M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 03h Project Abstract
For the Period Ending June 30, 2014

PROJECT TITLE: Evaluation of Biomass Harvesting Impacts on Minnesota's Forests
PROJECT MANAGER: Anthony D'Amato
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WEBSITE: http://www.forestry.umn.edu/silviclab/index.htm
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 03h

APPROPRIATION AMOUNT: $350,000

Overall Project Outcome and Results

Minnesota's forests are currently being viewed as potential feedstocks for production of renewable energy. A primary concern about harvesting forest biomass to generate renewable energy is the long-term impacts these harvests will have on soil nutrients and long-term ecosystem productivity, particularly in forests growing on nutrient poor soils. This project was designed to increase our understanding of the ecological impacts of biomass harvesting through establishment of a network of research sites in forests on nutrient poor soils. Treatments representing various levels of biomass removal and live-tree retention were implemented at four large-scale (80 acre) research sites in Becker, Hubbard, and Wadena Counties and were used to evaluate the importance of post-harvest slash and live-tree retention in maintaining the resilience and sustainability of jack pine forests under different biomass harvesting regimes. Treatments included current site-level guidelines for slash retention to allow for evaluations of the effectiveness of this practice at reducing impacts on long-term soil nutrients and forest vegetation. Field measurements from these sites were used to model the long-term effects of repeated biomass removals on ecosystem productivity. Results from this project indicate that there is no difference in post-harvest slash levels between areas in which slash was retained to meet current site-level guidelines and in places in which whole trees were harvested (i.e., no slash deliberately retained). The overall levels of slash retention in these areas were half those found after similar treatments in aspen-dominated forests on nutrient rich sites, highlighting the potential for greater nutrient depletion following biomass harvesting on nutrient poor sites and suggest a need for refinement of site-level guidelines to increase retention levels for nutrient poor soils. Long-term field data and model results indicate that biomass harvests that retain less than 40% of available residues may result in lower soil carbon stocks after several harvest rotations.

Project Results Use and Dissemination

The results of this project have been shared on numerous occasions with resource professionals, policy makers, citizens, and scientists over the past three years in efforts to inform forest conservation decisions regarding biomass harvesting impacts. These dissemination activities have included the development of a fact sheet for LCCMR members that was distributed on the LCCMR tour of Itasca State Park on July 18, 2013. In addition, an overview of the project and results were shared with private forest landowners through a University of Minnesota Extension Webinar to private forest landowners and county, state, and federal natural resource managers on December 9, 2013, as well as through a meeting of the Forest Operations and Planning Section of the Minnesota DNR Division of Forestry on January

8, 2014. Results were also presented at the Annual Meeting of the Ecological Society of America in Minneapolis, MN on August 5, 2013. Finally, results regarding the impact of different levels of post-harvest slash retention on soil nutrients have been discussed with members of the Minnesota Forest Resources Council and are being used to inform future guideline revisions. Publications resulting from this work are available for download from the Department of Forest Resources web site (www.forestry.umn.edu). Additional publications from this work that are currently in development will also be posted on this site and shared with LCCMR staff for dissemination.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2011 Work Plan Final Report

Date of Status Update:	8/11/2014
Date of Next Status Update:	Final Report
Date of Work Plan Approval:	6/23/2011
Project Completion Date:	6/30/2014

Is this an amendment request? _No____

Project Title: Evaluation of Biomass Harvesting Impacts on Minnesota's Forests

Project Manager: Anthony D'Amato

Affiliation: U of MN

Address: 1530 N Cleveland Ave

City: St Paul **State:** MN **Zipcode:** 55108

Telephone Number: (612) 625-3733

Email Address: damato@umn.edu

Web Address: http://www.forestry.umn.edu/silviclab/index.htm

Location:

Counties Impacted: Aitkin, Becker, Beltrami, Benton, Carlton, Cass, Clearwater, Cook, Crow Wing, Hubbard, Itasca, Koochiching, Lake, Lake of the Woods, Mahnomen, Marshall, Morrison, Otter Tail, Pennington, Pine, Polk, Red Lake, Roseau, St. Louis, Todd, Wadena

Ecological Section Impacted: Northern Minnesota and Ontario Peatlands (212M), Northern Minnesota Drift and lake Plains (212N), Northern Superior Uplands (212L), Southern Superior Uplands (212J), Western Superior Uplands (212K)

Total ENRTF Project Budget:

ENRTF Appropriation $:	350,000
Amount Spent $:	350,000
Balance $:	0

Legal Citation: M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 03h

Appropriation Language:
$175,000 the first year and $175,000 the second year are from the trust fund to the Board of Regents of the University of Minnesota to assess the impacts biomass harvests for energy have on soil nutrients, native forest vegetation, invasive species spread, and long-term tree productivity within Minnesota's forests. This appropriation is available until June 30, 2014, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Evaluation of biomass harvesting impacts on Minnesota's forests

II. PROJECT SUMMARY:

Minnesota's forests are currently being viewed as potential feedstocks for the production of renewable energy. A primary concern about harvesting forest biomass to generate renewable energy is the long-term impacts these harvests will have on soil nutrients and long-term ecosystem productivity. In particular, repeated nutrient removals in harvested material may result in soil nutrient depletion with negative cascading effects on important forest benefits by decreasing future forest growth, carbon storage, and reducing wildlife habitat.

This project is designed to increase our understanding of the ecological impacts of biomass harvesting through the establishment of a network of research sites in forests on nutrient poor soils in northern Minnesota. Treatments representing various levels of biomass removal and green-tree retention will be implemented at each site to evaluate the importance of site-level legacies (green trees and harvest residues) in maintaining the resilience and sustainability of these systems under different biomass harvesting regimes. In addition, empirically derived estimates of nutrient removals from these sites will be used to model the long-term effects of repeated biomass removals on ecosystem productivity. This project will establish treatment sites, collect and analyze baseline data, and implement harvest treatments to facilitate long-term monitoring of the ecological impacts of biomass harvesting. Results from this project will (1) provide critical information for informing management recommendations aimed at mitigating impacts of biomass harvesting on nutrient poor soils, and (2) will provide long-term predictions of the effects of this practice on the productivity of forest systems growing on nutrient poor sites.

III. PROJECT STATUS UPDATES:

PROGRESS SUMARY AS OF 9/8/11:

Amendment Request (9/8/11)

Amendment is requested to rebudget funds ($15,000) from personnel to Professional/Technical Contracts. This amendment is being requested to support the hiring of a consulting forester to locate field research sites on nutrient poor soils for assessing the impacts of biomass harvesting (Activity 1). Hiring this contractor is the most cost-effective and efficient way to locate and establish these sites due to their vast experience working with forest lands on these soil types and evaluating the impacts of biomass harvests.

Amendment Approved: September 13, 2011

Project Status as of January 2012:

We have located and established 4 study sites within jack pine forests on nutrient poor soils in Hubbard, Wadena, and Becker County. These sites include lands administered by the Minnesota Department of Natural Resources Division of Forestry, Becker County Land Department, and Hubbard County Land Department. We are currently working with these project partners in establishing timber sales to carry out the experimental treatments we have designed for examining the impacts of biomass harvesting.

Project Status as of September 2012:

We have completed pre-harvest measurements of vegetation across 3 of the 4 study sites within jack pine forests on nutrient poor soils in Hubbard, Wadena, and Becker County and will complete measurements on the remaining site by October 2012. In addition, baseline soils measurements have been collected across all 4 study sites and have confirmed the nutrient poor status at each of these areas. Lysimeters for measuring the levels of nutrient export following harvesting have been installed at each site across all treatments and will allow for a better characterization of biomass harvesting impacts on soil fertility.

Project Status as of January 2013:

We have completed pre-harvest measurements of vegetation and soils across all of the study sites within jack pine forests on nutrient poor soils in Hubbard, Wadena, and Becker County. Experimental treatments have been marked and all timber sales for carrying out treatments have been sold and will be completed by March 2013. Preliminary comparisons and modeling of the impacts of different levels of biomass removal from nutrient poor sites suggest that removal of all harvesting residues will result in declines in aspen forest regrowth relative to harvests retaining these residues. Measurements from the 2013 field season (June-September) will be used to examine the impacts of these treatments on jack pine forest regrowth.

Project Status as of September 2013: We have completed the establishment of four study sites within jack pine forests on nutrient poor soils in Hubbard, Wadena, and Becker County, including implementation of all experimental treatments. Preliminary assessments of slash levels retained in these areas indicate that harvesting operations in the spring/summer remove a higher level of biomass than winter harvests in other ecosystem types. As a result, biomass harvesting on these sites may remove a greater proportion of ecosystem nutrients than for other forest types or soils (i.e., aspen on nutrient rich soils). Preliminary comparisons and long-term (100 year) modeling of the impacts of different levels of biomass removal from nutrient poor sites suggest that removal of all harvesting residues will result in future soil calcium and potassium deficiencies. We are currently examining how these declines in soil nutrients may impact the growth of jack pine.

Project Status as of January 2014: We have completed synthesis of slash retention data collected from our experimental study sites examining the ecological impacts of forest biomass harvesting on nutrient poor soils in northern Minnesota. Results from these syntheses indicate that there is no difference in post-harvest slash levels between areas in which slash was retained to meet current site-level guidelines and in places in which whole trees were harvested (i.e., no slash deliberately retained). Both of these areas had significantly less slash than areas in which all slash was retained on site. In addition, the overall levels of slash retention in these areas (no slash retained and recommended guideline levels) were half those found after similar treatments in aspen-dominated forests on nutrient rich sites, highlighting the low levels of incidental breakage on nutrient poor jack pine sites. These differences underscore the potential for greater nutrient depletion following biomass harvesting on nutrient poor sites and suggest higher levels of deliberate retention (i.e., different guidelines) may be necessary to sustain long-term productivity of these areas. We are currently examining how these different levels of slash removal impact native plant biodiversity and growth of jack pine. In addition, we have finished calibrating models for simulating long-term impacts of nutrient removals via biomass harvesting on long-term soil nutrient availability and are currently finalizing model runs evaluating the long-term impacts of these practices.

FINAL PROJECT STATEMENT:

Minnesota's forests are currently being viewed as potential feedstocks for production of renewable energy. A primary concern about harvesting forest biomass to generate renewable energy is the long-term impacts these harvests will have on soil nutrients and long-term ecosystem productivity, particularly in forests growing on nutrient poor soils. This project was designed to increase our understanding of the ecological impacts of biomass harvesting through establishment of a network of research sites in forests on nutrient poor soils. Treatments representing various levels of biomass removal and live-tree retention were implemented at four large-scale (80 acre) research sites in Becker, Hubbard, and Wadena Counties and were used to evaluate the importance of post-harvest slash and live-tree retention in maintaining the resilience and sustainability of jack pine forests under different biomass harvesting regimes. Treatments included current site-level guidelines for slash retention to allow for evaluations of the effectiveness of this practice at reducing impacts on long-term soil nutrients and forest vegetation. Field measurements from these sites were used to model the long-term effects of repeated biomass removals on ecosystem productivity. Results from this project indicate that there is no difference in post-harvest slash levels between areas in which slash was retained to meet current site-level guidelines and in places in which whole trees were harvested (i.e., no slash deliberately retained). The overall levels of slash retention in these areas were half those found after similar treatments in aspen-dominated forests on nutrient rich sites, highlighting the potential for greater nutrient depletion following biomass harvesting on nutrient poor sites and suggest a need for refinement of site-level guidelines to increase retention levels for nutrient poor soils. Long-term field data and model results indicate that biomass harvests that retain less than 40% of available residues may result in lower soil carbon stocks after several harvest rotations.

Project Results Use and Dissemination

The results of this project have been shared on numerous occasions with resource professionals, policy makers, citizens, and scientists over the past three years in efforts to inform forest conservation decisions regarding biomass harvesting impacts. These dissemination activities have included the development of a fact sheet for LCCMR members that was distributed on the LCCMR tour of Itasca State Park on July 18, 2013. In addition, an overview of the project and results were shared with private forest landowners through a University of Minnesota Extension Webinar to private forest landowners and county, state, and federal natural resource managers on December 9, 2013, as well as through a meeting of the Forest Operations and Planning Section of the Minnesota DNR Division of Forestry on January 8, 2014. Results were also presented at the Annual Meeting of the Ecological Society of America in Minneapolis, MN on August 5, 2013. Finally, results regarding the impact of different levels of post-harvest slash retention on soil nutrients have been discussed with members of the Minnesota Forest Resources Council and are being used to inform future guideline revisions. Publications resulting from this work are available for download from the Department of Forest Resources web site (www.forestry.umn.edu). Additional publications from this work that are currently in development will also be posted on this site and shared with LCCMR staff for dissemination.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Develop a network of research sites on nutrient poor soils to assess impacts of biomass harvesting on biodiversity and productivity

Description: Currently, little information exists on the potential impacts of biomass harvesting on aspen-dominated systems growing on nutrient poor soils. To address this need, we will establish large-scale manipulations of pine-dominated forests on nutrient poor sites allowing us to assess the ecological impacts of biomass harvesting on these systems, and to evaluate potential management recommendations for sustaining the ecological functions of these site types within the context of this management regime. In particular, research will be conducted at 4 pine forest sites on nutrient poor outwash sands within northern Minnesota. Each site will be a minimum of 120 acres to accommodate each treatment, as well as buffers between treatment units. Study sites will be located on lands owned by county land departments and Minnesota Department of Natural Resources.

Summary Budget Information for Activity 1:		
	ENRTF Budget:	**$ 127,439**
	Amount Spent:	**$ 127,439**
	Balance:	**$ 0**

Activity Completion Date: April 1, 2013

Outcome	Completion Date	Budget
1. *Nutrient poor sites identified through work with MNDNR and counties*	October 2011	$20,189
2. *Pre-harvest measurements of forest and soil conditions completed*	October 2012	$81,879
3. *Timber sales completed on sites*	March 2013	$10,000

Activity Status as of January 2012: We have located and established 4 study sites within jack pine forests on nutrient poor soils in Hubbard, Wadena, and Becker County (Outcome 1). These sites are each at least 80 acres in size and are on lands administered by the Minnesota Department of Natural Resources Division of Forestry, Becker County Land Department, and Hubbard County Land Department. The smaller total stand size was chosen in response to the rarity of large blocks of mature jack pine within this portion of the state resulting from past jack pine budworm outbreaks. Given the speed with which we were able to find suitable study areas, we are on schedule to meet all proposed completion dates under Activity 1.

Activity Status as of September 2012:
We have completed pre-harvest measurements of vegetation across 3 of the 4 study sites within jack pine forests on nutrient poor soils in Hubbard, Wadena, and Becker County and will complete measurements on the remaining site by October 2012. In addition, baseline soils measurements have been collected across all 4 study sites and have confirmed the nutrient poor status at each of these areas. Lysimeters for measuring the levels of nutrient export following harvesting have been installed at each site across all treatments and will allow for a better characterization of biomass harvesting impacts on soil fertility. Experimental treatments have been marked at 3 of the 4 research sites and will be completed by December 2012. We are on schedule to meet all proposed completion dates under Activity 1.

Activity Status as of January 2013:
We have completed pre-harvest measurements of vegetation and soils across all of the study sites within jack pine forests on nutrient poor soils in Hubbard, Wadena, and Becker County (Outcome 2). Experimental treatments have been marked and all timber sales for carrying out treatments have been sold and will be completed by March 2013. We are on schedule to meet all proposed completion dates under Activity 1.

Activity Status as of September 2013: We have completed the establishment of the research sites (Outcome 3) and all outcomes under Activity 1.

Activity Status as of January 2014: We have completed all outcomes under Activity 1.

Final Report Summary: Four large-scale (80 acre) study sites were established in jack pine forests on nutrient poor soils in Hubbard, Wadena, and Becker County. Two sites were located on the Minnesota Department of Natural Resources landbase, whereas the other two sites were on Becker and Hubbard County lands, respectively. At each study area, ten different harvest treatments were assigned and implemented in spring/summer 2013. These treatments included three different levels of overstory tree retention (none, dispersed retention of live trees, and aggregate retention of live trees) crossed with three levels of biomass removal (no slash retained, 20% slash retained, and all slash retained) and also included unharvested control areas. The overstory tree retention treatments were based on Minnesota Forest Resources Council (MFRC) site-level guidelines with a minimum of 6-12 live trees per acre in dispersed tree treatments and a minimum of 5% of the harvested area in live-tree aggregates > 0.25 acres for aggregate retention treatments. The 20% slash treatment was also based on the current MFRC guideline for minimizing the impacts of biomass harvesting. All timber sales for implementing the treatments were conducted by the same logger minimizing the influence of logger preferences and equipment differences on our outcomes. Prior to treatment implementation, pre-harvest measurements of vegetation, downed woody debris, and soils were collected from all areas.

ACTIVITY 2: Determine the impacts of biomass harvesting on regeneration and growth of ecologically important tree species and spread of invasive species

Description: We will measure soil nutrient availability and monitor the survival and growth of planted tree regeneration and invasive plants in treatment areas. Seedlings monitored will consist of a mix of long-lived conifers, allowing us to address questions related to how these harvests affect potential restoration of those species. Results concerning the immediate impacts of biomass harvesting on soils, forest growth, and tree regeneration will be summarized in project reports and conveyed to managers through outreach activities.

Summary Budget Information for Activity 2:

ENRTF Budget:	**$ 181,956**
Amount Spent:	**$ 181,956**
Balance:	**$ 0**

Activity Completion Date: June 30, 2014

Outcome	**Completion Date**	**Budget**
1. *Post-harvest measurements of soils and vegetation conducted*	October 2013	$100,450
2. *Assessment of soil nutrients and forest vegetation for 2 years*	October 2013	$30,506
3. *Data synthesis and final report completion*	June 2014	$51,000

Activity Status as of January 2012: We are currently establishing research plots within the four study sites for examining post-harvest conditions related to soils and vegetation. Measurements will begin in October 2013 to assess these impacts. We are on schedule to meet all proposed completion dates under Activity 2.

Activity Status as of September 2012: We have completed the establishment of research plots for examining post-harvest conditions related to soils and vegetation at 3 of the 4 research sites. We have also installed lysimeters at each site to monitor post-harvest nutrient export. We are on schedule to meet all proposed completion dates under Activity 2.

Activity Status as of January 2013: We have completed the establishment of research plots for examining post-harvest conditions related to soils and vegetation across all research sites. We are on schedule to meet all proposed completion dates under Activity 2.

Activity Status as of September 2013: We have completed measuring the post-harvest response of soils and vegetation on 3 of the 4 research sites and will be completed with these measurements by September 30. We are on schedule to meet all proposed completion dates under Activity 2.

Activity Status as of January 2014: We have completed measuring post-harvest soil and vegetation conditions (Outcome 1) and our assessments of soil nutrients of forest vegetation over the two field seasons in this study (Outcome 2). We are currently analyzing the impacts of biomass harvesting on these soil nutrients and vegetation and are on schedule to meet all proposed completion dates under Activity 2.

Final Report Summary: The impacts of biomass harvesting on forest vegetation, soil nutrients, carbon, and forest regrowth were measured for two years at the four research sites established under Activity 1. Although these measurements are from a relatively short time period in relation to long-term forest dynamics, there are several important findings in relation to how different levels of biomass harvesting may impact future forest productivity and diversity. In particular, slash (tops and branches) retention data collected from our experimental study sites indicate that there is no difference in post-harvest slash levels between areas in which slash was retained to meet current site-level guidelines (20% retention) and in places in which whole trees were harvested (i.e., no slash deliberately retained). This lack of difference reflects the influence of incidental breakage of harvested trees in maintaining slash levels of sites where whole trees are harvested. Treatments in which all slash was retained on site had significantly greater levels of slash than areas applying current guidelines or where no slash was deliberately retained. The overall levels of slash retention areas with no slash retained and at recommended guideline levels were half those found after similar treatments in aspen-dominated forests on nutrient rich sites, highlighting the low levels of incidental breakage on nutrient poor jack pine sites. These differences underscore the potential for greater nutrient depletion following biomass harvesting on nutrient poor sites and suggest higher levels of deliberate retention (i.e., different guidelines) may be necessary to sustain long-term productivity of these areas. Findings from this aspect of Activity 2 are currently being considered in refinement of site-level guidelines for biomass harvesting to ensure adequate levels of post-harvest slash are retained on similar sites. Jack pine and red pine seedlings were planted across all sites during year 3 of this project and will continue to be monitored to assess the influence of biomass harvesting on forest growth and regeneration.

ACTIVITY 3: Model long-term sustainability of biomass harvesting on nutrient poor soils

Description: The ecological sustainability of biomass harvesting hinges on nutrient availability and potential nutrient limitations. We will integrate findings from Result 2 into ecological models to simulate multiple levels of biomass harvesting on a range of soil qualities. Results concerning sustainability of alternative biomass harvesting strategies will be summarized in project reports, conveyed to managers through outreach activities, and used to inform future revisions to Minnesota's forest management guidelines.

Summary Budget Information for Activity 3:

ENRTF Budget:	**$ 40,605**
Amount Spent:	**$ 40,605**
Balance:	**$ 0**

Activity Completion Date: June 30, 2014

Outcome	Completion Date	Budget
1. *Characterization of initial ecological impacts of biomass harvesting completed*	November 2013	$8,000
2. *Results incorporated into ecological models of long-term impacts*	November 2013	$22,605
3. *Project summaries published*	June 2014	$10,000

Activity Status as of January 2012: We have begun parameterizing several ecological models, including PnET and Landis-Century, to examine the long-term sustainability of biomass harvesting on forest soils. Measurements collected under Activities 1 and 2 will be integrated into these models to allow for field-based assessments of harvesting impacts. We are on schedule to meet all proposed completion dates under Activity 3.

Activity Status as of September 2012: We are currently conducting preliminary evaluations of the suitability of several ecological simulation models for examining the long-term sustainability of biomass harvesting on soils. These evaluations are being based on the ability of a given model to account for the impacts of varying levels of biomass retention on soil nutrient cycling. We are on schedule to meet all proposed completion dates under Activity 3.

Activity Status as of January 2013: Based on our evaluations of model performance, we have selected the Landis-Century model as the primary model for examining the long-term sustainability of biomass harvesting on forest soils. This selection was based on the ability of this model to account for the impacts of biomass harvesting on fine and coarse woody debris and the resultant effects on forest soil nutrient status. We are on schedule to meet all proposed completion dates under Activity 3.

Activity Status as of September 2013: We have completed initial long-term (100 year) models of the impacts of different levels of biomass removal from nutrient poor sites and are currently examining how projected declines in soil nutrients may impact the growth of jack pine. We are on schedule to meet all proposed completion dates under Activity 3.

Activity Status as of January 2014: We have completed characterizations of the initial ecological impacts of biomass harvesting (Outcome 1) and integrated these results into the Landis-Century model for evaluating long-term (100 year) effects of these initial impacts. We are currently examining how projected declines in soil nutrients may impact long-term ecosystem productivity and are on schedule to meet all proposed completion dates under Activity 3.

Final Report Summary: The long-term impacts of biomass harvesting on soil nutrient availability and forest productivity were examined by integrating field data collections from the research areas established under Activity 1 into ecological models. Comparisons between the three different slash retention scenarios were used to evaluate the impacts of different levels of slash retention on long-term nutrient availability. These modeled scenarios were also compared with long-term (> 15 year) measurements of soil nitrogen and carbon following biomass harvesting on different soil types (sand, loam, and clay soils) to provide empirical validation of model results and further examine the long-term impacts of biomass harvesting on forest soils. Long-term (100 year) models of the impacts of different levels of biomass removal indicated that removal of all harvesting residues depletes soil nutrient levels below natural deposition and weathering rates, particularly soil calcium, nitrogen, and potassium. In several instances, retention of current recommended slash levels also resulted in deficiencies in these nutrients, particularly when sites contained an aspen component, suggesting the need for greater levels of retention on these soils. Long-term field data and model results indicate that biomass harvests that retain less than 40% of available residues may result in lower soil carbon stocks after several harvest rotations. The impacts of these lower nutrient levels on forest regrowth and productivity were observed in field measurements of aspen forests growing on nutrient poor, sandy soils where aboveground productivity was lower on sites experiencing slash removals relative to sites were all slash was retained. Future integration of field measurements of jack pine seedling growth under Activity 2 will be used to examine how long-term productivity of these forests are impacted by biomass harvesting.

V. DISSEMINATION:

Description: The final product of this project will be an interpretive report describing (a) the early initial impacts of forest biomass harvesting on the plant communities and nutrient status of forest systems growing on nutrient poor soils in northern Minnesota and (b) predictive models of the long-term impacts of repeated biomass removals on these sites. This report will be made available on the internet as a Department of Forest Resources Staff Paper Report. In addition, several manuscripts will be written based on this research and submitted for publication in peer-reviewed journals. A fact sheet summarizing principal findings of this project will be distributed to LCCMR members and legislators at the state and federal level. Results will be presented at state and national forest management and forest health conferences, and notably to agency and individual participants in the Sustainable Forests Education Cooperative. All reports and publications from this project will be made available via the Department of Forest Resources web site (www.forestry.umn.edu).

Status as of January 2012: No activities to report at this time.

Status as of September 2012: No activities to report at this time.

Status as of January 2013: No activities to report at this time.

Status as of September 2013: A fact sheet summarizing the scope and initial findings of this project was developed and shared with LCCMR members during a tour of Itasca State Park on July 18, 2013.

Status as of January 2014: Results from this project were presented as part of a University of Minnesota Extension Webinar to private forest landowners and county, state, and federal natural resource managers on December 9, 2013. In addition, an overview of the project and results pertaining to post-harvest slash levels were presented at the meeting of the Forest Operations and Planning Section of the Minnesota DNR Division of Forestry on January 8, 2014

Final Report Summary: The results of this project have been shared on numerous occasions with resource professionals, policy makers, citizens, and scientists over the past three years in efforts to inform forest conservation decisions regarding biomass harvesting impacts. These dissemination activities have included the development of a fact sheet for LCCMR members that was distributed on the LCCMR tour of Itasca State Park on July 18, 2013. In addition, an overview of the project and results were shared with private forest landowners through a University of Minnesota Extension Webinar to private forest landowners and county, state, and federal natural resource managers on December 9, 2013, as well as through a meeting of the Forest Operations and Planning Section of the Minnesota DNR Division of Forestry on January 8, 2014. Results were also presented at the Annual

Meeting of the Ecological Society of America in Minneapolis, MN on August 5, 2013. Publications resulting from this work are appended to this final report and are also available for download from the Department of Forest Resources web site (www.forestry.umn.edu). Additional publications from this work that are currently in development will also be posted on this site and shared with LCCMR staff for dissemination.

VI. PROJECT BUDGET SUMMARY:

The total budget request is 350,000 over a three-year period (July 2011-June 2014). This budget includes salary and fringe (0.1812) for one post-doctoral research associate is budgeted for two years. This post-doc will assess the initial impacts of biofuels harvests on soil nutrient availability, forest regeneration, and plant community composition. Salary and fringe (0.3230) for one research associate (0.1 FTE) is budgeted for 3 2 years. This research associate will assist with field sample processing and project coordination. One month of summer salary and fringe is budged for three years for the PI on this project, Dr. Anthony D'Amato. This salary will be used to pay for time spent on coordinating researchers, as well as analyzing and summarizing research results from this project. Salary and fringe (0.0743) for a work study student is budgeted for three years and this student will assist with summer field sampling and the processing of collected samples during the school year.

The subcontract with the U.S. Forest Service, Northern Research Station in Grand Rapids is to support salary and fringe for one full-time field technician for all three years of the study. This technician will be responsible for collecting field data, as well as for coordinating field crews. This subcontract also includes salary and fringe for two undergraduate summer employees for two years. The technician and summer students will be employed by the US Forest Service because that is the most cost-effective approach and our need to have personnel dedicated to this research study who are located close to the field sites. Finally, $12,000 of this subcontract is for lab analysis of soil samples that will be conducted in the analytical laboratory at the Northern Research Station in Grand Rapids, MN.

The subcontract with a consulting forester is to support salary for locating and establishing research areas on nutrient poor soils in northern Minnesota. This consultant will be chosen out of a candidate pool of foresters that are qualified for conducting work of this nature; however, given the contract total ($15,000) a competitive bid process is not required by the University of Minnesota.

Due to the high number of study sites and logistics associated with establishing the harvest treatments and baseline data collection, $18,000 is budgeted for domestic travel within Minnesota. This money will be used to pay for mileage (75%) and lodging (25%) for researchers, the field technician, graduate students, and undergraduate students. Equipment for permanently marking research plots, collecting regeneration and soil samples, and measuring soil nutrient availability are budgeted at $5999.

A. ENRTF Budget:

Budget Category	$ Amount	Explanation
Personnel:	$184,001	-One month of faculty summer salary and fringe (0.1934) for three years(D'Amato, PI; 0.1FTE) -Salary and fringe (0.1812) for a post-doctoral researcher for two years (1.0 FTE) -Salary and fringe (0.3230) for a research associate for 2.0 years (0.1 FTE) -Salary and fringe (0.0743) for a work-study undergraduate student for 3 years
Professional/Technical Contracts: U.S. Forest Service	$127,000	This contract to Brian Palik includes: -funds for hiring one half-time field technician for all three years of the study (0.5 FTE; $87,000). -salary and fringe for two undergraduate summer employees for two years ($28,000).

		The technician and summer students will be employed by the US Forest Service because that is the most cost-effective approach and our need to have personnel dedicated to this research study who are located close to the field sites. -lab analysis of soil samples ($12,000; **reduced rate** donated by US Forest Service)
Contracts: Consulting forester	$15,000	This contract includes: -funds for hiring a consulting forester to locate and identify candidate research sites on nutrient poor soils in Minnesota -funds support salary for hired consultant at $50/hour
Equipment/Tools/Supplies:	$5,999	- Equipment includes rebar for permanently marking plot centers ($350), supplies for constructing resin bags for soil nutrient measurements ($4000), soil cores and corer ($110), Haglof distance measuring equipment ($700), stake whiskers for marking subplots ($110), scintillation vials for soil analyses ($730)
Travel Expenses in MN:	$18,000	- This money will be used to pay for mileage (75%) and lodging (25%) for researchers, the field technician, graduate students, and undergraduate students working at the field research sites.
TOTAL ENRTF BUDGET:	**$350,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $3,500: N/A

Number of Full-time Equivalent (FTE) funded with this ENRTF appropriation: 3.1

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
USDA Grant	$1,810,500	$	Personnel for ecological simulation modeling, collection of field data, and processing of samples.
TOTAL OTHER FUNDS:	**$1,810,500**	**$**	

VII. PROJECT STRATEGY:

A. Project Partners:

In addition to the Project Manager, other project team members are noted below.

Charlie Blinn

Department of Forest Resources
University of Minnesota
St. Paul, MN

John Bradford
USDA Forest Service
Northern Research Station
Grand Rapids, MN

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B. Project Impact and Long-term Strategy:

Due to the large component of Minnesota's forested landbase on nutrient poor soils, there is a critical need for research that can assess the potential impacts of biomass harvesting on our forests, as well as generate management strategies for sustaining the functioning of these systems in light of these management practices. This project is intended to be a 3-year study. This time period is necessary to allow for research site identification, treatment implementation, and 1 year of post-treatment measurements. This proposed project will build upon an existing project examining the impacts of biomass harvesting on nutrient rich sites within northern Minnesota established with $294,000 in grants from the Minnesota Forest Resources Council (MFRC). Given the long-term nature of forest growth and management, we will seek additional funds to continue monitoring these sites beyond the 3 year project period. In particular, project participants are committed to long-term maintenance and monitoring of sites established in this proposed project. Although we anticipate subsequent proposals to LCCMR, we are also seeking additional funds from the USDA, DOE, US Forest Service Forest Health Monitoring Program, and the National Science Foundation to support this work.

C. Spending History:

Funding Source	**M.L. 2008 or FY 2009**	**M.L. 2009 or FY 2010**	**M.L. 2010 or FY 2011**
USDA grant			$525,000
MFRC grant	$98,000	$98,000	$98,000
USDA Forest Service			$30,000

(add or remove rows and columns as needed)

VIII. ACQUISITION/RESTORATION LIST: N/A

IX. MAP(S):

X. RESEARCH ADDENDUM: See Research Addendum

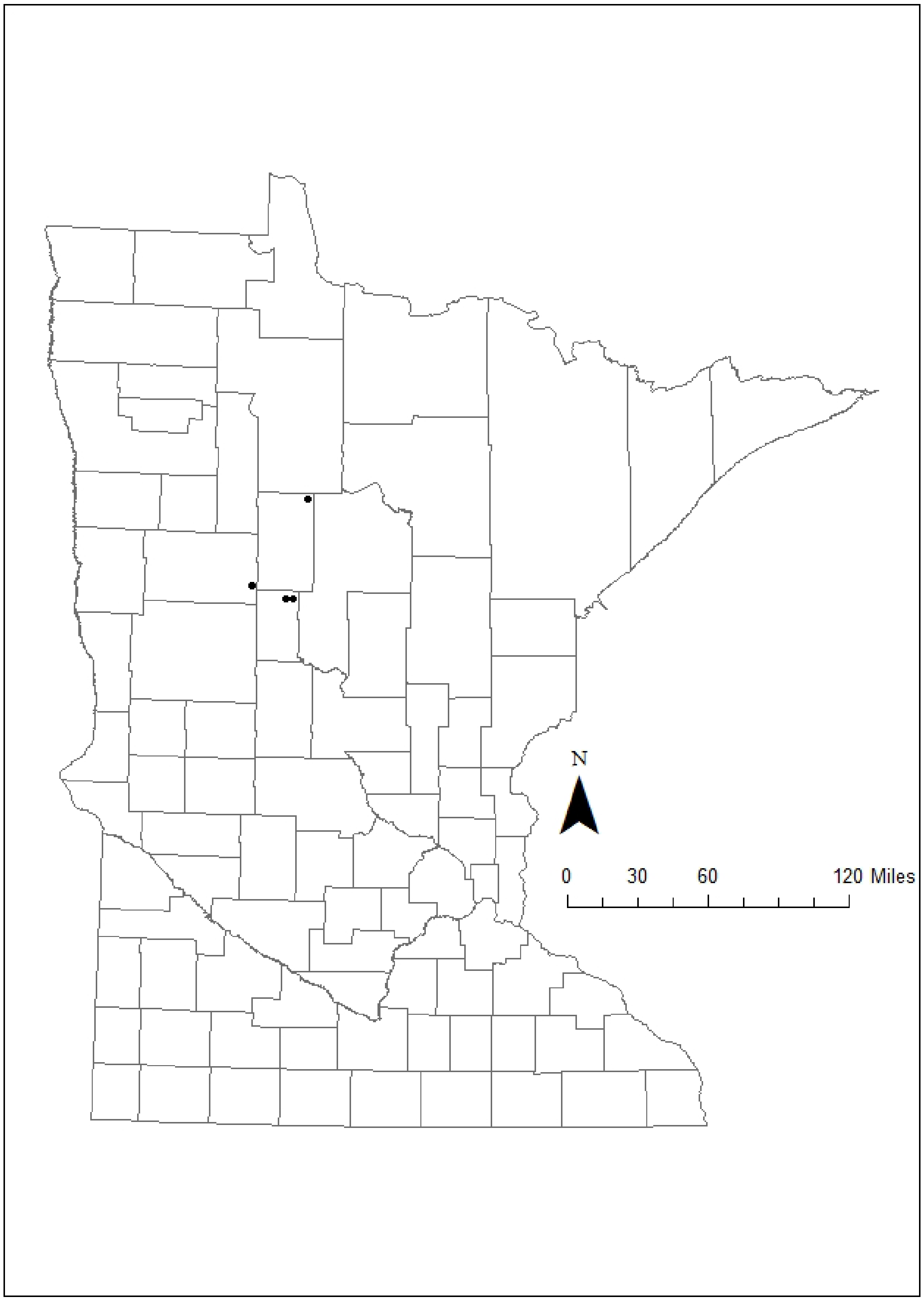
XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted not later than January 2012, September 2012, January 2013, September 2013, and January 2014. A final report and associated products will be submitted between June 30 and August 30, 2014 as requested by the LCCMR.

Attachment A: Budget Detail for M.L. 2011 (FY 2012-13) Environment and Natural Resources Trust Fund Projects

Project Title: Evaluation of Biomass Harvesting Impacts on Minnesota's Forests
Legal Citation:M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 03h
Project Manager: Anthony D'Amato
M.L. 2011 (FY 2012-13) ENRTF Appropriation: $ 350,000
Project Length and Completion Date: 3 years; August 30, 2014
Date of Update: January 14, 2014

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	**Activity 1 Budget**	**Amount Spent**	**Balance**	**Activity 2 Budget**	**Amount Spent**	**Balance**	**Activity 3 Budget**	**Amount Spent**	**Balance**	**TOTAL BUDGET**	**TOTAL BALANCE**
BUDGET ITEM	**Develop a network of research sites on nutrient poor soils to assess impacts of biomass harvesting on biodiversity and productivity**			**Determine the impacts of biomass harvesting on regeneration and growth of ecologically important tree species and spread of invasive species**			**Model long-term sustainability of biomass harvesting on nutrient poor soils**				
Personnel (Wages and Benefits)	30,000	30000	-	121,474	116033	5,441	32,527	23041	9,486	184,001	14,927
Anthony D'Amato, Project Manager; $30,999 (81% salary, 19% benefits); 10%FTE					20,666						
Post-doctoral researcher; $100,709 (82% salary, 18% benefits); 100%FTE					79,667			11,387			
Research associate; $40,605 (68% salary, 32% benefits); 10%FTE		30,000			15,700			11,654			
Undergraduate work-study; $26,688 (93% salary, 7% benefits); 50%FTE											
Professional/Technical Contracts											
US Forest Service (Dr. Brian Palik): funds for hiring one half-time field technician for all three years of the study (0.5 FTE; $87,000); salary and fringe for two undergraduate summer employees for two years ($28,000); lab analysis of soil samples ($12,000; reduced rate donated by US Forest Service	67,979	67979	-	50,943	46438	4,505	8,078	2284	5,794	127,000	10,299
Contract with consulting forester to locate field sites on nutrient poor soils in northern Minnesota. Funds are to support salary at $50/hour.	15,000	15000	-							15,000	0
Equipment/Tools/Supplies										0	0
Equipment tools and supplies, such as rebar for permanently marking plot centers ($350), supplies for constructing resin bags for soil nutrient measurements ($4000), soil cores and corer ($110), Haglof laser distance measuring equipment ($700), stake whiskers for marking subplots ($110), scintillation vials for soil analyses ($730)	3,000	3000	-	2,999	2999	-				5,999	0
Travel expenses for travel in Minnesota. This money will be used to pay for mileage (75%) and lodging (25%) for researchers, the field technician, graduate students, and undergraduate students working at the field research sites. Reimbursement of expenses is based on the University plan for travel expenditures and reimbursement.	11,460	11460	-	6,540	4500	2,040				18,000	2,040
COLUMN TOTAL	**$127,439**	**$127,439**	**$0**	**$181,956**	**$169,970**	**$11,986**	**$40,605**	**$48,366**	**$15,280**	**$350,000**	**$27,266**



Map 1. Location of large-scale (80 acre) study sites established in jack pine forests on nutrient poor soils in Becker, Hubbard, and Wadena County. At each study area, ten different harvest treatments designed to evaluate the impacts of biomass harvesting on soil nutrients and forest vegetation were implemented in 2013.

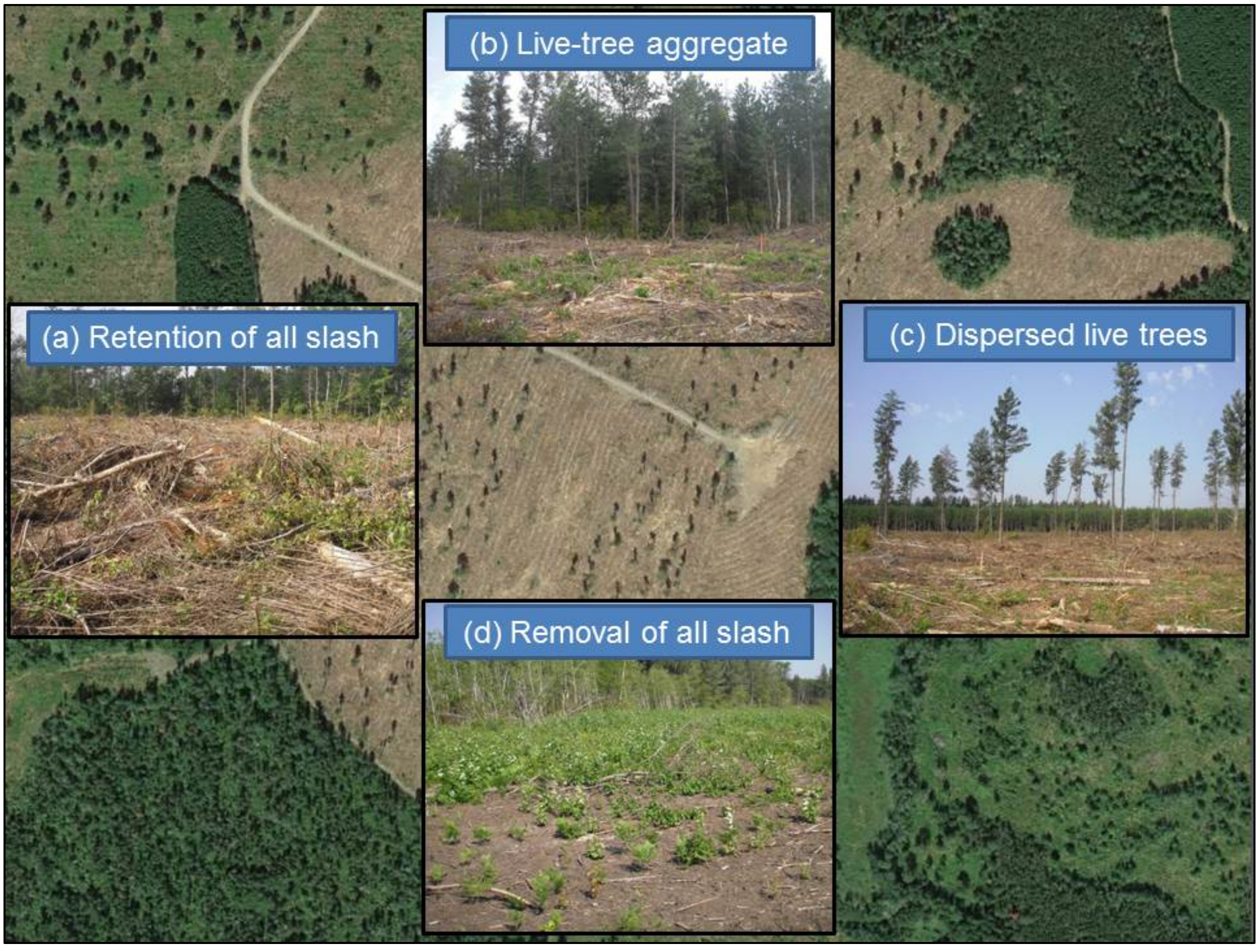


Figure 1. Biomass harvesting, by removing nutrient-rich tree branches and tops (i.e., slash) from the forest has the potential to negatively impact soil nutrients and forest plant communities. This project demonstrated that management practices, including retaining harvest slash (a) and living trees, both in groups (b) and singly (c) across harvested areas can minimize these negative impacts on jack pine forests growing on nutrient poor soils. Removal of all slash from these areas (d) is not recommended, as results indicate potential for long-term depletion of soil nutrients and carbon under this practice. Background photo is aerial image of one of four large-scale study areas established by this project.

Fifteen-Year Patterns of Soil Carbon and Nitrogen Following Biomass Harvesting

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The substitution of forest-derived woody biofuels for fossil fuel energy has garnered increasing attention in recent years, but information regarding the mid- and long-term effects on soil productivity is limited. We investigated 15-yr temporal trends in forest floor and mineral soil (0–30 cm) C and N pools in response to organic matter removal treatments (OMR; stem-only harvest, SOH; whole-tree harvest, WTH; and whole-tree plus forest floor removal, FFR) at three edaphically distinct aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) forests in the Great Lakes region. The OMR and temporal effects were generally site specific, and both were most evident in the forest floor and combined profile (mineral soil and forest floor) compared with the mineral soil alone. Forest floor and combined profile C and N pools were generally similar in the SOH and WTH treatments, suggesting that slash retention has little impact on soil C and N in this time frame. Temporal changes in C and N at one of the three sites were consistent with patterns documented following exotic earthworm invasion, but mineral soil pools at the other two sites were stable over time. Power analyses demonstrated that significant effects were more likely to be detected for temporal differences than the effects of OMR and in the combined profile than in the mineral soil. Our findings are consistent with previous work demonstrating that OMR effects on soil C and N pools are site specific and more apparent in the forest floor than the mineral soil.

Abbreviations: FFR, forest floor removal; OMR, organic matter removal; SOH, stem-only harvest; WTH, whole-tree harvest.

A growing interest in utilizing forest-derived biofuels as a substitution for fossil fuels has led to related questions about the long-term impacts of increasing organic matter removal on forest structure and function (Jurgensen et al., 1997; Janowiak and Webster, 2010; Berger et al., 2013). In particular, the removal of entire trees, including boles, tops, and branches (whole-tree removal, WTH), is likely to cause a greater depletion of soil organic matter and nutrients over time compared with conventional stem-only harvest (SOH), and this may ultimately limit site productivity (Proe and Dutch, 1994; Burger, 2002; Walmsley et al., 2009). Nonetheless, literature reviews and meta-analyses have often concluded that harvest-related impacts on mineral soil C pools are negligible (Johnson, 1992; Johnson and Curtis, 2001; Nave et al., 2010), and many broad-scale studies have been confounded by site-to-site complexity among climate, vegetation, and soil factors, which limits the ability to generalize the impacts of organic matter removal (Paré et al., 2002; Sanchez et al., 2006; Thiffault et al., 2006; Strömgren et al., 2013). Additional field experiments that assess medium- and long-term effects of WTH and SOH across a gradient of mineral soil textures and organic C contents would both improve cross-site comparisons and contribute to more robust meta-analyses (Johnson, 1992; Thiffault et al., 2011).

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Forest management practices that remove organic matter may be detrimental to long-term site productivity because organic matter is critical to many soil physical and chemical properties, including nutrient availability and aggregate stability (Powers et al., 1990; Henderson, 1995; Binkley and Fisher, 2013). In addition to the direct removal of organic material, harvesting may indirectly affect the soil environment, including altering the soil temperature and/or moisture content (Devine and Harrington, 2007; Slesak, 2013) and increasing extremes in soil temperature (Van Miegroet et al., 1992), both of which may influence rates of nutrient transformation and organic matter decomposition (Edwards and Ross-Todd, 1983; Slesak et al., 2010). Disruption of the forest floor during harvesting operations may intensify these effects and, depending on the moisture regime, increase nutrient loss via leaching (Henderson, 1995). However, despite the well-known importance of the forest floor to the mineral soil as a source of organic matter and physical protection (Currie, 1999), rarely have studies both manipulated the forest floor and documented its response over time.

Few studies have compared the medium-term responses (15–20 yr) of soil C and N pools to varying harvest intensities (e.g., SOH and WTH), and those with incremental measurements may have been confounded by natural temporal variability. For example, while specific management-related effects may not be observed, pool changes over time may still be detected (Johnson et al., 2002), and, indeed, interannual variability can be high (Knoepp and Swank, 1997). Medium- and long-term monitoring of various temperate forest types has suggested that temporal patterns of soil C and N pools can vary independently of harvesting (Knoepp and Swank, 1997; Johnson and Todd, 1998; Trettin et al., 1999; Johnson et al., 2007). Assessments of medium-term harvest impacts on soil C and N pools have suggested that differences between SOH and WTH are small and usually site specific, but they have not often included incremental measurements that could characterize temporal changes (Olsson et al., 1996; Johnson and Todd, 1998; Thiffault et al., 2006).

Our objective was to understand the medium-term (∼15 yr) effects of biomass harvesting on soil C and N pools at three different aspen-dominated sites in the Great Lakes region. The sites were fully replicated with three levels of manipulated organic matter removal, including SOH, WTH, and whole-tree harvest plus forest floor removal (FFR), and they represented a range of soil textures (silt loam, sand, and clay). We focused on the soil C and N pools (mineral soil and forest floor) because they are valuable indices of long-term site productivity given the relative importance of organic matter and the high potential for N limitation in intensively managed sites (Johnson 1994). We expected that responses would vary somewhat due to differences in soil texture but that, generally, forest floor C and N pools would be more susceptible to harvest-related impacts than those in the mineral soil, and the overall effects on the combined profile (forest floor plus mineral soil) would follow a disturbance gradient of organic matter removal (SOH > WTH > FFR). The second objective of our study was to assess the capacity of this long-term data set to detect the effects of organic matter removal and changes over time in soil C and N pools. We compared the calculated probabilities (power) of detecting significant main effects in our results with the goal of better informing future long-term study designs.

MATERIALS AND METHODS

Study Sites and Experimental Design

This study was conducted at three aspen forests in the Great Lakes region that are part of the Long-Term Soil Productivity Network (Powers et al., 2005; Powers, 2006). The sites vary climatically and edaphically (Table 1; Stone, 2001), but all

Table 1. Site characteristics and soil pretreatment properties (mineral soil: 0–30 cm) of the three aspen forest sites in the northern Great Lakes region.

Characteristic or property	Chippewa (Minnesota) silt loam	Huron (Michigan) sand	Ottawa (Michigan) clay
Latitude, longitude	47.32, −94.55	44.57, −83.98	46.63, −89.25
Year of treatment initiation	1993	1994	1992
Soil classification	Frigid Haplic Glossudalfs	Frigid Typic Udipsamments and Frigid Entic Haplorthods	Frigid Vertic Glossudalfs
Mean annual precipitation, cm	64	75	77
Mean annual temperature, °C	3.8	6.2	4.5
50-yr site index, aspen, m	23	19	17
Soil texture, %†			
Sand	45	93	23
Silt	51	6	27
Clay	4	1	50
Coarse fragments by mass, %	1.6	1.0	0
Bulk density, Mg m^{-3}	1.24	1.12	1.19
Total C, Mg ha^{-1}‡			
Forest floor	27.5	9.7	20.4
Mineral soil	25.8	30.6	41.9
Total N, Mg ha^{-1}‡			
Forest floor	1.3	0.4	0.9
Mineral soil	1.4	1.2	3.2

† Using hydrometer method.

‡ Total C and N determined by dry combustion. Mass was estimated using <2-mm bulk density.

were fully stocked, mature aspen stands before treatment. The Chippewa site (Chippewa National Forest, Minnesota) has till-derived silt loam soils, and co-occurring tree species include red maple (*Acer rubrum* L.), basswood (*Tilia americana* L.), sugar maple (*Acer saccharum* Marsh.), northern red oak (*Quercus rubra* L.), and eastern white pine (*Pinus strobus* L.). The Huron site (Huron National Forest, northeastern Lower Peninsula of Michigan) has sandy-textured soils that formed on an acidic outwash plain. Associated tree species include bigtooth aspen (*Populus. grandidentata* Michx.), red maple, northern red oak, eastern white pine, and black cherry (*Prunus serotina* Ehrh.). The Ottawa site (Ottawa National Forest, western Upper Peninsula of Michigan) has clay-textured soils that formed from calcareous, lacustrine clay parent material. Co-occurring species at Ottawa include white spruce [*Picea glauca* (Moench) Voss], balsam fir [*Abies balsamea* (L.) Mill.] and red maple.

Harvest treatments were initiated in consecutive years, beginning with Ottawa in 1992 and followed by Chippewa in 1993 and Huron in 1994. At each site, treatment plots (50 by 50 m) were randomly established in a 3 × 3 factorial randomized block design before harvest, with three levels of organic matter removal (OMR) and three levels of soil compaction. The OMR treatments were designed to represent a disturbance gradient: the SOH treatment removed boles, but slash (branches and tops) was left on site; the WTH treatment removed all woody biomass (trees and shrubs) from the site; and the FFR treatment removed all woody biomass as well as the forest floor material from the site. The FFR treatment represented an extreme disruption of the forest floor during harvest activities, which could potentially occur on landings or skid trails. We confined this study to the lowest level of soil compaction (no additional compaction beyond that accrued through harvest activities), given that we were primarily interested in the effects of biomass harvesting practices on soil productivity. Each treatment was replicated three times per site ($n = 3$ plots); however, an error during treatment application at the Ottawa site resulted in five plot replicates for the WTH treatment. Harvests occurred under frozen soil conditions in January or February of each treatment initiation year (Table 1), and the plots naturally regenerated to aspen following treatment. An unharvested control was added to each site 2 yr after treatment installation; however, inconsistencies in sampling intensity and timing preclude us from including this treatment in our analyses. Full descriptions of treatment applications were provided by Stone (2001).

Soils were sampled on five dates: in the summer before harvest (preharvest), in the fall following harvest (Year 0), and in the spring every 5 yr subsequently (Years 5, 10, and 15). Before harvest (pretreatment), two subsamples were randomly collected from each plot and composited for analysis. Subsequently, permanent subsample locations were established uniformly throughout each plot. Initially, eight subsample locations were established (Year 0), but one additional location was added for Years 5, 10, and 15 (nine subsamples). At each location, soils were sampled at a random azimuth and distance (1–3 m) from the permanent marker (>1 m from any previous sampling collections). Forest floor (organic horizon) and mineral soil (0–30 cm) samples were extracted using a stainless steel corer (6.35-cm diameter; 190.5-cm^3 volume) fitted with a plastic tube. Forest floor and mineral soil boundaries were delineated using changes in color and texture. Tubes were removed and taken to the laboratory for processing. To maintain consistency in sampling, one technician oversaw all of the soil collection at all of the sites throughout the 15-yr study period.

Soil Analyses

For each subsample, the forest floor thickness was recorded and then separated from the mineral soil. Forest floor material was dried at 70°C for 24 h. Plot subsamples were composited and then ground to 1 mm using a Thomas-Wiley laboratory mill. Mineral soil subsamples were divided into three depths (0–10, 10–20, and 20–30 cm), sieved to 2 mm, and oven dried at 105°C to a constant mass. Mineral soil plot subsamples were then composited, finely ground using a mortar and pestle, and pulverized on a roller mill for 2 d. Total C and total N were determined for forest floor and mineral soil samples by dry combustion. The initial results obtained incrementally using two different analyzers, a Carlo Erba Model NA 1500 series (CE Elantech, Inc.) for pretreatment to Year 10 and a Leco TruSpec CHN analyzer (Leco Corp.) for Year 15, were inconsistent over time, so all archived samples were reanalyzed in 2013 using the Leco analyzer. Nitrogen values that were below the instrument's detection limit (0.04%) were replaced with half the detection limit (0.02%). Total bulk density was calculated for each subsample at each depth using the oven-dried mass (including coarse fragments), sample volume, and moisture content; the fine fraction (<2-mm) bulk density plot mean at each sampling date was used to convert C and N values to a mass basis.

Statistical Analyses

The three study sites were analyzed separately because of variations in soil texture, climate, and treatment initiation year. Our goal was to be consistent with previous Long-Term Soil Productivity Network studies that examined mineral soil properties by 10-cm increments; however, we acknowledge the potential difficulties in delineating the boundary between the forest floor and the surface mineral soil in the field that could impede the accuracy of both measurements (Yanai et al., 2003; Don et al., 2012). To balance these issues, we chose to analyze pools of C and N and the C/N ratios for the forest floor and mineral soil (0–30 cm) separately and then combined (combined profile, forest floor + mineral soil; Homann et al., 2001). Combining the three mineral soil depths did not alter the overall conclusions. For each variable (C, N, C/N ratio, and total bulk density), we used a repeated measures analysis of covariance (ANCOVA) model that included OMR and time as fixed effects and plot as a random effect. Sample year (Years 0, 5 10, and 15) was the repeated factor within a first-order autoregressive covariance structure. The pretreatment data were included as a covariate to account

Table 2. Probabilities (*F* statistics) from repeated measures ANCOVA testing of main effects of organic matter removal (OMR) and time (T) on forest floor, mineral soil (0–30 cm), and combined profile (mineral soil + forest floor) C, N, C/N ratio, and bulk density (BD) for three aspen forest sites in the northern Great Lakes region. Time was the repeated factor, and pretreatment data were used as a covariate in the model. Italicized *p* values are significant ($p < 0.1$).

Source	Forest floor			Mineral soil				Combined profile		
	Total C	Total N	C/N ratio	Total C	Total N	C/N ratio	BD	Total C	Total N	C/N ratio
					Chippewa (silt loam)					
OMR	*0.072*	*0.021*	0.586	0.955	0.460	0.134	0.399	*0.060*	*0.056*	0.405
Time	*<0.001*	*0.001*	*0.036*	0.163	0.307	0.420	*0.003*	*<0.001*	*<0.001*	0.472
OMR × T	0.1328	0.326	*0.013*	0.656	*0.028*	*0.074*	*0.016*	0.225	*0.093*	0.140
					Huron (sand)					
OMR	*0.073*	0.135	0.659	0.793	0.425	0.315	0.487	0.114	0.142	0.264
Time	0.107	*0.020*	*0.070*	0.389	*0.001*	*0.003*	*0.059*	0.649	*0.034*	*0.002*
OMR × T	0.658	0.740	0.972	0.973	0.184	0.324	*0.065*	0.712	0.192	0.273
					Ottawa (clay)					
OMR	*0.025*	*0.041*	0.459	0.473	0.439	0.124	0.483	*0.001*	*0.049*	0.918
Time	*<0.001*	*<0.001*	*0.034*	*<0.001*	*0.025*	*0.0003*	*0.008*	*0.003*	0.160	*0.005*
OMR × T	0.141	0.224	*0.057*	0.290	*0.039*	*0.002*	0.252	0.499	*0.077*	*0.014*

for inherent soil variability (VandenBygaart, 2009), and degrees of freedom were assigned using the Satterthwaite approximation. Tukey–Kramer tests were used to separate means of significant main effects. When significant treatment effects or OMR × time interactions were encountered, the SLICE command was used to separate means within the two effects.

Residuals were visually inspected for each model, and data were transformed (inverse, square root, or natural logarithm) as necessary to meet the assumptions of ANOVA. An a priori significance level of $\alpha = 0.1$ was set because of low replication ($n = 3$) and the inherent variability in repeatedly sampled soils. All analyses were conducted using the MIXED procedure in SAS (Version 9.3, SAS Institute), which is effective when applied to unbalanced designs. The probability (power) of detecting a statistically significant ($\alpha < 0.1$) time or OMR treatment effect was assessed for each site and variable (C, N, and C/N ratio) using PROC MIXED in SAS based on the steps outlined by Littell et al. (2006).

RESULTS

Carbon

Forest floor C was generally more variable among OMR treatments and over time than mineral soil C (Tables 2, 3, and 4). At Chippewa, forest floor C was lower in the FFR than the SOH treatment ($p = 0.072$) and it peaked in Year 10 (Year 10 > Years 0, 5, and 15; $p < 0.001$). At Huron, forest floor C was also lower in the FFR than the SOH treatment ($p = 0.073$), but it did not change over time. At Ottawa, forest floor C was lower in the FFR than SOH and WTH treatments ($p = 0.025$), and it had a declining trend over time (Year 15 < Years 0, 5, and 10; Year 5 > Years 0 and 10; $p < 0.001$). Mineral soil C pools were not affected by the OMR treatments at any of the sites. Mineral soil C was stable over time at Chippewa and Huron but increased at Ottawa (Year 0 < Years 10 and 15; Years 5 and 10 < Year 15; $p < 0.001$).

The combined profile C responses were similar to those for the forest floor. At Chippewa, the combined profile C in the FFR was lower than the SOH treatment ($p = 0.060$), and it peaked in Year 10 (Years 0, 5, and 15 < 10; Year 5 > Year 15; $p < 0.001$; Fig. 1). At Huron, the combined profile C was not affected by the OMR treatments nor did it change over time (Fig. 1). At Ottawa, the combined profile C was lower in the FFR than the WTH and SOH treatments ($p = 0.001$), and it increased over time (Year 0 < Years 5 and 15; $p = 0.003$; Fig. 1).

Table 3. Forest floor total C and N for three aspen forest sites in the northern Great Lakes region in response to organic matter removal treatments (SOH, stem-only harvest; WTH, whole-tree harvest; and FFR, whole-tree harvest plus forest floor removal). Samples were taken before treatment (Pre), in the fall following treatment (Year 0), and 5, 10, and 15 yr following treatment.

Sampling time	Total C			Total N		
	SOH	WTH	FFR	SOH	WTH	FFR
			Mg ha^{-1}			
			Chippewa (silt loam)			
Pre	30.8 (6.9)†	29.7 (5.5)	22.1 (1.1)	1.4 (0.2)	1.2 (0.1)	1.2 (0.1)
Year 0	33.1 (3.8)	31.5 (4.8)	18.9 (0.8)	1.4 (0.1)	1.3 (0.1)	0.8 (0.1)
Year 5	39.0 (5.0)	23.7 (3.4)	18.5 (1.2)	1.6 (0.1)	1.1 (0.1)	0.9 (0.1)
Year 10	54.9 (3.7)	36.2 (9.9)	37.5 (9.5)	2.5 (0.2)	1.6 (0.3)	1.5 (0.4)
Year 15	30.5 (0.6)	21.1 (3.9)	16.6 (1.1)	1.3 (0.1)	1.1 (0.1)	0.7 (0.1)
			Huron (sand)			
Pre	6.4 (1.0)	14.6 (4.3)	8.0 (2.1)	0.2 (0.1)	0.5 (0.1)	0.3 (0.1)
Year 0	16.8 (3.5)	10.9 (2.1)	6.0 (2.7)	0.6 (0.1)	0.4 (0.1)	0.3 (0.1)
Year 5	9.4 (3.1)	9.4 (3.6)	2.2 (0.1)	0.3 (0.1)	0.3 (0.1)	0.1 (0.1)
Year 10	8.7 (1.2)	10.7 (4.7)	4.8 (0.1)	0.3 (0.1)	0.4 (0.2)	0.2 (0.1)
Year 15	10.8 (2.3)	11.9 (4.9)	4.8 (1.8)	0.4 (0.1)	0.5 (0.2)	0.2 (0.1)
			Ottawa (clay)			
Pre	17.0 (2.7)	22.7 (1.6)	20.0 (2.1)	0.7 (0.1)	1.0 (0.1)	0.8 (0.2)
Year 0	23.2 (1.9)	27.2 (2.8)	8.3 (2.5)	0.9 (0.1)	1.2 (0.1)	0.3 (0.1)
Year 5	26.3 (0.6)	30.8 (3.0)	15.8 (6.8)	1.1 (0.1)	1.2 (0.1)	0.8 (0.3)
Year 10	20.5 (1.2)	19.9 (3.1)	11.9 (1.7)	0.9 (0.1)	0.9 (0.1)	0.5 (0.1)
Year 15	14.3 (3.8)	10.2 (2.3)	5.3 (1.3)	0.6 (0.1)	0.4 (0.1)	0.2 (0.1)

† Values are means of three plots, with SE in parentheses.

Table 4. Mineral soil C, N, and bulk density (0–30 cm) for three aspen forest sites in the northern Great Lakes region in response to organic matter removal treatments (SOH, stem-only harvest; WTH, whole-tree harvest; FFR, whole tree harvest plus forest floor removal). Samples were taken before treatment (Pre), in the fall following treatment (Year 0), and 5, 10, and 15 yr following treatment.

Sampling time	Total C			Total N			Bulk density†		
	SOH	WTH	FFR	SOH	WTH	FFR	SOH	WTH	FFR
	Mg ha^{-1}						Mg m^{-3}		
				Chippewa (silt loam)					
Pre	27.6 (2.2)‡	25.7 (1.1)	24.0 (1.2)	1.4 (0.1)	1.5 (0.1)	1.3 (0.1)	1.28 (0.05)	1.23 (0.06)	1.20 (0.02)
Year 0	29.0 (1.1)	29.3 (1.7)	26.2 (2.2)	1.8 (0.3)	1.8 (0.1)	1.4 (0.1)	1.48 (0.07)	1.38 (0.05)	1.35 (0.06)
Year 5	29.1 (2.7)	28.7 (1.2)	29.9 (2.9)	1.7 (0.2)	1.7 (0.2)	1.5 (0.4)	1.39 (0.08)	1.29 (0.05)	1.38 (0.07)
Year10	31.4 (3.4)	28.9 (1.2)	30.1 (1.1)	1.6 (0.1)	2.0 (0.4)	2.0 (0.4)	1.45 (0.04)	1.35 (0.03)	1.42 (0.07)
Year15	26.9 (2.1)	28.5 (3.4)	24.9 (4.0)	1.9 (0.2)	2.1 (0.3)	1.1 (0.1)	1.46 (0.06)	1.38 (0.06)	1.43 (0.07)
				Huron (sand)					
Pre	29.1 (1.7)	31.1 (1.7)	31.4 (4.5)	1.0 (0.1)	1.2 (0.1)	1.3 (0.2)	1.19 (0.05)	1.12 (0.02)	1.06 (0.03)
Year 0	30.0 (1.3)	29.0 (4.2)	26.9 (2.6)	1.0 (0.1)	1.1 (0.2)	0.9 (0.1)	1.27 (0.01)	1.30 (0.02)	1.29 (0.02)
Year 5	31.4 (2.2)	33.0 (1.9)	31.2 (4.6)	1.5 (0.1)	1.5 (0.1)	1.2 (0.1)	1.28 (0.03)	1.23 (0.02)	1.25 (0.02)
Year10	29.7 (2.1)	31.3 (0.7)	31.4 (2.1)	1.8 (0.3)	1.6 (0.2)	1.8 (0.2)	1.25 (0.02)	1.22 (0.02)	1.27 (0.01)
Year15	31.2 (1.5)	33.5 (5.8)	31.7 (2.8)	1.5 (0.4)	2.0 (0.1)	1.0 (0.1)	1.22 (0.02)	1.27 (0.04)	1.27 (0.01)
				Ottawa (clay)					
Pre	37.4 (2.7)	41.9 (1.9)	46.5 (7.4)	3.0 (0.1)	3.0 (0.3)	3.6 (0.2)	1.12 (0.03)	1.25 (0.06)	1.17 (0.04)
Year 0	37.6 (1.7)	41.8 (2.9)	40.5 (1.2)	3.0 (0.2)	3.0 (0.1)	2.8 (0.1)	1.26 (0.01)	1.23 (0.02)	1.24 (0.01)
Year 5	43.4 (2.2)	43.5 (2.0)	42.8 (3.6)	3.5 (0.8)	3.5 (0.3)	2.1 (0.4)	1.30 (0.01)	1.28 (0.02)	1.26 (0.03)
Year10	46.1 (6.8)	50.2 (4.2)	51.9 (3.7)	3.1 (0.3)	3.5 (0.2)	3.5 (0.4)	1.14 (0.06)	1.23 (0.02)	1.22 (0.05)
Year15	62.1 (4.9)	70.0 (4.9)	56.4 (2.5)	3.4 (0.1)	3.5 (0.2)	3.4 (0.1)	1.27 (0.02)	1.30 (0.02)	1.28 (0.04)

† Bulk density average of 0–10-, 10–20-, and 20–30-cm depths.

‡ Values are means of three plots, with SE in parentheses.

Nitrogen

The overall forest floor and mineral soil N response patterns were similar to those for C (Tables 2, 3, and 4). At Chippewa, forest floor N was lower in the FFR than the SOH treatment ($p = 0.021$), and it peaked in Year 10 (Year 10 > Years 0, 5, and 15; $p < 0.001$). At Huron, forest floor N was not affected by OMR, but it varied slightly over time (Year 0 > Year 5; $p = 0.020$). At Ottawa, forest floor N was lower in the FFR than the SOH and WTH treatments ($p = 0.041$), and it declined over time (Year 0 < Year 5; Year 5 < 10; Years 0, 5, and 10 < Year 15; $p < 0.001$). The interaction between OMR and time was significantly related to mineral soil N at Chippewa ($p = 0.028$); temporal differences were primarily within the FFR treatment (Year 10 > Year 15), but no OMR differences were observed. At Huron, mineral soil N was not affected by the OMR treatments, but it increased slightly over time (Year 0 < Years 5, 10, and 15; Year 5 < Year 10; $p = 0.001$). At Ottawa, a significant OMR × time interaction existed for mineral soil N ($p = 0.039$), with OMR differences in Year 5 (FFR < WTH) and time differences in the FFR treatment (Year 5 < Years 10 and 15).

The responses of combined profile N reflected those for forest floor N. There was a significant OMR × time interaction ($p = 0.009$) for combined profile N at Chippewa (Fig. 1); subsequent pairwise comparisons revealed changes over time in the FFR treatment (Year 0 < Year 10; Year 10 > Year 15) and the SOH treatment (Year 0 < Year 10), as well as OMR treatment differences in Year 15 (FFR < SOH and WTH). Combined profile N at Huron was not affected by OMR but changed over time (Years 0 and 5 < Year 10; $p = 0.034$; Fig. 1). At Ottawa, the effects of the OMR treatments on the combined profile N varied among the sample years (OMR × time interaction $p = 0.077$; FFR < SOH and WTH in Year 5; Fig. 1).

Carbon/Nitrogen Ratio

The responses of the C/N ratios were less consistent than those of the total C and N pools (Table 2). At Chippewa, the forest floor C/N ratio varied over time by treatment (OMR × time interaction $p = 0.013$; Year 5 < Year 10 in the FFR treatment). The OMR treatments did not affect the forest floor C/N ratio at Huron, but it showed a slight declining trend over time (Year 5 > Year 15; $p = 0.070$). Despite a significant OMR × time interaction ($p = 0.057$) for the forest floor C/N ratio at Ottawa, no specific temporal or OMR treatment differences were detected by Tukey–Kramer analysis. Similarly, a significant OMR × time interaction in the mineral soil C/N ratio at Chippewa ($p = 0.074$) did not result in differences among treatments or years. At Huron, the mineral soil C/N ratio decreased slightly over time (Year 0 < Year 10; $p = 0.001$). A significant OMR × time interaction ($p = 0.002$) occurred for the mineral soil C/N ratio at Ottawa, with the C/N ratio varying among the OMR treatments in Year 5 (FFR < SOH and WTH) and over time in the FFR treatment (Year 0 < Year 5; Year 5 > 10) and the WTH treatment (Years 0, 5, and 10 < Year 15). The combined profile C/N ratio at Chippewa was not affected by the OMR treatments nor did it change over time. At Huron, the combined profile C/N ratio was not affected by the OMR treatments, but it declined slightly over time (Year 0 > Year 10; $p = 0.002$). A significant OMR × time interaction ($p = 0.014$) existed at Ottawa for the combined profile C/N ratio; subsequent Tukey–Kramer analyses revealed treatment-specific temporal changes (FFR: Year 0 <

Year 5; WTH: Years 5 and 10 < Year 15) and OMR treatment effects at Year 5 (FFR > WTH).

Bulk Density

The mineral soil bulk density responses to the OMR treatments and time varied inconsistently among the three sites. At Chippewa, temporal changes in bulk density varied among the OMR treatments (OMR × time interaction $p = 0.016$; FFR: Year 0 < Year 10 and Year 15; WTH: Year 5 < 15). Similarly, a significant OMR × time interaction ($p = 0.065$) occurred at Huron, but Tukey–Kramer analyses did not detect significant differences over time or among treatments. At Ottawa, bulk density varied over time across the OMR treatments (Year 10 < Years 5 and 15; $p = 0.008$).

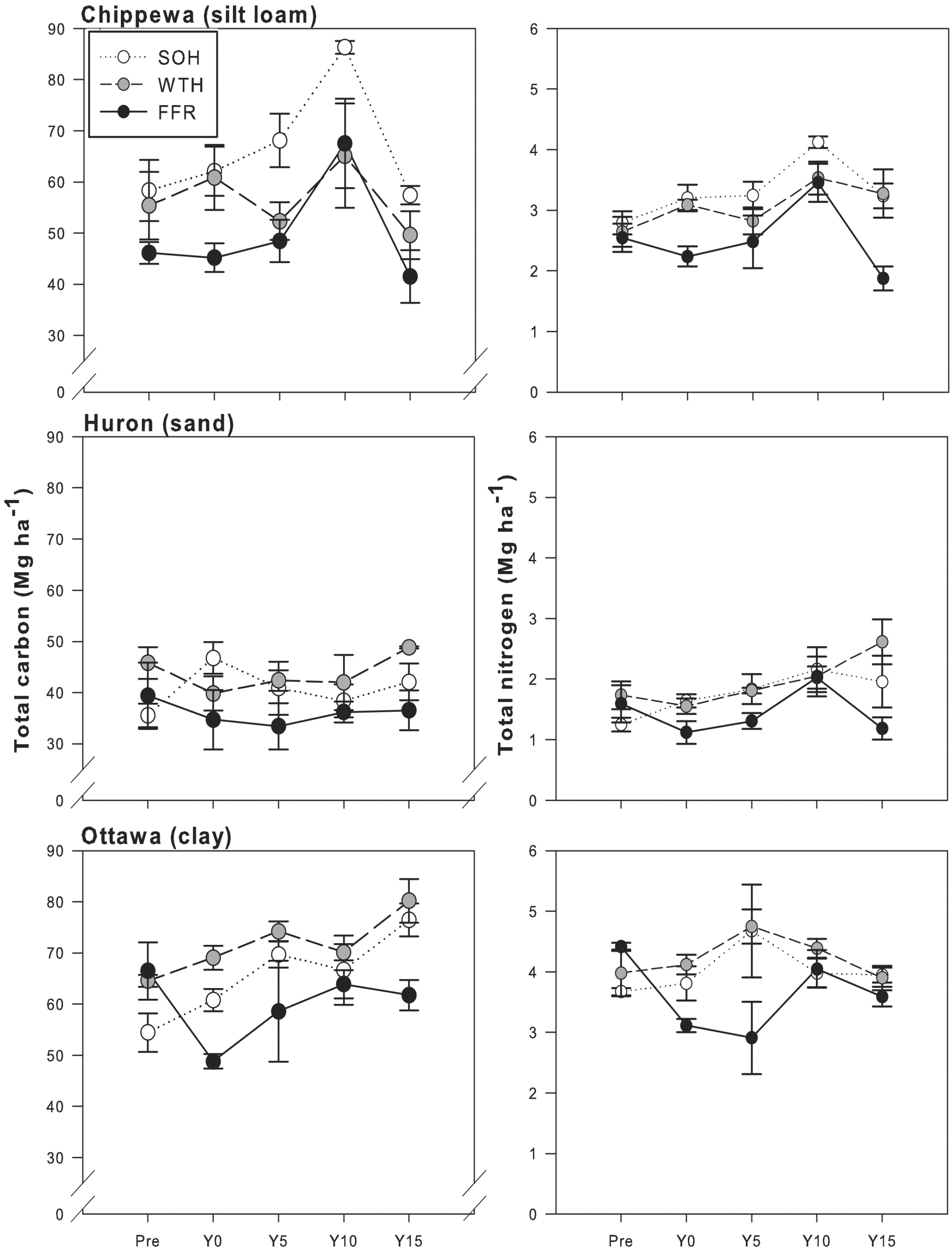

Fig. 1. Combined profile (forest floor + mineral soil, 0–30 cm) total C (left) and N (right) pools over time since organic matter removal treatments of stem-only harvest (SOH), whole-tree harvest (WTH), and forest floor removal (FFR) at three aspen forest sites in the northern Great Lakes region.

Power Analysis

The probabilities (power) of observing a statistically significant OMR treatment effect was generally higher in the forest floor (55–86%) and combined profile (51–99%) than the mineral soil (11–25%; Fig. 2). Temporal changes in C and N (73–100% for forest floor; 31–100% for the mineral soil; 25–100% for the combined profile) were generally more likely to be detected than OMR treatment effects. In general, when probabilities for either OMR or temporal effects were >80%, significant ANCOVA effects were observed, with the exception of the combined profile C at Huron. Additionally, for six site and variable combinations, significant OMR treatment effects were observed despite relatively low detection probabilities (50–80%; Chippewa forest floor and combined profile C, Huron forest floor C, Chippewa combined profile N, and Ottawa forest floor and combined profile N).

DISCUSSION

Our results show that the long-term impacts of harvest and forest floor removal on soil C and N pools in aspen forests of the Great Lakes region are site specific, and they illustrate the complex interactions that regulate soil organic matter dynamics, including edaphic conditions, climate, and vegetation (Thiffault et al., 2011). In particular, soil parent material (Paré et al., 2002), texture (Borchers and Perry, 1992; Sanchez et al., 2006), and soil order (Nave et al., 2010) have been associated with influencing forest management effects on site biogeochemistry. For example, coarse-textured soils are expected to be more sensitive to alterations in organic matter inputs from forest management (Carlyle, 1993; Henderson, 1995; Thiffault et al., 2011), while finer textured soils have more physically protected N, which can buffer losses due to treatment (Borchers and Perry, 1992). Our findings from these three edaphically different sites were counter to these predictions. The sandy soil site (Huron) was the least impacted by harvest treatment (combined profile). High variability at this site, as demonstrated by consistently higher coefficients of variation (data not shown), may have made it difficult to detect harvest treatment effects and suggests that more intensive sampling is required in coarse-textured soils.

Harvest effects on C and N pools were most evident in the forest floor and the combined profile rather than the mineral soil, as we predicted based on previous research (Johnson, 1992; Nave et al., 2010; Thiffault et al., 2011). Forest floor and combined profile C pools were lower in the most extreme FFR treatment than the two more moderate SOH and WTH treatments at Ottawa (clay) and lower for FFR than SOH at Chippewa (silt loam). These results partially support our prediction that soil C in the combined profile would decrease as the severity in the disturbance gradient increased (SOH > WTH > FFR), and they suggest that SOH and WTH have similar impacts on soil C pools in these forests. Powers et al. (2005) suggested that removal of the forest floor has the greatest consequences for soil productivity compared with SOH or WTH harvest, and both medium-term empirical and long-term modeling results suggest

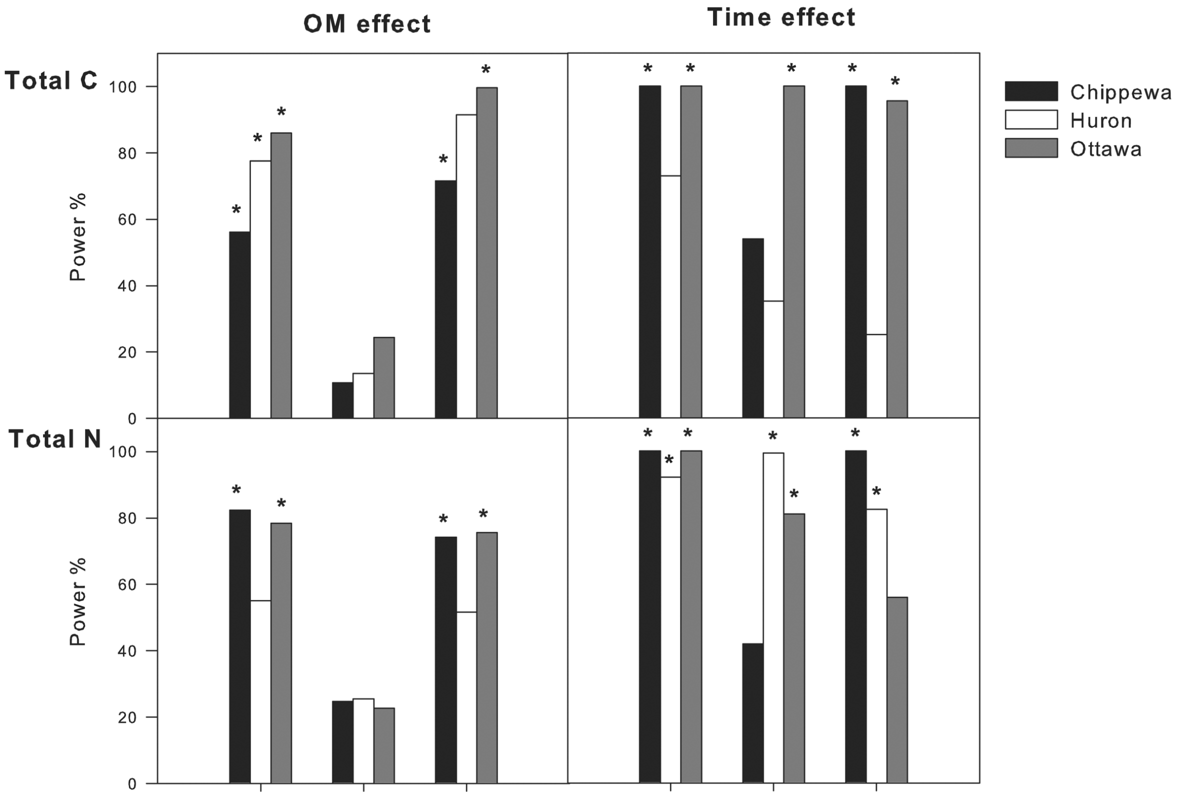

Fig. 2. Probability (power) of detecting a statistically significant ($p < 0.1$) organic matter (OM) removal treatment (left) or time effect (right) in total C and N in the forest floor, mineral soil (0–30 cm), or the combined profile (combined forest floor + 0–30-cm mineral soil) at three aspen forest sites in the northern Great Lakes region. *Statistically significant main effect was observed.

that the differences between SOH and WTH on soil C pools are small (Bengtsson and Wikstrom, 1993; Olsson et al., 1996). This is potentially because the majority of C in logging debris is released to the atmosphere over time as CO_2 (Mattson et al., 1987; Johnson and Todd, 1998; Palviainen et al., 2004).

Harvest residue removal may indirectly influence both mineral soil C and N pools, either through modification of the soil microclimate (Van Miegroet et al., 1992; Slesak, 2013), which could influence belowground decomposition, or by reducing the amount of substrate for microbes, which would result in lower microbial biomass (Hassett and Zak, 2005; Tan et al., 2005) and exacerbated N losses via leaching (Vitousek and Matson, 1985). Both of these may affect site productivity; indeed, differences in aboveground productivity between the SOH and WTH treatments have been observed at these sites (Voldseth et al., 2011). Thus, although our results suggest that residue removal (SOH vs. WTH) does not affect soil C and N pools in the medium term in these forests, these results are not necessarily indicative of other ecosystem-level responses, and treatment effects may be more visible after multiple rotations.

A key strength of this study is the documentation of soil C and N pools over time since treatment. Mineral soil C pools often increase initially following harvest (Alban et al., 1994; Butnor et al., 2006; Sanchez et al., 2006), potentially as a result of fine root mortality and decomposition, but they are predicted to decline over time (Powers et al., 2005). Similar to previous work at these sites, we did not observe this pattern (Voldseth et al., 2011); instead, the mineral soil pools of C and N were relatively stable at two of the sites we studied (Chippewa and Huron) and increased over time at the third (Ottawa). Changes in bulk density over time were spurious and do not explain the trends observed at Ottawa. However, forest floor C and N pools declined over time at Ottawa (Table 3), and mineral soil C in the 0- to 10-cm depth showed an increasing trend over time (data not shown). Therefore, we might attribute these changes to sampling inconsistencies; for example, variability in how the forest floor was separated from the mineral soil could lead to inconsistent amounts of organic matter in both pools (Homann et al., 2001; Yanai et al., 2003). Still, this seems unlikely because: (i) the changes were steady over time; (ii) they occurred at only one of the three study sites; and (iii) the combined profile C and N pools also increased over time. Instead, the temporal pattern at Ottawa appears more consistent with C trends observed in the region on earthworm-invaded sites (Alban and Berry, 1994; Hale et al., 2005). Verification of this explanation was precluded by the lack of unharvested reference plot data and early records of earthworm abundance at this site; however, earthworm presence was confirmed anecdotally at Ottawa in 2012 (J. Elioff, personal communication).

Soil C pools and fluxes in aspen-dominated systems may differ markedly from other temperate forests. Harvested aspen forests regenerate quickly via suckering and require little to no site preparation or planting (Frey et al., 2003). The decomposition of fine roots is thought to be a major source of soil C following harvest in temperate forests (Powers et al., 2005); however, because of suckering, the proportion of aspen roots that die and decompose to those that carry over to the next generation following harvest may be lower than in other forest types. Although extensive fine root mortality has been noted in the first 2 yr following harvest in aspen forests (Visser et al., 1998), the specific amount of mortality and the rate of decomposition are uncertain. The effects of fine root decay may be more transient for aspen than associated species because aspen tissues have higher nutrient concentrations (Alban et al., 1978) and thus may decompose faster. Taken together, the rapid growth, nutrient uptake, and potential carryover of root biomass may moderate short- and medium-term harvest treatment effects on belowground C and N pools in aspen forests and explain why we did not observe marked differences between SOH and WTH. However, over the long-term, conducting WTH for multiple rotations in aspen forests may eventually lead to site nutrient limitations given the relatively high nutrient concentration of aspen tissues (Alban et al., 1978).

Treatment effects were more evident when we analyzed the forest floor as well as the combined profile (forest floor and mineral soil) compared with the mineral soil alone (0–30 cm). However, by limiting our study to surface sampling of the mineral soil, we potentially missed subsurface changes in C (Strahm et al., 2009). Surface sampling is not always informative compared with sampling at depth (~60 cm; Harrison et al., 2011), especially when assessing management effects, because harvesting may destabilize soil C (Diochon and Kellman, 2009). Further, aspen forests tend to hold greater amounts of organic C at depth than coniferous species in boreal (Laganière et al., 2013) and western seasonally dry (Woldeselassie et al., 2012) forests. Collectively, this suggests that future work in the Great Lakes region should examine subsurface C pools, especially in coarse-textured Spodosols (e.g., Huron) where downward redistribution of C may be high (Ussiri and Johnson, 2007).

Spatial variability in mineral soils and forest floors is high in most forests (Conant et al., 2003; Yanai et al., 2003; Oliver et al., 2004), which increases the likelihood of committing a Type II error (i.e., failing to reject a false null hypothesis). However, a lack of statistical difference in soil C pools does not necessarily mean that no differences exist, and, in such situations, post-hoc power analysis is recommended (Kravchenko and Robertson, 2011). In our study, where replication was relatively low ($n = 3$), treatment and temporal effects were inconsistent among sites, especially in the mineral soil, and the probability of detecting an OMR effect on the mineral soil C or N was <30%. Statistical power increased when the combined profile was analyzed, probably because OMR treatment and temporal differences were more detectable in the forest floor. Power was also higher for detecting temporal changes than OMR effects, which suggests that long-term study designs need to be sufficiently intensive to capture treatment effects within potential temporal variability. Our study illustrates that an experiment designed to achieve 80% power may be adequate for detecting treatment effects on a combined profile; however, soil texture has a large influence. Coarser textured soils (e.g., Huron) with low levels of organic material have more spatially heterogeneous C and N pools and therefore may require greater sampling intensity (Conant et al., 2003).

We emphatically endorse the recommendations outlined by Lawrence et al. (2013) for the implementation and maintenance of long-term soil studies. In our study, one technician managed all of the sample collection throughout the entire study period, and thus we are reasonably confident that sampling inconsistencies that may occur among technicians (for example, inconsistently defining the forest floor and mineral soil boundary; Yanai et al., 2003) were minimized. Soil processing methodologies were standardized and all samples were carefully archived. However, our initial statistical analysis revealed that the total C and N analyses done incrementally were inconsistent (data not shown), and, had we not reanalyzed all of the archived samples (data presented), these analyses may have led us to falsely conclude that levels of C and N declined in the mineral soil at Year 15. The inconsistencies in C and N analysis that we encountered highlight the importance of not only archiving samples from long-term studies but also of conducting repeated analyses. Different analytical methods for quantifying soil C and N can alter results and conclusions, especially at low concentrations (Brye and Slaton, 2003), and interannual variability may be high (Knoepp and Swank, 1997; Brye et al., 2002; Johnson et al., 2002). This highlights the need to reanalyze archived samples from long-term studies when instruments are replaced and to continuously and meticulously monitor data for instrument-based error.

SUMMARY AND CONCLUSIONS

The global significance of the forest soil C pool, as well as the influence of soil C on site productivity (Dixon et al., 1994; Jurgensen et al., 1997; Grigal and Vance 2000), underscores the need to quantify the responses of forest soil C stocks to management. This need is particularly acute because of an increased focus on the removal of woody residues and other traditionally non-merchantable material (e.g., stumps) for biofuel feedstocks (Berger et al., 2013). In our regionally replicated experiment, OMR effects varied among the three sites but soil C and N did not differ between the SOH and WTH treatments, suggesting that logging debris from a single harvest does not substantially contribute to these pools within the 15-yr time frame; however, differences may be more apparent after multiple rotations. The OMR effects on soil C and N were greatest with WTH plus FFR, which emphasizes the importance of minimizing forest floor disruption during harvest activities. Sites on coarse-textured soils are more variable than those on finer textured soils, and they may require greater sampling intensity to detect management effects. Finally, our study highlights the need to carefully design and maintain medium- and long-term studies to capture both management and temporal changes.

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Harvest residue removal and soil compaction impact forest productivity and recovery: Potential implications for bioenergy harvests

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ABSTRACT

Understanding the effects of management on forest structure and function is increasingly important in light of projected increases in both natural and anthropogenic disturbance severity and frequency with global environmental change. We examined potential impacts of the procurement of forest-derived bioenergy, a change in land use that has been suggested as a climate change mitigation strategy, on the productivity and structural development of aspen-dominated ecosystems. Specifically, we tested the effects of two factors: organic matter removal (stem-only harvest, whole-tree harvest, whole-tree harvest plus forest floor removal) and soil compaction (light, moderate, and heavy) over time. This range of treatments, applied across three sites dominated by aspen (*Populus tremuloides* Michx.) but with different soil textures, allowed us to characterize how disturbance severity influences ecosystem recovery.

Disturbance severity significantly affected above-ground biomass production and forest structural development with responses varying among sites. At the Huron National Forest (sandy soils), the removal of harvest residues reduced above-ground biomass production, but no negative effect was observed following whole-tree harvest at the Ottawa and Chippewa National Forests (clayey and loamy soils, respectively) relative to stem-only harvest. Maximum diameter and the density of stems greater than 5 cm DBH exhibited negative responses to increased disturbance severity at two sites, indicating that structural development may be slowed. Overall, results suggest that disturbance severity related to procuring harvest residues for bioenergy production may impact future productivity and development, depending on site conditions and quality.

1. Introduction

Forests have been suggested as a supply of alternative sources of energy feedstocks for offsetting fossil fuel consumption (Millar et al., 2007; Becker et al., 2009; Aguilar and Saunders, 2010; Buford and Neary, 2010); however, increases in demand for forest-derived bioenergy feedstocks could translate to an increase in harvest-related disturbance severity and frequency with associated ecological impacts (Berger et al., 2013). At the same time natural disturbance events (windthrow, fire, etc.) and stressors (e.g. drought) may also increase in frequency and severity as climate change progresses (Dale et al., 2001; Turner, 2010). Uncertainty regarding how ecosystems will respond to changes in disturbance, both natural and anthropogenic, poses a serious challenge to the development of long-term sustainable forest management and conservation strategies (Dale et al., 2001; Joyce et al., 2009).

Given the uncertainty surrounding ecosystem responses to potential increases in disturbance, sustainable forest management requires a better understanding of how disturbance severity affects forest productivity and successional development. Generally, forest development occurs more quickly on more fertile sites (Franklin et al., 2002; Larson et al., 2008; Ryan et al., 2008; Hardiman et al., 2011), but disturbance itself can degrade site quality through depletion of nutrients and changes in the understory environment (Stoeckeler, 1948; Thiffault et al., 2011). Also, increased disturbance severity or compound disturbance events may push ecosystems outside the range of natural variation (Paine et al., 1998; Lindenmayer et al., 2004). These changes in disturbance severity may favor the establishment and growth of dense understory layers (Royo and Carson, 2006) as has been observed in white spruce forests (Eis, 1981) and, to some extent, with trembling aspen (*Populus tremuloides* Michx.; Landhausser and Lieffers, 1998) in boreal regions. Such an understory can interfere with the establishment of tree species historically adapted to a site, thus slowing or changing forest developmental trajectories (Royo and Carson, 2006).

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Results from studies examining the effects of harvest residue removal to date have varied depending on site quality, time since disturbance, and forest type. In nutrient-poor forests, removal of harvest residues (i.e., slash) can reduce nutrient availability and tree growth (Walmsley et al., 2009; Helmisaari et al., 2011; Morris et al., 2014); however, negative effects may not be detected in some cases until 10–20 years following harvest (Egnell and Valinger, 2003; Helmisaari et al., 2011; Mason et al., 2012; Vanguelova et al., 2010). Findings from Long Term Soil Productivity (LTSP) study sites in boreal aspen and black spruce forests suggest that while tree densities may not respond negatively to the removal of harvest residues, tree height can be detrimentally impacted (Kabzems, 2012; Morris et al., 2014). Even where site productivity appears to recover, the reduction in above-ground biomass caused by initial post-harvest declines in site productivity can persist for over 30 years (Egnell, 2011). On richer sites the effects are more difficult to discern (Smolander et al., 2008, 2010; Roxby and Howard, 2013). Fully assessing ecosystem response to disturbance requires quantifying severity in terms of not only the death or removal of biomass, but also impacts to soil given the pervasive influence harvest-related soil disturbance may have on forest community development (Halpern, 1988; Roberts, 2007). The design of the LTSP study network allows assessing these different effects in a way applicable to bioenergy harvests.

Studies that consider impacts to soil, herbaceous biomass, shrub biomass, and other ecological response variables, will increase understanding of the potential long-term impacts that increased levels of feedstock harvests may have on ecosystem structure and function. For example, quantifying productivity in non-tree plant species concurrently with tree species can elucidate competitive interactions among different guilds and the processes behind community disturbance responses (Grewal, 1995; Royo and Carson, 2006). Additionally, the rate of post-disturbance structural development gives an indication of engineering resilience (hereafter ‘resilience’; Larson et al., 2008), which represents the length of time required for a system to return to its pre-disturbance state (Holling, 1996). If disturbance severity influences species composition, structural development, and resilience, then anticipated impacts on future functions will vary similarly, as will the degree to which forest stands accommodate different management objectives (Schwenk et al., 2012).

We examined how aspen-dominated forests growing on three different soil textures across the northern Lake States region respond to a gradient of disturbance severity created through different combinations of biomass removal and soil compaction. We show how above-ground productivity and structure respond to experimentally-controlled variations of stand-replacing disturbance and that responses vary across a range of sites. The responses to differing disturbance severities are used to demonstrate how forests may respond to bioenergy feedstock procurement of differing severity and whether some sites may be more resilient to such practices. Because of potential nutrient losses and greater departure from natural disturbance, we hypothesized that above-ground productivity would decrease with increasing disturbance severity across all sites. We also expected that structural development following the most severe disturbance would lag behind less severely impacted stands because of lowered site quality, which is known to be directly tied to the rate of structural development (Franklin et al., 2002; Ryan et al., 2008). These hypotheses were tested using experimental sites associated with the LTSP network, established in the early 1990s. Three LTSP installations in the Lake States located within the Chippewa, Ottawa, and Huron-Manistee National Forests, provide the opportunity to assess how forests dominated by the same species but distributed across a landscape respond to different levels of disturbance severity over 15 years.

2. Methods

2.1. Study sites

The study includes three sites within the Laurentian Mixed Forest Province extending from northern Minnesota, USA to Lower Michigan, USA. Each site was dominated by aspen (*P. tremuloides* Michx.) prior to harvest. The Chippewa National Forest (Chippewa) installation (47°18′N, 94°31′W) occurs on silty loam Frigid Haplic Glossudalfs, receives approximately 64 cm precipitation each year, and is the most productive of the three sites (site index 23 m height at age 50 (SI_{50}) for aspen; Voldseth et al., 2011). Important species prior to harvest included aspen (Curtis Importance Value = 58%), sugar maple (*Acer saccharum* Marshall, 11%) and basswood (*Tilia americana* L., 9%). In terms of relative biomass, aspen maintained a similar dominance 15 years after harvest (52.0%). The Huron-Manistee site (Huron; 44°38′N, 83°31′W) has a SI_{50} of 19 m for aspen (Stone, 2001). Soils are sandy, classified as Frigid Entic Haplorthods and Frigid Typic Udipsamments and annual precipitation is approximately 75 cm (Voldseth et al., 2011). Before harvest important species in addition to aspen (57%) included big-toothed aspen (*P. grandidentata* Michx., 31%) and white pine (*Pinus strobus* L., 4%). Site-wide species composition was similar 15 years post-harvest with aspen (41.8%) and big-toothed aspen (34.1%) dominating, followed by red oak (11%). The Ottawa National Forest installation (Ottawa; 46° 37′ N, 89° 12′ W) occurs on clayey Frigid Vertic Glossudalfs. This site receives approximately 77 cm precipitation annually and has a SI_{50} of 17–18 m for aspen (Voldseth et al., 2011; Stone, 2001). Following aspen (50%), balsam fir (*Abies balsamea* [L.] Mill., 33%) and white spruce (*Picea glauca* [Moench] Voss, 14%) dominated prior to harvest. Aspen abundance was comparatively greater 15 years post-harvest (87.5%) with balsam fir (4.7%) and white spruce (0.01%) making up smaller components than pre-harvest levels.

2.2. Experimental design

The severity of disturbance has been quantified in terms of organic matter removal and soil compaction, two factors likely affected during the procurement of biofuel feedstocks from forests. These two factors, each with three levels, were crossed using a factorial design resulting in nine treatments examined over time.

The three organic matter removal levels are named according to the traditional harvest method they most closely resemble. These levels included: (1) stem-only harvest (SOH), in which shrubs and merchantable tree boles were removed leaving behind harvest residues (branches and non-merchantable tops); (2) whole-tree harvest (WTH) in which all aboveground portions of trees and shrubs were removed; and (3) whole-tree harvest plus forest floor removal (FFR) in which the forest floor was removed in addition to all above-ground woody biomass. Shrubs such as hazel (*Corylus cornuta* Marshall and *C. americana* Walter) often grow densely in this region and can inhibit tree regeneration, so they were removed from all treated plots at the time of harvest. WTH is a best approximation of the harvest practices associated with biomass feedstock procurement, given the focus of these harvests on removing materials, such as tree tops, and tree limbs which normally would be left on site after traditional harvests. Some states and countries have developed guidelines that recommend removal of only a portion of harvest residues for use in bioenergy production (i.e. MFRC, 2007); this study, as it was originally designed in the 1990s, only allows assessment of extremes within the range of residue levels that might be removed as bioenergy feedstocks.

The compaction levels included no additional compaction above normal levels associated with conventional harvesting (C0), moderate compaction (C1), and heavy compaction (C2). Moderate compaction and heavy compaction were intended to increase soil bulk density by 15% and 30%, respectively, over levels normally associated with harvesting (Stone, 2001). Actual results varied slightly by soil texture and depth (Voldseth et al., 2011). Plots at the Ottawa, Chippewa, and Huron National Forests were harvested during winter in 1991, 1992, and 1993, respectively. Stands regenerated naturally, mostly through root suckers and stump sprouts. At the Chippewa installation, late season snow delayed the compaction application for 10 plots, so aspen seedlings were planted to compensate for any suckers damaged during treatment. The majority of these seedlings died due to the high level of compaction. Harvest operations are described in detail by Stone (2001).

Treatments were applied to 0.16 ha plots (40 m × 40 m) as well as to 5 m buffers surrounding these plots (0.25 ha total area) and generally replicated three times at each location. Treatment implementation at the Ottawa differed slightly from the other sites with five replicates of the WTH/C0 treatment, two replicates of SOH/C1, and only one replicate with SOH/C2. Woody vegetation was sampled in four 1.26 m radius (5 m^2) circular subplots per plot at Chippewa and Ottawa 5 years following harvest. During the 10 and 15 year sampling periods at these sites and all three sampling periods at the Huron NF, nine 1.78 m radius (10 m^2) circular subplots per plot were sampled. For each individual stem at least 15 cm tall, species and diameter at 15 cm were recorded. In each measurement year, a random azimuth and distance (range of 1 to 3 m) from a permanent sample point center was used to determine the location of five 1 m^2 clip-plots per treated plot for sampling above-ground herbaceous vegetation. Clip-plot locations in subsequent years were constrained to be at least 1 m from the previous sample location. Herbaceous vegetation was clipped at the peak of the growing season (late July or early August), oven-dried at 60° C for 48 h, and weighed to determine biomass.

2.3. Analysis

Above-ground biomass of woody species was calculated 5, 10, and 15 years post-harvest with species-specific allometric equations developed using material from several locations across the Lake States, including the Chippewa and Ottawa National Forests (Perala and Alban, 1994). Woody species that can occupy dominant canopy positions in closed canopy conditions at some stage of development in these forests were classified as ‘trees’. The ‘shrubs’ category comprised all remaining woody species except for the genus *Rubus* which was included with herbaceous plants during sampling. Live standing biomass at each measurement period was used as a surrogate for net aboveground productivity in our analyses.

Three attributes were used to assess forest structural development in response to organic matter removal and compaction over time. These included density of stems and quadratic mean diameter, two conventional measures of forest structure. Additionally, we analyzed the maximum basal diameter (maxBD) as a response variable. Larger diameter trees and greater variability in tree diameter are both commonly used to describe structural development, particularly when comparing the structure of managed forests to that of old-growth (i.e. Larson et al., 2008; Silver et al., 2013). The forests sampled for the present study are young, so “large” trees are absent, but the diameter of the largest trees present in each stand provides some indication of structural development at this early stage.

Diameter was measured at a height of 15 cm (basal diameter, BD) in the field with diameter at breast height (DBH, 1.4 m) measured for only a subset of stems. To enable comparison with other studies DBH was estimated using the following equation:

$$\mathrm{DBH} = 0.88 * \mathrm{BD} - 0.254 \ (r^2 = 0.9476, p < 0.0001) \tag{1}$$

where DBH is diameter at breast height (cm) and BD is basal diameter (cm).

The influence of organic matter removal and compaction on productivity and structure was assessed with mixed-model repeated measures ANOVA using the SAS MIXED procedure (SAS Institute, Inc., 2010). The statistical model used was as follows:

$$\begin{aligned} Y_{ijkl} = {} & \mathrm{OMR} + \mathrm{CPT} + \mathrm{TIME} + (\mathrm{OMR} * \mathrm{CPT}) + (\mathrm{OMR} * \mathrm{TIME}) \\ & + (\mathrm{CPT} * \mathrm{TIME}) + (\mathrm{OMR} * \mathrm{CPT} * \mathrm{TIME}) + e_{ijkl} \end{aligned} \tag{2}$$

where OMR is organic matter removal, CPT is compaction, TIME is the number of years since harvest, and Y_{ijkl} is above-ground biomass, stem density, or diameter at the ith level of OMR, the jth level of CPT, the kth level of time, and the lth level of plot. Plots were included as random effects while OMR, CPT, and TIME were treated as fixed effects. Type III sums of squares were used for all analyses to account for the unbalanced design at the Ottawa NF. Each site was analyzed separately because soil texture, the main characteristic distinguishing them, was not replicated. Some response variables required power transformations to meet ANOVA assumptions for equal variances among groups and normally distributed residuals. Tukey-adjusted multiple comparisons were used to distinguish among effects of factor levels where warranted.

3. Results

3.1. Biomass production

Both main factors and their interaction (OMR * CPT) resulted in significant differences in total above-ground biomass at all three sites (Table 1). Removing harvest residues did not negatively affect total standing biomass at the Chippewa or Ottawa sites (Fig. 1). In fact, with the addition of light compaction (C1) both WTH (23.894 ± 4.367 Mg/ha) and FFR (24.329 ± 5.498 Mg/ha) yielded higher total above-ground biomass at Chippewa compared with SOH (11.426 ± 2.360 Mg/ha; Fig. 1). Similarly at Ottawa, WTH resulted in higher biomass when combined with C1 (23.183 ± 6.525 Mg/ha) or C2 (14.867 ± 3.801) compared to FFR (9.402 ± 3,235 and 10.554 ± 3.520 Mg/ha, respectively) with SOH intermediate (Fig. 1). In contrast, removing residues did result in decreased total above-ground biomass at the Huron site (sandy soils) except when compaction was most severe (C2) in which case the biomass among OMR severity levels did not differ (Fig. 1, Appendix A).

With respect to compaction, no trends in total standing biomass were consistent among the sites. Total biomass declined with increasing CPT at Chippewa (Fig. 1). At Ottawa, the intermediate compaction level (C1) appears to increase total biomass, but only when combined with SOH or WTH (Fig. 1). At Huron, there were no significant differences among CPT levels when OMR was held constant even though CPT was a significant factor by itself (Table 1, Appendix A) and biomass appears to increase with an increase in compaction above C0 (Fig. 1).

When total biomass is divided into its component guilds, responses to disturbance again varied by site. Trees consistently dominated the biomass pools. Accordingly, trends in tree biomass followed those reported above for total above-ground biomass (Fig. 1). Shrub biomass increased with increasing disturbance at Chippewa. Shrub biomass at this site was greatest following FFR (FFR > SOH, WTH; p = 0.0397, 0.0004). Increasing compaction also resulted in greater shrub biomass (Fig. 1), but the CPT factor was not significant by itself. Because of the TIME * CPT interaction, we analyzed shrub biomass independently for the 15 year sampling period, and compaction did have a significant effect (F = 5.54,

Table 1
Summary of type III tests of fixed effects for aboveground biomass in different pools over 15 years following biomass harvest. The response variable "herbaceous biomass" refers to the percent of total biomass constituted by herbaceous species. Abbreviations for the factors are as follows: organic matter removal, OMR; compaction, CPT. Results are reported for LTSP installations at the Chippewa National Forest, Minnesota (CH), the Huron-Manistee National Forest, Michigan (HM), and the Ottawa National Forest, Michigan (OT). Effects with $p \leqslant 0.05$ are shown in bold.

	Source	df	Above-ground biomass		Tree biomass		Shrub biomass		Herbaceous biomass	
			F	*P*-value	*F*	*P*-value	*F*	*P*-value	*F*	*P*-value
CH (loamy)	OMR	2	**3.86**	**0.0272**	**8.73**	**0.0005**	**8.95**	**0.0004**	0.61	0.5496
	CPT	2	**45.92**	**<0.0001**	**131.92**	**<0.0001**	0.83	0.4404	**89.81**	**<0.0001**
	TIME	2	**154.97**	**<0.0001**	**148.56**	**<0.0001**	**58.73**	**<0.0001**	**72.94**	**<0.0001**
	OMR * CPT	4	2.49	0.0543	**4.15**	**0.0053**	2.41	0.0605	**3.17**	**0.0209**
	OMR * TIME	4	1.17	0.3338	0.19	0.9418	0.19	0.9423	0.17	0.9516
	CPT * TIME	4	1.81	0.1409	2.01	0.1063	**5.62**	**0.0008**	2.04	0.1019
	CPT * OMR * TIME	8	0.47	0.8728	0.28	0.971	0.33	0.9514	0.33	0.9514
HM (sandy)	OMR	2	**7.59**	**0.0013**	**6.94**	**0.0021**	**11.58**	**<0.0001**	2.45	0.0961
	CPT	2	**3.51**	**0.037**	**3.22**	**0.0478**	1.34	0.2701	2.58	0.0856
	TIME	2	**83.94**	**<0.0001**	**67.17**	**<0.0001**	1.24	0.2976	**23.14**	**<0.0001**
	OMR * CPT	4	**2.71**	**0.0395**	2.3	0.0707	1.2	0.3199	1.64	0.1767
	OMR * TIME	4	0.09	0.9857	0.05	0.9946	0.1	0.9805	0.33	0.8551
	CPT * TIME	4	0.03	0.9985	0.05	0.9945	0.1	0.9819	0.2	0.9377
	CPT * OMR * TIME	8	0.07	0.9997	0.04	1	0.17	0.9938	0.12	0.9983
OT (clay)	OMR	2	**12.12**	**<0.0001**	**10.06**	**0.0002**	**5.16**	**0.0091**	**11.14**	**<0.0001**
	CPT	2	**5.51**	**0.0069**	**3.56**	**0.0358**	**4.27**	**0.0195**	**8.23**	**0.0008**
	TIME	2	**144.53**	**<0.0001**	**79.41**	**<0.0001**	**10.71**	**0.0001**	**9.16**	**0.0004**
	OMR * CPT	4	**5.18**	**0.0014**	**6.06**	**0.0005**	**3.16**	**0.0215**	**7.73**	**<0.0001**
	OMR * TIME	4	0.77	0.5519	0.65	0.6281	0.78	0.542	1.47	0.2243
	CPT * TIME	4	0.17	0.9518	0.03	0.9987	0.42	0.7938	0.08	0.9885
	CPT * OMR * TIME	8	1.26	0.2839	0.94	0.4956	2.03	0.0617	1.87	0.0863

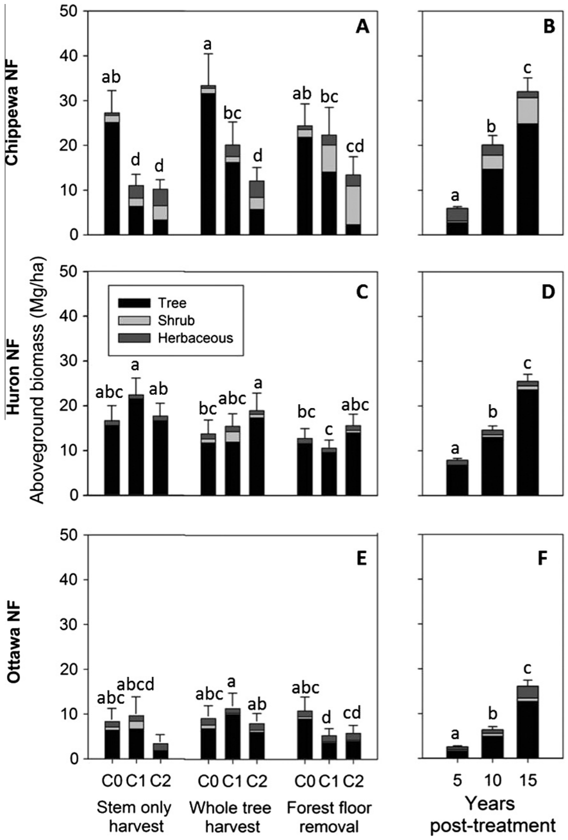

Fig. 1. Total above-ground biomass including trees, shrubs, and herbaceous plants at Chippewa (panel A), Huron (panel C), and Ottawa (panel E). Panels on the right (B, D, F) show corresponding trends in above-ground biomass across treatments over time. Treatments are abbreviated as follows: C0, no compaction; C1, minimal compaction; C2, moderate compaction. Bars indicate standard error. No standard error or significance is shown for the SOH/C2 treatment at Ottawa because this treatment was not replicated.

$p = 0.0133$) with shrub biomass greater following C2 than C0 ($p = 0.0126$). In contrast, shrubs exhibited a negative response to greater disturbance at Ottawa. Where heavy compaction occurred shrub biomass decreased with increasing organic matter removal (SOH > WTH, FFR; $p = 0.0404$, 0.0533). When combined with WTH, increasing compaction also decreased shrub biomass (C0 > C1, $p = 0.0301$). At Huron, WTH may have favored shrub biomass (Fig. 1), but the effects were not significant. Likewise, herbaceous biomass showed no relationship to the disturbance severity associated with either factor. However, at both the Chippewa and Ottawa locations, increasing compaction increased the proportion of biomass allocated to herbaceous plants (C1, C2 > C0 at both sites; Fig. 1, Appendix A). At Ottawa, FFR increased herbaceous biomass over WTH when in combination with increased compaction (C1 or C2, Appendix A).

Most biomass measures varied significantly with time (Table 1, Appendix B). The only exception was shrub biomass at the Huron site which constituted a very small proportion of total aboveground biomass (Fig. 1). Tree biomass increased over time at all three sites. At the Chippewa site, in particular, shrub biomass was greater where severe compaction decreased tree biomass at the 15 year sampling period (Fig. 1). Herbaceous biomass decreased over time at Chippewa NF, but continued to increase up to 15 years after harvest at Ottawa NF.

3.2. Structure

Both main factors and their interaction significantly influenced diameter at the Chippewa and Ottawa sites (fine-textured soils) whereas at Huron (sandy soils) only OMR and the OMR * CPT interaction were significant effects (Table 2). Holding OMR constant at SOH, increasing compaction (C1 or C2) reduced the mean for the largest diameter trees (maxBD) at Chippewa (Fig. 3). Increased compaction also reduced max diameter when combined with FFR (Fig. 3, Appendix A). Maximum diameter increased at Chippewa following WTH compared to SOH, but only in combination with intermediate compaction (C1; Fig. 3, Appendix A). Similarly, at Huron maxBD was greater following SOH compared with WTH

Table 2
Summary of type III tests of fixed effects for forest structural attributes following biomass harvest. Abbreviations are as follows: organic matter removal, OMR; compaction, CPT; maximum basal diameter (99th percentile), BDmax; quadratic mean diameter, QMD. Results are reported for LTSP installations at the Chippewa National Forest, Minnesota (CH), the Huron-Manistee National Forest, Michigan (HM), and the Ottawa National Forest, Michigan (OT). Effects with $p \leqslant 0.05$ are shown in bold.

	Source	df	BDmax		QMD		Stem density	
			F	*P*-value	*F*	*P*-value	*F*	*P*-value
CH (silty loam)	OMR	2	**5.04**	**0.01**	**11.4**	**<0.0001**	**3.67**	**0.032**
	CPT	2	**23.76**	**<0.0001**	**9.99**	**0.0002**	**53.55**	**<0.0001**
	TIME	2	**205.1**	**<0.0001**	**150**	**<0.0001**	**21.22**	**<0.0001**
	OMR * CPT	4	**3.18**	**0.0204**	2.34	0.067	0.17	0.9521
	OMR * TIME	4	0.71	0.5878	2.44	0.0585	0.22	0.9267
	CPT * TIME	4	0.83	0.5117	**0.92**	**0.4612**	0.46	0.766
	OMR * CPT * TIME	8	0.23	0.9834	0.33	0.9509	0.23	0.9828
HM (sandy)	OMR	2	**8.86**	**0.0005**	**3.43**	**0.0398**	0.95	0.3934
	CPT	2	0.1	0.2571	1.73	0.1871	0.61	0.549
	TIME	2	**216.2**	**<0.0001**	**53.4**	**<0.0001**	**10.57**	**0.0001**
	OMR * CPT	4	**3.77**	**0.0091**	0.86	0.4953	2.6	0.0858
	OMR * TIME	4	0.64	0.6372	0.02	0.9994	0.08	0.9874
	CPT * TIME	4	0.09	0.9842	0.14	0.9685	0.15	0.9628
	OMR * CPT * TIME	8	0.08	0.9997	0.06	0.9999	0.09	0.9994
OT (clay)	OMR	2	**6.51**	**0.0031**	**12.7**	**<0.0001**	**3.56**	**0.036**
	CPT	2	**9.03**	**0.0004**	2.83	0.0685	0.79	0.4579
	TIME	2	**259.8**	**<0.0001**	**231**	**<0.0001**	**71.92**	**<0.0001**
	OMR * CPT	4	**3.88**	**0.0081**	**4.56**	**0.0032**	**2.59**	**0.0481**
	OMR * TIME	4	0.37	0.8281	0.96	0.4368	0.67	0.6165
	CPT * TIME	4	0.31	0.8686	1	0.419	**3.44**	**0.0147**
	OMR * CPT * TIME	8	0.78	0.6223	1.08	0.3983	1.83	0.0941

and FFR when combined with C1 ($p = 0.0396$, $p < 0.0001$; Appendix A). At the Ottawa site, pairwise comparisons yielded no significant differences in diameter attributable to OMR severity levels even though the main effect was significant in the model (Table 2).

At Chippewa NF, both the CPT factor and CPT * TIME interaction significantly affected stem density. Holding TIME constant, density decreased with increasing compaction (C0 > C1 > C2, $p < 0.05$) during each time period. At the Ottawa site, both OMR and the OMR * CPT interaction showed a significant effect on tree stem density over time (Table 2), but no pairwise comparisons between OMR levels emerged as significant. An assessment of trees >5 cm DBH in the last sampling period alone (15 years post-harvest) confirms the significant effect of OMR on density ($F = 6.12$, $p = 0.0106$). The greatest stem densities occurred following WTH, but significant differences only emerge when that treatment is combined with intermediate compaction (C1: WTH > FFR, $p = 0.0077$; Fig. 2). At the Huron NF, neither main factor affected tree stem densities over time when all diameters are considered (Table 2). However, if analysis is limited to stems ⩾5.0 cm DBH 15 years post-harvest, OMR does have an effect ($F = 5.30$, $p = 0.0163$) with densities significantly greater when harvest residues are retained (SOH > WTH, FFR; $p = 0.0380, 0.0245$).

As would be expected, tree diameter and stem density changed significantly over time at all three sites. At Chippewa stem density did not differ significantly between years 5 and 10, but did decrease substantially by year 15 (Y5, Y10 > Y15; $p = 0.0068, 0.0325$). At Ottawa NF, OMR * TIME was significant, so changes over time were assessed while holding OMR constant. Only with WTH did densities differ among years (5 > 15, $p = 0.0089$). At Huron NF, stem density decreased between 5 and 10 years post-harvest, but year 15 did not differ from year 10 (5 > 10, 15; $p < 0.0001$). Both measures of diameter (QMD and maxBD) increased over time at all sites (Y15 > Y10 > Y5, $p < 0.0001$).

4. Discussion

Across sites, standing biomass was generally greatest where both diameter (QMD and maxBD) and density were also greatest (Fig. 3). Treatment effects varied among sites, but within sites these three aspects of structure responded to disturbance severity in concert. At Chippewa and Ottawa, the removal of harvest residues did not detrimentally impact total above-ground standing biomass or diameter growth. At the Huron installation, however,

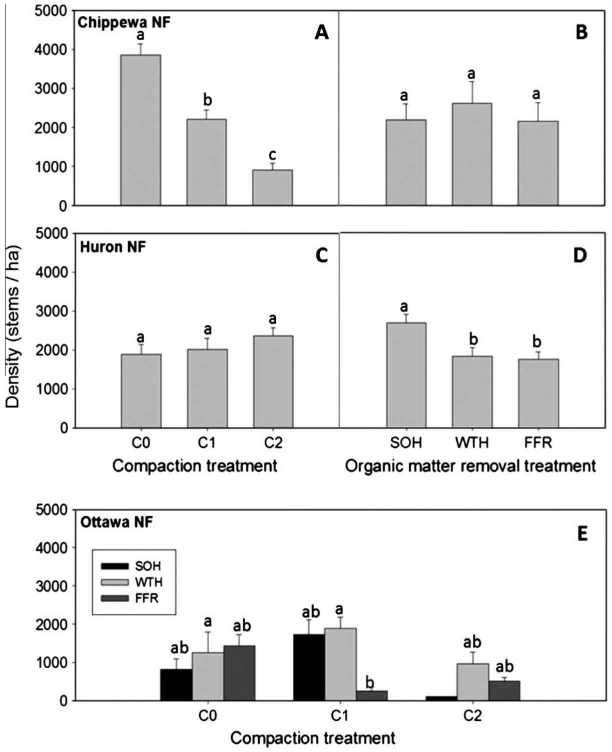

Fig. 2. Density of trees greater than 5 cm DBH 15 years following harvest. For the Chippewa and Huron National Forests, there was no significant effect of OMR * CPT, so means are presented for each factor individually. Panels A and B show mean density according to levels of compaction and organic matter removal, respectively, at Chippewa NF. Panels C and D show mean density by levels of compaction and organic matter removal, respectively, at Huron NF. A significant OMR * CPT interaction was observed at Ottawa NF, so means are presented for each individual factorial combination for this site in panel E. Bars indicate standard error and letters indicate where significant differences among treatments occur. No standard error or significance is shown for the SOH/C2 treatment in Panel E because there was no replication for this treatment.

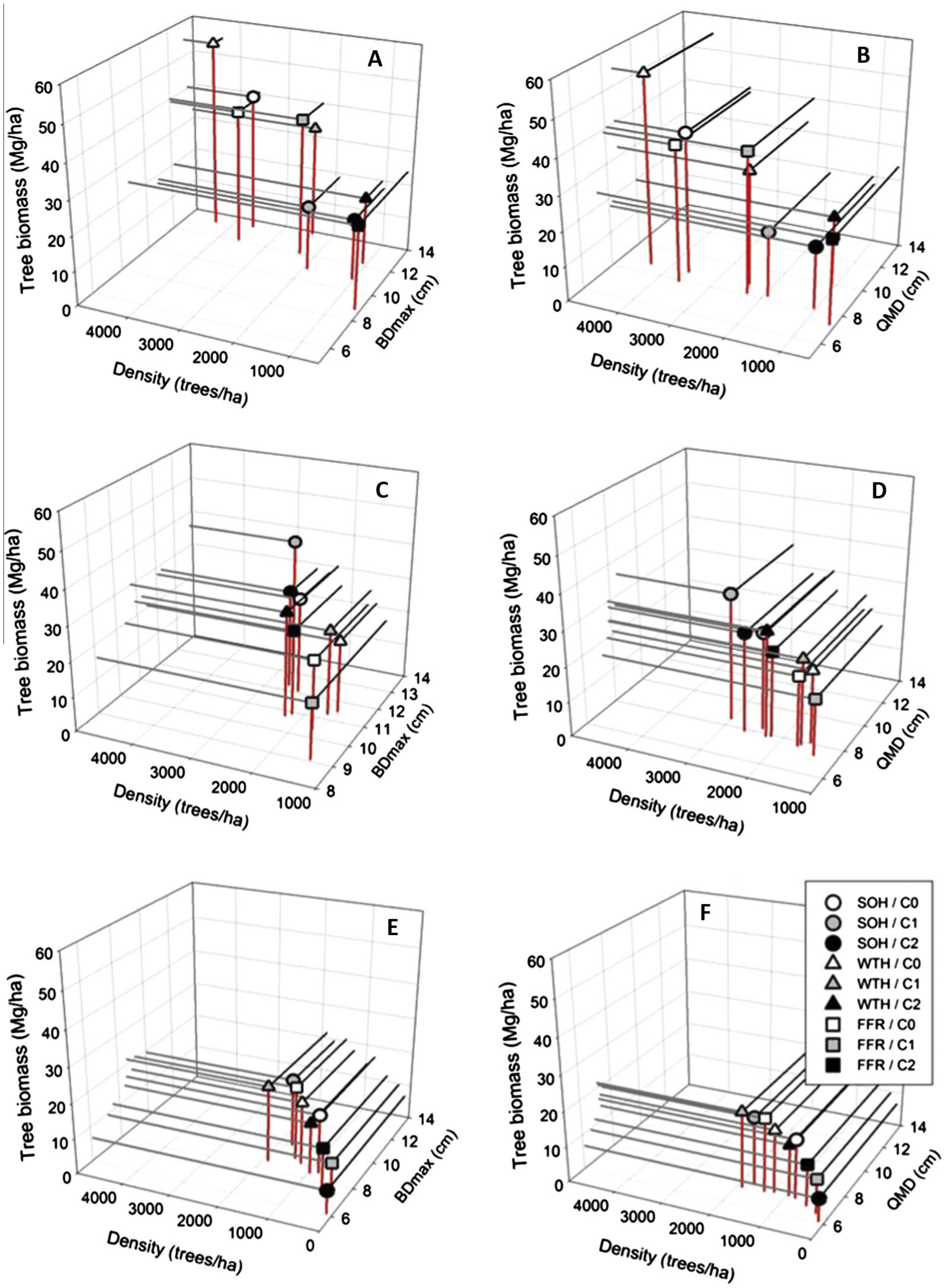

Fig. 3. The relationships among tree biomass, tree stem density, and diameter 15 years following harvest at Chippewa (panels A and B), Huron (panels C and D), and Ottawa (panels E and F) study sites. A tree was defined as having diameter at breast height > 5.0 cm. Symbol shape (circle, square, triangle) corresponds to the OMR factor (SOH, stem-only harvest, WTH, whole-tree harvest, FFR, forest floor removal). Symbol color (white, grey, black) indicates the CPT factor level (C0, no compaction; C1, minimal compaction; C2, moderate compaction).

standing biomass, diameter growth, and tree density all declined with increasing organic matter removal (Fig. 3).

The short period of time (15 years) since stand-replacing disturbance somewhat limits assessment of structural development, but even at this early stage, severe compaction at Chippewa and Ottawa and severe organic matter removal (FFR) at all three sites appeared to delay the accumulation of larger trees (Appendix B). At the Ottawa NF, the temporal trend in stem density gives some indication of structural development. In contrast to the other two sites, stem density declined little over time at this site except where WTH occurred (Appendix B). As a stand develops, there is generally a predictable decline in stem densities due to self-thinning processes, so a delay in decreasing densities may indicate slower structural development in general compared to the other sites. While removing harvest residues (WTH) may improve growing conditions for species (like aspen) that regenerate through root suckers and hasten development compared with SOH, the additional loss of nutrients associated with removing the forest floor (FFR) may have had a negative effect.

One advantage of looking at the effects of soil compaction and harvest removal over time rather than exclusively at an ‘endpoint’ is a greater ability to discern the processes affecting changes in the main variables of interest, such as above-ground biomass. At the Chippewa, those stands most severely impacted in terms of soil compaction showed an increase in shrub biomass 15 years post-harvest that coincided with decreased tree biomass relative to other treatments. Because the shrub response to compaction did not emerge until 15 years had passed (Fig. 1), we can infer that the original disturbance negatively impacted tree regeneration in a direct way, possibly through damage to aspen root systems because of rutting (Bates et al., 1993). Shrubs have likely increased over time in response to that original impact on trees rather than directly outcompeting trees because of some advantage conferred immediately following the disturbance (Royo and Carson, 2006). It should cause concern that the most severe disturbance treatment (FFR/C2) results in a community dominated by shrubs 15 years after harvest with no indication of return to the pre-disturbance composition or structure (Fig. 1).

While the lack of replication prevents statistical comparisons among soil textures in our analysis, other studies have observed different responses depending on soil texture (Powers et al., 2005; Morris et al., 2014) or general site quality (Page-Dumroese et al., 2000; Thiffault et al., 2011) and this may contribute to the differences we observed. With the addition of compaction (C1 or C2), removing harvest residues resulted in higher aboveground biomass at the Chippewa and Ottawa sites despite evidence that K decreased with increasing organic matter removal at Chippewa (Voldseth et al., 2011). The soils at Chippewa and Ottawa are considered more nutrient-rich than at Huron, so it may be that where nutrients are not already limiting, the effect of retained harvest residues on the microenvironment can hinder tree establishment and growth. In other regions where forest regeneration depends more on sexual reproduction or planting than the aspen-dominated forests discussed here, harvest residues and litter tend to benefit seedling germination and growth by decreasing soil moisture loss and mitigating extreme conditions in the microenvironment (Gray and Spies, 1997; Roberts et al., 2005; Walmsley et al., 2009; Thiffault et al., 2011) or by reducing competing vegetation (Stevens and Hornung, 1990; Roberts et al., 2005). Additionally, harvest residues eventually provide valuable substrate for species that require decaying woody debris for seedling germination (Shields et al., 2007; Marx and Walters, 2008; Cornett et al., 2001). When the dominant species can regenerate vegetatively through root suckering and is managed using a coppice system, as with aspen in this study, these effects may not prove beneficial for total aboveground biomass production. Instead, the decrease in soil surface temperatures that results from shading by woody debris or dense understory cover (Zabowski et al., 2000) can potentially shorten the growing season and decrease annual growth rates in aspen (Zasada and Schier, 1973; Grewal, 1995; Landhausser and Lieffers, 1998; Fraser et al., 2002).

Forest regrowth and productivity at Huron was negatively impacted by increasing severity of residue removal even though only the two extremes (SOH and FFR) differed significantly once the interaction of main effects was considered. Because sandy soils tend to be of poorer nutrient quality, the detrimental impact of residue removal might be explained by an associated loss of nutrients (Federer et al., 1989; Thiffault et al., 2011). While mineral soil C and N pools have not exhibited a response to OMR over 15 years at this site (Kurth et al., 2014) an analysis of soil cations 10 years after harvest indicated a significantly lower concentration of Ca associated with FFR when compared to SOH 10–20 cm below the surface (Voldseth et al., 2011). This supports concerns expressed in other studies about the potential for Ca losses with residue removal following harvest of aspen and other species that store large amounts of Ca in their tissue (Alban, 1982; Silkworth and Grigal, 1982; Federer et al., 1989). Additionally, the higher levels of fine and coarse woody debris following SOH may alter the microenvironment by reducing exposure and increasing soil moisture (Gray et al., 2002; Roberts et al., 2005; Walmsley et al., 2009), thus increasing biomass production compared to FFR. Leaving residues on site (SOH) increased total above-ground biomass over other OMR treatments except when the most severe compaction treatment (C2) was held constant (Fig. 1, Appendix A). The increase in compaction resulting from C2 would be expected to decrease soil pore space and increase water-holding capacity (Greacen and Sands, 1980; Powers, 1999; Stone, 2001), which may have equalized the moisture-retaining effects of SOH relative to WTH and FFR. The positive (but insignificant) relationship between greater biomass production and increasing compaction (Fig. 1) indicates that water may be limiting as has been observed in other LTSP studies on sandy soils (Powers, 1999; Powers et al., 2005), providing some support for this hypothesis.

An analysis of bulk density 10 years after harvest at each site indicates that the soils at Huron and Chippewa had started to recover from the compaction treatments (Voldseth et al., 2011). However, no significant differences in bulk density at the Ottawa site (clay soils) were observed between sampling periods immediately following harvest and 10 years post-harvest (Voldseth et al., 2011). Based on these trends, we suspect that the responses to compaction observed in biomass production and structure at the Chippewa site, even 15 years post-harvest, were largely realized immediately after treatment. Wet conditions were present when compaction was applied, so damage to aspen root systems may have occurred, which combined with effects of compaction on conditions for seedlings and sprouts during their first growing season, may have generated differences that are still evident 15 years later. At the Ottawa site, however, it is not possible to distinguish between these effects and how continued compaction might affect hydrology, gas exchange, or other processes that influence forest growth.

Some studies have concluded that richer sites should not experience nutrient deficiencies that limit regeneration following WTH (Boyle et al., 1973; Silkworth and Grigal, 1982) with any nutrients lost via harvesting having little noticeable effect on productivity. Recent research indicates that soil disturbance has greater potential to negatively impact net primary productivity than stand mortality or dead wood removal (Peters et al., 2013). Our results at the Chippewa and Ottawa sites align with these findings at present, but as has occurred in other studies, negative effects on productivity may manifest later in stand development (Egnell and Valinger, 2003; Mason et al., 2012).

5. Conclusions

The LTSP network provides a unique opportunity to study the medium-term ecological effects of removing harvest residues. This is particularly important as interest in using those residues for bioenergy production increases and organizations develop management guidelines in anticipation of potential impacts. Our results demonstrate that increased disturbance severity resulting from the removal of harvest residues for bioenergy feedstocks may have a negative effect on structural development and, at least on some sites, above-ground biomass production. While no intermediate levels of harvest residue removal were tested, this study does affirm the need for management guidelines that include provisions for retaining living and dead tree biomass following harvest and for minimizing soil disturbance. Further research should investigate the effects of retaining a portion of residues across a range of sites.

Additionally, our results highlight the importance of accounting for site differences when developing guidelines intended to mitigate impacts from bioenergy feedstock procurement. Such considerations have been integrated by some regional site-level guidelines (Herrick et al., 2009); however, most recommendations generically apply to all site types (e.g., MFRC, 2007). While removing residues may improve the growing environment on fine-textured soils for species that regenerate vegetatively as occurred at the Chippewa and Ottawa sites, care should be taken to minimize soil disturbance as reductions in tree biomass may occur and, if the disturbance is severe enough, shrubs may increase in dominance. On poorer, sandy soils such as those at the Huron NF, the removal of harvest residues may not be appropriate both because of potential for nutrient losses as well as reductions in moisture availability, particularly in light of projections for more severe and more frequent drought conditions in the future.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2014.05.056.

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