Understanding Recovery and Sustainability of Forest Residue Harvest

Trevor L.D. Roberts and Robert E. Froese (PI)

School of Forest Resources and Environmental Science
Michigan Technological University, Houghton, MI 49931, U.S.A.

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Preface

In this report, unless otherwise specified, values for mass of biomass are reported in SI units (tonnes) on an oven-dry basis.

Executive Summary

Forest residue products are those typically left after timber harvest and include tree tops, branches, standing dead wood, downed dead wood, and non-merchantable trees. Removing residues from forests represents a substantial source of biomass feedstock for biofuel applications. This scale of removal calls for research to understand the sustainability of residue removal from forests. The scope of the research objective is to address the efflux of carbon (C) and nutrients released from forest residue products, which would otherwise be left on site, and to address recovery of forests' productivity following harvest operations when residue removal is increased. Recovery of soil productivity after harvesting is directly affected by forest management and there is a need to identify the level of organic matter that can be sustainably harvested. Results from previous studies indicate that C and nutrient pools and fluxes are extremely sensitive to site specific conditions and require site specific models to be built. Quantifying the pools and fluctuation of C and nutrients in organic material within the Northern Hardwood Forest Ecosystems is crucial to understanding the sustainability of residue harvesting in Michigan and the neighboring states. An assessment of Biomass Harvesting Guidelines and literature review is used as a baseline to discuss potential impacts of residue removal.

Introduction

Biomass broadly defined is living material produced directly or indirectly by the fixation of carbon dioxide (CO_2) through photosynthesis (Barnes, 1998). The term has become more refined in the forestry discipline to describe the by-products, or residues, of management, restoration, and fuel load reductions, which includes limbs, tops, needles, leaves and woody debris (Becker, 2009). This refined definition is of particular interest in production of alternative energy. On a mass basis wood is about 50% Carbon (C) and is a substantial source of heat energy when combusted to produce energy (Becker et al. 2009, Van Miegroet and Johnson 2009, Jenkins et al. 2004, Powers et al. 2005). Many states of the Great Lakes Region are accelerating biomass utilization to meet renewable portfolio standards. Michigan has specifically targeted 10% of all energy utilities by 2015 to be produced from renewable resources. Forest products have the potential to be a key component of meeting renewable energy standards and many companies have already invested in utilizing biomass for combined heat and power production, and even the production of liquid-fuels in the form of cellulosic ethanol.

Residue removal from forest harvesting represents a substantial source of biomass feedstock for biofuel applications. These logging residues are being increasingly removed and utilized as part of operations to augment management, fuels loads reduction, and to generate additional revenue from harvesting. This scale of removal calls for research to understand the sustainability of forest productivity following harvesting and residue removal. Comprehensive life-cycle analyses are needed to address recovery of forests from intensified harvest operations and to build an accurate regional C budget. Contributing environmental impact assessments to these life cycle analyses is imperative in establishing sustainable management in biomass and residue harvesting. Research has identified critical environmental components in life-cycle analyses as soil organic matter and nutrient pools and fluxes. The long-term productivity of soils is dependent upon adequate organic matter and nutrient to sustain forest productivity. There are many uncertainties in the effects of residue harvest on forests under different silvicultural treatments. This uncertainty highlights the need to estimate the scale of current and future removals and assess how that will effect future management of our forests. These uncertainties and discrepancies in soil biogeochemistry will need to be addressed with site-specific research (Van Miegroet and Johnson 2009).

For the purposes of this review and study the focus has been limited to Northern Hardwood Ecosystems. This ecosystem was chosen in part because of a lack of consensus as to the effects of residue removal under different silvicultural practices. This ecosystem also represents a huge source of feedstock for biomass power plants and cellulosic ethanol production. Current

Table 1. Growth and Removal estimates in cubic meters from FIA, and % of growth removed, by ownership class

Ownership		Growth total (m^3)	Removal total (m^3)	% Growth removed
All ownerships	Total	19,654,029	9,166,680	46.64
	Softwoods	6,087,113	2,189,501	35.78
	Hardwoods	13,566,916	6,977,179	54.03
National Forest	Total	2,375,346	412,527	18.07
	Softwoods	1,226,786	256,867	20.94
	Hardwoods	1,148,560	155,660	14.94
Other federal	Total	250,470	0	0
	Softwoods	119,690	0	0
	Hardwoods	130,779	0	0
State and local	Total	3,651,148	1,666,746	48.26
	Softwoods	1,483,590	581,622	38.90
	Hardwoods	2,167,558	1,085,124	54.79
Private	Total	13,323,391	6,276,633	47.71
	Softwoods	3,239,652	1,147,694	35.02
	Hardwoods	10,083,739	5,128,938	51.65
Other	Total	53,674	810,775	1468.07
	Softwoods	17,394	203,318	1149.52
	Hardwoods	36,280	607,457	1587.89

growth to removal estimates from FIA data are represented in Table 1.

Site productivity is strongly governed by physical, chemical, and biological processes affected directly by management and there is a need to identify and quantify the level of organic matter (OM) being removed (Jenkins et al. 2004, Powers et al. 2005). The OM being described as residue products have a high nutrient content, as well as play a pivotal role in trophic cycles within and between ecosystems. Nutrients critical to Net Ecosystem Productivity (NEP) include nitrogen (N), magnesium (Mg), calcium (Ca), phosphorus (P), potassium (K), and sulfur (S). Increased harvest intensity will invariably represent an increase in the removal of OM and thereby removal of nutrients from forest stands. The level of this removal necessitates research to further understand the short and long-term impacts. Long-term study sites need to be established to record baseline data from target forest types to follow nutrient and forest recovery from intensified harvesting.

Biomass Harvesting Guidelines

Biomass Harvesting Guidelines generally make management recommendations for the following criteria. These criteria are reflective of best management practices (BMP's), but specifically written to address how biomass harvesting and residue removal can potentially impact these ecosystem processes and services (Evans and Perschel 2009, Janowiak and Webster 2010, Shepard 2006.

1. *Dead woody material*
2. *Wildlife and Biodiversity*
3. *Water Quality and Riparian*
4. *Soil Productivity*
5. *Silviculture*
6. *Disturbance Considerations*

Dead woody material – Harvesting guidelines generally recommend a percent retention of coarse/fine woody material and standing snags. These retention guidelines represent an area of great uncertainty. While most of these accomplish a pre-emptive goal in sustainable management, they fail in truly representing a quantitative impact assessment of residue removal under different retention guidelines as well as under different harvest intensities. For instance, retaining 1 in 3 tree tops from a minimal harvest will have a very different impact compared to retaining 1 in 3 tree tops from a clear cut or maximum selection cut. For the purpose of the research represented here this is the area that needs the most research, monitoring, and assessment. This will be discussed in greater detail to follow.

Wildlife and Biodiversity – In some instances residue harvesting could have negative impacts on wildlife and overall biodiversity in forest stands. These guidelines recommend environmental impact-type assessment of species composition of harvest area and connectivity to sensitive species/ecosystems.

Water Quality and Riparian Zones – Best Management Practice (BMP's) were drafted in part as a response to the clean water act, and the connection to biomass harvesting guidelines recommend and highlight very similar concerns. Operational and residue removal recommend environmental impact-type assessment of riparian zones, wetlands, and hydrology that have connectivity to the harvest area.

Soil Productivity – Soil productivity is central to all ecosystem processes and services. Assessing the short-term and long-term impacts of residue removal is pivoted on how soil conditions are impacted.

These guidelines highlight the need to make site-specific assessments of soil conditions to understand impacts and recovery time. The soil conditions that have short-term, and potentially long-term impacts, center on nutrient cycles, soil compaction, and biological material.

Silviculture Treatment – Management objectives are highly variable, from site to site, and even within the same cover types. Recommendations generally center around implementing treatment objectives for a harvest area, with particular respect to planning, selection harvesting, regeneration timeline, operations, road/trail layout, re-entry, aesthetics, and post-operation treatment. The incorporation of residue removal into silvicultural prescriptions and objectives is imperative to sustainable use of residues.

Disturbance Considerations – Management objectives and silvicultural prescriptions must assess the size and type of disturbance from harvesting having a direct impact on species composition, disease/pest susceptibility, and fire/fuels management.

There is currently little consensus on how northern hardwood forests will recover from residue removal. Meta-analysis has shown that site conditions and harvest intensities have highly variable impacts to recovery of forest stands to variable levels of disturbance (Janowiak and Webster 2010, Mroz et al 1985). This variability highlights the need for additional research and for the active practice of adaptive management. Dynamic relationships exist between the quality and quantity of tree removal and the recovery of forests from harvests.

To enumerate these relationships on an ecosystem level is vital to understanding the sustainability of increased removal of residues. These relationships include the cycles of C and nutrients, the temperature and moisture regimes of the ecosystem, as well as how silvicultural treatment affects the interaction of each of these components.

Summary of Regional Biomass Harvesting Retention Guidelines.

The criteria mentioned above are represented to some degree or another in all state biomass harvesting guidelines (Table 2). The greatest differences between BMP's, or Forest management guidelines (FMG's), pertain to retention of wood material and operational changes associated with residue removal. Where additional or specialized management consideration have not been identified (e.g.-sensitive species and habitats) retention recommendations are, or should be, based upon organic matter and nutrient budgets.

Table 2. Summary of biomass harvesting guidelines by state, recommended retention of tree tops/fine woody debris.

State	Retention of tree tops
Michigan	1/6 to 1/3 of harvested trees
Minnesota	1/5 to 1/3 of harvested trees
Wisconsin	1/10+ of harvested trees
Maine	Variable, site specific
Pennsylvania	1/10 to 1/3, variable

Wisconsin's Forestland Woody Biomass Harvesting Guidelines (WIDNR 2008), and the supplementary document Rationale for Guidelines, demonstrate particularly well the rationale and considerations when implementing residue removal. Conversely, the "Considerations and Recommendation for Retaining Woody Biomasss on Timber harvest Sites in Maine" demonstrates the need for land managers to make site specific assessments, and goes on to discuss ecological indicators which are imperative to monitoring short-term and long-term impacts to the ecological processes and services. Ecological indicators will be discussed it greater detail to follow.

Biogeochemical Processes

Physical, chemical, and biological processes are driving forces behind site productivity. A conceptual model of how an ecosystem cycles organic matter and nutrients is illustrated in Figure 1. CO_2 is fixed through photosynthesis to form carbohydrates in the form of biomass. Biomass is accumulated until plant senescence and is afterwards decomposed, which leads to formation of CO_2, or becomes incorporated into other forms of biomass, soil organic carbon, and, to a smaller degree, recalcitrant organic compounds. The fixation of carbon through photosynthesis is strongly correlated with the availability of nutrients necessary for biological compounds, which mediate and facilitate photosynthesis. Nutrients enter the system by atmospheric deposition, mineralization, or through biological fixation (i.e.- $N_2 \rightarrow NH_4^+$) and leave the system through leaching or gaseous loss. Carbon and nutrients within a system are tightly cycled through litter production, decomposition, and subsequent assimilation into biomass of the ecosystem.

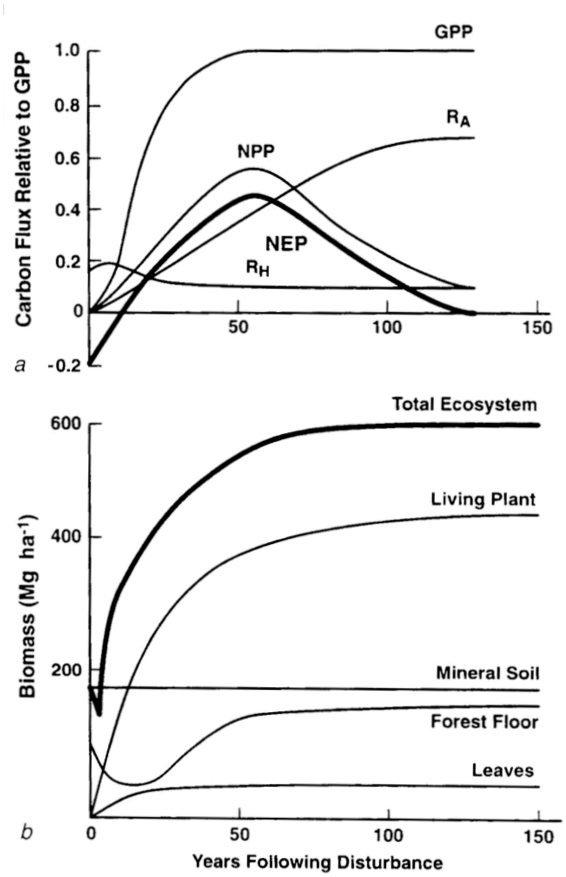

Figure 1. Carbon balance and rate of biomass accumulation following stand-level disturbance (reproduced from Barnes 1998).

The formation and decay of organic matter is an integral process regulating atmospheric, hydrospheric, and biospheric processes at a global scale. The composition and interaction of these biogeochemical processes within forest stands and across landscapes makes comprehensive life-cycle analyses difficult. Similarly, site specificity lends a great deal of uncertainty to drawing large-scale conclusions. Managing forest resources and assessing the environmental impact of management are ingrained in making sustainable use of these resources and making accurate life-cycle analyses.

Carbon Cycling

Carbon pools, fluxes, and the sequestration potential of forests have become a defining focus due to the action of CO_2 as a greenhouse gas. Forest systems within the U.S. have been estimated to contain 35 percent of C in live vegetation, 52 percent in soils, and 14 percent in dead organic material (e.g., DDW; Woodall 2010). While biomass is theoretically a "carbon neutral" fuel source, because of its ability to "close the C loop" through sequestration by subsequent re-growth of forests, this model may not be pragmatic in addressing the effects on soil C pools and efflux of CO_2 through edaphic processes (Luiro 2010).

The relationships between Gross Primary Production (GPP), Net Primary Production (NPP), Net Ecosystem Production (NEP), Autotrophic respiration (R_A), and Heterotrophic Respiration (R_H) are illustrated in Figure 1. NEP is a good measure of the total C-sequestering capacity of an ecosystem as a whole because NEP = GPP-R_A-R_H. After a major stand-level disturbance event, a net emission of CO_2 can be observed due to heterotrophic respiration from decomposition of organic matter outpacing Net Primary Production (NPP). As GPP from new growth begins to rise NEP will become positive because of the fixation of CO_2 into live woody biomass. It should be noted however that in Northern Hardwoods R_H will actually steadily increase with the accumulation and decomposition of DDW. This explains the steady decline of NEP at longer time-scales. The decomposition of DDW actually offsets much of the CO_2 sequestered through photosynthesis.

While NEP is a good indication of annual sequestration of CO_2, it does not fully reflect the accumulation or efflux of C compounds within soil. Decomposition of woody organic matter, typified by high C content, can be measured in terms of each constituent's rate of decay. Constituent C groups include glucose, proteins and simple sugars, cellulose, hemicellulose, and lignin. Decomposition is defined by the relationship $A_t = A_0 e^{-kt}$, where A_t is the substrate remaining, A_0 is initial concentration, k is the rate constant for a given compound (in $days^{-1}$, $months^{-1}$, or $years^{-1}$). Values for k for different organic compounds are shown in Table 3. These decompositions were performed under laboratory conditions by measuring the decline in a substrate during decomposition (Barnes 1998). A higher k value indicates a faster rate of decomposition. From these indices a direct relationship can be drawn between decomposition and use for microbial biosynthesis.

Table 3. Rate constants for the decomposition of organic compounds contained in plant litter. $A_t = A_0 e^{-kt}$.

Compound	Rate Constant for k (day^{-1})
Glucose	0.500 to 1.000
Proteins and Simple Sugars	0.200
Cellulose	0.036 to 0.080
Hemicellulose	0.030 to 0.080
Lignin	0.003 to 0.010

After Barnes et al., from (Veen 1984, Alexander 1997, Paul and Clark 1996)

Lignin is a complex and highly recalcitrant material and produces precursors, along with microbial activity, for the accruement of humic compounds in soils (Paul and Clark 1996). This represents a significant C pool within Northern Hardwood Forests.

Decomposition is also strongly governed by C:N ratios. The availability of N will regulate the rate of decomposition by the ability of microbes to synthesize essential cellular material. Residue products with the highest C:N ratio are leaves and needles, followed by branches, then bole-wood, and this ratio progressively goes down as dead wood becomes more decomposed (Luiro 2010, Andrew and Dean

2006). The removal of N rich biomass then has the potential to affect the soil productivity on a longer time-line than typical with stem-only harvests (Andrew and Dean 2006, Johnson et el. 1982, Weatherall et al. 2006a, Weatherall et al. 2006b). Johnson et al. (1982) note however that “soil reserves and atmospheric inputs may be adequate to sustain total N, P, and K supplies with whole-tree harvesting, but soil amendments may be necessary to sustain Ca supplies.”

Davidson and Janssens (2006) note that empirical models can relate the efflux of CO_2 from soils to an optimal temperature curve, and to some scalar of soil water content or precipitation, and that this much is not controversial. However, there are myriad reactions and feedback mechanisms that ultimately govern soil C cycles relating to disturbance events. Many studies have been conducted to compare whole tree harvest (WTH) to bole-only (or stem-only) harvest (Jenkins et al. 2004). Covington (1981) produced a study in 1981 that became definitive for forest floor decomposition, and was widely cited. Covington reported that during the first 15 year after clearcutting the forest floor decreased by 30.7 Mg/ha, which is a decline of over 50%. It became generally accepted that this loss of forest floor biomass was due to increased surface temperatures and availability of moisture, leading to increase microbial decomposition. This assumption has been accepted to the point of becoming a paradigm and has even come to point of no longer being cited in literature (Evans and Pershal 2009, Janowiak 2010). Yanai et al. (2003) present an in depth discussion about the merits of this work and present research that challenges the “Covington curve” and explanation for measured changes in forest floor mass. In summary, there have been many decomposition studies which have presented widely varying results (e.g., Yanai et al. 2003, Harmon 2010, Moore 2006, Moore 2005). The variability of physical, chemical, and biological conditions from site to site makes it inherently difficult to generate data that can be applied over landscapes. Researching and predicting carbon and nutrient cycles is an inherently difficult area of research because of site-specific conditions and the long-term nature of carbon and nutrient cycling itself. This also highlights the importance of adaptive management being incorporated into silvicultural management.

Nitrogen Cycling

C and N cycles are tightly coupled within an ecosystem by way of the essentiality of N to accumulate C via the composition of living biomass. Nitrogen is most commonly the limiting nutrient in forest ecosystems (when moisture and temperature are not limiting), and can govern the productivity of a forest. Bioavailable N typically comes in the form of ammonium (NH_4^+) and nitrate (NO_3^-). N as an essential nutrient is used in chlorophyll, amino acids (and hence proteins which catalyze biochemical reactions), nucleic acids (DNA, RNA), and secondary metabolites. For this reason N cycling in forests is relatively closed, that is to say that N loss is relatively low in mature forest stands (Barnes 1998). Intensive harvesting can cause increased nitrification ($NH_4^+ \rightarrow NO_3^-$) through microbial processes. NO_3^- is water-soluble and is subject to leaching through hydrologic export.

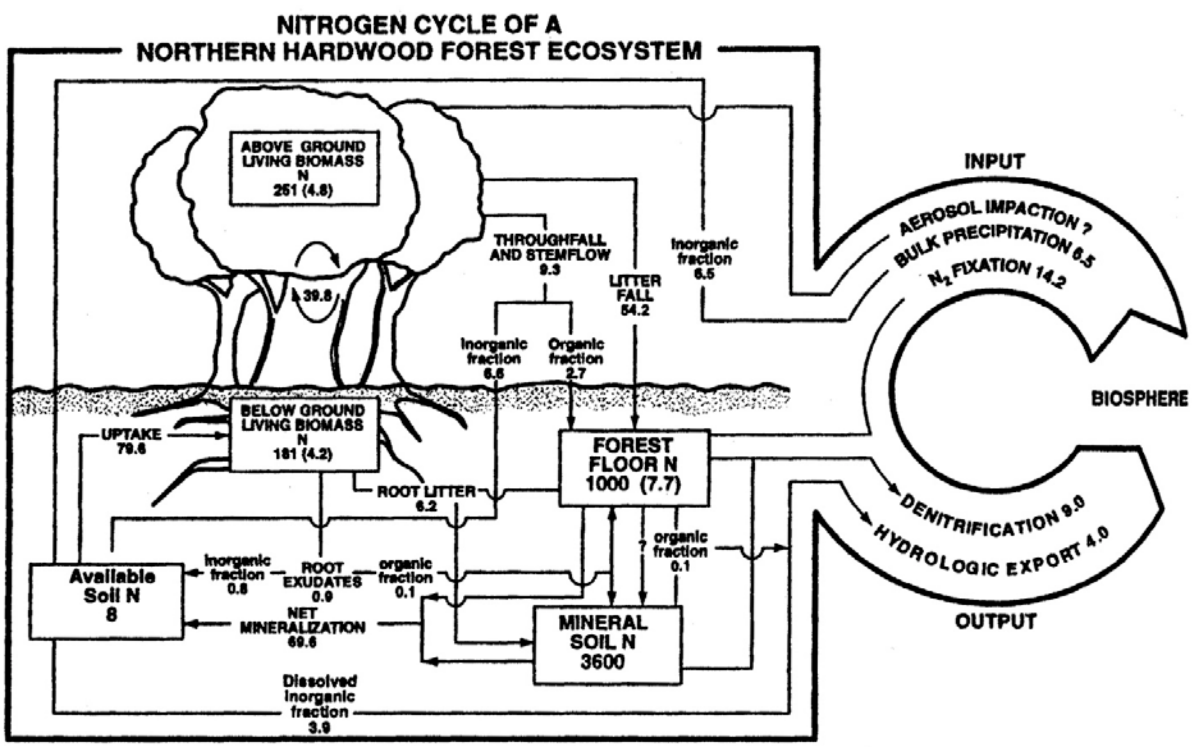

Figure 2. Nitrogen cycle of a northern hardwood ecosystem (reproduced from Barnes 1998).

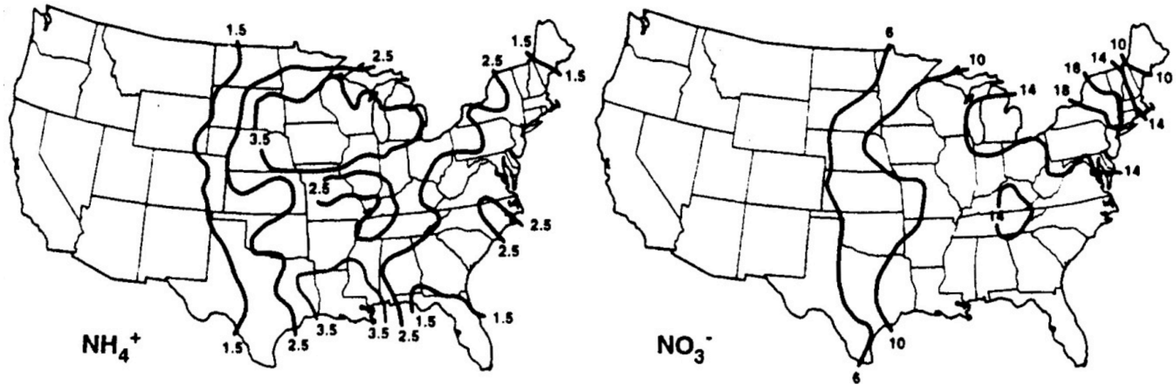

Figure 3. Atmospheric nitrogen deposition in the U.S. (reproduced from Barnes 1998).

Recovery of N, and other nutrients, on the Eastern portion of the contiguous 48 states is ameliorated, in part, due to atmospheric deposition (Figure 3), as well as microbial N fixation.

Mg, Ca, K, P, S Cycling

While N is commonly the limiting nutrient to growth in an ecosystem with adequate moisture and favorable temperature, there are two other nutrients considered essential macronutrients for plant growth, which are K and P. K is required for osmotic regulation and carbohydrate translocation, and P is required for energy (ATP, ADP), in nucleic acids, and phospholipids. Mg, Ca, and S are considered secondary macronutrients, but can impose moderate to severe limitation on plant growth and overall stand-growth. Mg is an integral metallic factor in chlorophyll and thereby photosynthesis. S is a constituent of several amino acids and plays a direct role in N use efficiency. Ca is an integral part of cell wall formation in plant tissues and can adverse impacts on stand-level productivity. Atmospheric deposition of Ca is low (Figure 4), especially relative to N deposition and potential Ca losses with biomass harvest.

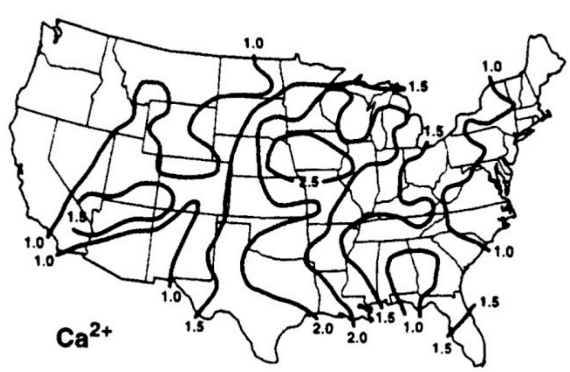

Figure 4. Atmospheric Calcium Deposition in the U.S. (reproduced from Barnes 1998).

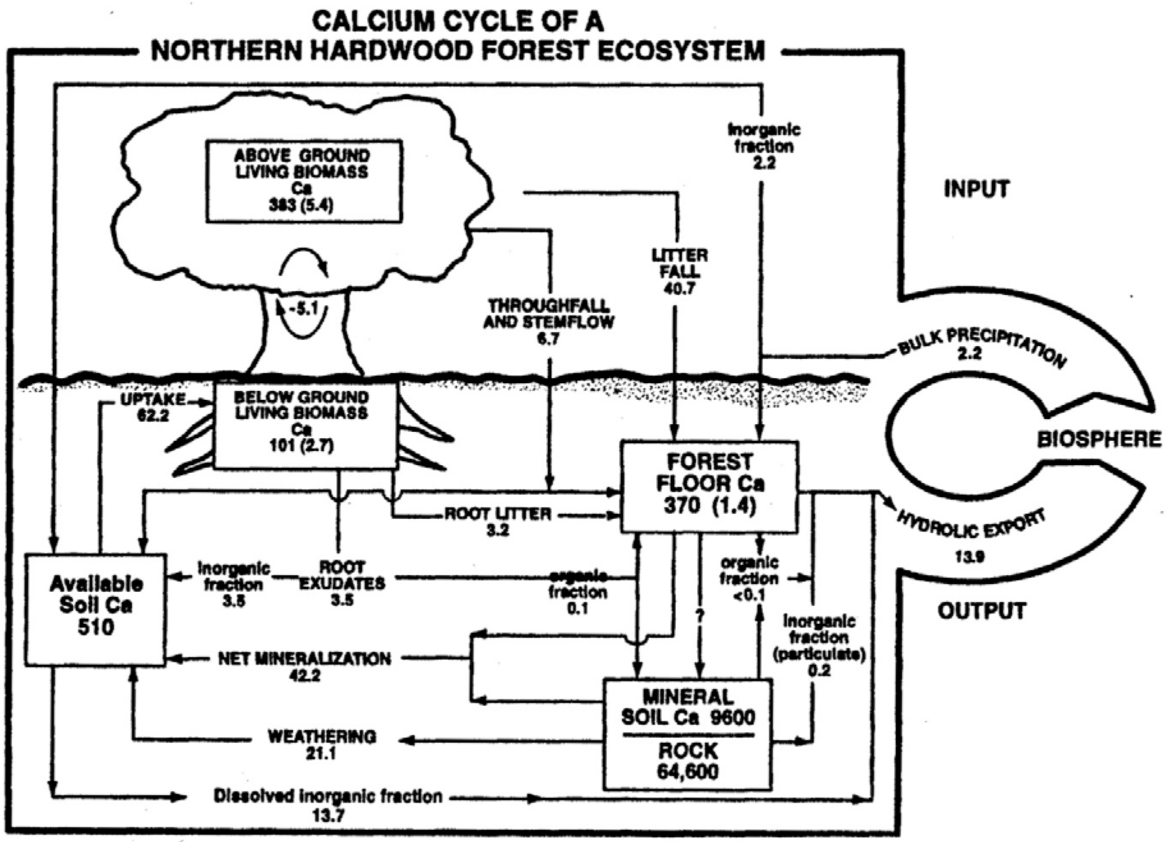

Figure 5. Calcium Cycle of a Northern Hardwood Forest Ecosystem (Barnes 1998)

Figure 7 shows Ca pools in kg ha^{-1}, and fluxes in kg ha^{-1} yr^{-1}, of a Northern Hardwood Forest Ecosystem. Conceptually this model can be fit to other secondary nutrients although the specific amount held within pools and levels of flux will vary.

Calcium has been found to be the slowest nutrient to recover after harvest losses in Northern Hardwood Systems (Jenkins 2004, Silkworth and Grigal 1982). This is explained, in part, by how labile Ca is within soils and the associated potential for loss through leaching. A complete model of nutrient balance after whole-tree harvest of trembling aspen ecosystems in Minnesota is given by Silkworth and Grigal (1982; Table 4). While this forest type is fairly divergent from the Northern Hardwood Forest Ecosystem, it does have bearing on nutrient balance after stand-level disturbance events. Loss of productivity due to Ca (and Mg) deficiency could be ameliorated through ash fertilization and eventually through atmospheric deposition.

Operational Considerations

Maine's biomass harvesting guidelines summarize very well the importance of adaptive and 'on-the-ground' management when integrating residue removals into roundwood harvest. Precedence should be given in implementing Best Management Practices (BMP's) to minimize impact to water quality, sensitive habitats, and so forth. Implementing residue removal as a standard portion of silvicultural prescription is the most responsible way to reduce the potential impacts to stand level ecosystem services.

In many cases the precedence of BMP's will dictate how and to what degree biomass is available for removal. In this way, biomass harvesting guidelines also echo what has already been outlined in BMP's.

Table 4. Nutrient Balance for Whole-Tree Harvested *Populus tremuloides* Ecosystems in Minnesota (Silworth and Grigal 1982).

	N	P	K	Ca	Mg kg ha^{-1}
Annual Input					
Precipitation	6.9	2.6	9.5	5.0	1.7
Mineral weathering	0.0	0.4	8.7	20.8	10.4
N_2 fixation	3.0*	-	-	-	-
Annual output					
Normal annual leaching	0.4	0.6	3.6	28.8	11.3
Net annual gain					
(input-output)	9.5	2.4	14.6	-3.0	0.8
Harvest losses					
Leaching due to harvest	0.0	0.0	0.0	62.3	0.0
Removal in biomass	452	43.1	354.6	1034	94.5
Years to replenish harvest losses	48	18	24	No	118
Ecosystem storage	4834	148	643	9081	1866

***Nitrogen input from fixation in the Northern Hardwood Forest Ecosystem can be up to 14.2 kg ha^{-1} year^{-1}.**

Augmenting harvesting operations with residue removal has the potential to offset other costs of harvesting, including the silvicultural prescription, and treating forest health issues such as overstocking, and salvage operations which utilize timber and residues from disease and insect caused mortality (Benjamin, 2009). But these products are still viewed as low value products and present problems in economic viability to utilize (Becker 2009, Benjamin, 2009, Andersson, 2009).

Residue products are handled within the existing operation, and to be utilized are brought to a landing area and fed into a chipper or a grinder on site and loaded into a chip van. As stated by Benjamin (2009), existing operations are not designed to utilize this low quality and smaller material, which makes it a risk for loggers to invest time and resources into new endeavors. Specialized equipment is at a high cost which is risky for such a low value product and when there is uncertainty as to the demand for wood chips (Benjamin, 2009, Flynn, 2002, Becker, 2009).

Operationally, this turns residue removal into utilization of tree tops, which are non-merchantable branches < 4" in diameter and including the foliage depending on season of harvest, non-merchantable cut trees, and standing live trees below merchantable size. In this way the sustainability of residue removal must draw upon silvicultural treatment objectives and the sustainability of whole-tree harvesting.

Methods

A combined sampling plan was implemented to inventory forest stands harvested in the Upper and northern Lower Peninsulas of Michigan. A field inventory of all above ground biomass and downed dead wood, along with sample collection of soils and leaf litter, was used as a baseline survey to answer the research questions outlined in the introduction. Field inventory was an essential baseline survey to establish an estimate of forest stand conditions pre- and post-harvest. This inventory is also a keystone in establishing long term monitoring sites to track additional long term changes in various stand conditions.

Measurement of above ground vegetation was done in a way to reconstruct pre-harvest condition and make predictive measurement of current stand conditions. Measurement focused on tree identification and measurement of diameter at breast height (dbh).

Field Inventory

In this field program an assessment was being made of production and harvest removals from northern hardwood forest types in Michigan, under State, Non-Industrial Private Forest, and Corporate ownerships. A common thread is the assessment of production and sustainability under current and alternative management scenarios. The basic sampling design involved two phases: stand selection and within-stand field measurement. Stands were selected by identifying a pseudorandom sample from planned or recently completed timber sales within three ownership types.

Site Selection

The stands in which measurements are being made are under three types of ownership. Stands are within State Forests managed by the Department of Natural Resources and Environment (DNRE), on property under non-industrial private ownership and management, as well as industrial or corporate ownership.

Stands have been selected for inclusion on the basis of the following criteria.

1. Northern hardwoods cover type
2. 20 acres or larger in size
3. Harvested within the 6 years prior to field sampling in 2010.

State timber harvests were sampled proportionally, based on the number of northern hardwoods timber sales open in each Forest Management Unit (FMU) in 2009. DNR employees identified the stands meeting our criteria and a total of 42 stands on state land were sampled.

Non-industrial lands were located using two different methods. Initially, landowners were selected randomly from a previously compiled list of Michigan forest landowners. They were contacted and asked if their properties met our criteria, and then asked to include their lands in the study. The sample of stands generated from this approach was supplemented by contacting consulting foresters working throughout the Upper Peninsula and northern Lower Peninsula. A total of 30 non-industrial private forest stands were sampled. An additional 31 corporate stands were sampled through contact with three different corporate forest land owners.

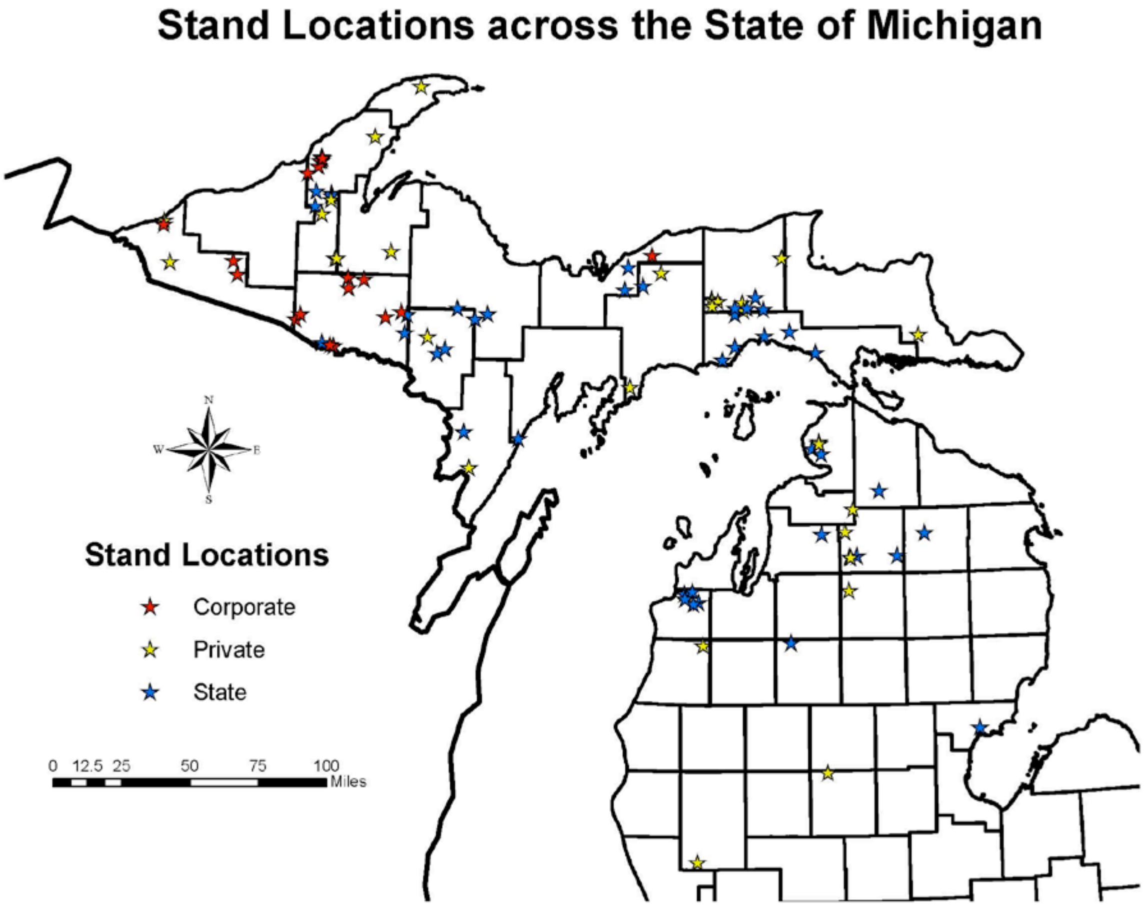

Figure 6. Locations of the stands sampled by owner-class.

Stand Level Sample Protocol

The basic sampling unit in each stand is a set of fixed-area plots. Plot centers are established through random points generated within ESRI ArcMap software. A total of 12 points were generated in an effort to sample at least 10 plots per stand and plot locations were adjusted or not sampled to accommodate for harvest boundaries, or areas within a stand that were not harvest and were not representative of the harvested population of interest. These fixed-area plots used a nested design to sample a range of attributes efficiently.

The basic unit was a 100 m^2 circular plot. On every plot, overstory and downed dead wood attributes were measured; a subset, of half the plots within a stand, includes an additional set of measurements and sampling of understory vegetation, leaf litter and soils. These are termed extensive and intensive sampling plots, respectively (Figure 7).

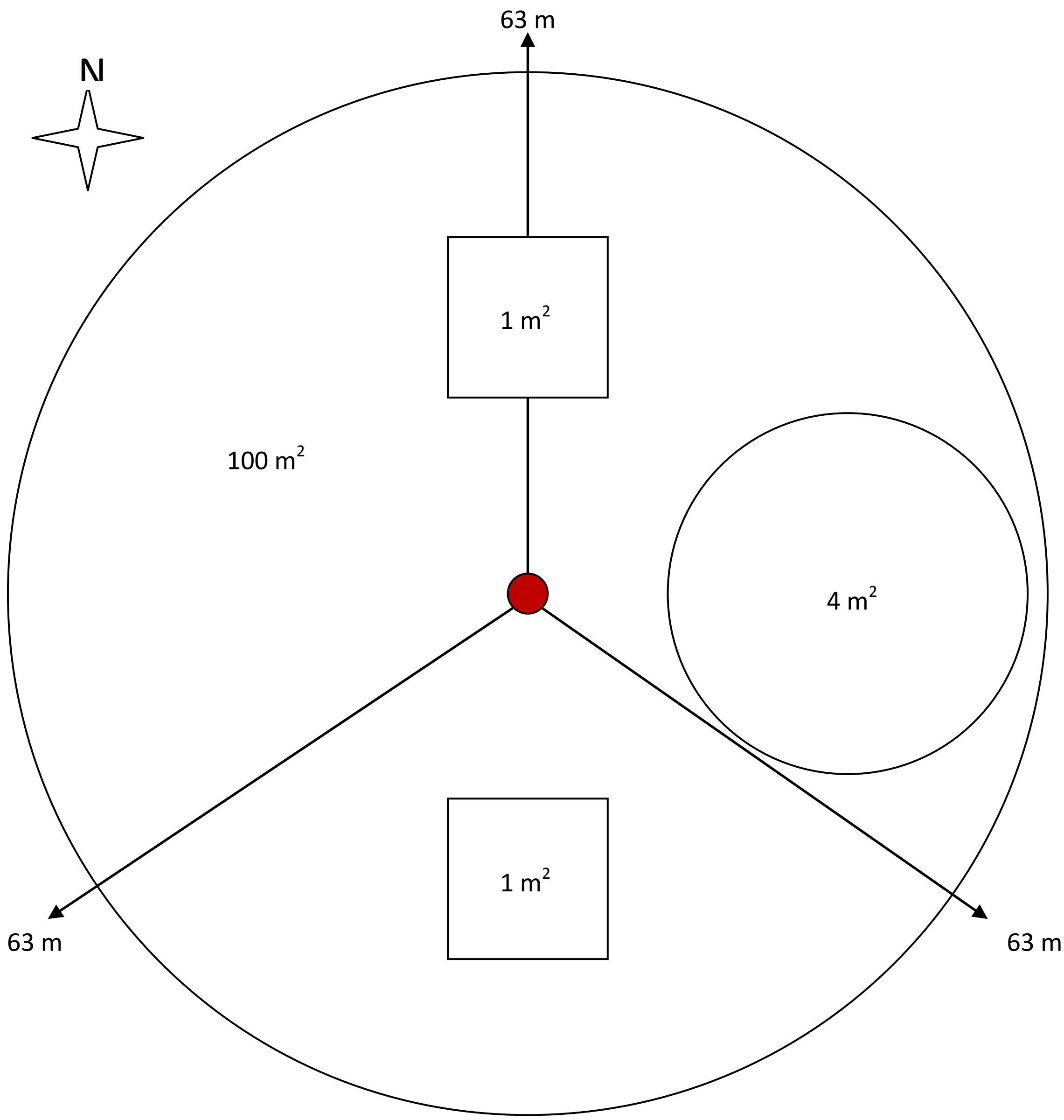

Figure 7: Field plot layout.

The detailed field protocol used during field sampling was as follows:

100 m^2 plot - Extensive

1. Record stand-level attributes including slope, aspect, elevation, GPS coordinates, microtopography.

2. Measure the diameter at stump height and height for every stump included in the plot that appears to have been cut in the last five years. Record the tree species as well.

3. Measure the diameter and species of every tree >10 cm DBH. Record whether the tree is acceptable growing stock or unacceptable growing stock. Estimate crown ratio.

4. For each species, measure DSH and height at DSH on at least the same amount of stranding trees as the amount of stumps within a plot.

5. Measure the height of each standing tree which had DBH and height at DSH measured. Make sure this includes the height of the largest tree by DBH.

6. Measure the percent canopy cover at the center of the plot by taking four measurements in each cardinal direction using a spherical densiometer.

7. Use the plot center to measure coarse woody debris using Limiting Distance Sampling. Characterize each log by decay class, using the criteria attached to this document.

8. Take a photograph due north from plot center.

100 m^2 plot - Intensified

Within each intensified plot all of the extensive measurements are recorded. In addition, three nested subplots are established. One is a 4 m^2 circular plot offset from plot center within which woody species < 10 cm dbh are measured. The other two are 1 m^2 square subplots within which observations of understory vegetation and forest floor are made. Also, forest floor and soil samples are collected adjacent to both of the 1 m^2 subplots.

4 m^2 circular subplot

Establish a circular subplot, 2.82 m on center, due east of the center of the 100 m^2 plot. Within this subplot, measure the following:

1. Record the diameter of woody stems by species 0.5 m tall to 10 cm DBH. Measure diameters at 10 cm above ground for stems < 1 in DBH. For stems <1 cm and less than 10 cm DBH measure diameters at breast height.

2. Measure the heights of all individuals for which diameters were measured.

1 m^2 square subplots

Establish two subplots, 2.82 m on center, due north and due south of the 100 m^2 plot center. Within each subplot, measure the following:

1. Record the percent coverage of herbaceous vegetation by species/group using the following cover classes: 0-1, 1-2, 2-5, 5-10, 10-25, 25-50, 50-75, 75-95, 95-100. Some individuals will only be identified to group (e.g., grasses, sedges, mosses, lichens).

2. Record the percent coverage of the forest floor in the following classes: leaf litter (duff), bare soil, CWD, fine woody debris (< 10 cm midpoint diameter, FWD), rocks, and other (e.g., water, stumps, fungi, etc).

3. Record the percent of the plot that shows evidence of logging-related physical disturbance to the forest floor (e.g., soil compaction, duff displacement).

4. Measure the forest floor depth at location of leaf litter sample collection.

Down Dead Wood Sampling

Downed dead wood was sampled using a limiting distance sampling protocol called "Line Intersect Distance Sampling" (Affleck 2008, 2010). Three 63 m transects are run out from plot center at 0˚, 120˚, and 240˚ bearings. DDW is measured along each transect with the smallest pieces being most likely to be counted close to plot center, as the transect distance increased the limiting distance for diameter of the DDW becomes greater. For those particles of DDW which fall within the limiting distance the decay class is recorded based on the characteristics in Table 5.

Table 5. Characteristics of DDW decay stages adapted from Maser et al. (1979) and Pyle and Brown (1998). Table reproduced from Jenkins et al. (2004).

Decay Class Description
Stage 1
-bark firmly attached
-exposed wood not stained by weathering
-log is round
-small branches present
-log is resting on surface
-primary surface substrate: sound bark
Stage 2
-bark not firmly attached, patchy
-exposed wood may be bleached
-log is round
-small branches absent
-wood is mostly solid
-log is resting on surface
-primary surface: hard wood, decayed bark
Stage 3
-bark generally absent, but may be present in patches
-log structure is solid, not brittle, firm when kicked
-dry log surface flaky
-wet log surface spongy
-log partially sunk into ground
-primary surface substrate: soft wood
Stage 4
-log is no longer solid, although some fairly solid segments remain
-log breaks into pieces when kicked
-log oval or flattened, one third or more sunk into ground
-primary surface substrate: spongy or powdery wood
Stage 5
-log is flat, mostly sunken into the ground
-log is soft and powdery in texture
-log is often obscured by litter
-primary surface substrate: loosely aggregated blocks

Forest Floor and Soil Sampling

Immediately adjacent to the 1 m^2 subplots south of plot center locate a 25 cm x 25 cm subplot to collect litter layer for laboratory analysis.

1. Using a metal sampling frame and a knife/spatula, extract the forest floor down to the surface of the bare mineral soil and place this in a paper bag for transport back to the lab.

2. Use a 2" diameter, 45 cm length soil core sampler to extract a soil core from the center of the cleared forest floor.

Soil samples were kept in coolers until returned to the lab at which point they were put into a chest freezer at -17 C until processing. Leaf litter samples were kept as cool and dry as possible in the field. Upon return to the lab they were preferably oven dried at 70 C for 48 hours or put into cold storage at 4 C until they could be oven dried.

Sample Processing

Soil and leaf litter sample processing occurred concurrent with collection and was completed following summer field inventory. Soil and leaf litter was stored as aforementioned until ready for oven drying and subsequent procession. Procedures below outline processing.

Leaf Litter

Leaf litter was removed from the oven and weighed as soon as possible and within no longer than 2 hours from removal from the oven. Sticks larger than 1 cm in diameter were removed prior to weighing. Leaf litter was then sealed in ziplock bags and stored at room temperature until grinding.

Each sample was ground to ~1mm particle sizes in a milling machine. After course grinding, the samples were finely ground in a ball mill. The ball mill cylinder, cap and steel balls were washed, sanitized, and dried between leaf litter samples to minimize contamination. Leaf litter was afterwards returned back to a paper cup and mixed together. One vial sized leaf litter sample was removed from each cup, and sealed in a vial.

Afterwards, finely ground samples were prepared for elemental analysis. Using a microbalance a silver foil cap was filled with a subsample from each vial and weighed. Mass was recorded and the silver foil was sealed. Soils then proceeded to elemental analysis.

Soil Samples

Field samples were spread on freezer paper for air-drying (approx. 1 to 1.5 days.). Once air-dried the soil samples were gently crushed, using a mortar and pestle, to destroy clods. Samples were placed in a 2 mm sieve to separate material into three possible sub-samples:

1. < 2 mm material
2. > 2 mm rock fragments, and
3. > 2 mm roots and organic material.

Light pressure was placed on soil in the sieve, when necessary, to reduce clods such that they pass. Sub-samples were then bagged with proper identification noted on bag, and it was ensured that the sieve was free of all material.

The < 2mm soil samples and organic material samples that did not pass the 2 mm sieve were placed in foil pans with a paper identification label and oven dried at 70 degrees C for 48 hours. Oven-try weight was obtained and soils were kept in labeled plastic bag for future storage.

Rock fragments (> 10 mm) were cleaned and dried, and then weighed. Then, an approach using water displacement in a graduated cylinder was used to obtain the volume of fragments. If the sample was large and contained fragments > 10 mm, then instead of measuring volume for the entire sample up to three large fragments were selected, weighed, and volume of each was determined. Again, all samples were re-bagged for long-term storage.

Using a ball mill, soil samples were further ground. The ball mill was washed, sanitized and dried between soil samples. Afterwards, soil was returned to the paper cup and mixed together. One vial sized soil sample was removed from each cup, and sealed in a vial. Later, a subsample from each vial was taken and the specified amount placed into the silver cap. The mass was recorded, and the cap placed in a sample collection tray pending elemental analysis.

Elemental Analysis

Elemental Analysis of carbon and nitrogen content was completed using a Fissons NA 1500 Elemental Combustion System. Protocol for EA analysis, software interface, and data interpretation was developed from user's manual and personal communication with lab technicians at the MTU Forest Ecology Laboratory.

Data Analysis

Data analysis relied largely upon established allometric relationships between biomass and field inventory mensuration. Diameter at breast height (DBH) is the most common metric for allometric calculation of values of above ground biomass, below ground biomass, and component biomass. To establish pre-stand conditions tree stumps were measured for diameter and height from ground surface of measurement, these metrics were used to estimate DBH of trees prior to harvest.

The following work to generate diameter at breast height (DBH) from diameter at stump height (DSH) was done by Nan Pond, a fellow graduate student working in cooperation.

Generating accurate estimates of pre-harvest basal area of harvested trees requires a method of predicting the diameter at breast height (DBH) of each harvested tree. Species, stump diameter (DSH), and height at which diameter was measured were recorded for each stump and potentially useful predictor variables. Our data set includes 4,400 trees of 29 species for which DSH and DBH measurements were made, and 2011 stumps of 22 species for which predictions are necessary.

Prediction equations available in peer-reviewed literature and technical reports were reviewed for utility. The oldest equations described were simple linear regression equations based on a simple ratio of DBH:DSH (Horn and Keller 1957, Bones 1960). Other simple linear regressions using only DSH as a variable were published for Indiana (Johnson and Weigel 1990), the southeast (Bylin 1982) and northeast

(Wharton 1984). More complex equations including stump height as an additional predictor also exist for southeastern and northern species (McClure 1968; Raile 1977).

After several decades of silence in the literature on this subject, a more complex set of equations for 18 species groups common to the northeast was published by Westfall (2010). Westfall's equations are of the form:

$$DBH = DSH * \left(\frac{4.5}{H}\right)^{B_0} + B_1 * (4.5 - H)$$

Where DBH and DSH are in inches and H is stump height in feet.

Notable to this equation form is the inclusion of stump height as both an absolute and relative predictor. Our data set includes stumps measured at a wide range of heights, and we chose to utilize Westfall's equations to include stump height as a variable. Westfall's coefficients were created using a dataset from 13 northeastern states, which did not include Michigan.

Species groups were assigned following Scott (1981). Westfall's published coefficients were used to generate predictions using a prediction data set composed of the 3,857 stems from 15 species groups. 542 stems were removed from the data set because they were from multi-stemmed trees, or determined from review of the original data sheets, residuals, and plots of DSH versus DBH to be extreme outliers. Predictions and residuals were plotted and visually examined. Equations were re-fit for all species groups representing 2% or greater of the fitting data set; i.e., those groups with more than 88 data points.

Equations were re-fit with a nonlinear generalized least squares approach, using the `gnls()` function in the `nlme()` package for the R Environment for Statistical Computing, using the coefficients provided by Westfall as a starting point. Increasing variance as DBH increased was observed in keeping with Westfall (2010)'s findings. Heteroscedasticity was accounted for by weighting DBH within the `gnls()` function; for all species groups, the resulting coefficients were determined by ANOVA to be significantly different from those generated from a non-weighted gnls approach and from those provided by Westfall.

Most published equations are species- and region-specific. The development of substantially different prediction equations in different regions suggests that there are notable growth differences between states and regions. Our Michigan-specific coefficients generate more accurate predictions for our data set than any of the available equations and predictions, suggesting that this straightforward exercise was worthwhile.

Coefficients generated were subsequently used to predict the DBH from the DSH of all measured stumps. Then, the predicted DBH could be used with allometric equations to estimate above-ground biomass components.

Allometry and Calculations for Above Ground Biomass

In accordance to Jenkins (2003) above ground biomass (AGB) is calculated from generalized DBH to biomass conversion equations of the form:

$$\textbf{Total BM} = \textbf{Exp}(\beta_0 + \beta_1 \ln \textbf{dbh})$$

Where: **BM** = total aboveground biomass (kg dry weight) for trees 2.5 cm dbh and larger, **Exp** = exponential function, **dbh** = diameter at breast height (cm), **ln** = log base e (2.718282), parameters β_0 and β_1 are unique to species groups. See Jenkins (2003; 2004) for detailed information on the use, accuracy, and additional discussion about the application of these allometric equations.

Allometry and Calculations for Component Biomass

Biomass for tree components is derived from total biomass using component ratio multipliers from Jenkins (2003). Components are broken down into the following categories:

1. Foliage
2. Branches
3. Course roots
4. Stem bark
5. Stem wood

Biomass for each component is calculated from input parameters input into the equation of the form:

$$\textbf{Ratio multiplier} = \mathbf{Exp}(\beta_0 + \beta_1/\mathbf{dbh})$$

Where: **Exp** = exponential function, **dbh** = diameter at breast height (cm), parameters β_0 and β_1 are unique to component for hardwood and softwood species. The ratio multiplier is then multiplied against the Total BM equation aforementioned. Figure 8, reproduced from Jenkins (2003), show graphically how component biomass varies as a function of DBH.

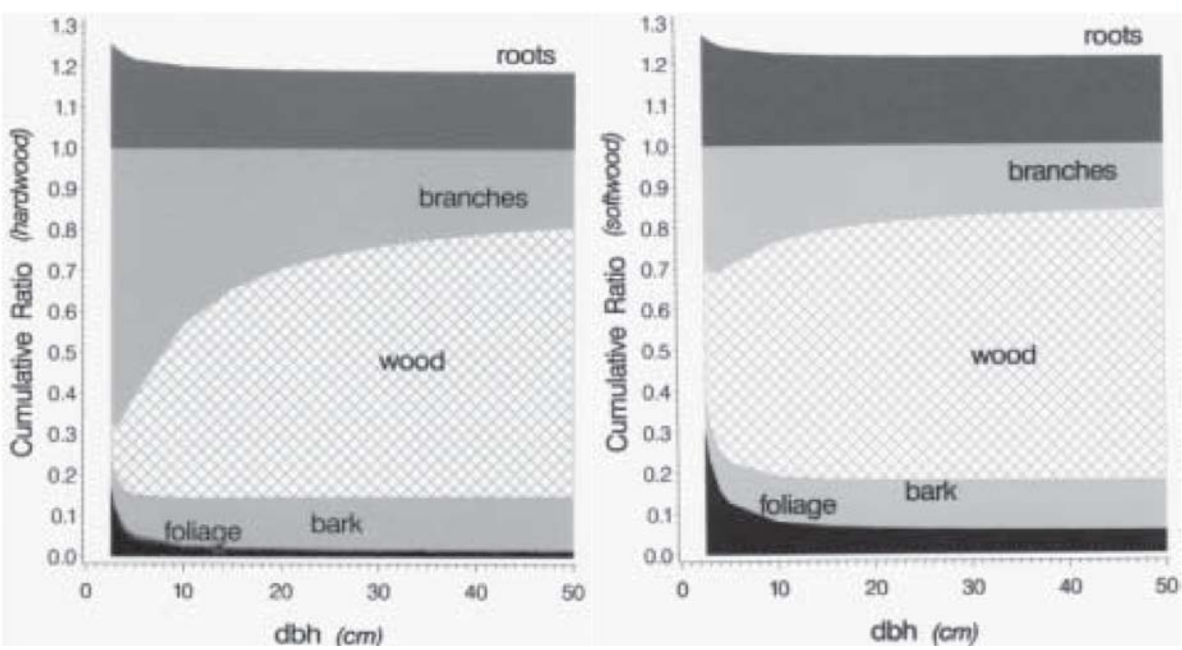

Figure 8. Proportion of aboveground biomass for hardwood and softwood species groups (left and right, respectively). Reproduced from Jenkins (2003).

See Jenkins (2003), and Jenkins (2004) for detailed information on the use, accuracy, and additional discussion about the application of these allometric equations.

Allometry and Calculations for Downed Dead Wood

The DDW sampling protocol followed Affleck (2008) and is a direct calculation based on particle tally. The total volume is calculated as follows:

$$\text{Volume (m}^3\text{/ha)} = (\text{PI()}*(10000)/\ (2*900))*(\text{Transect tally})$$

Volume was calculated for each transect by decay class, then averaged to plot level and stand level. Then a total mass was calculated by assigning density to each decay class, following Harmon et al. (2008):

$$\text{Mass}_{\text{DC-Sp-S}}\ (\text{Mg/ha}) = \text{Volume (m}^3\text{/ha)}*\text{Density (Mg/m}^3\text{)}$$

$$\text{Uncertainty Mass}_{\text{DC-Sp-S}}\ (\text{Mg/ha}) = \text{Volume (m}^3\text{/ha)}*\text{Uncertainty}_{\text{Density}}\ (\text{Mg/m}^3\text{)}$$

Since species distribution was not available for tallies of DDW we assumed that the DDW distribution matched the pre-harvest BA distribution. Thus, the density multiplier for each decay class was calculated by a weighted average of pre-harvest BA percentage by species for each stand:

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i},$$

Where w_i is the pre-harvest BA percent by species, and x_i is the density multiplier, of each decay class, for each species.

Allometry and Calculations for Soils

Soil carbon estimation in the case of measuring the < 2 mm fraction was done with an Elemental Analyzer machine, percent carbon of this fraction can then be multiplied back to density to obtain an estimation of total carbon by density. Organic matter fraction > 2 mm was weighed and can be multiplied by a factor of 0.5 to obtain carbon by density. Inorganic fractions > 2 mm were weighed and volume displaced for density and are assumed to contain no organic carbon.

Results

Above Ground Biomass

Table 6 summarizes averaged harvest intensity on a landscape level (all stands) in terms of basal area per hectare, and trees per hectare.

Table 6. Landscape level average of harvest intensities.

Pre-harvest Basal Area/Hectare	Post-harvest Basal Area/Hectare	Basal Area removed	Pre-harvest trees/hectare	Post-harvest trees/hectare	Trees/hectare removed
33.2783	22.0974	11.1809	736.0591	539.3114	196.7477

Standing Live Biomass

Results for standing biomass, both pre- and post-harvest, are presented in Table 7 through Table 11.

Table 7. Pre- and post-harvest above ground biomass in tones/hectare.

Pre-harvest Above Ground Biomass (tonnes/hectare)		Post-harvest Above Ground Biomass (tonnes/hectare)	
Mean	463.5976	Mean	284.1188
Standard Error	10.2942	Standard Error	8.3900
Standard Deviation	103.4554	Standard Deviation	84.3184
Sample Variance	10703.0219	Sample Variance	7109.5873
Range	479.6559	Range	429.9014
Minimum	292.7582	Minimum	100.0043
Maximum	772.4141	Maximum	529.9057

Table 8. Pre- and post-harvest live branch biomass in tones/hectare.

Pre-harvest Branch (tonnes/hectare)		Post-harvest Branch (tonnes/ha)	
Mean	66.2356	Mean	41.9846
Standard Error	1.3520	Standard Error	1.1542
Standard Deviation	13.5870	Standard Deviation	11.5998
Sample Variance	184.6068	Sample Variance	134.5549
Range	60.0681	Range	56.6780
Minimum	42.6290	Minimum	17.1963
Maximum	102.6971	Maximum	73.8742

Table 9. Pre- and post-harvest live foliage biomass in tones/hectare.

Pre-Harvest Foliage (tonnes/hectare)		Post-harvest Foliage (tonnes/hectare)	
Mean	10.6320	Mean	6.6266
Standard Error	0.6207	Standard Error	0.4114
Standard Deviation	6.2378	Standard Deviation	4.1348
Sample Variance	38.9107	Sample Variance	17.0962
Range	30.5785	Range	19.4996
Minimum	5.2292	Minimum	1.8462
Maximum	35.8078	Maximum	21.3458

Table 10. Pre- and post-harvest live stem wood in tonnes/hectare.

Pre-harvest Stem Wood (tonnes/hectare)		Post-harvest Stem Wood (tonnes/ha)	
Mean	326.2434	Mean	198.5383
Standard Error	7.4284	Standard Error	5.9855
Standard Deviation	74.6548	Standard Deviation	60.1532
Sample Variance	5573.3387	Sample Variance	3618.4100
Range	355.1336	Range	308.7689
Minimum	198.7997	Minimum	67.9316
Maximum	553.9333	Maximum	376.7004

Table 11. Pre- and post-harvest live stem bark in tonnes/hectare.

Pre-harvest Stem Bark (tonnes/hectare)		Post-harvest Stem Bark (tonnes/ha)	
Mean	60.4866	Mean	36.9692
Standard Error	1.3757	Standard Error	1.1107
Standard Deviation	13.8254	Standard Deviation	11.1627
Sample Variance	191.1423	Sample Variance	124.6053
Range	66.7468	Range	57.0037
Minimum	35.6193	Minimum	13.0302
Maximum	102.3661	Maximum	70.0339

Standing Live Biomass Removed

Results for live biomass removed in the most recent harvest are presented in Table 12 through Table 14.

Table 12. Above ground biomass removed in tonnes/hectare.

Removed Above Ground Biomass (tonnes/hectare)	
Mean	179.4788
Standard Error	8.2895
Standard Deviation	83.3082
Sample Variance	6940.2497
Range	405.7909
Minimum	31.4143
Maximum	437.2052

Table 13. Branch and foliage biomass removed*in tonnes/hectare. *Removed in case of these harvest areas does not mean site removal, as they were left on site.

Removed* Branches (tonnes/hectare)		Removed* Foliage (tonnes/hectare)	
Mean	24.2510	Mean	4.0053
Standard Error	1.0949	Standard Error	0.2720
Standard Deviation	11.0033	Standard Deviation	2.7331
Sample Variance	121.0721	Sample Variance	7.4700
Range	55.1420	Range	15.0029
Minimum	4.0294	Minimum	0.5418
Maximum	59.1715	Maximum	15.5447

Table 14. Stem wood and Stem bark removed in tonnes/hectare.

Removed Stem Wood (tonnes/hectare)		Removed Stem Bark (tonnes/hectare)	
Mean	127.7051	Mean	23.5174
Standard Error	5.9545	Standard Error	1.0991
Standard Deviation	59.8421	Standard Deviation	11.0457
Sample Variance	3581.0771	Sample Variance	122.0070
Range	289.8579	Range	53.7141
Minimum	22.6716	Minimum	4.1716
Maximum	312.5294	Maximum	57.8857

Downed Dead Wood

Results for estimates of DDW by decay class are presented in Table 15 through Table 19.

Table 15. DDW Biomass – Decay Class 1, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 1 kg/ha		*Biomass uncertainty* - Decay Class 1 kg/ha*	
Mean	12.9975	Mean	0.8318
Standard Error	0.9768	Standard Error	0.0646
Standard Deviation	9.4204	Standard Deviation	0.6233
Sample Variance	88.7439	Sample Variance	0.3885
Range	46.5246	Range	2.9121
Minimum	0.0000	Minimum	0.0000
Maximum	46.5246	Maximum	2.9121

Table 16. DDW Biomass – Decay Class 2, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 2 kg/ha		*Biomass uncertainty* - Decay Class 2 kg/ha*	
Mean	9.3561	Mean	1.6498
Standard Error	0.8045	Standard Error	0.1396
Standard Deviation	7.7582	Standard Deviation	1.3461
Sample Variance	60.1890	Sample Variance	1.8120
Range	38.1217	Range	7.7918
Minimum	0.2514	Minimum	0.0476
Maximum	38.3732	Maximum	7.8393

Table 17. DDW Biomass – Decay Class 3, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 3 kg/ha		*Biomass uncertainty* - Decay Class 3 kg/ha*	
Mean	3.4187	Mean	0.5718
Standard Error	0.1730	Standard Error	0.0313
Standard Deviation	1.6683	Standard Deviation	0.3023
Sample Variance	2.7834	Sample Variance	0.0914
Range	6.9921	Range	1.4392
Minimum	0.5592	Minimum	0.0808
Maximum	7.5514	Maximum	1.5200

Table 18. DDW Biomass – Decay Class 4, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 4 kg/ha		*Biomass uncertainty* - Decay Class 4 kg/ha*	
Mean	1.3871	Mean	0.2967
Standard Error	0.0936	Standard Error	0.0274
Standard Deviation	0.9030	Standard Deviation	0.2640
Sample Variance	0.8154	Sample Variance	0.0697
Range	4.3647	Range	1.3269
Minimum	0.0000	Minimum	0.0000
Maximum	4.3647	Maximum	1.3269

Table 19: DDW Biomass – Decay Class 5, and uncertainty* in allometric calculation. *Equivalent to one standard error of the mean.

Biomass - Decay Class 5 kg/ha		Biomass uncertainty* - Decay Class 5 kg/ha	
Mean	0.9704	Mean	0.1940
Standard Error	0.0708	Standard Error	0.0180
Standard Deviation	0.6824	Standard Deviation	0.1737
Sample Variance	0.4656	Sample Variance	0.0302
Range	3.1850	Range	1.1079
Minimum	0.0000	Minimum	0.0000
Maximum	3.1850	Maximum	1.1079

Leaf Litter

Most leaf litter samples were of relatively low density, below about 0.06 g/cm^3 (Figure 9; Table 20). Total C content was about 45% and N content 1.3%, yielding a C:N ratio of about 32:1 (Table 21).

Table 20: Leaf litter densities in g/cm^3

Density (g/cm^3)	
Mean	0.0519
Standard Error	0.0017
Standard Deviation	0.0526
Sample Variance	0.0028
Range	0.4170
Minimum	0.0030
Maximum	0.4201
Confidence Level(95.0%)	0.0033

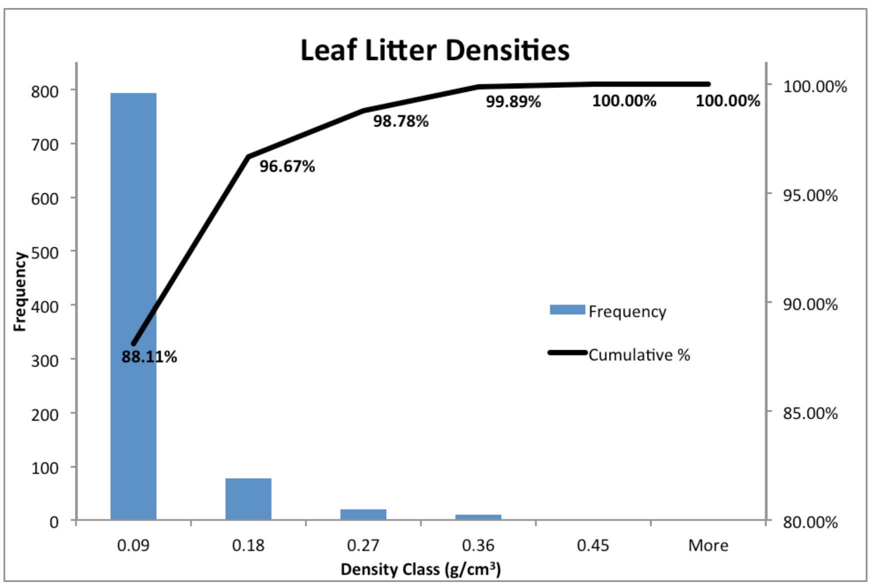

Figure 9: Frequency of leaf litter density by class and cumulative percentage represented in each density class.

Table 21. Percent nitrogen, percent carbon, and carbon:nitrogen ration for leaf litter.

% Nitrogen		% Carbon		C:N	
Mean	1.3480	Mean	43.5714	Mean	32.4975
Standard Error	0.0350	Standard Error	1.0984	Standard Error	1.0150
Standard Deviation	0.1212	Standard Deviation	3.8048	Standard Deviation	3.5160
Sample Variance	0.0147	Sample Variance	14.4766	Sample Variance	12.3626
Range	0.4210	Range	12.8120	Range	12.7589
Minimum	1.1330	Minimum	34.5350	Minimum	26.7299
Maximum	1.5540	Maximum	47.3470	Maximum	39.4887
Confidence Level(95.0%)	0.0770	Confidence Level(95.0%)	2.4175	Confidence Level(95.0%)	2.2340

Below Ground Biomass

Coarse Roots

Table 22. Pre- and post-harvest coarse roots for live trees in tonnes/hectare.

Pre-harvest Course Roots (tonnes/hectare)		Post-harvest Course Roots (tonnes/hectare)	
Mean	87.6849	Mean	53.8405
Standard Error	1.9524	Standard Error	1.5879
Standard Deviation	19.6218	Standard Deviation	15.9584
Sample Variance	385.0153	Sample Variance	254.6719
Range	88.5255	Range	79.5276
Minimum	54.4027	Minimum	18.6592
Maximum	142.9282	Maximum	98.1868

Table 23. Coarse roots associated with cut trees in tonnes/hectare.

Removed* Course Roots (tonnes/hectare)	
Mean	33.8444
Standard Error	1.5474
Standard Deviation	15.5516
Sample Variance	241.8528
Range	75.1308
Minimum	5.8072
Maximum	80.9380

Soils

Soil Carbon

Table 24. Density of soil fraction < 2 mm in grams/cm^3

Density (g/cm3)	
Mean	1.0970
Standard Error	0.0128
Standard Deviation	0.2806
Sample Variance	0.0787
Range	1.6529
Minimum	0.0755
Maximum	1.7284

Table 25. Percent carbon for soils.

% Carbon	
Mean	2.8944
Standard Error	0.1620
Standard Deviation	3.6897
Sample Variance	13.6137
Range	47.2840
Minimum	0.3250
Maximum	47.6090

Table 26. Organic matter fraction > 2 mm weight in grams.

Organic matter > 2mm Weight (g)	
Mean	4.3126
Standard Error	0.1556
Standard Deviation	3.4620
Sample Variance	11.9857
Range	29.0300
Minimum	0.1300
Maximum	29.1600

Soil Nitrogen

Table 27. Percent carbon for soils.

% Nitrogen	
Mean	0.1681
Standard Error	0.0075
Standard Deviation	0.1699
Sample Variance	0.0289
Range	1.8590
Minimum	0.0230
Maximum	1.8820

Carbon Nitrogen ratio

Table 28. Carbon:nitrogen ratio for soils.

C:N	
Mean	16.7972
Standard Error	0.1980
Standard Deviation	4.5107
Sample Variance	20.3460
Range	36.2256
Minimum	11.0882
Maximum	47.3138

Predicting DDW Volume production

Predicting the amount of material produced from a conventional harvest has made it difficult to estimate what amount of residue material is functionally available. As mentioned in the operational considerations section, predicting DDW production as a function of harvest intensity can assist land managers in all facets of operations: economically, meeting management guidelines, and meeting management objective which improve forest health and productivity. The relationship shown in Figure 10 can be used to forecast residue production from pre-harvest cruise data.

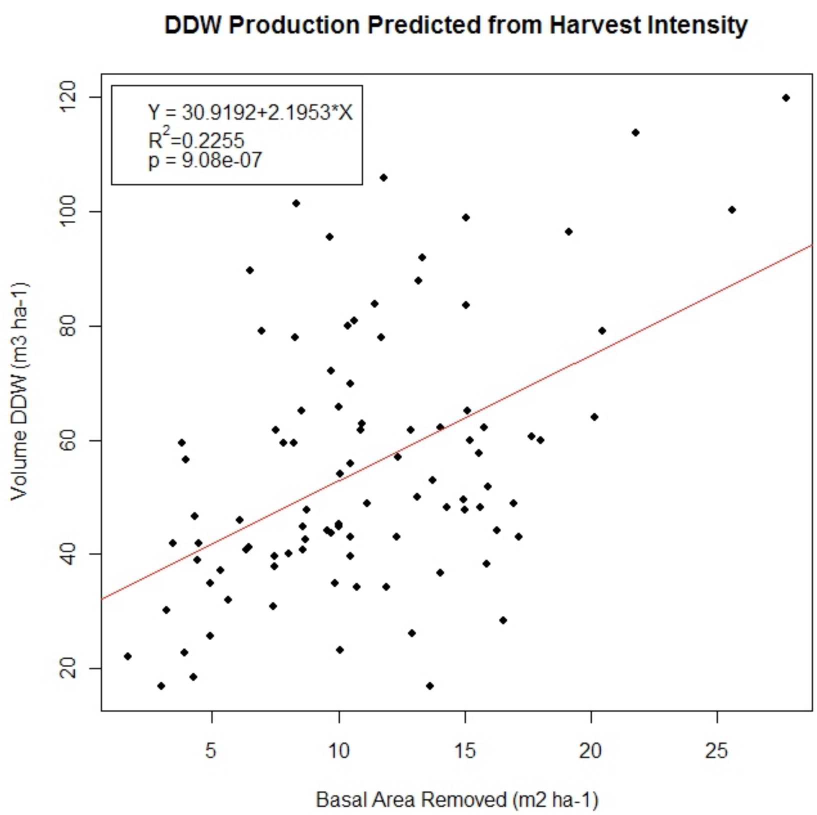

Figure 10. Predicting volume of DDW production from harvest intensity (BA removed).

Discussion

An analysis of the sustainability of biomass harvest with requires application of the three pillar model of sustainability: social, economic, and environmental constraints and concerns. Biomass harvesting represents a significant feedstock for the generation of heat, power, and liquid fuels. However there are many constraints which limit its economic and social viability. Similarly, there are environmental concerns over its impacts on forest productivity and wildlife habitat. This scope of this research requires an analysis of models for sustainability and their specific application to biomass utilization.

The mode and quantity of utilizing energy resources is a keystone of sustainable development in our society. Biomass utilization for the production of liquid fuels, as well as electricity and heat, has become a focal point in satisfying renewable energy policy standards. The immediacy of renewable energy utilization has spurred a proliferation of research and development into biologically sourced energy (Kajikawa & Takenda, 2008). The appeal of a carbon-neutral energy sources from potentially closed-loop systems, in terms of biomass, has lead to the increased utilization of energy resources such as energy crops, forest residues, food wastes. Utilization of forest residue products for the production of heat, power, and liquid bio-fuels (i.e. – ethanol and biodiesel) is gaining popularity as a way to meet the renewable energy demands of our society (Perlack et al. 2005).

Forest residue products are typically left after timber harvest and include tree tops, branches, defective and non-merchantable trees. Removing these residues from forests represents a substantial source of biomass feedstock for bioenergy applications; however this potential scale of removal calls for research to understand the sustainability of residue utilization.

While environmental impacts are at the core of understanding the sustainability of residue harvest, as well as the utilization of energy crops, etc., there is a largely undertreated dimension of sustainability science which deals with the normative nature of resource management (Hagan and Whitman, 2007, Hagan and Whitman, 2006, Vucetich and Nelson 2010, Kajikawa, 2008).

Society, Economics, and Sustainability

A superficial treatment of the social and economic nature of sustainability will be discussed in this paper, inasmuch as it is a grossly overlooked when discussing the science of sustainability. Kajikawa (2008) highlights this point succinctly noting that “Defining sustainability is ultimately a social choice about what to develop, what to sustain and for how long, and is thus a deeply normative process”. The treatment of models of sustainability in this paper will briefly cover the three pillar model which has been a commonly used model for sustainable enterprise. The aspects of the three pillar model are the social, economic and environmental dimensions. This model serves as a foundation for many scientific endeavors toward development in the direction of each pillar, as it were, in the effort to attain “sustainability”. While this model serves well as a conceptual foundation toward defining sustainability, in many ways it does not address the normative process directly, and moreover, does not further answer the question of whether human needs define the limits of sustainability, or if economic or environmental constraints should define the limits of human need and utilization (Vucetich & Nelson, 2010).

Defining human need is similarly a deeply normative process which involves making conscientious decisions in defining standard of living and quality of life. Ideally speaking, without resource scarcity, this would involve a quality of life which is defined by physical health, namely the availability to nutrition, clean water, and shelter. A standard of living is similarly defined in a socially normative way which reflects what a society has come to expect as an acceptable standard of consumption. It is not the intent for this discussion to address the standard of living as it is ethically debatable what should constitute defining standard of living. It should not go without saying however that this question in and of itself is what needs discussion and agreement when defining the sustainability of any resource use.

The United Nations defined sustainability in such a way by saying "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (UN General Assembly, 2005).

Forest Health and productivity

At the core of this discussion are inherent difficulties in sampling methodology with an enormous potential to introduce bias. Contrasting, anomalous, and even conflicting data has been found from studies such as the North American Long-term Soil Productivity (LTSP) Experiment (Powers et al. 2005), as well as those mentioned above (Covington, Yanai et al. 2003, Moore 2005, Moore 2006). The LTSP study notes no general decline in soil C concentrations, after a decade, in treatments where all aboveground living vegetation was removed, with the exception of the forest floor being retained. In a second treatment all organic matter, including leaf litter, exposing mineral soil, was removed. Results for this treatment were anomalous in that soil C concentration increased for some sites over the decade. Possible explanations are posited ranging from sampling error to bias sampling due to mixing of organic matter into mineral soils during harvest operations, to overall bulk density increase from soil compaction at sample sites. Similarly, Covington's sample design is questionable in that plots were selected based on non-random assumptions about the behavior of the forest floor. Overall, this illustrates the dynamic nature of edaphic processes. While conflicting data can result in lack of consensus about the effects of residue harvest, we can make some generalized assumptions that are supported in literature:

1. Complete removal, or at least large proportions, of nutrients in the form of biomass, leaf litter, and down dead wood will at some point have deleterious effects on soil productivity (Vance, 2000, Burger 2002, Fisher and Binkley, 2000, Van Miegroet, 2009).

2. Harvesting operations on short rotation will have a higher probability of having negative short- and long-term impacts on soil productivity.

3. Certain ecosystems are more susceptible to nutrient depletions. This is most dependent upon soil characteristics, such as shallow soil depths, texture (course sandy being most susceptible), pH (site dependent and nutrient capital dependent), and extremely poorly drained sites (Benjamin 2009). For example Wisconsin identifies "dysic Histosols" as sites for completely restriced for removing woody debris.

4. Harvest operations should follow BMP's for reducing impact to soils either through compaction or tillage (Sheperd 2006).

Historically, human need has come to define the limits of a resource use, until it becomes scarce. Much to this effect, forests in past have been utilized in an environmentally un-sustainable way, which has typically led toward strongly governed use of a scarce resource. A recent example would be the practice of litter raking in Europe, which was widely socially acceptable through the mid-1900's, until it became known that it was steadily diminishing forest productivity (Van Miegroet, 2009). This boom and bust cycle is repeated throughout history and to varying degrees, and today is becoming more of a reality with respect to a diminishing fossil fuel supply.

The more immediate problem has become an ever increasing energy demand, and the ultimate scarcity of resources to satisfy this increase. As a confounding problem, greenhouse gas emission of anthropogenic sources is changing our climate and consequently the ecological world which thrives upon it. For this reason alternative and renewable energy resources, such as forests, have had a resurgence of interest in their sustainable utilization (Kajikawa and Takenda, 2008). If forest products are used to offset fossil fuel consumption, there is a potential to realize a closed-loop system of utilization. A closed-loop system of carbon involves the sequestration of carbon emissions through photosynthesis of trees.

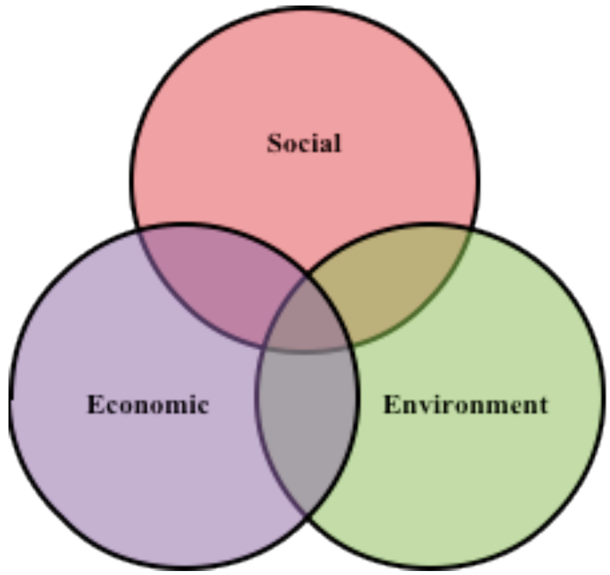

Figure 11. Stand-alone 3-pillar model.

Answering the complex question of sustainability of residue harvesting from forests comes down to what we value in a forest. For the purpose of this discussion, site productivity is the focal point as a proxy of forest health to meet human needs. It could go without saying that valuation of site productivity alone does not satisfy the three pillar model of sustainability, due to added values of ecosystems, such as biodiversity, aesthetics, ecosystem services and trophic cascades, clean water, etc. For this reason, shifting values in how we utilize our forest resource represents a shift in the normative values that define how we view the sustainability of forest harvesting.

The three pillar model on its own is an acknowledgement of the multi-dimensional nature of sustainability science, where social, economic, and environmental considerations are all recognized as important factors to sustainable development. On its own it serves well in balancing management directives that have at their core the interest of satisfying all three dimensions. Figure 11 is a Venn diagrammatic representation of this idea, where the areas of overlap are those that satisfy more than one component, and similarly, the area in the middle where all three overlap is conceptually where we attain sustainable development that can satisfy all three dimensions. Alternatively, Figure 12 is a conceptually different model where we define goals of sustainability by the limits within the environmental dimension. The concept between these models is quite different and can be said to represent a very different set of normative values.

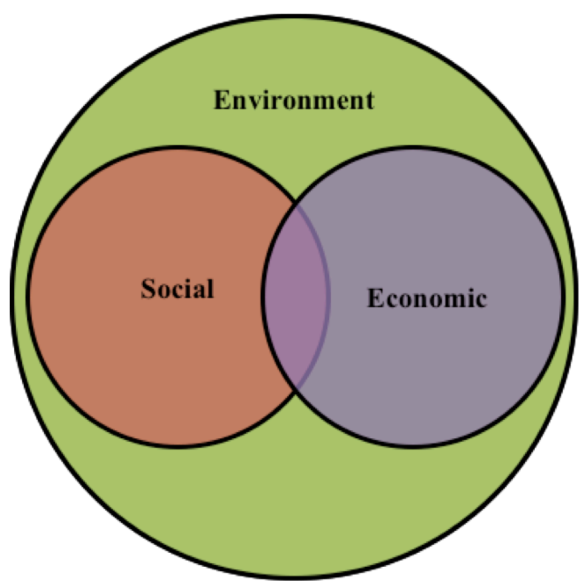

Figure 12. 3-pillar model defined by the limits of environmental sustainability.

To this effect many historical examples show a shift from the stand alone three-pillar model to the environmentally constrained model of sustainability. An immediately relevant example is the establishment of "Best Management Practices (BMP's)". Similarly, the drafting and adoption of Biomass Harvesting Guidelines is a reflection of the acknowledgement that impacts to environmental health have a large effect on long-term economic and social sustainability. Each of these management directives represents a shift in a normative valuation resulting from a potentially "un-sustainable" use of forest resources.

By approaching resource management from a scientific approach with these dimensions of sustainability in mind we can make more informed and educated decision. Making more informed and conscious decisions in management highlights the importance of adaptive management. To highlight this difference, Kajikawa, 2008 states:

"Sustainability literally means the ability to sustain…The term has been used to express the state in which levels of harvest in agriculture, fisheries, and forestry are maintained within the capacity of the ecosystem, which is therefore recoverable. In that sense, sustainability means environmental sustainability – in other words sustainability of the ecosystem's function to provide us with food, fish, and other products and services. It is not the same as conservation, where the intention is to preserve the ecosystem regardless of human purpose."

It is thereby important to designate that, while not mutually exclusive, sustainability and conservation represent two very different sets of normative values, again highlighting the importance of adaptive management. To this extent BMP's represent a valuation for human providence from forest productivity. Similarly, Biomass Harvesting Guidelines reflect a value of forests beyond strictly short-term economic or social gain.

As mentioned previously Biomass Harvesting Guidelines generally recognize the following criteria as components of impacts in consideration (Evans and Perschel 2009):

- *Dead woody material* – includes percent retention recommendations of coarse/fine woody material and standing snags.
- *Wildlife and Biodiversity* – environmental impact on species composition in harvest area and with connectivity to sensitive species/ecosystems.
- *Water Quality and Riparian Zones* – environmental impact on riparian zones, wetlands, and hydrology that have connectivity to harvest area.
- *Soil Productivity* – recovery rates that affect sustainability of harvest with respect to nutrients, soil compaction, and biological material.
- *Silviculture Treatment* – implementing treatment objectives for harvest area with respect to planning, variable retention harvesting, regeneration timeline, operations, road/trail layout, re-entry, aesthetics, and post-operation treatment.
- *Disturbance Considerations* – size and type of disturbance from harvesting having a direct impact on species composition, disease/pest susceptibility, and fire/fuels management.

These guidelines represent at their core a valuation of these ecosystem services and characteristic for either their inherent value or their value to meet the needs at present, without compromising the social, economic, and environmental needs of future generations.

Site productivity is strongly governed by physical, chemical, and biological processes affected directly by management (Pritchett and Fisher, 1987). Figure 11 showed a conceptual model of how carbon and nutrients are cycled through and within an ecosystem, and represent the areas of interest in measurement as indicators of ecosystem health. Sustaining these processes for future utilization of these resources is integral in the long-term sustainability of biomass harvesting for bioenergy feedstock. An adaptive framework for application to different management objectives is necessary to attain long-term sustainability. This includes discourse and establishments of indicators to hallmark whether we are sustainably developing renewable energy sources from biomass.

The following frame outlined by Kajikawa, 2008, is a systematic approach which synthesizes the multi-faceted goals of BMP's and Biomass Harvesting Guidelines. Application of such a framework pre-emptively to biomass harvesting can in itself help assess whether we are sustaining each dimension of sustainability. The framework is outlined in such a way:

Research Core and Framework of Sustainability Science (Kajikawa, 2008):

I. Goal setting- normative goal setting.

II. Indicator setting- Targets are quantitative values of indicators for attaining the goal at a specific time or within a certain timeframe.

III. Indicator measurement- Indicators are quantitative measures selected to assess progress toward or away from a stated goal.

IV. Causal chain analysis- Complexity, vulnerability, and resilience are the key concepts to understanding and modeling a coupled human-environment system.

V. Forecasting- predictive modeling for goal setting from conception to completion

VI. Backcasting- predictive modeling for goal from completion to conception.

VII. Problem–solution chain analysis- predictive model of foreseeable problems and solutions.

This framework as applied to biomass harvesting encompasses the dimensions outlined in the three pillar models of sustainability. While the social dimension is in part reflected in our goals for biomass harvesting, it is important to also apply this framework to the social dimension of sustainability is a systematic way to assess our successes, or failures, toward social sustainability. Indicators can be applied to both economic and environmental dimensions as well, where these will serve the function of indicating whether it is economically feasible and will maximize an ecosystems ability to provide to human needs. Objectives IV-VII outline the need for adaptive management during the process of biomass harvesting.

"Goal setting is a normative process based on visions and social and political processes rather than on scientific activity per se, but it should have some rational basis" (Kajikawa, 2008). The rational basis for this is founded on the state of the science. From this information a systematic and adaptive approach needs to be taken when addressing the sustainability of biomass harvesting. This framework of management can be incorporated into BMP's and Biomass Harvesting Guidelines, and to a large degree is reflected in those recommendations. Forest harvesting operations aimed at meeting these recommendations have to the best of their ability addressed the impacts of increased harvested intensity. However, these decisions need to be made on the ground and explicitly targeted at specific management objectives. This to a large extent has gone undone, and as well to a large extent is not based in concrete knowledge of the impacts that residue removal will have. Adaptive management, analogous to silvicultural management, needs to be implemented on a site by site and case by case basis. This requires more definitive research to be done in the area of harvesting in Northern Hardwood forests to calculate the impacts of residue harvesting. While this research is needed immediately, it does not have to halt the utilization of this resource. Implementing the research framework outlined above can serve as research in itself to answer the question of how sustainable is residue harvesting. Loggers, consultants, and forest resource managers should incorporate residue removal and retention in an adaptive and prescriptive manner.

Biomass harvesting for use as a resource for biofuel feedstock has a huge potential to satisfy each dimension of sustainability. Given the current economic, social, and environmental climates, this alternative energy source used in a sustainable way has the potential to meet renewable energy standards, improve forest health, improve the socio-environmental interaction, and the socio-economic interaction. A systematic framework of research, monitoring, and oversight of biomass harvesting needs to be established. With a systematic and adaptive framework this renewable energy resource can be used as piece of the puzzle in meeting the ever increasing demand for energy while mitigating the growing problem of anthropogenic sources of greenhouse gas emissions. In balancing each dimension of sustainability in a rational way based on current science we can utilize this resource to its maximum potential. The realization of that potential can only be made through scientific research into each dimension and by satisfying all three dimensions.

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