673176.7	5054385.1
6	L	CWD	II/III	2	673191.2	5054390.6
6	L	CWD	II/III	3	673189.7	5054394.2
6	L	CWD	IV/V	1	673193.6	5054382.0
6	L	CWD	IV/V	2	673189.6	5054388.5
6	L	CWD	IV/V	3	673192.0	5054386.0
6	L	FWD	s	1	673189.2	5054377.3
6	L	FWD	s	2	673189.3	5054392.6
6	L	FWD	s	3	673178.4	5054386.3
6	L	FWD	r	1	673193.1	5054382.4
6	L	FWD	r	2	673179.9	5054385.5
6	L	FWD	r	3	673195.7	5054382.5

Table A1 (cont.)

Plot	Subplot	CWD/FWD	Decay Class	Replicate	X-coordinate (UTM)	Y-coordinate (UTM)
12	L	CWD	I	1	673295.7	5054795.2
12	L	CWD	I	2	673291.2	5054802.5
12	M	CWD	I	3	673266.9	5054828.6
12	L	CWD	II/III	1	673293.8	5054788.4
12	M	CWD	II/III	2	673264.5	5054826.8
12	M	CWD	II/III	3	673276.3	5054830.1
12	L	CWD	IV/V	1	673307.8	5054799.0
12	L	CWD	IV/V	2	673299.1	5054785.1
12	M	CWD	IV/V	3	673265.3	5054826.4
12	L	FWD	s	1	673305.5	5054789.4
12	L	FWD	s	2	673298.5	5054795.5
12	M	FWD	s	3	673265.4	5054829.0
12	L	FWD	r	1	673301.3	5054806.3
12	M	FWD	r	2	673272.5	5054821.9
12	M	FWD	r	3	673268.2	5054833.6
13	L	CWD	I	1	673137.3	5054708.6
13	L	CWD	I	2	673133.9	5054707.8
13	L	CWD	I	3	673128.0	5054707.7
13	L	CWD	II/III	1	673138.3	5054704.7
13	L	CWD	II/III	2	673135.2	5054708.9
13	L	CWD	II/III	3	673138.5	5054721.1
13	L	CWD	IV/V	1	673123.2	5054713.0
13	M	CWD	IV/V	2	673153.9	5054681.9
13	M	CWD	IV/V	3	673157.0	5054687.8
13	L	FWD	s	3	673126.3	5054707.4
13	L	FWD	s	2	673123.8	5054718.4
13	L	FWD	s	1	673123.8	5054720.9
13	L	FWD	r	1	673139.5	5054711.5
13	M	FWD	r	3	673167.8	5054684.3
13	M	FWD	r	2	673165.8	5054686.8

Table A1 (cont.)

Plot	Subplot	CWD/FWD	Decay Class	Replicate	X-coordinate (UTM)	Y-coordinate (UTM)
17	L	CWD	I	1	672730.4	5054895.8
17	L	CWD	I	2	672725.0	5054895.3
17	M	CWD	I	3	672761.2	5054929.5
17	L	CWD	II/III	1	672727.1	5054891.5
17	L	CWD	II/III	2	672726.1	5054909.0
17	M	CWD	II/III	3	672755.6	5054925.3
17	L	CWD	IV/V	1	672727.4	5054894.8
17	L	CWD	IV/V	2	672728.9	5054897.4
17	L	CWD	IV/V	3	672724.0	5054891.4
17	L	FWD	s	1	672719.2	5054899.7
17	L	FWD	s	2	672726.6	5054904.8
17	L	FWD	s	3	672727.6	5054902.8
17	L	FWD	r	1	672721.9	5054893.5
17	L	FWD	r	2	672725.7	5054906.6
17	L	FWD	r	3	672732.0	5054903.1
18	L	CWD	I	1	672627.1	5054870.1
18	L	CWD	I	2	672626.4	5054878.2
18	L	CWD	I	3	672638.6	5054872.1
18	L	CWD	II/III	1	672632.3	5054883.8
18	L	CWD	II/III	2	672634.7	5054868.5
18	M	CWD	II/III	3	672672.9	5054901.7
18	L	CWD	IV/V	1	672628.2	5054883.2
18	L	CWD	IV/V	2	672633.5	5054871.6
18	M	CWD	IV/V	3	672671.6	5054915.9
18	L	FWD	s	1	672624.2	5054872.1
18	L	FWD	s	2	672636.4	5054882.2
18	L	FWD	s	3	672632.4	5054865.6
18	L	FWD	r	1	672635.1	5054877.5
18	L	FWD	r	2	672637.5	5054873.1
18	M	FWD	r	3	672668.8	5054907.6

Table A1 (cont.)

Plot	Subplot	CWD/FWD	Decay Class	Replicate	X-coordinate (UTM)	Y-coordinate (UTM)
20	S	CWD	I	1	672505.3	5054562.2
20	S	CWD	I	2	672500.7	5054563.6
20	S	CWD	I	3	672497.2	5054565.7
20	M	CWD	II/III	1	672484.6	5054517.3
20	S	CWD	II/III	2	672493.0	5054552.5
20	S	CWD	II/III	3	672492.3	5054574.1
20	S	CWD	IV/V	1	672508.2	5054564.8
20	S	CWD	IV/V	2	672509.1	5054562.2
20	S	CWD	IV/V	3	672502.9	5054561.0
20	S	FWD	s	1	672497.7	5054572.6
20	S	FWD	s	2	672508.9	5054573.8
20	S	FWD	s	3	672509.5	5054560.3
20	S	FWD	r	1	672498.1	5054575.7
20	S	FWD	r	2	672494.5	5054567.7
20	M	FWD	r	3	672487.2	5054518.0
27	L	CWD	I	1	672305.9	5054616.6
27	L	CWD	I	2	672313.6	5054627.3
27	L	CWD	I	3	672312.1	5054631.5
27	L	CWD	II/III	1	672303.9	5054613.2
27	M	CWD	II/III	2	672275.4	5054653.8
27	M	CWD	II/III	3	672277.4	5054655.5
27	L	CWD	IV/V	1	672300.9	5054625.5
27	L	CWD	IV/V	2	672310.7	5054612.2
27	L	CWD	IV/V	3	672315.5	5054612.5
27	L	FWD	s	1	672309.1	5054621.4
27	L	FWD	s	2	672320.7	5054618.6
27	L	FWD	s	3	672317.1	5054618.4
27	L	FWD	r	1	672307.8	5054626.6
27	L	FWD	r	2	672308.2	5054622.7
27	L	FWD	r	3	672299.4	5054622.2

Table A1 (cont.)

Plot	Subplot	CWD/FWD	Decay Class	Replicate	X-coordinate (UTM)	Y-coordinate (UTM)
31	L	CWD	I	1	672041.4	5054843.3
31	L	CWD	I	2	672040.5	5054839.8
31	L	CWD	I	3	672048.0	5054846.7
31	L	CWD	II/III	1	672043.0	5054834.5
31	L	CWD	II/III	2	672042.7	5054847.4
31	L	CWD	II/III	3	672034.2	5054850.8
31	L	CWD	IV/V	1	672038.4	5054832.7
31	L	CWD	IV/V	2	672036.4	5054841.2
31	L	CWD	IV/V	3	672033.3	5054844.3
31	L	FWD	s	1	672032.1	5054842.9
31	L	FWD	s	2	672048.3	5054848.2
31	L	FWD	s	3	672045.8	5054844.3
31	L	FWD	r	1	672034.8	5054829.9
31	L	FWD	r	2	672042.7	5054836.5
31	L	FWD	r	3	672045.1	5054838.4
32	L	CWD	I	1	672220.0	5055271.7
32	L	CWD	I	2	672213.3	5055267.8
32	L	CWD	I	3	672223.7	5055264.7
32	L	CWD	II/III	1	672217.1	5055265.5
32	L	CWD	II/III	2	672226.4	5055267.6
32	L	CWD	II/III	3	672214.5	5055279.4
32	L	CWD	IV/V	1	672214.1	5055281.1
32	L	CWD	IV/V	2	672214.6	5055269.1
32	M	CWD	IV/V	3	672250.5	5055242.5
32	L	FWD	s	3	672222.1	5055274.5
32	L	FWD	s	1	672225.9	5055264.9
32	L	FWD	s	2	672211.2	5055274.7
32	M	FWD	r	2	672251.6	5055240.9
32	M	FWD	r	3	672254.8	5055239.4
32	M	FWD	r	1	672246.1	5055234.6

Appendix B. Additional Deliverables

Experiential Education Internship Program

The Flambeau Experiment's internship program, also established with WDNR and USDA funding, provided diverse experience in applied ecological research for college undergraduates and recent graduates from various universities. In 2008, we employed seven female and three male undergraduate interns from colleges and universities across the country, including the University of Denver, Shippensburg University, Michigan Technological University, Edgewood College, Scripps College, UW-Stevens Point, University of Minnesota, Bethel University, Queens University, and Northern Michigan University. Interns were trained in a team environment in order to develop academic breadth and hands-on skills for future ecological studies. We provided an overview of the background and design of the experiment as well as journal readings and discussions in order to facilitate academic knowledge to supplement their hands-on field experience.

Students were also encouraged to develop independent research projects within the larger Flambeau Experiment. This provided interns with a complete small-scale research experience, including developing novel research questions within the context of an existing study site, experimental design and set-up, data collection and analysis, and interpreting and presenting results in a formal presentation.

Projects from 2008 included:

- The effect of browsing on stump sprouts in the Flambeau Research Area
- Ferns of the Flambeau: A study of ferns and soil moisture
- The use of snags by pileated woodpeckers
- Comparison of ant abundance in gap and forested areas in the Flambeau River State Forest
- Fungal infections of *Claytonia virginica* and *Anemone quinquefolia*: distribution and relationship to environmental factors
- Avian microhabitat study of the Flambeau River State Forest