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Wisconsin's Forestland Woody Biomass Harvesting Guidelines

Rationale for the Guidelines

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This document reviews the rationale behind Wisconsin's Forestland Woody Biomass Harvesting Guidelines. Since Wisconsin used Minnesota's Biomass Harvesting Guidelines for Forestlands as a starting point, this document also includes a listing of guidelines from Minnesota and whether Wisconsin adopted, modified or deleted the MN guidelines.

Rationale

Introduction

Traditional timber harvests generally include the cutting and removal of wood products greater than four inches diameter. Whole tree harvesting includes the cutting and removal of the entire upper portion of a tree consisting of trunk, branches, and leaves or needles. Forestland woody biomass harvesting includes the cutting and removal of both coarse and fine woody materials, such as tree trunks and branches, shrub stems and branches, and dead woody materials (standing or downed). Forest woody biomass harvesting strategies encompass whole tree harvesting, the harvest of small diameter trees, the harvest of shrubs, and the harvest of down woody debris. Such harvests can occur in stands managed following even-aged or uneven-aged silvicultural systems. The harvest of fine woody material from forests results in increased materials being removed from a site as compared to traditional timber harvesting.

The forestland woody biomass harvesting guidelines focus on the sustainable harvest of woody biomass from forested areas within the context of generally accepted forestry practices, while protecting soil, water, and biodiversity that are characteristic of sustainable forest ecosystems. The guidelines provide considerations and recommendations applicable to stand and site-level management. They are intended to facilitate operational analysis and informed decision-making regarding the harvest of fine woody material and potential impacts on other forest resources.

The guidelines are a “work-in-progress” based on best available information, and will be subject to periodic review and revision as better information becomes available. This white paper documents the scientific rationale in the areas of biodiversity, soil nutrients, soil physical properties, and water quality that led to the development of each of the guidelines.

Biodiversity

Applicable Guidelines: 1A, 2A, 3A, 4A, 5A
1B, 2B, 3B, 4B, 5B

The conservation of biodiversity has been identified to be a statewide goal (WDNR 1995, WDNR 2004). Management for biodiversity conservation often focuses on the identification and protection of specific occurrences of rare species and exceptional examples of community types (element occurrences). However, the conservation of a wide array of wildlife and plant species requires the conservation of a wide array of habitat conditions. To effectively conserve biodiversity, species, sites, and landscapes must be assessed and managed to maintain viable populations of all species and a full array of habitat conditions (e.g. forest developmental and successional stages). Landscape level planning and management is critical to the conservation of biodiversity, and to allocate resources and benefits. To conserve biodiversity at the regional and landscape levels, the extent and intensity of biomass harvests should be variable within and across landscapes.

This portion of the rationale addresses the potential impacts of woody biomass harvesting on the conservation of biodiversity within forest ecosystems, including the sustainability of wildlife, plants, endangered resources, and exceptional communities and sites. The management of forest dynamics provides the context for sustainable habitat management. Recommendations provided in the guidelines attempt to maintain or improve ecological complexity and avoid or mitigate potential negative impacts of woody biomass harvesting at the stand level.

Ecosystem condition and forest dynamics interact to create ecological complexity. Forest succession, stand development, and disturbance processes guide changes in forest community composition and ecosystem structure.

Silvicultural practices are implemented to create disturbance with the intent to manipulate stand composition and structure. Both active and passive management systems provide tools to develop ecological complexity.

The woody biomass harvesting guidelines will enable the perpetuation of some habitat elements within harvested stands. However, intensive and extensive biomass harvesting will limit ecological complexity at stand and landscape scales. To conserve biodiversity while producing wood resources, a variety of management strategies should be implemented within and across forested landscapes, including biomass harvests, traditional timber harvest, extended rotations, and passive management. The appropriate allocation of resources and management strategies can be guided by science, but is also a social issue.

Biodiversity - Specific Species, Community Types, and Site Types of Concern

Applicable Guidelines: 1B, 2B, 3B, 4B

Endangered and Threatened Species – Element Occurrences

Federal and State endangered and threatened species are, by definition, rare (WDNR 2003). Populations have been limited by environmental conditions. Often, rare species occur in specialized habitats (WDNR 2003). Modern land management has reduced available habitat for some rare species.

The conservation of rare species is fundamental to the conservation of biodiversity. The sustainability of viable populations and habitat maintenance are management concerns. Recommended conservation strategies include the identifcation, protection, and sustainable management of element occurrences of endangered and threatened species and their habitat (Crow et al. 1994, Rogers and Premo 1997, WDNR 2003, National Commission on Science for Sustainable Forestry 2007). The Wisconsin Natural Heritage Inventory (WNHI) provides a database that identifies known element occurrences (http://dnr.wi.gov/org/land/er/wlist/working_list_2006.pdf). Laws to protect rare species govern some management activities. Management guidelines are available for some species.

Most commonly, when rare species are encountered in forested habitats, passive management will be prescribed to sustain the occurrence and the habitat. Some species may tolerate or benefit from low intensity management, but additional biomass harvesting may be inappropriate. For example, in habitat occupied by American marten, forest woody biomass harvesting would not generally be recommended. A few species may require intensive community disturbance, and biomass harvests may be compatible. For example, biomass harvests may be compatible with the management of habitat for Karner blue butterfly. If woody biomass harvests are being considered for sites with known element occurrences, then consult with forestry, wildlife, and endangered resources specialists to assess species habitat requirements and to determine appropriate management activities.

Special Concern Species and Species of Greatest Conservation Need (those not listed as Federal or State endangered or threatened)

These species are limited in abundance and/or distribution, and the sustainability of viable populations is a management concern. Populations have been limited by environmental conditions. Modern land management is an environmental variable that can alter habitat availability. Habitat management is critical to the sustainable management of these species.

The conservation of a wide array of wildlife and plant species requires the conservation of a wide array of habitat conditions. Recommended conservation strategies include the identification, protection, and sustainable management of species of concern and the habitat that supports viable populations. Management guidelines are available for some species.

Depending on the species of concern, forest management strategies will be variable. Recommended disturbance can range from none (passive management), to low severity (minor habitat manipulation), to moderate severity (partial cutting with timber harvest), to severe (complete clearcut). Woody biomass harvesting probably would not be appropriate habitat manipulation for most forestland species of concern, but in some cases could be tolerated or even beneficial. Landscape composition and structure may be critical in determining potential management alternatives for individual stands and impacts on habitat management. If woody biomass harvests are being considered for sites that provide important habitat for species of concern, then consult with forestry, wildlife, and endangered resources specialists to assess species habitat requirements and to determine appropriate management activities.

Wisconsin Natural Heritage Inventory (WNHI) Forest Community Element Occurrences

WNHI element occurrences of forest community types demonstrate uncommon compositional or structural attributes (WDNR 2003). Environmental conditions, including modern disturbance regimes dominated by anthropogenic activities, have limited the development of these community conditions. Forest community element occurrences often harbor rare species and/or uncommon assemblages of species.

Recommended conservation strategies include the identification, protection, and sustainable management of forest community element occurrences (Crow et al. 1994, Rogers and Premo 1997, WDNR 2003). The Wisconsin Natural Heritage Inventory (WNHI) provides a database that identifies known element occurrences (http://dnr.wi.gov/org/land/er/wlist/working_list_2006.pdf). Management guidelines for community types can assist assessment of management alternatives.

Within forested ecosystems, community element occurrences often are forests in the later states of stand development. These old forests and old-growth forests, once predominant, have been replaced by managed forests that are maintained in early developmental stages to optimize timber growth and productivity. Old-growth forests are rare, ecologically complex, and retention of representative stands is critical to the conservation of biodiversity (Crow et al. 1994, Komonen 2003, Hammond et al. 2004, WDNR 2006, National Commission on Science for Sustainable Forestry 2007). Reserved old-growth forests can provide refugia for rare species and sources for recolonization (Niemela 1997, WDNR 2006).

Most commonly, when forest community element occurrences are identified, passive management will be prescribed to sustain the occurrence (WDNR 2003). The perpetuation of some community types will require periodic disturbance, at relatively long or short intervals, but most woody materials would be retained on site. For example, within old-growth forests, biomass harvests would not generally be recommended. The perpetuation of some rare forested community types may require severe disturbance, and in some cases biomass harvesting could be appropriate. For example, biomass harvests may be compatible with the restoration of savanna or barrens habitat. If woody biomass harvests are being considered for sites with known forest community element occurrences, then consult with forestry, wildlife, and endangered resources specialists to determine appropriate activities

Exceptional Communities and Sensitive Sites (those not listed as WNHI element occurrences)

These community types demonstrate uncommon compositional or structural attributes and are limited in abundance and/or distribution. These site types are susceptible to degradation. Uncommon community types and sensitive site types often support unusual plant and animal communities (DeGraaf et al. 1992, Rogers and Premo 1997). For example, small wet spots embedded within forests, such as seeps and vernal pools, provide specialized habitat and increased biodiversity (DeGraaf et al. 1992, Rogers and Premo 1997, WDNR 2003). Sensitive sites, such as small seeps, are susceptible to degradation from direct disturbance. Examples of exceptional community types and sensitive site types occurring within forested ecosystems are: old-growth forest, old forest, large bogs, vernal pools, seeps, cliffs, rock outcrops, ravines, and caves (WDNR 1995, Rogers and Premo 1997, WDNR 2003).

Recommended conservation strategies include the identification, protection, and sustainable management of exceptional communities and sensitive sites. Follow management guidelines if available. A commonly recommended forest management strategy for these systems is to protect from degradation and maintain a management buffer (Rogers and Premo 1997, WDNR 2003). However, depending on the community or site of concern, forest management strategies will be variable. If woody biomass harvests are being considered within or adjacent to exceptional communities or sensitive sites, then assess potential impacts and determine if woody biomass harvesting will be consistent with management to sustain these community and site types; consult with forestry, wildlife, and endangered resources specialists to determine appropriate activities.

Biodiversity – Habitat Management

Natural Disturbance Regimes and Biological Legacies

Applicable Guidelines: 1A, 2A, 3A, 4A, 5B

Over millennia, native species have adapted to utilize niches created by natural disturbance regimes and forest developmental processes. The conservation of biodiversity in managed forest landscapes probably will be most successful if a full range of similar conditions is perpetuated, and the compositional and structural disparity between managed stands and natural (unmanaged) forests is reduced (Crow et al. 1994, Christensen et al.1996, Seymour and Hunter 1999, OMNR 2002, Franklin et al. 2007, MFRC 2007, National Commission on Science for Sustainable Forestry 2007). Silvicultural systems that more closely emulate natural disturbance and stand development processes are more likely to sustain ecological complexity and biodiversity (Crow et al. 1994, Niemela 1997, Seymour and Hunter 1999, OMNR 2002, Franklin et al. 2007, MFRC 2007, National Commission on Science for Sustainable Forestry 2007).

In natural systems, severe disturbances that eliminated all trees and woody biomass were rare; usually, biological legacies were retained (Seymour and Hunter 1999, OMNR 2002, Franklin et al. 2007). Biological legacies are organisms, reproductive portions of organisms, and biologically derived structures and patterns inherited from a previous ecosystem (Helms 1998). Compositional and structural legacies typically persist in heterogeneous patterns and forms. Compositional legacies influence ecosystem function, and can include trees, understory plants, fungi, invertebrates, and other animals. For example, mycorrhizal fungi and microbial decomposers are potential compositional legacies whose nutrient cycling functions are essential in maintaining site productivity. Structural legacies, such as trees, snags, and surface organic matter (including down woody debris) also influence ecosystem function, and provide habitat for organisms. Biological legacies influence reorganization and recovery processes in post disturbance ecosystems; they can sustain functional roles and modify the post-disturbance environment (Amaranthus 1998, National Commission on Science for Sustainable Forestry 2005, Franklin et al. 2007).

Large structural legacies, such as live trees, snags, and coarse woody debris, can provide a “lifeboat” function that contributes to the conservation of biological diversity (Seymour and Hunter 1999, Franklin et al. 2007). These structures facilitate the perpetuation of some biota (plant and animal species and genotypes) on site. They perpetuate habitat for re-colonization, occupation, and dispersion (OMNR 2002, Hammond et al. 2004, Franklin et al. 2007). They can improve landscape connectivity, facilitating the movement of some organisms (OMNR 2002, Franklin et al. 2007). The retention of large trees can maintain seed sources and provide future recruitment of large snags and down coarse woody debris (Seymour and Hunter 1999).

Traditional forest management systems often create simplified ecosystems (Crow et al. 1994, Niemela 1997, Seymour and Hunter 1999, OMNR 2002, Hammond et al. 2004, Hura and Crow 2004, Woodley et al. 2006, Franklin et al. 2007). Of widespread significance, even-aged rotational harvest methods often do not include the retention of significant structural legacies that typically persisted following natural stand replacement disturbances. For these even-aged management systems, the retention of compositional and structural legacies is critical to the development and implementation of adaptive silvicultural methods that strive to integrate the conservation of biodiversity (Crow et al. 1994, Seymour and Hunter 1999, Hammond et al. 2004, Franklin et al. 2007, MFRC 2007).

In forests managed for timber production, variable retention harvesting retains biological legacies from the harvested stand for integration into the new stand to achieve ecological objectives (Helms 1998). Structural legacies selected for retention often include large reserve trees, large snags, and large down logs to provide refugia and to structurally enrich the new stand (Crow et al. 1994, Christensen et al.1996, Fridman and Walheim 2000, OMNR 2002, Hammond et al. 2004, Hyvarinen et al. 2006, Franklin et al. 2007, MFRC 2007). Large structures take a long time to develop and are not easily replaced. Important characteristics of reserve trees selected as biological legacies are: species diversity; size class representation, especially very large trees; tree health, including both healthy and decadent trees; and heterogeneous distribution as dispersed individuals and aggregated patches. Reserve trees intended for future harvest provide biological legacies as living (usually large) trees. Reserve trees can be allowed to persist, developing into large trees, snags, and eventually large coarse woody debris. Within stands where fine woody materials will be harvested, Astrom et al. (2005) suggest that leaving more tree clusters and creating and protecting large woody debris would be especially important and would improve habitat for organisms.

Silvicultural practices are designed to manipulate vegetation to achieve management objectives (Smith 1962, WDNR 1990, Nyland 1996). At its foundation, silviculture is based on understanding and working with ecological processes. Most natural disturbance regimes and events retain compositional and structural legacies in heterogeneous patterns and create ecological complexity. Adaptive silvicultural methods that develop and maintain biological legacies in managed stands can facilitate the promotion of stand level heterogeneity, compositional and structural complexity, and the conservation of biological diversity.

Habitat elements – composition and structure

Applicable Guidelines: 1A, 2A, 3A, 4A, 5B

Guidelines for sustainable forest management include considerations and recommendations for biodiversity and wildlife management. The Wisconsin Forest Management Guidelines (WDNR 2003) identifies the importance of retaining leave trees, snags, coarse woody debris and slash, conifers, and mast trees for wildlife as part of sustainable forestry operations. The Silviculture Handbook (WDNR 1990) offers recommendations and quantitative guidelines for the retention of reserve trees, wildlife trees, and snags, and offers management considerations pertaining to wildlife and biodiversity. At the stand level, vegetation composition and structure provide habitat for organisms, and compositional and structural diversity generally increases ecological complexity and niche availability.

Large trees

Large trees are comparatively large for the stand and site. In general, large trees are at least 12 inches DBH, and ideally at least 18 inches DBH; very large trees are at least 29 inches DBH. Comparatively large trees tend to be comparatively old trees. Large trees (>18 inches diameter), and consequently large snags and large woody debris, currently are uncommon within forests in Wisconsin, because of historic forest exploitation and more recent forest management strategies.

Large trees provide habitat used by many animals and some plants. They provide nesting sites and high exposed perches for birds, such as hawks, bald eagle, osprey, herons, flycatchers, ravens, and turkey vultures (DeGraaf et al. 1992, WDNR 2003, MFRC 2005). Large trees can become large cavity trees, large snags, and large coarse woody debris. The best wildlife trees are large, vigorous trees that are long-lived and strong compartmentalizers; they have the potential to persist for a long time (centuries) and provide a succession of structural wildlife benefits (Degraaf and Shigo 1985, DeGraaf et al. 1992). The retention of large trees is important to the conservation of biodiversity (Crow et al. 1994, Niemela 1997, Rogers and Premo 1997, McGee et al. 1999, National Commission on Science for Sustainable Forestry 2007).

Mast trees

Mast provides food consumed by many species of animals (WDNR 2003). Both trees and shrubs produce mast. Retaining a variety of mast producing species can provide an abundant and diverse source of food.

Cavity (den) trees

Cavity trees are partially hollow living trees used by many wildlife species. Cavity trees provide wildlife with sites to den, nest, rear young, feed, store food, and escape from predators and inclement weather (Degraaf and Shigo 1985, DeGraaf et al. 1992, Bunnell et al. 2002, McComb 2007). Large cavity trees are a keystone to forest wildlife management.

Although both large and small cavity trees provide useful habitat, large diameter cavity trees are particularly important (Degraaf and Shigo 1985, DeGraaf et al. 1992, Goodburn and Lorimer 1998, McComb 2007). In general, the larger the cavity tree, the better for wildlife habitat. Large cavity trees can host more kinds of wildlife, including large bodied animals, such as Pileated woodpecker, American marten, fisher, raccoon, porcupine, and even bear. Useful cavity trees are a minimum of 6 inches DBH, and potential benefits increase for trees 12 inches DBH and larger. Large cavity trees, 18 inches DBH and larger, provide the greatest potential benefits (Degraaf and Shigo 1985, DeGraaf et al. 1992). Very large cavity trees, over 29 inches dbh, provide exceptional benefits, but are rare in most current forests; developing some of these very large cavity trees will provide structural diversity and improve wildlife habitat. Large cavity trees can require many years to develop, can persist for many years, and then can provide important wildlife habitat as large snags and large coarse woody debris; development and decay can require centuries.

Cavity tree retention and management can enable improved wildlife habitat. Cavity trees provide critical wildlife habitat throughout all stages of forest stand development and succession. Retaining cavity trees through even-aged rotations and within plantations would improve habitat and help maintain populations of some wildlife species that preferentially utilize cavity trees, such as cavity-dependent birds (Woodley et al 2006, McComb 2007). The retention of cavity trees is important to the conservation of biodiversity (Degraaf and Shigo 1985, DeGraaf et al. 1992, Bunnell et al. 2002, Woodley et al 2006, McComb 2007).

Tree retention – reserve trees and wildlife trees

Reserve trees retained through even-aged rotations provide compositional and structural legacies. Reserve trees and wildlife trees (large vigorous trees, mast trees, large cavity trees) provide habitat for organisms. Therefore, during forest woody biomass harvest operations, retain reserve trees and wildlife trees as patches, groups, and individuals. Patch retention (0.1-2.0 acres) is generally preferred, but some scattered trees should also be retained. Patch retention will maintain structure and composition, including species diversity, size classes, vertical structure, snags, coarse woody debris, fine woody debris, shrubs, herbs, and forest floor. Scattered small groups and individuals also provide benefits and can be used to create feathered edges to ameliorate edge effects. Retention of large diameter trees (at least 12 inches, and preferably greater than 18 inches in diameter) is recommended. Tree species diversity and conifer retention are important elements of tree retention for habitat diversity.

Actual amounts to retain depend on management goals, site, forest type, and stand condition. General wildlife management guides often recommend retain as much as possible. Management for specific wildlife species can run the gamut of recommended retention levels. Studies of historic, remnant, and current forests can identify ranges of representation and variability for some forest types and site types. Minimum tree retention levels recommended in these general guidelines are for stands managed for wood production, and specifically for forest woody biomass harvesting. The goal is to retain at least a minimal amount of specific habitat structure, and to maintain some ecological complexity in most stands to benefit a broad array of plants and animals.

For comparison, general tree and snag retention guidelines developed by several forest management agencies within the western Great Lakes region are summarized:

Minnesota MFRC guidelines for all timber harvests (MFRC 2005):

- Live tree and snag retention – even-aged rotations
  - Preferred - retain >5% of area in clumps >1/4 acre
  - Alternative – retain 6-12 individual trees per acre (3-15+ depending on variables)
  - Leave tree size: >6 inches dbh, 50% >12 inches, and 1-2 trees per acre >18 inches
  - Leave tree condition - vigorous trees, potential cavity trees, cavity trees
  - Retain all snags, except for safety or aesthetic reasons
- Retention during other harvests
  - Retain at least 6 potential cavity trees, cavity trees, and snags per acre

Michigan DNR guidelines for state-owned lands (MIDNR 2006):

- For all timber harvests (exceptions must be documented):
  - Even-aged rotations – maintain 3-10% of area in live tree retention
  - Even-aged thinnings and Uneven-aged – 3-10% of basal area in live tree retention
  - Special areas (e.g. inoperable sites or sensitive habitat) – contribute but don't fully satisfy retention requirements
- Live tree retention:
  - Large super-canopy trees – at least 1 tree per 10 acres
  - Mast trees – at least 3 trees per acre >10 inches dbh if feasible
  - Cavity trees – at least 3 trees per acre >10 inches dbh if feasible
- Snags – retain all snags not a safety risk

Ontario – OMNR guidelines for Crown timberlands (OMNR 2002):

- Even-aged rotations – retain all of the following:
  - Retain 2-8% of stand area in insular patches
    - Minimum patch size 0.6 acres
    - Not available for future harvest
  - Retain 8-28% of stand area in peninsular patches
    - 50% available for future harvest
  - Retain at least 10 well-spaced individual live trees and snags per acre
    - Include at least 2.4 large diameter cavity/potential cavity trees per acre

Chequamegon-Nicolet National Forest (USDA FS 2004):

- Even-aged stands
  - reserve 2-5 trees per acre >11 inches dbh
  - reserve islands/clumps (regeneration harvests) that total up to ½ acre for every 10 acres managed (5%)
  - emphasize tree diversity, cover, and mast
- Uneven-aged stands – reserve 3-7 trees per acre >11 inches dbh
- Retain all snags and live den trees up to 10 per acre – emphasize large individuals
- Some special management units have higher retention guidelines.

The development and retention of large trees, both vigorous and decadent individuals, provides habitat and is important to the conservation of biodiversity. Large trees can eventually be harvested, or retained to complete their lifespan. The recruitment of large snags and large coarse woody debris requires the retention of some large trees through senescence and death.

Snags

Snags are standing dead trees, sometimes termed "critter condos." They provide habitat for over 70 kinds of mammals, birds, reptiles, and amphibians in Wisconsin (WDNR 1995, WDNR 2003). In addition, snags provide habitat for many insects, other invertebrates, and wood-decaying fungi. Abundant invertebrates provide a food source for larger animals. Snags provide wildlife with sites to den, nest, rear young, feed, store food, perch, preen, court, and escape from predators and inclement weather (Degraaf and Shigo 1985, WDNR 1995, Goodburn and Lorimer 1998, McGee et al. 1999, Bunnell et al. 2002, WDNR 2003, MFRC 2005, McComb 2007). Snags provide structural diversity and critical wildlife habitat (Crow et al. 1994, McGee et al. 1999, Hura and Crow 2004, Woodley et al 2006).

Although both large and small snags provide useful habitat, large snags are particularly important (WDNR 1995, Goodburn and Lorimer 1998, Bunnell et al. 2002, Hammond et al. 2004, McComb 2007). Large snags can host more kinds of wildlife, including large bodied animals, such as Pileated woodpecker, American marten, raccoon, and bear. Large snags provide the most potential benefits if they are at least 15 inches dbh or larger (WDNR 1995). Large snags result from the death of large trees which require many years to develop.

Snag retention and management can enable improved wildlife habitat (Degraaf and Shigo 1985, WDNR 1995, WDNR 2003, Woodley et al 2006, McComb 2007). Retaining snags through even-aged rotations and within plantations would improve habitat and help maintain populations of some wildlife species that preferentially utilize snags, such as cavity-dependent birds (Woodley et al 2006, McComb 2007). The retention of snags is important to the conservation of biodiversity (Degraaf and Shigo 1985, Crow et al. 1994, WDNR 1995, Rogers and Premo 1997, Seymour and Hunter 1999, Fridman and Walheim 2000, Bunnell et al. 2002, WDNR 2003, Hammond et al. 2004, Hura and Crow 2004, Astrom et al. 2005, National Commission on Science for Sustainable Forestry 2007, Woodley et al 2006, Franklin et al. 2007, McComb 2007).

Snags provide critical habitat for organisms. Therefore, snags should be retained in situ to the extent possible; if determined to be a threat to human safety, then snags can be dropped and retained as coarse woody debris. Future snags will be supplied by the retention of reserve trees and wildlife trees, as well as natural stand development processes.

Coarse woody debris

Coarse woody debris (CWD) is dead woody material, greater than or equal to 4 inches diameter inside bark at small end, on the ground in forest stands or in streams. Down coarse woody debris provides habitat for many animals and plants (DeGraaf et al. 1992, Crow et al. 1994, WDNR 1995, McGee et al. 1999, Tyrrell and Crow 1994, Goodburn and Lorimer 1998, Fridman and Walheim 2000, Bunnell et al. 2002, Komonen 2003, WDNR 2003, Norden et al. 2004, Hammond et al. 2004, Hura and Crow 2004, MFRC 2005, McComb 2007). Animals that utilize down coarse woody debris include: bear, bobcat, foxes, otter, marten, weasels, ermine, mink, skunk, opossum, chipmunks, mice, voles, shrews, moles, grouse, wrens, warblers, ducks, snakes, turtles, salamanders, newts, and frogs (DeGraaf et al. 1992, WDNR 1995, Demaynadier and Hunter 1998, Herbeck and Larsen 1999, Bunnell et al. 2002, WDNR 2003, McComb 2007). In addition, coarse woody debris provides critical habitat for many insects (e.g. saproxylic beetles), other invertebrates, and wood-decaying fungi, including rare species (Crow et al. 1994. Niemela 1997, Bunnell et al. 2002, Komonen 2003, Gunnarsson et al. 2004, Hammond et al. 2004, Norden et al. 2004, Hyvarinen et al. 2006).

Wildlife populations can be limited where coarse woody debris is depauperate (Goodburn and Lorimer 1998, Bunnell et al. 2002, Hammond et al. 2004). In Eastern hardwood forests, small coarse woody debris is abundant, but larger woody debris, more than 13 inches in diameter, generally is lacking (Goodburn and Lorimer 1998, McGee et al. 1999, Hura and Crow 2004, Woodall et al. 2007). However, structurally diverse large diameter coarse woody debris provides a wide range of substrates and microhabitats, and the greatest array of benefits to a diverse array of wildlife species (Goodburn and Lorimer 1998, Bunnell et al. 2002, Hammond et al. 2004, Hura and Crow 2004, McComb 2007). To increase the representation of large diameter down coarse woody debris in the forest, it is necessary that large trees, snags, and downed wood be retained during timber harvesting operations (Crow et al. 1994, Fridman and Walheim 2000, Bunnell et al. 2002, McComb 2007). The retention of large coarse woody debris is important to the conservation of biodiversity (Degraaf and Shigo 1985, DeGraaf et al. 1992, Crow et al. 1994, WDNR 1995, Niemela 1997, Rogers and Premo 1997, Seymour and Hunter 1999, Fridman and

Walheim 2000, Bunnell et al. 2002, WDNR 2003, Hammond et al. 2004, Hura and Crow 2004, Astrom et al. 2005, National Commission on Science for Sustainable Forestry 2007, Hyvarinen et al. 2006, Franklin et al. 2007, McComb 2007).

Coarse woody debris provides critical habitat for organisms. Therefore, current coarse woody debris should be retained in situ to the extent possible. Future coarse woody debris will be supplied by the retention of reserve trees, wildlife trees, and snags, as well as natural stand development processes. To increase the representation of large diameter coarse woody debris, it will be necessary to retain some trees to grow to large sizes and allow them to develop into large snags and eventually large downed woody debris.

<u>Fine woody debris</u>

Fine woody debris (FWD) is dead woody material, less than 4 inches diameter inside bark at large end, on the ground in forest stands or in streams. For the conservation of biodiversity, the effects of removing fine woody debris during biomass harvests are poorly understood (Gunnarsson et al. 2004, MFRC 2007). It has been suggested that fine woody materials do not provide critical wildlife habitat, and, compared to coarse woody debris, have less ecological value, because of rapid decomposition (Fraver et al. 2002, Hura and Crow 2004). However, slash can moderate the environment at and near the soil surface; it can provide shade, slow wind, moderate temperatures, and reduce desiccation (McInnis and Roberts 1994, Astrom et al 2005, Hacker 2005). Slash retained following clearcutting can affect microhabitat complexity and provide habitat for animals and plants (Ecke et al. 2002, Gunnarsson et al. 2004, Norden et al. 2004, Astrom et al. 2005).

There are few studies documenting the impacts of fine woody debris removal on animals. For small mammals, Ecke et al. (2002) concluded that the retention of logging residues can increase structural heterogeneity, cover, shelter, and food, and positively influence species richness. Manning and Edge (2005) conclude that the retention of FWD benefits mice and vole populations. Gunnarsson et al. (2004) stated that complex environments generally harbor more diverse arthropod faunas than do simpler ones, and concluded that extensive slash removal in clearcuts can lead to impoverished species richness of Coleoptera (beetles) at a local scale.

Creating slash piles by piling logging residues has been a recommended wildlife management strategy, particularly for small mammals. Slash piles provide structure used for habitat by some species. Wildlife known to use slash piles include: bear, weasels, ermine, skunks, opossum, cottontails, chipmunks, voles, mice, wrens, snakes, turtles, frogs, salamanders, newts, and beetles (DeGraaf et al. 1992, WDNR 1995, Gunnarsson et al. 2004, Manning and Edge 2005).

Several studies have examined the impacts of fine woody debris removal on tree regeneration. McInnis and Roberts (1994) identified few impacts on tree regeneration following clearcuts; slash removal appeared to have minor positive impacts on hardwood regeneration and minor negative impacts on conifer regeneration. Other studies have identified variable impacts of slash removal on tree regeneration composition, survival, and growth caused by impacts on surface environment, soil compaction, and nutrient availability (Hacker 2005).

Several studies have examined the impacts of fine woody debris removal on plants. Olsson and Staaf (1995) found small changes that decreased over time, in vascular plant composition and abundance following clearcutting and slash removal compared to sites where logging residue was retained. Astrom et al. (2005) stated that impacts on vascular plants are highly variable, and, in general, the vascular plant community is not seriously affected, even though minor changes may occur; however, the species richness of mosses and liverworts can be significantly reduced by slash harvests in clearcuts. Norden et al. (2004) concluded that fine woody debris is important for diversity of wood-inhabiting fungi, especially in managed forests, and that whole tree harvesting can negatively affect fungal diversity. Brakenhielm and Liu (1998) concluded that whole tree harvesting in clearcuts can impact plant species composition, including vascular plants, mosses, and lichens on dry, nutrient poor sites (by reducing nutrient availability). In summary, the removal of fine woody debris has been associated with negative impacts on mosses, liverworts, and fungi, and impacts on plants may be greatest on dry, nutrient poor sites.

Deer can have significant impacts on forest community composition. Browsing of tree seedlings and herbs can directly impact plant composition, and alter habitat for wildlife. Impacts of deer browsing are highly variable depending on seasonal deer populations and habits, and landscape factors. Under certain conditions, fine woody debris may act as a barrier and inhibit localized browsing of seedlings and herbs.

Fine woody debris can influence nutrient availability (see Soil Nutrients section), and thereby cause potential cascading effects that impact animal and plant communities. For example, as previously summarized, Brakenhielm and Liu (1998) concluded that whole tree harvesting in clearcuts can reduce nutrient availability on dry, nutrient poor sites and thereby impact plant species composition. Hamburger et al. (2003) correlated soil calcium supply with the abundance of snails (shells contain calcium). Hames et al. (2006) correlated soil calcium supply with the abundance of calcium rich invertebrates, such as snails, millipedes, and centipedes; furthermore, the presence of Wood Thrush during the breeding season was correlated to the abundance of these calcium-rich invertebrate prey species. Bailey et al. (2004) suggest that where calcium is limiting, sugar maple undergoes nutrient stress and becomes predisposed to compounding stressors and decline.

Forest management recommendations pertaining to biodiversity and logging residues are varied. Most recommendations for the management of down woody debris emphasize the importance of large diameter coarse woody debris. Astrom et al. (2005) clarify that slash harvesting is an intensification of forest management that reduces the woody substrate and alters the surface environment (reducing shelter). To mitigate potential negative impacts, they recommend the retention of clustered trees with intact undergrowth, the protection and creation of coarse woody debris, and the preservation of old forest stands. Gunnarsson et al. (2004) indicates that slash heaps left on site may provide important habitat for ground-active beetles. Ecke et al. (2002) recommends that logging debris be retained to provide habitat for small mammals. Brakenhielm and Liu (1998) recommend slash retention and spreading on dry, nutrient poor sites. In Sweden, for clearcuts, it is recommended to retain 20% of slash following stand harvest (Gunnarsson et al. 2004). In Finland, it is recommended to retain 30% of logging residue for biodiversity management (MFRC 2007). In Minnesota, biomass harvesting guidelines recommend the retention of about 33% of the fine woody debris on site (MFRC 2007). In Ontario, biodiversity considerations are addressed by significant retention of reserve trees, snags, and coarse woody debris; logging slash retention is recommended (avoid full-tree harvesting) on coarse textured soils and shallow soils to conserve nutrients (OMNR 2002). Clearly, potential impacts of fine woody debris removal on the conservation of biodiversity are variable and often uncertain, and recommended management techniques to avoid or mitigate negative impacts are variable.

Knowledge of typical amounts and ranges of fine woody debris in pre-historical, historical, and current forests across forest types and site types could provide a guide to help develop appropriate retention levels to satisfy variable forest management goals. Unfortunately, few studies and little data address this information need. The historic range of variability will be difficult to estimate, because of altered disturbance regimes and different factors causing mortality (Wilson and McComb 2005).

Recent Forest Inventory and Analysis (FIA) data can be used to estimate amounts of FWD in current forests, but sampling intensity is low, so data stratification is limited. For FIA sampling and analysis, fine woody materials are defined as down woody material less than 3 inches diameter at transect intersection. Chojnacky et al. (2004) estimate that there is an average of 3 tons per acre of fine woody materials in eastern forests, including Wisconsin. An independent analysis of recent data gathered in Wisconsin reinforces this average estimate, although there is a large standard deviation. This same analysis estimates an average crown weight of 13 tons per acre.

For these biomass harvesting guidelines, fine woody debris will be retained in reserve patches and will accumulate as stands develop. The necessity of retaining additional fine woody debris on site following harvest for biodiversity conservation is uncertain; however, the precautionary principle would indicate that some additional retention is appropriate. A logical retention guideline may be to retain current average amounts of FWD, and a little extra to prolong associated benefits (biodiversity and nutrients) until new materials begin to accumulate in significant quantities. Therefore, the current guidelines recommend the retention of approximately 4 tons per acre. The source of materials retained would typically come form a mix of FWD already present and fine woody materials cut during harvest operations. On average, 4 tons/acre would represent about 30% of crown weight in a typical Wisconsin forest, but could often vary from 20-50%, depending on forest type and stand conditions.

Shrubs and small diameter trees (understory brush)
Retaining shrubs and small diameter trees has often been a recommended wildlife management strategy (DeGraaf et al. 1992, WDNR 1995). Dense brush provides cover for some wildlife species, and the lack of brush may limit some populations (DeGraaf et al. 1992). Animals that commonly use shrubby habitat include: white-tailed deer, bear, fox, bobcat, many small mammal species, ruffed grouse, wild turkey, American woodcock, flycatchers, wrens, thrushes, vireos, and warblers (DeGraaf et al. 1992). Shrub and small tree development contribute to horizontal and vertical diversity, and thereby habitat structure (DeGraaf et al. 1992). Small trees and shrubs will be retained in reserve patches and in stands where these materials are not harvested.

Non-woody biomass
Non-woody biomass represents most of the biodiversity in the forest and is critical to the conservation of biodiversity. These guidelines pertain only to the harvest of woody biomass. Non-woody biomass, including the forest litter layer (mostly non-woody), will be retained.

Biodiversity – Salvage Operations

Applicable Guidelines: 5B

Severe natural disturbances, such as tornados and crown fires, alter forest structure, but natural processes and functions are not significantly disrupted (Foster and Orwig 2006). Biological legacies remaining following disturbance influence reorganization and recovery processes; they can sustain functional roles and modify the post-disturbance environment (Amaranthus 1998, National Commission on Science for Sustainable Forestry 2005, Franklin et al. 2007). The structures produced by severe natural disturbances are important to ecosystem processes and the conservation of biodiversity (Foster and Orwig 2006).

Salvage harvests are implemented to achieve economic returns. Often, salvage harvests do not retain significant structural legacies (Foster and Orwig 2006). The retention of compositional and structural legacies is critical to the development and implementation of adaptive silvicultural methods that strive to integrate the conservation of biodiversity (Crow et al. 1994, Seymour and Hunter 1999, Hammond et al. 2004, Franklin et al. 2007, MFRC 2007). There are potential ecological benefits by foregoing some salvage operations, because intensive salvage logging can alter ecosystem processes (Foster and Orwig 2006). Therefore, for the conservation of biodiversity, leave some potential salvage sales, or portions thereof, unharvested (Crow et al. 1994, Bunnell et al. 2002).

Biodiversity – Roads and Landings

Applicable Guidelines: 5A

Roads and landings can provide barriers to the movement of some species, avenues of invasion for some undesirable species, and access for increased anthropogenic disturbance. For the conservation of biodiversity, minimize, to the extent feasible, the establishment of roads and landing, and close roads when harvesting is completed. (Crow et al. 1994).

Soil Nutrients

Applicable Guidelines: 2A, 3A, 6B, 7B, 8B. The Soil Nutrients section summarizes information from scientific literature that addresses the roles and functions of soil organic matter, carbon, and mineral nutrients, as well as nutrient cycling processes and effects of forest harvest.

Rationale

Sustainable forest management has been defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs. Maintaining site productivity is essential to sustainable forest management over the long term. A portion of a site's nutrients are inevitably removed when trees are harvested, and concerns about effects of these removals on forest productivity have appeared in the scientific literature since the 1950's (Rennie 1955). Amounts of nutrients removed vary by species, site, stand age, rotation length (or frequency of entry in partial harvests), and type of harvest. Biomass harvests remove more nutrients than bole-only harvests. For biomass harvest guidelines, it is important to assess nutrient removals and attempt to predict consequences for short and long-term forest productivity and sustainability.

Several review papers summarize information about site nutrients, nutrient cycling, availability to trees, and forest harvest effects (Rennie 1955, Boyle et al. 1973, Vitousek and Reiners 1975, Hornbeck 1977, Likens et al. 1978, Malkonen 1976, Morrison and Foster 1979, Federer et al. 1989, Attiwill and Adams 1993, Grigal 2000, Hacker 2005). General conclusions are that inputs of total nitrogen (N), and sulfur (S) from atmospheric deposition are of sufficient quantity, but available forms of these nutrients are limited and could potentially be removed through harvesting in amounts that could affect a regenerating forest; also, excess N inputs could contribute to leaching of cations (Boyle et al 1973, Grigal 2000, Bockheim and Crowley 2002). Phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg) are also of concern, and on some sites estimated inputs are not sufficient to balance removals. Available forms of P are also a concern, and the biological role of root exudates and mycorrhizal associations in solubilizing P compounds is paramount (Attiwill and Adams 1993), indicating the importance of retaining biological legacies. Most reviews cite Ca as the element most likely to be depleted by harvesting. However, the consequences of these changes in nutrient status have not been studied sufficiently, largely because current methods of estimating nutrient inputs are inadequate, and ultimate effects on forest productivity are unclear (Grigal 2000). There are no studies that look at changes in forest productivity related to nutrient removals over more than a few decades, so it is not possible to say with any certainty what the long-term effects will be.

The nutrient content of forest trees, and of tree components (e.g. foliage, branches, bole, bole bark, roots), is important to our estimates of harvest removals. There have been several studies in the Lake States that examined nutrient amounts in trees, and similar studies have been conducted in the northeast U.S. However, the body of work is not exhaustive. The nutrient content of most tree species has been evaluated in a number of studies (Young and Guinn 1966, Hornbeck 1977 and 1986, MacLean and Wein 1977, Morrison and Foster 1979, Freedman et al. 1981, Johnson et al. 1982, Perala and Alban 1982, Silkworth and Grigal 1982, Hornbeck and Kropelin 1983, Weetman and Algar 1983, Pastor and Bockheim 1984, Smith et al. 1986, Tritton et al. 1987, Alban and Perala 1990, Morrison 1990, Rutkowski and Stottlemyer 1993, Hubbard Brook Interactive Biomass Program online), but for some species (e.g. white pine) has not been reported. Some studies provide data as elemental concentrations in tree tissues rather than measures in weight per unit area, while others report aboveground nutrient content as a total rather than by component; biomass equations must be used to convert these data to common area-based measures. There are few studies that report actual data on changes in nutrient content as trees age, or on site-related differences, sufficient to provide the basis for calculations of nutrient budgets broken down by age or site. Nearly all the descriptive studies of tree nutrient content were conducted in the 1970's and 1980's, and it is possible that environmental conditions have changed since then. Data from all the published studies we could locate, in addition to some unpublished research data, are compiled in Appendix 3.

The relatively small number of samples when the data are broken down by individual tree species or cover types and sites makes uncertainty a problem in estimates of nutrient content. Further uncertainty is introduced by the use of biomass equations to estimate weight of tree components. While there are an ample number of biomass equations available for species of interest (see, for example, Ter- Mikaelian and Korzukhin 1997) the use of biomass equations is invariably a source of uncertainty because they are not developed specifically for site conditions at the sampled location. Generalizing the results across a variety of sites and a range of stand ages makes the estimates even more uncertain. When nutrient content data are used in calculations of total nutrient budgets, additional uncertainty is incorporated in estimates of nutrient inputs from atmospheric deposition, nitrogen fixation, and mineral weathering, and also in the actual amount of woody biomass removed in timber harvests. Thus, the scientific basis for estimating nutrient losses in timber harvest is incomplete and inexact. Additional research is urgently needed.

Carbon storage, sequestration, and release to the atmosphere

Carbon storage in organic material on forested sites is a consideration in limiting CO_2 release to the atmosphere. Forest carbon pools are affected by successional status, rate of net ecosystem production, and time since disturbance. Stored carbon pool sizes generally increase with forest age (Pregitzer and Euskirchen 2004). Forests release carbon to the atmosphere for some period after a disturbance; for clearcut harvests, stands can be a carbon source for 6-39 years depending on forest type and location. An aspen-dominated forest at Pellston, MI, was a carbon source for only six years (Gough et al. 2007). After this initial period of carbon loss, the amount of stored carbon increases to a maximum as succession continues, and then levels off or declines slightly in mature stands.

Factors that impact site productivity, such as decreased soil fertility or other stressors, or loss of productive area to permanent roads or landings, can contribute to reduced potential of sites to store carbon. Maintaining site quality is important in ensuring that forests continue to store carbon at their maximum capacity. There is experimental evidence that Lake States forests, due to wide-scale clearcutting and slash fires in the late 19th and early 20th centuries, have lost some ability to store carbon because of the replacement of pine and hemlock-hardwood forests with aspen, changes in soil nutrition due to reduction of the forest litter layer, and changes in disturbance frequency and intensity (Gough et al. 2007).

It has been hypothesized that increases in CO_2 in the atmosphere will result in increased forest growth rates and increased rates of carbon capture that will lead to larger amounts of stored carbon in forests. However, models predict that many native tree species will not be able to survive in Wisconsin a hundred years hence, and that net growth will be slowed by a combination of extreme weather events, changes in insects and diseases, and the negative impacts of increasing levels of ozone (Karnosky et al. 2007; Lee Frelich cited in Benson 2006; Scheller and Mladenoff 2005).

There are questions about whether biomass harvests have a positive or negative effect on global and site-level carbon balances. Removing biomass from a forest removes carbon and decreases the site carbon pool; carbon re-accrues on the site as the forest regrows, and the site may or may not eventually store the same amount of carbon as it did prior to harvest. At a global scale, if harvested materials are utilized in a process that captures and stores carbon, the activity may not immediately release carbon dioxide (CO_2) to the atmosphere and can be a net benefit to global atmospheric carbon balances, at least in the short term.

"When a forest is harvested, some carbon is immediately released to the atmosphere via the logging operation or milling process (about one-half or two-thirds is emitted at or near the time of harvest, depending on the product and region), but some is tied up in wood products for a number of years" (EPA 2005). Howard et al. (2004) describe the results of a case study of a clearcut in Alberta, where carbon fate was measured after a bole-only clearcut. Of the carbon harvested, 16% was directly emitted as CO_2 during processing, 17% was emitted in biomass burning at the mill, and the remainder was split among lumber, pulp, and landfill pools. Approximately 37-56% of the C was thought to remain in storage long-term (more than 100 years) in products and landfills.

Wood products have variable periods of use; short-lived products (e.g., paper) release their carbon more rapidly than long-lived products (e.g., housing lumber). No complete life cycle analyses have demonstrated that there is a net storage of carbon in wood products from cradle to grave (Gower 2003). Carbon is returned to the atmosphere when wood products are incinerated, or slowly decomposed in landfills in an anaerobic process that releases 50-60% of carbon as methane (CH_4). Methane is a greenhouse gas (GHG) that is 21 to 25 times more potent in terms of heat absorption than CO_2 (EPA 2005, Skog and Nicholson 2000), so even though wood products may never completely decompose in landfills, the effect of methane release can be 40% to 500% as much as if the wood product was incinerated and released its carbon as CO_2 (calculations based on data in Skog and Nicholson 2000). In landfills that burn methane, the carbon is converted to CO_2; Skog and Nicholson (2000) stated that 15% of landfills burn methane, and more are expected to do so in the future.

A report from Australia used GHG emission factors calculated as follows: "if one tonne of paper and paper board is disposed of to landfill, it will generate 2.5 tonnes of carbon dioxide equivalent greenhouse gas emissions. This is based on the fact that paper and paper board has a default degradable organic carbon (DOC) content of 40 per cent, half of which is assumed to produce landfill gas, which contains approximately 50 per cent methane, a global warming potential 21 times as much as carbon dioxide" (Warnken ISE 2007). Wood had an emission factor of 3.2, according to this report. There is not yet general agreement on how landfilled wood products will be dealt with in carbon accounting systems.

If biomass is utilized for energy without carbon capture technology, CO_2 is released immediately and has a negative effect on atmospheric carbon. By comparison, if woody biomass is left on-site and decomposes, a portion of the carbon is released to the atmosphere over 6-39 years (Gough et al. 2007); meanwhile, the carbon cycles within the soil and forest floor carbon pools and provides a food source for organisms that carry out ecosystem functions including nutrient cycling. Carbon from plant material is important to ecosystem function because it is the basis for sustenance of all faunal species and fungi.

The temporal aspects of carbon release and capture are important; when older forests (representing a large quantity of stored carbon) are harvested and replaced with fast-growing young forests (representing a faster rate of carbon capture or sequestration), a pulse of carbon can be released to the atmosphere that may take more than a hundred years to recapture (Harmon et al. 1990). The release of carbon that occurs when older forests are harvested is due to decomposition or incineration of logging and milling residues, and sometimes the incineration of harvested woody biomass, as well as accelerated decomposition of forest litter on the harvested site. Even though the regenerating forest grows rapidly, it takes some time for an equivalent amount of carbon to be recaptured on the site. Given the high levels of atmospheric CO_2, it has been suggested that maintaining the currently stored pools of carbon in forests and fossil fuels could help alleviate potential peak concentrations of atmospheric CO_2.

Forest litter layer attributes and processes

The forest litter layer, or forest floor, is an important ecosystem component where most organic material is decomposed and nutrient cycling occurs. The forest litter layer and down woody debris are also important in maintaining soil temperature, aeration, and limiting moisture loss (Powers et al. 2005), providing a suitable seedbed for germination and establishment of trees and other plants, and cushioning the soil from equipment compaction and raindrop impact, and a site for microbial activity (Grigal and Vance 2000). Organic material moves from the litter layer into mineral soil, where it performs valuable functions in water retention, cation storage and exchange (especially important in forest soils which often lack clay), and mineral weathering (Grigal and Vance 2000).

The forest litter layer consists of different zones, the topmost being made up of undecomposed plant material, the middle being partially decomposed, and the lower stratum consisting of fully decomposed material such that plant parts are not distinguishable. The weight of the litter layer varies depending on geographic location, drainage, and forest composition. In New Hampshire, the average weight of the forest floor in several studies ranged from 41,755 lbs/acre to 71,400 lbs/acre (Gosz et al. 1976, Covington 1981, Federer 1984). In northeast lower Michigan, forest floor weights of oak and northern hardwood stands averaged 13,038 lbs/acre; this figure does not include the weight of any undecomposed woody material (Padley 1989). In old-growth forest in western upper Michigan (Sylvania) the forest floor under hemlock weighed 25,873 lbs/acre and under sugar maple weighed 19,628 lbs/acre, including twigs up to 1 cm in diameter (Campbell and Gower 2000). Forest floor weights (it is not known whether these values included woody debris) for sites in northern Wisconsin and western upper Michigan were 45,947 lbs/acre in northern hardwoods and 50,943 lbs/acre in hemlock, with no significant differences between old-growth and managed stands (Bockheim 1997). Old-growth sugar maple stands in Ontario had forest floor masses of 26,706 lbs/acre (Morrison 1990). Forest floors typically accumulate greater weights under conifers than under deciduous species (Grigal and Vance 2000). At Oak Ridge, TN, the litter layer of a tulip poplar stand weighed 8,251 lbs/acre (Edwards and Harris 1977). Forest floor biomass estimates for the eastern U.S. were calculated from FIA plot data (Chojnacky et al. 2004). Estimated litter layer weights were: Northeast region - 16,413 lbs/acre, North Central -11,598 lbs/acre, and South - 12,491 lbs/acre. With the weight of fine woody debris (3" diameter) included, the estimates are: Northeast region – 22,926 lbs/acre, North Central – 17,754 lbs/acre, and South – 18,112 lbs/acre, but authors caution about applications of these data, noting that these are first approximations with relatively few plots. In general, it appears that the forest litter layer in our area weighs between 5.5 and 13 tons/acre, depending on forest composition and moisture status of the site.

Replenishment of the forest floor occurs through litter production. At Hubbard Brook, NH, a one-year sample produced 3,050 lbs/acre of deciduous litter over three elevation zones (Gosz et al. 1972). In northern Wisconsin, leaf and twig litter production was 2,153 lbs/acre on an aspen site, 2,474 lbs/acre on aspen-maple-birch, and 3,324 lbs/acre on maple-birch-aspen (Crow 1978). Zak (1986) found that autumn litter production in northwest lower Michigan for black and white oaks was 1,560 lbs/acre, sugar maple-red oak was 2,836 lbs/acre, and sugar maple-basswood was 2,341 lbs/acre. In northeast lower Michigan, in second-growth stands ranging from 53-112 years in age, autumn litterfall weighed 2,922 lbs/acre in mixed oak-northern hardwood stands, 2,473 lbs/acre in northern hardwoods, 2,521 lbs/acre in red oak, and 2,272 lbs/acre in pin-black oak; the average weight across sites was 2,575 lbs/acre (Padley 1989). At Sylvania, annual litterfall was 3,916 lbs/acre for old-growth sugar maple and 3,069 lbs/acre for hemlock (Campbell and Gower 2000). Litter production, like forest floor weight, varies depending on location and species composition, and is highly variable within a stand. Autumn litter input was about 20% of the forest floor weight in the northeast Michigan stands and in the sugar maple stand at Sylvania; however, the hemlock site studied by Campbell and Gower (2000) returned only about 11% of the forest floor weight in annual litterfall.

Mean residence times (MRT) can be estimated for organic material in the litter layer. The method assumes that annual litterfall input is roughly equal to annual forest floor decomposition, and is calculated by dividing forest floor weight by the weight of annual litterfall (Fassnacht and Gower 1999). MRT for organic material on sites in north central Wisconsin ranged from 2.1 to 6.4, being shorter for deciduous than coniferous forests, and possibly related to the presence of more recalcitrant carbon compounds on resource-poor sites (Fassnacht and Gower 1999). On the northeast Michigan sites and at Sylvania, the forest floor would be replaced approximately every five years. Using the estimates from FIA and for the hemlock site at Sylvania, including coarse and fine woody debris as well as organic forest floor layers, it would take approximately 10 years of litterfall to replace these materials. This suggests that MRT may be shorter for forest types with litter that is more easily decomposed (contains less lignin and phenols).

When a forest overstory is opened, the exposed litter layer becomes warmer and moister, favoring more rapid decomposition, release of carbon to the atmosphere through the respiration of decomposer organisms, and mineralization of nutrients from organic material. Estimates of increased carbon release due to accelerated decomposition after forest harvest are now thought to be lower than earlier research indicated, because studies have shown that the litter layer and woody debris can be partially mixed into mineral soils during forest harvest. Organic matter is typically more slowly decomposed in the mineral soil than in the litter layer (Yanai et al. 2003).

Results from the Long Term Soil Productivity Study (LTSP), conducted on sites throughout North America, indicate that decomposition and carbon release from woody debris after forest harvest may vary by climatic zones (Powers et al. 2005). The authors suggest that in warmer and dryer climates carbon is mainly respired and released to the atmosphere rather than being incorporated into the soil. In wetter and cooler climates, much of the carbon may eventually be moved into the soil. The carbon content of mineral soil has been shown to be relatively stable despite harvesting disturbances to forest stands (Johnson and Curtis 2001), but response of the forest litter layer is more variable and difficult to quantify, and is affected by site conditions, amount of woody residue, and site preparation practices (Grigal and Vance 2000, Gower et al. 2006).

When microbial decomposition proceeds more rapidly after a harvest, the forest litter layer can be gradually reduced in volume. At the same time, inputs of FWD and CWD are also reduced because all or part of the forest overstory has been removed, so the litter layer is not as rapidly replenished with new organic material. Johnson and Curtis (2001) suggest that the amount of woody residue left after harvest is a "dominant control" of the forest floor, although as noted by Yanai et al. (2003), the "roles of woody litter in forest floor dynamics remain difficult to assess… rates of woody litter inputs and the rates of fragmentation, decay, and stabilization that control residence time in the forest floor remain relatively unknown". Even though forest floor processes are highly variable and not fully understood, research examining this topic has consistently found that the loss or alteration of the litter layer has implications for soil fertility and populations of forest organisms. Grigal and Vance (2000) summarize studies involving the removal of organic material: "Removal… affects both the nutrient and water status of the forest system, and either or both may be the cause of reported declines in productivity".

Powers et al. (2005) discuss the role of the forest floor in soil fertility, particularly its importance as a reservoir for available nitrogen (N) and phosphorous (P). Removing all of the forest litter layer at the LTSP sites resulted in "sizeable declines in soil C and N concentrations and consistent declines in potentially mineralizable N", but effects were most pronounced on a droughty conifer site in California. In the ten-year study results, removal of the litter layer measurably affected biomass on aspen sites, but on the other forest types productivity was not significantly affected. Similarly, Bockheim et al. (2005) found reductions in aspen stocking, height, diameter, and basal area growth under treatments of compaction and forest floor removal in northern Wisconsin, although forest floor and woody debris removal alone did not statistically significantly reduce growth. Jurgensen et al. (1997) note that "a number of studies have linked substantial reduction in mycorrhizae development and tree growth to high levels of soil disturbance, or removal of organic horizons" and that timber harvesting and extensive site preparation… reduces the amount of surface organic material."

Microbial communities and other soil organisms are affected by the loss of organic material. Belleau et al. (2006) associated the amount of woody debris retained in boreal aspen stands with favorable soil nutrient levels, and concluded that the amount of slash left after harvest was "the main factor found to affect soil microbial community characteristics and soil nutrient availability". Battigelli et al. (2004) reported one-year findings for a LTSP site in British Columbia, focusing on Oribatid mite species (beetle mites that feed on living and dead plant material, and fungi, and are active in decomposition). "Soil compaction and organic matter removal significantly reduced the density and diversity of soil mesofauna", with the loss of organic material being of greater concern than compaction.

The amount of woody debris to retain in order to avoid significant adverse impacts on microbial communities, mycorrhizae, and forest productivity is still unclear. Olsson (1996), in a study in Sweden, found that clearcutting conifers with bole-only removal had a much larger effect on reduced soil C and N than additional utilization of FWM: "The overall conclusion is that the pronounced effects of clear-felling on soil C and N storage overshadowed the differences related to logging residue utilization." Jurgensen et al. (1997), in a summary paper on productivity considerations for the Intermountain West, provide one of the few discussions of the issue of how much woody residue is needed to maintain soil organic matter levels. They note that various guidelines in the region ranged from 4.5 tons/acre (for all woody debris, including CWD and FWD) up to 56 tons/acre. The lower values applied to dry conifer sites; based on slow cycling rates for these systems it was thought that the lower levels of residue retention would be sufficient to maintain soil organic matter. Fire risk was also a consideration. Higher levels of woody residue retention were suggested for mixed conifer forests in the northern Rocky Mountains.

Nitrogen and phosphorus

Nitrogen in forest systems is nearly entirely bound to organic matter. Very little of the total pool of N is available to plants; only about 2.5% of total organic N is released annually (Grigal and Vance 2000). The rate of N release from organic matter (mineralization) is controlled by microbial decomposition, which in turn is controlled by environmental factors as well as the amount and chemical composition of organic matter (Drury et al., 1991, Grigal and Vance 2000) (but Reich et al. (1997) did not find differences in N mineralization rates between conifer and deciduous forest stands in the Lake States; differences were more related to soil texture). Mineralization is highly spatially variable within stands (Campbell and Gower 2000). The availability of N from organic matter has been said to "most often limit the productivity of temperate forests" (Hassett and Zak 2005, citing Vitousek and Howarth 1991 and Aber et al. 1989).

Literature indicates the importance of logging residues in supplying available forms of N during early periods of stand growth after harvest (Malkonen 1976, Hyvonen et al. 2000). Dead woody material left after logging provides carbon-rich material for microbes to feed upon, and typically microbial populations increase after forest harvests due to the input of logging residues. As populations increase, microbes immobilize nitrogen in their tissues and limit losses that could otherwise occur through leaching or volatilization. As dead woody material gradually decomposes during the 15-20 years following harvest, microbial populations decline and release the nitrogen slowly to re-growing vegetation. Reductions in amounts of logging residue associated with merchantable bole aspen clearcuts and WTH harvests in Michigan resulted in decreased microbial activity, including decreased N mineralization and immobilization, but results did not vary significantly by type of harvest (Hassett and Zak 2005). There are few studies that specifically compare microbial activity under WTH and bole-only clearcuts, but in this study, biomass removal above and beyond bole-only harvest did not exacerbate the decline in nitrogen cycling.

A study in North Carolina found that nearly all the N and much of the P that moved down through the litter layer into mineral soil was in organic forms as a result of microbial transformations of organic matter in the forest floor (Qualls et al. 1991). This is relevant to the question of how much woody residue should be retained after harvesting, because it indicates that some N and P can be moved from FWD into the forest floor and thence to mineral soil where it may be stable for a longer period than in the litter layer.

Nitrogen fixation is a process whereby atmospheric N is captured in a forested system. At Hubbard Brook, logging residues were identified as a site for microbial N fixation (Likens et al 1978). In young stands with a large amount of dead wood left after harvest, the rate of N fixation was highest. As woody debris decomposed, the rate of fixation declined until litter inputs from the growing stand began to be a factor; after that point, fixation increased with the supply of dead woody material (Roskoski 1980). Most fixation occurred in wood of 1" diameter and larger, although the size of the largest wood was not specified. Roskoski (1980) speculated that this was due to the higher and more stable moisture content of larger pieces of wood. At sites in Montana, N fixation was reduced by 10% after clearcutting and prescribed burning, and by 22% after clearcutting followed by intensive removal of woody residue. Clearcutting with large amounts of woody residue left on site greatly increased N fixation as compared with the uncut control (Jurgensen et al. 1992.).

Nitrogen inputs to forests from atmospheric deposition are increasing and there are questions about whether some forests have reached N saturation. Reich et al. (1997) did not find evidence of N saturation in Lake States forests in the 1990s. Galloway et al. (2004) note that N can be retained in forested systems, primarily in soils, up to a point; retention is dependent on climate, vegetation, and past disturbance. When systems become saturated, N will be lost to the atmosphere and aquatic systems. This transition "is unlikely to exceed several decades in most ecosystems". In the Michigan Gradient study, sites approached N-saturation after experimental additions of nitrate over eight years, indicating that these northern hardwood systems are susceptible to relatively rapid saturation from atmospheric deposition (Pregitzer et al. 2004).

Phosphorous is another element that in forest soils is mainly supplied, in forms available to plants, by the microbial breakdown of organic materials. When P is deficient, it can limit plant metabolism of N. As atmospheric deposition of N increases, there is some evidence that limitations to tree growth could be switching from N to P (Gradowski and Thomas 2006). Phosphate supply in spring and early summer has been found to limit the rate of nitrification (conversion of ammonium to nitrate) in the forest floor at a site in central Wisconsin (Pastor et al. 1984).

Mineral supply of P is also important, and P deficiencies are more likely to occur in older, weathered soils that are low in mineral P. Roots of many species are able to exude compounds such as organic acids that solubilize mineral P, but availability is determined by competition among plants, microorganisms, and chemical bonds with minerals and organic materials in the soil (Attiwill and Adams 1993).

Many forest soils are acidic, and at low pH levels, some aluminum (Al) and iron (Fe) become solubilized. Soluble Al and Fe react quickly with inorganic P to form insoluble compounds that are unavailable to most plants (Pritchett 1979). Soluble Al also damages tree seedling growth by interfering in uptake of water and nutrients, but several studies have shown that mycorrhizal fungi can help alleviate the negative effects of Al (Cumming and Weinstein 1990, Jentschke and Godbold 2000, Klugh and Cumming 2007). Increased acidic deposition can result in additional solubilization of Al in soils, and can be an additional mechanism of forest stress in areas impacted by acid deposition.

Lindo and Visser (2003) reported on effects of clearcutting and partial harvest with regard to N and P in the forest floor 2.5 years following harvest. Phosphate, ammonium, microbial biomass, and mesofaunal abundance were reduced in clearcuts as compared with uncut controls, while nitrate increased in clearcuts. Kim et al. (1996) found that various levels of canopy opening in Michigan red pine and oak forests, including clearcutting, had little effect on litter decomposition or N and P release during the first 2 years after harvest, except in red oak clearcuts. Phosphorus in sites that had been whole-tree harvested at Hubbard Brook, NH, were compared with uncut forests after two years (Yanai 1991). Total-P in the forest floor was elevated under whole-tree harvests, and a greater amount of P was moved from the litter layer into mineral soil; these effects were attributed to reduced plant uptake of P. Available P in mineral soils remained low after harvests, likely due to strong bonding of P with Al and Fe. At the Sierra Nevada LTSP site, available P decline after clearcut harvest was also documented, along with reduced biological activity needed to transport P from the litter layer into the mineral soil (Gressel et al. 1996). At Walker Branch watershed in Tennessee, aggrading forests of oak-hickory and yellow poplar have lost available P over the 21-year measurement period, again likely due to bonding with Al and Fe in the mineral soil, suggesting the possibility of future P limitations to forest growth (Trettin et al. 1999).

Proposed biomass harvest guideline 3.A. calls for retention of a minimum of 4 tons/acre of FWD. This would supply one ton/acre of FWD above the average amount that currently occurs on forested sites in Wisconsin. Based on information in the literature, a portion of the organic matter, carbon, N, and P is likely to be retained in the forest litter layer and mineral soil after microbial decomposition of FWD, providing at least part of the nutrition needed by the regenerating stand and beneficial soil organisms. Whether this amount of retention is sufficient to provide available forms of N and P in quantities needed to sustain forest growth is uncertain and should be the focus of long-term monitoring.

Base cations

The base cations include Ca, Mg, K, and Na. Of these, Ca, Mg, and K are particularly important to tree nutrition.

Several recent studies indicate the important role of Ca in sugar maple. In the northeast U.S., acid deposition has been identified as a possible contributing cause in Ca depletion of soils. Calcium additions to northern hardwood forests at Hubbard Brook resulted in increased foliar concentrations of Ca in sugar maples as compared to controls, as well as improved crown conditions, greater seedling establishment and survival, decreased foliar Mn concentrations, and greater mycorrhizal colonization of seedling and mature sugar maple roots (Juice et al. 2006). Manganese concentrations in sugar maple leaves have been associated with susceptibility to oxidative stress and decline. One study showed that nutrient-poor sites had higher foliar Mn concentrations and lower foliar Ca and Mg as compared with nutrient-rich sites. Foliar nutrient imbalances corresponded with lower rates of photosynthesis and higher antioxidant enzyme activity (an indicator of oxidative stress) (St. Clair et al. 2005). Increased mobilization of Mn could be associated with increased soil acidity, and Mn interferes with Ca in sugar maple synthesis of phenolic compounds (Sager and Hutchinson 2006). Additions of Ca to sugar maple seedlings in a greenhouse led to significantly increased mycorrhizal colonization, foliar Ca, and photosynthesis; 50% of the increase in photosynthesis was related to stimulation of mycorrhizae (St. Clair and Lynch 2005). This illustrates the importance of Ca to tree nutrition.

The availability of Ca and Mg has also been implicated in the presence and abundance of herbaceous plants in the northeast U.S. Indicator plants were identified that corresponded with a gradient of these nutrients, and a group of rich mesic flora served as an indicator of sites where Ca and Mg levels were high enough that sugar maple forests could be resistant to multiple stresses from defoliation, drought, and deep soil freezing (Horsley et al. 2008).

Some tree species accumulate a relatively larger amount of Ca and other elements in aboveground biomass or tree components than others (See, for example, values shown in Appendix 3, also Fujinuma et al 2005, Rutkowski and Stottlemyer 1993, Morrison 1990, Ruark and Bockheim 1988, Perala and Alban 1982, Pastor and Bockheim 1981, Morrison and Foster 1979, Alban et al. 1978, MacLean and Wein 1977, Young and Guinn 1966), so the amount of nutrients removed in harvesting varies by forest type and harvest type (e.g. bole-only, whole-tree, biomass). These differing levels of nutrient removal have been described in a number of papers (Johnson et al 1988, Tritton et al 1987, Smith et al. 1986, Weetman and Algar 1983, Johnson et al 1982, Freedman et al 1981, Silkworth and Grigal 1980, Hornbeck 1977).

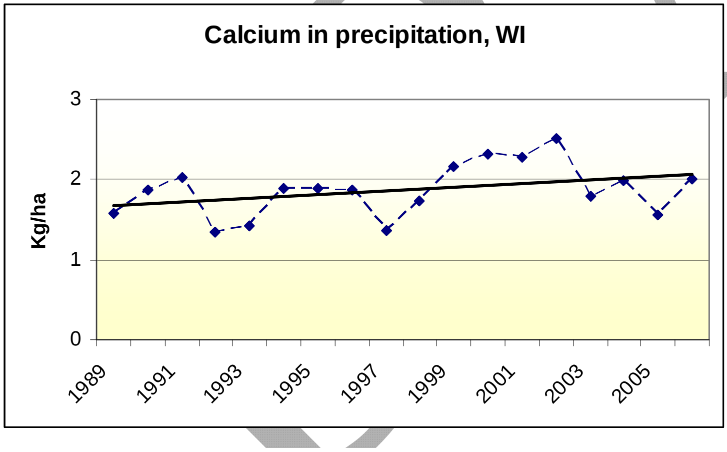

Figure __. Amount of calcium deposited annually in precipitation (wet deposition) at five NADP sites in Wisconsin from 1989 through 2006.

Calcium inputs in precipitation have been decreasing over the past several decades in the northeast U.S., but the trend is not apparent in MN (Grigal 2000). Data from five NADP sites in WI show a slight increase from 1989 to 2006, so we are not concerned about decreased Ca inputs in WI at this time (Figure __).

Studies on the Ottawa National Forest found "striking" losses of base cations (Ca, Mg, K) through leaching under both old growth and managed northern hardwood forests, in fragic and nonfragic soils. Losses were partly attributed to NO_3 and SO_4 from atmospheric deposition (Bockheim and Crowley 2002). Ongoing leaching losses of Ca have been reported at Hubbard Brook, but it has been assumed that losses there are accelerated due to acid deposition (Johnson et al. 1994, Federer et al. 1989). A gradient of acidic deposition occurs across the Lake States; it is lowest in northern Minnesota and increases in a southeast direction to reach its highest level in Ohio. Leaching losses of Ca and Mg, exacerbated by sulfate in atmospheric deposition, were found at all study sites along the gradient (MacDonald et al. 1992). Although none of the study sites fell within Wisconsin, it can be inferred that some level of accelerated loss of Ca and Mg is occurring here. Ca losses at most sites were at or above the maximum estimated weathering rates of 18.7 lbs/acre/year.

The literature has expressed a larger concern for potential Ca depletion than for other base cations. Federer et al. (1989) have written, "…most studies of nutrient removal by whole-tree harvest in the northeastern United States and eastern Canada have found that Ca was the element most likely to be depleted (Weetman and Weber 1972, Boyle and others 1973, Silkworth and Grigal 1982. Mann and others (1988) summarize a number of studies nationwide, all of which indicate a potential problem with Ca. In these and other studies (White 1974, Jorgenson and others 1975), inadequate knowledge of atmospheric inputs, imprecise estimates of leaching losses, lack of measurements of total pool sizes, and questions about weathering rates result in considerable uncertainty about interpretation."

Grigal (2000) describes "the uncertainties associated with the effects of nutrient removal on productivity, even in the case of Ca where there appears to be some concern. These uncertainties confirm the status of the effects of nutrient removal on productivity as being a postulate, in need of further examination. Major issues requiring further work are the need to identify fragile sties at risk for nutrient loss (Weetman 1998) and to understand the relationship between available nutrients and those removed in harvest."

Micronutrients

Micronutrients, or trace elements, are essential to plant growth but only in very small amounts. They include iron (Fe), manganese (Mn), boron (B), copper (Cu), molybdenum (Mo), cobalt (Co), chlorine (Cl), and zinc (Zn). Instances of deficiencies are described in textbooks, although it is said that these seldom occur in forest soils. Iron is the micronutrient most often found to be deficient in nurseries, and Cu, B, and Zn deficiencies are also reported (Pritchett 1979). There are few studies of micronutrient supplies in forest soils of the Lake States. In Minnesota, concentrations of Zn were higher in surface soils, while Cu and Ni were higher in subsoil and parent materials; variation among soil series was low (Pierce et al 1982). Decreased levels of Mn, Zn, and Fe in the upper mineral soil of forested dunes near Lake Michigan were attributed to natural soil weathering processes (Lichter 1998). In a study in Belgium, clay and organic matter content of soils was used to partially predict the content of Zn, Cu, and Ni (Tack et al 1997).

A few studies have looked at micronutrients in relation to tree nutrition. Foliar content of B and Mn were correlated with site index in a study of trembling aspen in Alberta (Chen et al. 1998). Pastor (1989), citing Gerloff et al. (1966), noted that Zn is accumulated by aspen in WI "in amounts seven times higher than the minimum required by most plants". Zinc concentrations in aspen branches were found to be significantly greater than in sugar maple branches (Pastor and Bockheim 1984), although stand-level content values appear similar between aspen and northern hardwood stands, with the bark of sugar maple being especially high in Zn (Appendix 3). Tree species and component differences indicate that there could be differential removals of micronutrients in forest harvests. Information on the soil supply of these trace elements, and their removal in harvests, is largely lacking and is a potential research topic.

Nutrient budgets and balances

Nutrient budgets, also known as mass balance equations, are calculated based on inputs to the system that accrue through mineral weathering and atmospheric deposition, and outputs attributable to accelerated leaching and removals in harvest. Budgets can include nutrient cycling within an ecosystem, such as annual litterfall, normal amounts of leaching, or animal consumption. Here, we are interested in comparing inputs and outputs as affected by harvesting and are not considering internal cycling processes. The nutrient balances thus derived are considered estimates and do not include processes for which there is little data, such as nutrient loss in runoff from forested sites, or losses that are thought to be minor effects of forest harvests (e.g. nitrogen volatilization).

Inputs

Mineral weathering - Ranges of inputs for mineral weathering are taken from Grigal (2004) as calculated from data in Kolka et al. (1996). This is the most recent and thorough study of mineral weathering for our area to date, looking at five different soil types and using four methods of assessing mineral weathering. However, mineral weathering rates are poorly understood and soils experts are not confident in these estimates. Kolka's studies indicate a lower weathering rate than had been previously assumed because they are based on soil pedons rather than watersheds, and the use of these new values in nutrient balance calculations estimates a larger net loss as compared with nutrient balances reported in earlier studies.

Table __. Estimates of nutrient inputs through mineral weathering and atmospheric deposition in Wisconsin.

	Ca, lb/acre/yr			Mg, lb/acre/yr			K, lb/acre/yr			N, lb/acre/yr			P, lb/acre/yr		
	Low	avg	high	low	avg	high	low	avg	high	low	avg	high	low	avg	high
Atmospheric deposition															
wet (1)	1.24	1.71	2.02	0.16	0.23	0.33	0.13	0.18	0.25	7.39	9.14	10.85	0.05	0.12	0.20
dry (2)	1.24	1.71	2.02	0.16	0.23	0.33	0.13	0.18	0.25	7.39	9.14	10.85	0.05	0.12	0.20
Mineral weathering (3)	1.70	3.70	5.00	0.90	1.50	2.00	0.70	1.50	2.00				0.20	0.60	0.80
Total	4.17	7.12	9.04	1.22	1.95	2.65	0.97	1.86	2.51	14.77	18.28	21.71	0.30	0.84	1.20

(1) Data from five NADP stations in Wisconsin, 1997-2006, except P deposition data from Robertson (1996). High P values are in SE WI.
(2) Dry deposition is estimated to be approximately equal to wet deposition.
(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996), except P and Na from Grigal and Bates (1992).

Atmospheric wet deposition - Data on atmospheric wet deposition in Wisconsin was gathered from the National Atmospheric Deposition Program/National Trends Network (NADP/NTN), a nationwide network of precipitation monitoring sites (http://nadp.sws.uiuc.edu/). The purpose of the NADP/NTN network is to collect data on the chemistry of precipitation for monitoring of geographical and temporal long-term trends. Precipitation at each station is collected weekly according to strict clean-handling procedures. It is then sent to the Central Analytical Laboratory where it is analyzed for hydrogen (acidity as pH), sulfate, nitrate, ammonium, chloride, and base cations (such as calcium, magnesium, potassium and sodium). A quality assurance program ensures that the data are accurate and precise (http://nadp.sws.uiuc.edu/QA/).

Total wet deposition data was gathered from NADP monitoring sites in Northeast, Northwest, Central, Southeast and Southwest Wisconsin (Appendix 4). Stations were selected based on regional placement and the availability of data from the last 10 years (1997-2006). Data from the following NADP monitoring stations were used:

Northeast Wisconsin – WI09 Popple River, Florence County
Northwest Wisconsin – WI37 Spooner, Washburn County
Central Wisconsin – WI28 Lake Dubay, Portage County
Southwest Wisconsin – WI98 Wildcat Mountain, Vernon County
Southeast Wisconsin – WI99 Lake Geneva, Walworth County

Atmospheric dry deposition

Atmospheric deposition is a significant source of nutrients for plant communities. However, the relative contribution of wet vs. dry deposition is highly dependent on the specific nutrient and individual sites characteristics. Dry deposition tends to be more spatially and temporally variable and therefore estimates are subject to a high degree of uncertainty. Current standard methods, like bulk deposition collectors, are thought to significantly underestimate the contribution of dry deposition to nutrient cycling.

Lindberg et al (1986) studied dry deposition in a mature oak-hickory forest at Walker Branch Watershed in Tennessee. Dry deposition was a significant mechanism in the total annual flux of ions to this forest, contributing 32% of NH_4, about 50% of SO_4 and H^+, about 60% of K^+ and NO_3, and about 70% of Ca^{2+}. This deposition occurred primarily as vapor uptake for S and N and by particle deposition for Ca and K. However, deposition estimates were subject to considerable uncertainty, up to 20% for wet deposition and 50% to 75% for dry. A previous study of this forest found that dry inputs accounted for 18% to 52% of the annual total atmospheric input, and that 75% of dryfall input occurred during the growing season (Lindberg and Harriss, 1981). Data from these studies supports the hypothesis that dry deposition is a major source of atmospheric inputs for some forest systems, and that standard bulk deposition methods significantly underestimate this contribution.

Swank (1984) compared atmospheric nutrient inputs and harvesting losses from forested systems in Walker Branch Tennessee; Coweeta, North Carolina; Hubbard Brook, New Hampshire; Duke Forest, North Carolina; H.J. Andrews, Oregon; and Thompson Research Center, Washington. The study found significant spatial/regional variations in nutrient input, as well as year to year and seasonal variations for specific sites and nutrients. The importance of atmospheric nutrient deposition to site nutrient cycling is highly variable across time and space, highlighting the need for quantification of these inputs from a variety of systems over long periods of time.

Outputs

Leaching

Leaching is a continuous process in soils, occurring naturally as water moves through them. In forests without recent disturbance, vegetation takes up nutrients that are soluble in water and leaching losses are negligible. After a drastic disturbance, however, leaching is elevated above background levels for a few years until vegetation regrows sufficiently to begin accumulating nutrients. When forests reach old-growth stages, growth slows and trees are no longer able to take up all available nutrients, and a slight increase in nutrient leaching occurs (Vitousek and Reiners 1975, Bockheim and Crowley 2002).

Silkworth and Grigal (1982) studied leaching in several soils after whole-tree harvesting in northeastern MN, and found that a small but statistically significant amount of Ca, a total of 55.6 lbs/acre, was lost over the course of five years. Leaching of Mg was also slightly elevated by 29.1 lbs/acre over the same period, but this figure was not statistically significant. N, P, and K were not leached after whole-tree harvests in this study. Silkworth and Grigal's (1982) values were used in calculating nutrient budgets because these data are reported as quantities exported over time, and because the study site was located close to Wisconsin.

Leaching losses have been studied extensively at Hubbard Brook, NH, but higher levels of acid precipitation in that region cause more base cations to be mobilized and leached, so results are not considered comparable. Hornbeck (1986) found that elevated leaching losses after bole-only clearcuts at Hubbard Brook totaled 42.5 lb/acre over the first several years following harvest.

Nutrients in aboveground tree components

Nutrient content data for aboveground components of trees are summarized in Appendix 3. These data were compiled from published literature, and from an unpublished M.S. thesis. When the useable data were broken down by species, there were too few studies conducted within the Lake States, so information from the northeast U.S. and from Canada was included.

Data in Appendix 3 indicate some generalizations about nutrients contained in components of forest types typically found in the Lake States, although some of these data come from sites in the northeast U.S. and in Canada.

- Bole wood contains a relatively small proportion of nutrients.
- Bole bark of some species contains a relatively high proportion of nutrients. This is particularly true of aspen and sugar maple. Oak species may be similar, based on the high total amount reported for bole + bark, but separate figures for oak bark are not available.
- Foliage of conifers contains a relatively high amount of nutrients.
- In average total weights for all tree species, Ca (538 lbs/acre) is the element most accumulated in aboveground tree biomass, followed by N (297 lbs/acre), K (187 lbs/acre), S (46 lbs/acre), magnesium (Mg) (47 lbs/acre), manganese (Mn) (36 lbs/acre), P (30 lbs/acre), iron (Fe) (5 lbs/acre), zinc (Zn) (5 lbs/acre), and copper (Cu) (0.8 lbs/acre).

Harvest removals
The amount of nutrients removed during a forest harvest depends on the tree species being harvested, age of the stand, site quality, rotation length in even-aged management or frequency of entry in partial harvests, and the type of harvest. A bole-only harvest that removes only bole wood and leaves the bark on site removes a minimum amount of nutrients. Bark contains a disproportionately high amount of nutrients for its weight; Ca values in Appendix 3 averaged across all tree species show that nearly 40% of aboveground Ca is found in bole bark. Branches and foliage account for another 40% of Ca, and bole wood for about 20%. Biomass harvests are assumed to remove boles, bark and approximately 2/3 of tops, branches, and foliage, for a total of around 85% of the aboveground Ca.

Seasonal changes
Seasonal nutrient translocations among tree components are of interest in deciding whether to harvest in the summer, when foliage is present on deciduous trees and would be removed in biomass harvests, versus harvesting in winter. Textbooks describe the translocation of 1/4 to 2/3 of N out of the leaves of deciduous trees in autumn (Kozlowski and Pallardy 1997). In a study in Vilas Co., WI, aspen retained more of its nutrient pool in perennial tissues than did sugar maple, and also translocated more of its nutrients out of leaves prior to abscission in autumn (Pastor and Bockheim 1984). The amount of translocation for the two species was considerable, amounting to nearly half the N in leaves. However, unlike the other nutrients, Ca and Zn actually increased in leaves prior to abscission. Similarly, Tew (1970) noted that content of Ca, Mg, Na increased in aspen leaves during the growing season, while N, P, and K decreased significantly. Pastor (1989) noted that aspen returns less than half the annual uptake of nutrients in litterfall, throughfall and stemflow, and that Ca, S, and Zn were especially well-retained. Alban (1985) found that foliage of aspen suckers 1-3 years old showed particularly large seasonal variation in N and P content because of translocation out of leaves in autumn.

Data for aspen components in Appendix 3 indicate that an average of only 4% of aboveground Ca is contained in foliage. Around 22% of aboveground N and 19% of P is in foliage, so if aspen stands are harvested for biomass with foliage on, with 2/3 of tops removed, the foliage would represent a loss of an additional 7% of aboveground N and 6% of P as compared with a winter harvest. We are not including seasonal restrictions as a biomass harvest guideline for nutrient considerations, because the amount of impact would not be large on most sites and we are already limiting harvest on the most nutrient-poor soils. We may include a note about this topic as a consideration in the guidelines. Note, however, that seasonal restrictions may be important for other reasons, such as avoiding nesting disturbances to threatened and endangered species.

Stand age
Nutrient accumulation in tissue changes as stands age, but the most rapid rate of uptake occurs in young stands. The charts included here indicate that beyond age 20, aspen, jack pine, and hardwood stands level off somewhat in their accumulation of additional nutrients (Perala 1979, MacLean and Wein 1977).

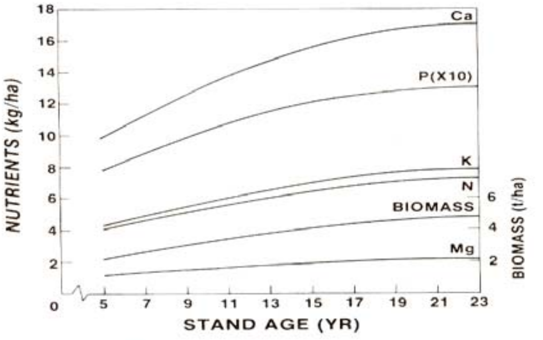

Figure 4.– Mean annual above-ground accumulation of nutrients and biomass in aspen (except leaves). Integrated from Einspahr (1977) and Perala (1973).

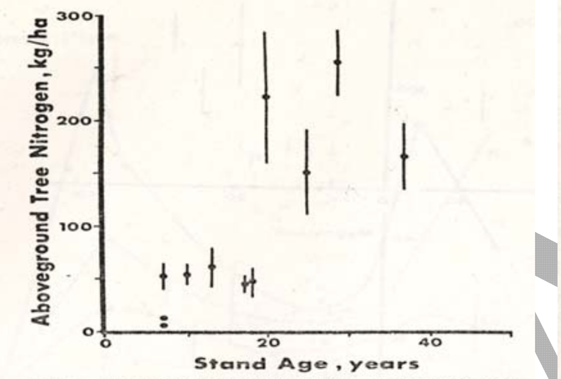

FIG. 4. Nitrogen accumulation with stand age in the aboveground tree layer of 11 hardwood stands. Standard errors of the mean are represented as bars.

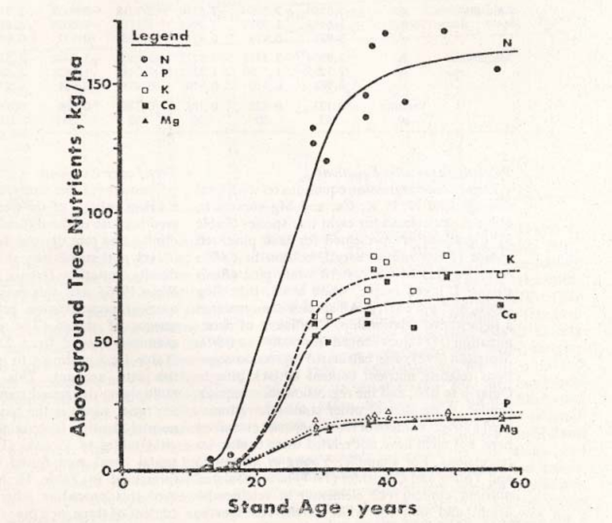

FIG. 3. Patterns of accumulation of N, P, K, Ca, and Mg in the aboveground tree layer with stand age for 12 jack pine stands. Curves are for data adjusted to normal stocking.

Ruark and Bockheim (1988), tracking aboveground aspen biomass, indicated that between ages of 18 and 32 years, total biomass increased from 49 to 104 Mg/ha, while from age 32 to 63 years it increased to 128 Mg/ha, indicating that the rate of biomass accumulation had leveled off. However, some nutrients in some tree components, particularly N, Ca, and Mg in branches and bole bark, increased by a relatively large amount between age 32 and 63 years. We did not have enough data to consider how stand age impacts potential nutrient removals in biomass harvests, and have averaged nutrient data for mature stands. Nevertheless, this remains an area of uncertainty where more information would be valuable.

Calculations

Nutrient budgets are of the form [(wet + dry atmospheric deposition + mineral weathering) x years of rotation] – harvest removals – leaching loss = nutrient balance. It is acknowledged in the literature that for some nutrients, under some harvesting regimes, this mathematical approach will show negative numbers. Wilson and Grigal (1995) have summarized the situation for Ca as follows:

> "Many studies of impacts of harvesting on nutrient status have implicated Ca as the macronutrient most likely to be depleted with time, because the rate of loss in the product and by leaching exceeds the natural rate of replacement by weathering and atmospheric deposition (Boyle et al. 1973, Silkworth and Grigal 1982, Johnson and Todd 1987, Mann et al. 1988, Federer et al. 1989)."

Further discussion on the topic of nutrient budgets is found in Grigal (2004), p. 23-27, who calculated negative values for both K and Ca; however, these losses were a relatively small percentage of soil nutrient capital and were not thought to affect forest productivity.

Nutrient budgets were calculated for some of Wisconsin's forest types using the best available information on inputs and outputs to the system. Several of the nutrient budget calculations are summarized here, and additional calculations appear in Appendix 3.

The following table shows an example of a nutrient balance calculation for nitrogen in a biomass harvest of aspen on a 40-year rotation, using N values for the six aspen-dominated stands shown in Appendix 3. Clearly, total N inputs to this system are not of concern.

Nitrogen budget for aspen biomass harvest, 40-yr rotation

Inputs	
Atmospheric deposition:	18.3 lb/acre/year x 40 years = 731 lb/acre
Mineral weathering:	0
Outputs/losses	
Leaching:	0
Harvest:	181 lb/acre N removed in bole wood and bark, 75 lb/acre removed in 2/3 of tops, limbs, and foliage
Budget	
Inputs - outputs:	731 - 181 - 75 = **475** lbs/acre total N gained over the rotation

For partial harvests that are commonly applied to northern hardwood stands, a meaningful way to sum nutrient removals accumulated during several stand entries is to calculate them on an equivalent basis as the amount that would be removed if the whole stand were harvested at once. If a northern hardwood stand is entered each 15 years, and 33% of volume is removed each time, this removes the same amount of nutrients as a 45-year even-aged rotation. That is, in 45 years the stand will have been harvested three times, with a third of the nutrients removed each time. The following example shows a biomass harvest that illustrates N removal for this level of stand entry, for the five northern hardwood stands in Appendix 3. Again, total N balance for northern hardwoods is not of concern.

Nitrogen budget for northern hardwood biomass harvest, 45-yr rotation equivalent	
Inputs	
Atmospheric deposition:	18.3 lb/acre/year x 45 years = 823 lb/acre
Mineral weathering:	0
Outputs/losses	
Leaching:	0
Harvest:	197 lb/acre N removed in bole wood and bark, 161 lb/acre removed in 2/3 of tops, limbs, and foliage
Budget	
Inputs - outputs:	823 - 197 - 161 = **465** lbs/acre total N gained over the rotation

Calcium is the nutrient most often cited in the literature as being potentially of concern for depletion. The Ca budget for an aspen biomass harvest on a 40-year rotation is shown below, using Ca values averaged for the 16 aspen-dominated stands shown in Appendix 3. This is the nutrient budget that shows the greatest amount of loss as compared with other species. The nutrient budget for K is similar, showing a relatively large negative value of -139 lb/acre K for aspen biomass harvests on 40 year rotations.

Calcium budget for aspen biomass harvest, 40-yr rotation	
Inputs	
Atmospheric deposition:	3.4 lb/acre/year x 40 years = 137 lb/acre
Mineral weathering:	3.7 lb/acre/year x 40 years = 148 lb/acre
Outputs/losses	
Leaching:	55.6 lb/acre during the first 5 years
Harvest:	497 lb/acre Ca removed in bole wood and bark, 119 lb/acre removed in 2/3 of tops, limbs, and foliage
Budget	
Inputs - outputs:	285 - 497 - 119 - 56 = -387 lbs/acre Ca lost over the rotation

The next example shows the Ca budget for northern hardwood biomass harvests on the equivalent of a 45-year rotation (i.e. three partial harvests at 15-year intervals, removing 1/3 of volume each time). The calculated value for Ca loss is similar to that for aspen biomass harvests on 40-year rotations.

Calcium budget for northern hardwood biomass harvest, 45-yr rotation equivalent	
Inputs	
Atmospheric deposition:	3.4 lb/acre/year x 45 years = 154 lb/acre
Mineral weathering:	3.7 lb/acre/year x 45 years = 167 lb/acre
Outputs/losses	
Leaching:	0
Harvest:	487 lb/acre Ca removed in bole wood and bark, 227 lb/acre removed in 2/3 of tops, limbs, and foliage
Budget	
Inputs - outputs:	321 - 487 - 227 = -393 lbs/acre Ca lost over the rotation

The following table shows a calcium budget for jack pine biomass harvest on a 40-year rotation. Here, we have assumed a low rate of mineral weathering, as jack pine forests are largely restricted to droughty sand sites. Because jack pine does not accumulate Ca to the extent that aspen and northern hardwoods do, this budget shows a small positive increment for Ca.

Calcium budget for jack pine biomass harvest, 40-yr rotation	
Inputs	
Atmospheric deposition:	3.4 lb/acre/year x 40 years = 137 lb/acre
Mineral weathering:	1.7 lb/acre/year x 40 years = 68 lb/acre
Outputs/losses	
Leaching:	55.6 lb/acre during the first 5 years
Harvest:	78 lb/acre Ca removed in bole wood and bark, 24 lb/acre removed in 2/3 of tops, limbs, and foliage
Budget	
Inputs - outputs:	205 - 78 - 24 - 56 = 47 lbs/acre Ca gained over the rotation

Red pine calcium budgets are shown in the next example. Data are from a thinned red pine stand of SI=60 with final harvest at 120 years (Bassett 1984). The stand was originally established with 800 trees/acre, and was thinned to 90 sq ft of BA at ages 30 and 40; it was thinned to 120 sq ft of BA at ages 50, 60, and 70, and to 150 sq ft of BA at age 90. Biomass for stand components was estimated using biomass equations for red pine in the Upper Great Lakes area (Ter-Mikaelian & Korzukhin 1997). Concentration data for Ca were from 39- and 41-year old stands described in Perala & Alban (1982). This example uses the average mineral weathering rate and shows a net gain of 216 lb/ac Ca, but if the budget is calculated using the low input rate, the outcome is -137 lb/acre, which indicates that biomass harvest of red pine on nutrient-poor sites may be borderline in terms of calculated nutrient budgets. Shorter rotations are even more problematic; calculations for a 60-year rotation with thinnings at 30, 40, and 50 years on a nutrient-poor site give a result of -137 lb/acre Ca, which if repeated in a second rotation would remove twice as much Ca over 120 years as compared to the example with final harvest at 120 years

Calcium budget for red pine with biomass harvests at each thinning, 120-yr final harvest	
Inputs	
Atmospheric deposition:	3.4 lb/acre/year x 120 years = 411 lb/acre
Mineral weathering:	3.7 lb/acre/year x 120 years = 444 lb/acre
Outputs/losses	
Leaching:	55.6 lb/acre during the first 5 years
Harvest:	351 lb/acre Ca removed in bole wood and bark, 223 lb/acre removed in 2/3 of tops, limbs, and foliage
Budget	
Inputs - outputs:	855 - 351 - 232 - 56 = 216 lbs/acre Ca gained over the rotation

Results of nutrient budget calculations vary widely among forest types because tree species accumulate nutrients differently. The budgets of concern are Ca and K for aspen and northern hardwoods, and Ca for red pine on sites with low inputs from mineral weathering. Budgets for Mg and P are borderline for aspen. As discussed previously, only a portion of total N and P are available to plants, and the supply of these nutrients from microbial transformations of organic material is critical. It is clear that FWD is needed for cycling of N and P, but there is uncertainty about what amounts are required to maintain the microbial populations that carry out this cycling.

Nutrient capital for Wisconsin's soils

Nutrient capital is the total amount of exchangeable nutrients stored in soils, summed to the depth available to tree roots. Calculations of nutrient budgets that show negative balances are of less concern when the amount of the nutrient lost is low relative to the amount held in soils. Because of the concern for potential Ca and K depletion, we are in the process of evaluating Wisconsin's soil nutrient capital.

Soils data from research studies in the Lake States has been assembled by Dr. David Grigal. The database includes 326 plots in MI, WI, and MN. The database was analyzed for Ca status to identify nutrient-poor soils (Appendix 5).

Data analysis by Dr. Grigal shows a high correlation between soil Ca and clay content in Lake States soils. Particle size data from the Natural Resources Conservation Service (NRCS) are being used to identify soil series with very low clay content, and thus low Ca content. The K and Mg content of soils is highly correlated with Ca, so identifying those soils with low Ca should also capture those low in the other base cations. A list of soil series with low nutrient capital will be produced; we are tentatively planning to list those soils with 3% or less clay in the upper 40 inches, based on a correlation with an exchangeable Ca content of 1000 kg/ha. This amount of Ca in the soil nutrient pool is estimated to supply slightly over two rotations of aspen biomass harvest under a worst-case scenario of low nutrient inputs for Ca of 4.17 lbs/acre/year. The low input scenario is appropriate, because mineral weathering inputs are comparatively low for extremely sandy soils such as these.

A significant extent of Wisconsin's soils are calcareous, meaning that free $CaCO_3$ is present within the soil or parent material, and can supply ample amounts of Ca to forests. Many of these soils are in agricultural uses, but where forest occurs on these Ca-rich soils, we would not be concerned about depletion.

Soils with water tables near the surface, even if they are very sandy and otherwise nutrient-poor, appear to be able to acquire nutrients from groundwater. This has been demonstrated by K uptake in red pine on a coarse sand soil in New York (Jurgensen and Leaf 1965) and in a forested wetland of jack pine-spruce-larch, with an organic surface over sand in central Upper Michigan (Trettin et al., in review).

Summary of nutrient status estimates and specific rationale for Guidelines 6.B., 7.B., and 8.B.

Based on calculations of nutrient budgets, Ca and K are the nutrients that may be removed in biomass harvests in amounts greater than inputs. We have described the considerable uncertainties in the estimates, and these uncertainties make it difficult to apply the results of nutrient budget calculations as absolutes. The negative values indicate a concern, rather than a conclusion, that nutrient depletion is occurring.

Fertilization is a possible way to compensate for nutrient removals, either using traditional fertilizers, wood ash, or other amendments. If we compare the depletion of 300 lbs/acre of Ca in an aspen biomass harvest to that amount of removal by an agricultural crop, in the cropland setting an application of a ton of aglime (ground limestone fertilizer) per acre would be indicated to ameliorate the potential loss of soil fertility. Fertilization is an uncommon practice in Lake States forests, and while the cost of aglime is relatively low at around $20 per ton, the cost of application in a forest would likely be high.

There are considerations with the use of wood ash and other soil amendments; wood ash may be contaminated with metals, and the amount applied must be controlled to avoid excess alkalinity. Any potential applications of nontraditional fertilizer materials will require further analysis.

Guideline 7.B.

We are proposing restricting harvest above and beyond bole-only removals on our most acidic and nutrient-poor soils in the interest of maintaining soil cations (Ca, Mg, and K). If future research findings indicate a greater supply of soil nutrients than is currently known, then restrictions could be relaxed to allow biomass harvest on nutrient-poor soils.

We are in the process of developing a map of these low-nutrient soils, highlighting areas where nutrient-poor soils are common in the state. The small map reproduced here from Fig. 2-24 of Hole's (1976) book, Soils of Wisconsin, indicates the locations of sandy soils; we anticipate that the ~~a~~ map of low-nutrient soils produced from modern soil surveys would identify similar locations.

The map of nutrient-poor soils is being developed based on queries of NASIS and SSURGO, the soils database and GIS layer created by the Natural Resources Conservation Service. Nutrient-poor soils are tentatively identified as having less than 3% clay in the upper 40 inches, no free carbonates within the pedon, no water table within the pedon, and no layers with textures of loam or heavier soil within the pedon below the 40 inch depth. The map is proving difficult to create because of challenges in combining county-level soil GIS layers and attribute tables from the 72 counties in Wisconsin.

Figure 2-24. Sandy surficial soil horizons commonly total more than 36 inches in thickness and are underlain by acid sand glacial outwash.

Figure from Hole (1976). This map may approximate the location of nutrient-poor sandy soils.

Guideline 6.B.
This guideline restricts harvest of FWD on shallow soils of 20 inches or less over bedrock. These soils have half (or less) the amount of nutrients calculated as being available in the upper 40 inches of soil and are thus more susceptible to nutrient depletion. Shallow soils are also susceptible to compaction and erosion. These soils can be squeezed between equipment and bedrock, destroying soil structure so that rainfall can move the soil easily, and sometimes creating ruts. See discussion of these impacts in the 'Physical Properties of Soil' section.

Guideline 8.B.

The rationale for this guideline, and nutrient budget calculations, are given in Grigal (2004). Organic peatland soils receive nutrient inputs from atmospheric deposition, but are largely isolated from nutrient inputs from mineral weathering. The potentially high loss of K and P relative to site nutrient capital is the reason for restricting biomass harvest on these sites.

"Organic soils pose a greater problem [than mineral soils] in terms of nutrients. Although natural inputs of N, Ca, and Mg are sufficient to balance outputs, about 30% of the system K and 20% of the P would be lost in each 50 year rotation. It is clear that organic soils are much more susceptible to loss of nutrients and hence of productivity than are mineral soils. This is a consequence of the low rates of natural K and P replacement in peatlands, and implies a high potential for deficiencies to occur with intensive harvest. Fertilization with K and P may be necessary if whole tree harvesting is routinely practiced on those soils.

On peatlands… aggressive biomass removal is likely to lead to K and P deficiencies without fertilization."

Minnesota's guidelines restricted FWD harvest on ombrotrophic peatlands (low in nutrients) with 24 inches of organic material at the surface. Thick organic surface layers and saturated conditions limit tree rooting depth and access to nutrients in the mineral soil, as well as restricting nutrient uptake within the organic layer under anaerobic conditions. On soils with thinner organic surface layers, it is more likely that roots can reach mineral soil and access some level of nutrients supplied from mineral weathering, and that water table fluctuations may contribute to better aeration in the mineral soil. However, nutrient budgets in Grigal (2004) indicated a significant net loss of P and K relative to soil nutrient capital even in situations where groundwater contributed some nutrients to the site.

We are proposing a Wisconsin guideline that would restrict FWD harvest on soils classified as dysic Histosols, both for ease of identification and to allow harvest on forested wetlands where nutrient supplies are considered adequate. Histosols have 18 inch thick surface layers, and are easily identified on soil maps. Organic soils with 24 inch surface layers cannot be reliably identified from soil maps. Dysic Histosols have an average pH of less than 4.5 in the control section (the control section for most Histosols is the 0 to 51 inch depth, or the depth to mineral soil or bedrock). When organic soils are mapped, vegetation is used as an indicator and local soils experts feel that the dysic reaction class provides a credible separation of low-nutrient forested wetlands (Dave Hvizdak, pers. comm.). Since Forest Habitat Types are not complete for Wisconsin's forested wetlands, and we were not confident that practitioners would be able to distinguish between ombrotrophic and minerotrophic peatlands, we felt that relying on soil classification was the best approach because these soils can be identified on soil maps.

Physical Properties of Soil

Applicable Guidelines: 2A, 3A, 4A, ~~6~~5A, 6B, 8B, 9B, 10B, 11B

Rationale. Maintaining soil quality is a recognized tenet of responsible forest management. This section discusses the potential effects of harvesting equipment on soil structure. These effects include the compaction, churning, rutting, mixing, displacement and removal of soil. The goal of the guidelines, as they relate to the physical properties of soil, is to avoid or minimize potential adverse impacts on soil structure and soil processes.

One of the primary methods to limit the effects of harvesting equipment on a site is to limit the land area devoted to roads, landings and skid trails. The extent of soil compaction is then confined to designated areas of the harvest area. In addition, harvesting activities on sites which are especially susceptible to soil disturbances should also be limited. Examples of sensitive sites include shallow soils, wetlands and riparian zones (Pierce et al 1993).

During harvesting operations, the soil is disrupted as surface vegetation and organic matter are removed either intentionally or unintentionally by equipment. Biomass harvesting, in general, is expected to occur in conjunction with traditional timber harvesting operations. This means not only will the traditional processors, forwarders and skidders be on-site, but additional equipment for the biomass harvesting may also be on-site, resulting in more intensive use of roads, landings and skid trails (Hornbeck et al 1986). With repeated passes of equipment, the soil becomes compacted. As the soil becomes more and more compacted, it will either begin to erode or fail. At this point, soil disturbances include churning, rutting, mixing, displacement and removal.

Heavy equipment can alter soil properties, which can impact tree growth and ultimately, soil productivity. These impacts may have immediate effects on the physical characteristics of soil or on residual trees, and they can also have long-term impacts on soil processes (Wang et al 2007). Soil disturbances can also impact water quality (Martin and Hornbeck 1994).

Soil Disturbance Studies. A study in Washburn County, Wisconsin found increased soil densities after a thinning operation. The first part of the study showed that one pass of a feller-buncher followed by four or fewer passes of a skidder increased soil bulk density by almost the same amount as one pass of the feller-buncher and eight passes by the skidder. The second portion of the study used controlled loading of a forwarder, and found that there was a significant increase in soil bulk density as compared with controls, but little difference among load size and number of passes. The study showed that the first few passes of equipment (four or fewer) resulted in most of the increase of bulk density and that additional passes or loading conditions made little difference (Shetron et al. 1988).

Research conducted in West Virginia found similar results with most of the increases in bulk density occurring after one pass of loaded machinery on skid trails. In this study, 95% of the increase in bulk density occurred after five passes of equipment (Wang et al 2007).

A study on Menominee Tribal Enterprises land used a skidder and forwarder, and compared costs, productivity, damage to residual trees, and soil impacts. The study found that costs were lowest and productivity (in terms of product removed) was greatest when using a forwarder that was not restricted to designated trails. The use of skidder had similar costs and productivity regardless of whether it was restricted to trails. The authors noted that "soil impacts occurred wherever logging equipment traveled", and "restricting either machine to a designated trail resulted in less soil disturbance". Again, most of the soil compaction occurred during the first few passes of logging equipment (Thompson et al. 1995).

These studies illustrate the concerns regarding soil compaction and traditional harvesting techniques. With the expectation that biomass harvesting will increase the amount of equipment travel in forests, limiting the amount of harvest area dedicated to roads, landings and skid trails to designated areas can minimize the extent of the soil compaction found in forests.

Impacts on Tree Growth. Directly, tree growth can decline as roots and trunks are damaged or severed by heavy equipment. Water and nutrient uptake may be reduced and the damage may provide entry points for disease or insects, leading to a decline in tree growth. If the damage is severe enough, it may cause tree mortality.

Soil compaction reduces root growth by narrowing the range of moisture potential (tension) at which roots grow in their optimum ranges. Root growth is generally greatest at or near field capacity – when large soil pores have been drained by gravity – because this moisture level provides the best balance among factors that impact root growth. As soils dry below field capacity, both water tension and mechanical resistance increase. Both contribute to reduced root growth. Root growth is also reduced in soils that are wetter than field capacity. At this range of soil moisture conditions, reduced availability of oxygen and accumulation of toxic metabolites contribute to a decline in root growth (Pierce et al 1993; Eavis 1972 in NCASI 2004).

Tree growth is also impacted as soil compaction and degradation of soil structure affect temperature relationships, microbial and faunal activity, and pathogens. Changes in soil moisture-holding capacity, thermal capacity, and conductivity can modify temperatures regimes. Root growth decreases in a linearly relationship as soil temperatures decline below the optimum range (Warkentin 1971; Ballard 2000). Populations of arthropods, fungi, nematodes, and bacteria are generally lower in compacted soils than in noncompacted soils (Smeltzer et al. 1996 in NCASI 2004). Resulting decreases in nutrient mineralization and availability may also contribute to reduced root growth (Phillipson and Coutts 1977 in NCASI 2004). Faunal activity helps to create macropores and soil texture, but is often found to be reduced in compacted soils (Dexter 1978; Whalley et al. 1995 in NCASI 2004). Lastly, changes in soil properties resulting from soil compaction can lead to reduced oxygen availability and root physiology, which can increase incidence of pathogens (Jacobs and MacDonald 1990 in NCASI 2004).

Despite these and other studies, our ability to predict to how trees will respond to soil compaction under field conditions is limited. While there is much research that establishes relationships between root growth and growth limiting factor in soil, most of the available research is on agricultural crops and under laboratory or greenhouse conditions. In the field, however, variations in root growth factors occur in response to short-term and seasonal cycles of soil wetting and drying. At a given site, root growth may be limited by poor aeration during wet periods and by mechanical impedance during dry periods (Carr 1987). Also, unlike most agricultural plants, trees are long lived and have a greater capacity to adapt to poor soil conditions through changes in their root system, limiting our predictions to generalizations for the responses of tree growth to soil compaction.

Impacts on Soil Productivity. While information is available that shows that soil compaction by heavy equipment is likely to impact root growth of trees to some degree, it is beneficial to translate these impacts into effects on overall productivity. In the National Forest Management Act of 1976 (16 USC 472a), “long-term productivity” is defined as the potential of the land to produce wood at consistent levels of quality and volume over hundreds of years without significant reduction in the quality of soil and water resources. It is important to recognize however, that potential wood production is impacted by factors other than just soil, including climate, tree species, stand density, silvicultural practices, and time (Berger et al 2004).

It is difficult to isolate all these factors from one another, because a change may be enhanced or counterbalanced by changes in other factors. For instance, a reduction in soil quality may be offset by silvicultural practices that alter tree species, stand density, competing vegetation or nutrient availability. It is important to keep mind the various factors that can influence productivity when weighing the impact of soil disturbances.

During commercial thinnings and selection harvests, ground-based equipment is typically used for group or individual tree selection. Because fewer trees are removed than in clearcutting, soil disturbances are usually less widespread and less severe. Roots or boles of residual trees, however, can be physically damaged by equipment and logs. When heavy equipment is used in these situations and soil compaction, churning, mixing or displacement is observed, short-term reductions in diameter or basal area growth of 15% or more is commonly observed. Larger growth reductions are observed with greater severity of soil disturbance (NCASI 2004).

In clear-cuts, lower growth rates are usually reported on skid trails, however these is little information on how that translates into changes in stand volume or stand yield. In one study in Oregon, researchers observed yield loss after a 4.4-ha plot was tractor yarded. About 10% of the total area was in primary skid trails. Tree volumes on skid trails was 34 m^3/ha, 97 m^3/ha on transition zones, and 129 m^3/ha on control portions of the harvest. Reduced stocking in skid trails and transition zones accounted for a volume loss of 12% for the total plot (Wert and Thomas 1981 in NCASI 2004). In some cases, however, greater volume production is reported on skid trails because of lack of competing vegetation.

Soil compaction usually reduces tree growth potential. Sandy soils may see an increase in tree growth following compaction; however when combined with removal of organic matter, aspen productivity can be reduced by 15% or more (Stone et al 1999). Actual or measurable reductions in growth are not always observed, however, in part because soil disturbances can reduce vegetative competition. It is difficult to generalize the likelihood or severity of a decline in forest productivity because the consequences of soil disturbances are impacted by other site-specific, growth-determining factors. In most reports, short-term growth of seedlings or saplings on skid trails is less than on adjacent non-skid trail areas, but this may or may not result in a decline in overall forest productivity. Rather than trying to determine how much soil disturbance a site can handle without a decline in forest productivity, it is preferable to avoid soil disturbances in the first place.

In light of the uncertainty of the scope of the impact of soil compaction on tree growth and soil productivity it is recommended that the guidelines err on the side of caution by limiting the extent of roads, landings and skid trails and by minimizing traffic on areas susceptible to soil disturbances. Minimizing the potential for soil disturbances and avoiding susceptible sites are preferred over relying on natural recovery of degraded soils. The North American long-term soil productivity experiment found that soils rarely recovered from severe compaction in 10 years, regardless of their initial bulk densities (Powers et al 2005).

Water Quality

Applicable Guidelines: 2A, 3A,4A, ~~6~~5A, 6B, 8B, 9B, 10B, 11B

Rationale. Forests play a vital role in purifying and maintaining clean water for lakes, streams and wetlands. These forested areas adjacent to lakes, streams and wetlands help maintain water quality by:

- Providing shade and moderating stream temperatures
- Supplying large woody debris
- Filtering sediment, nutrients and other pollutants from surface water runoff (NCASI 2000).

One of the basic principles of sustainable forestry is to ensure that forestry management activites do not adversely affect water quality. Following Wisconsin's Best Management Practices (BMPs) for Water Quality provides foresters, loggers and landowners with practical and cost-effective methods to help protect clean water (Holaday 1995). Whole-tree harvests, however, remove about twice the biomass of bolewood-only clearcuts and there is increased potential for soil disturbance and erosion (Pierce et al 1993). As a result, BMPs must be closely adhered to and taking additional steps to protect water quality is recommended.

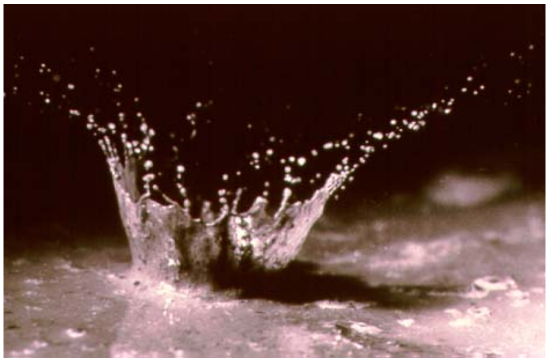

Image X. Raindrops fall at a speed of approximately 30 ft/sec and can splash bare soil up to two feet in the air and five feet away (Miller and Gardiner 2001).

Erosion Processes. During a rain event, precipitation is either intercepted by vegetation or it falls directly on the soil surface. When rain hits a tree or shrub, the rain wets the leaves and branches. Then the excess rainwater drips down from the canopy or flows down stems to the soil. The rainwater that is retained in the canopy of trees and shrubs is lost by evaporation. As much as one-quarter of the gross rainfall may be lost through evaporation in broadleaf trees in this region during the summer (White 1997).

When trees are harvested, there is less vegetation available to intercept rainfall and more rainwater will fall onto the soil. The litter layer on the forest floor both protects the soil from rain drops and soaks up water, preventing runoff (Johnson et al 1987). The interception of rainfall is not greatly reduced by timber harvesting, if the logging residue (stumps, branches and foliage) and remaining understory continue to intercept moisture (Anderson 1976).

Of the rain that reaches the soil, some will infiltrate or soak into the ground. Runoff occurs when water is being applied to soil faster than it can infiltrate. Runoff commonly occurs during snowmelt and sustained rain storms. Soil erosion occurs as soil particles become detached – either by the impact of raindrops on exposed soils or by the flow of runoff. As these soil particles separate, they are carried by runoff as suspended sediment. As the muddy water flows downhill, it picks speed and erosive force, scouring channels along the way and picking up more sediment (Anderson et al 1976). Eventually the runoff may reach a lake, stream or wetland, depositing sediment and other pollutants.

Table X. Examples of Soil Erosion Impacts

Where the Soil is Eroded	Where the Soil is Deposited
▪ Loss of soil nutrients ▪ Decreased soil tilth ▪ Lower levels of soil organic matter ▪ Decreased forest productivity	▪ Decreased water clarity as soil clouds the water ▪ Degraded fish and wildlife habitat as sediment settles on gravel spawning beds and buries aquatic vegetation ▪ Injured fish as sediment cuts their gills ▪ Reduced oxygen levels in water, stressing fish, as nutrients carried by the runoff fuel algal blooms

The Universal Soil Loss Equation (USLE) and the revised USLE (RUSLE) were developed to estimate soil loss from cultivated fields, rangelands and forestlands. These models estimate soil loss at a site by considering the influence of the following factors:

- the amount and intensity of rainfall the area receives (R),
- the erodibility of the soil (K),
- the length and degree of slope of the area (LS),
- the vegetative cover of the area (C), and
- what practices are used to control soil erosion (P) (Miller and Gardiner 2001).

The potential for soil erosion can increase based on a changes in these factors. Silt loams erode more easily than clays. Long steeps slopes are more prone to erosion than flat areas. Areas that are poorly vegetated are more likely to erode than well-vegetated areas (Anderson et al 1976). Biomass harvesting may increase soil loss at a site by decreasing the vegetative cover over the area.

In order to limit the potential for soil erosion, the guidelines focus on high risk areas and recommend maintaining vegetative cover in these areas by limiting harvests to bolewood utilization. The tops and limbs of harvests, small unmerchantable trees and brush will be left at these sites, helping to prevent soil erosion.

Roads, Landings and Skid Trails. The primary cause of degraded water quality associated with forest management activities is erosion from disturbed areas such as roads, landings and skid trails. Poorly designed and sited roads, landings and skid trails increase the likelihood that surface water runoff will intersect the access system, increasing the potential for erosion and sedimentation (Germain and Munsell 2005; Patric 1976). If the amount of land devoted to this infrastructure is limited, this will aid in preventing soil erosion.

Erosion Prone Sites. Some landscapes, such as steeply sloping landscapes with loamy soils, are susceptible to soil erosion (Grigal 2000). To easily define and identify these erosion prone sites, the guidelines rely on “severe” or very severe” erosion hazard ratings (off-road, off-trail) developed by the USDA NRCS. The erosion hazard rating indicates the hazard of soil loss from off-road and off-trail areas after disturbance activities that expose the soil surface. The ratings are based on slope and soil erosion factor K. The soil loss is caused by sheet or rill erosion in off-road or off-trail areas where 50 to 75 percent of the surface has been exposed by logging, grazing, mining, or other kinds of disturbance.

The hazard ratings are "slight," "moderate," "severe," or "very severe." A rating of "slight" indicates that erosion is unlikely under ordinary climatic conditions; "moderate" indicates that some erosion is likely and that erosion-control measures may be needed; "severe" indicates that erosion is very likely and that erosion-control measures, including revegetation of bare areas, are advised; and "very severe" indicates that significant erosion is expected, loss of soil productivity and off-site damage are likely, and erosion-control measures are costly and generally impractical.

The erosion hazard is based on numerical ratings that indicate the severity of individual limitations. The ratings are shown as decimal fractions ranging from 0.01 to 1.00. They indicate gradations between the point at which a soil feature has the greatest negative impact on the specified aspect of forestland management (1.00) and the point at which the soil feature is not a limitation (0.00) (USDA NRCS 2008).

The guidelines recommend retaining fine woody materials (FWM) on these erosion prone sites in order to protect the forest floor and to minimize the potential for soil erosion.

Dry Washes and Non-Navigable Streams. The guidelines retain fine woody materials (FWM) in a 35-foot buffer around dry washes and non-navigable. These water resources, unlike navigable streams and lakes, do not have minimum required basal area to be retained in a riparian management zone (RMZ) following harvest. To ensure that these water resources are adequately protected during biomass harvest, FWM is retained in order to protect the forest floor, prevent soil erosion, capture any eroded soil, reduce nutrient losses and preserve some wildlife habitat (Johnson et al 1987). A 35-foot wide partially harvested buffer has also been shown to allow only minor increases in stream temperature on headwater streams (Wilkerson et al 2006). The guidelines are consistent with Minnesota's RMZs for dry-washes.

Table X. Comparison of Wisconsin and Minnesota Guideline Widths

Water Resource	WI RMZ	MN Filter Strip	MN RMZ
Dry washes			25 feet
Non-navigable streams	35 feet		
Navigable intermittent streams	35 feet	50-150 feet	50-200 feet
Navigable perennial streams	100 feet	50-150 feet	50-200 feet
Lakes	100 feet	50-150 feet	50-200 feet
Wetlands		50-150 feet	

Wetlands. The guidelines retain fine woody materials (FWM) in a 100-foot buffer around wetlands. Wetlands, unlike navigable streams and lakes, do not have any RMZ or buffer requirements around them. To provide habitat, protect water quality and prevent erosion, a 100-foot buffer which retains FWM is recommended. Habitat management guidelines for amphibians and reptiles in the Midwest recommend a 50 to 500 foot buffer, if possible (Kingsbury and Gibson 2002). The 100-foot wetland buffer guideline is consistent with Minnesota's wetland filter strips.

Literature Cited

Aber, J.D., K.J. Nadelhoffer, P. Steudler, and J.M. Melillo. 1989. Nitrogen saturation in northern forest ecosystems. *Bioscience* 39: 378–386.

Alban, D.H. 1985. Seasonal changes in nutrient concentration and content of aspen suckers in Minnesota. *Forest Science* 31(3):785-794.

Alban, D.H., D.A. Perala, and B.E. Schlaegel. 1978. Biomass and nutrient distribution in aspen, pine, and spruce stands on the same soil type in Minnesota. *Can J. For. Res.* 8(3): 290–299

Amaranthus, M.P. 1998. The importance and conservation of ectomycorrhizal fungal diversity in forest ecosystems: lessons from Europe and the Pacific Northwest. USDA For. Serv., Pac. NW Res. Stn., Gen. Tech. Rep. PNW-GTR-431

Anderson, H. W., M. D. Hoover and K. G. Reinhart. 1976. *Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Supply*. USDA Forest Service General Technical Report PSW-18.

Astrom, M., M. Dynesius, K. Hylander, and C. Nilsson. 2005. Effects of slash harvest on bryophytes and vascular plants in southern boreal forest clear-cuts. *J. Appl. Ecol.* 42:1194-1202

Attiwill, P.A., and M.A. Adams. 1993. Tansley Review No. 50. Nutrient Cycling in Forests *New Phytologist* 124(4): 561-582

Bailey, S.W., S.B. Horsley, R.P. Long, and R.A. Hallett. 2004. Influence of edaphic factors on sugar maple nutrition and health on the Allegheny Plateau. *Soil Sci. Soc. Am. J.* 68:243-252

Ballard, T. M. 2000. Impacts of forest management on northern forest soils. *Forest Ecology and Management* 133: 37-42.

Battigelli, J.P., J.R. Spence, D.W. Langor, and S.M. Berch. 2004. Short-term impact of forest soil compaction and organic matter removal on soil mesofauna density and oribatid mite diversity. *Can. J. For. Res*. 34: 1136-1149.

Benson, L. Forest changes linked to global warming. Minnesota Public Radio. March 8, 2006. http://minnesota.publicradio.org/display/web/2006/03/03/globaltrees/. Accessed June 2008.

Berger, A. L., K. J. Puettmann and G. E. Host. 2004. Harvesting impacts on soil and understory vegetation: the influence of season of harvest and within-site disturbance patterns on clear-cut aspen stands in Minnesota. *Can. J. For. Res.* 34: 2159-2168.

Bassett, J.R. 1984. Red pine plantation management in the Lake States: a review. IFSIM Publication No. 3. University of Michigan, School of Natural Resources. Ann Arbor, MI. 15 p.

Belleau. A., S. Brais, and D. Pare. 2006. Soil nutrient dynamics after harvesting and slash treatments in boreal aspen stands. *Soil Sci. Soc Am. J.* 70:1189-1199.

Bockheim, J.G. 1997. Soils in a hemlock-hardwood ecosystem mosaic in the Southern Lake Superior Uplands. *Can. J. For. Res*. 27: 1147-1153.

Bockheim, J.G., and S. E. Crowley. 2002. Ion Cycling in Hemlock–Northern Hardwood Forests of the Southern Lake Superior Region: A Preliminary Study. *J. Environ. Qual.* 31(5):1623-9.

Bockheim, J.G., H. Park, and J. Gallagher. 2005. Genotypic variation and recovery of Populus tremuloides from biomass removal and compaction in northern Wisconsin, USA. *Can. J. For. Res.* 35: 221-228.

Boyle, J.R., J.J. Phillips, and A.R. Ek. 1973. "Whole Tree" Harvesting: Nutrient Budget Evaluation. *Journal of Forestry* 71(12):760-762.

Brakenhielm, S. and Q. Liu. 1998. Long-term effects of clear-felling on vegetation dynamics and species diversity in a boreal pine forest. *Biod. and Cons.* 7:207-220.

Bunnell, F.L., I. Houde, B. Johnston, and E. Wind. 2002. How dead trees sustain live organisms in western forests. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-181

Campbell, J.L., and S.T. Gower. 2000. Detritus production and soil N transformations in old-growth eastern hemlock and sugar maple stands. *Ecosystems* 3: 185-192.

Carlson, W.C. 1986. Root system considerations in the quality of loblolly pine seedlings. *Southern Journal of Applied Forestry*, 10: 87-92.

Carr, W. M. 1987. *The Effect of Landing Construction on Some Forest Soil Properties*. Vancouver, B.C.. Terrasol and BC Economic and Regional Development Agreement.

Chojnacky, D.C., R.A. Mickler, L.S. Heath, and C.W. Woodall. 2004. Estimates of down woody materials in Eastern US forests. *Env. Mgmt.* 33 (1): S44-55

Chen, H.Y.H., K. Klinka, and R.D. Kabzems. 1998. Site index, site quality, and foliar nutrients of trembling aspen: relationships and predictions. *Can J For Res* 28(12):1743-1755

Christensen, N.L., A.M. Bartuska, J.H. Brown, S. Carpenter, C. D'Antonio, R. Francis, J.F. Franklin, J.A. MacMahon, R.F. Noss, D.J. Parsons, C.H. Peterson, M.G. Turner, and R.G. Woodmansee. 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. *Ecol. Appl*. 6(3): 665-691

Covington. W.W. 1981. Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods. *Ecology* 62:41-48.

Crow, T.R. 1978. Biomass and production in three contiguous forests in northern Wisconsin. *Ecology* 59:265-273

Crow, T.R., A. Haney, and D.M. Waller. 1994. Report on the scientific roundtable on biological diversity convened by the Chequamegon and Nicolet National Forests. USDA For. Serv., NCFES, Gen. Tech. Rep. NC-166

Cumming, J.R., and L.H. Weinstein. 1990. Aluminum-mycorrhizal interactions in the physiology of pitch pin seedlings. *Plant and Soil* 125: 7-18.

DeGraaf, R.M. and A.L. Shigo. 1985. Managing cavity trees for wildlife in the Northeast. USDA For. Serv., NEFES, GTR NE-101

DeGraaf, R.M., M. Yamasaki, W.B. Leak, and J.W. Lanier. 1992. New England wildlife: management of forested habitats. USDA For. Serv., NE For. Exp. Stn., Gen. Tech. Rep. NE-144.

Demaynadier, P.G. and M.L. Hunter Jr. 1998. Effects of silvicultural edges on the distribution and abundance of amphibians in Maine. *Conserv. Biol*. 12(2): 340-352

Dexter, A.R. 1978. Tunneling in soil by earthworms. *Soil Biology and Biochemistry*, 10: 447-449.

Drury, C.F., R.P. Voroney, and E.G. Beauchamp. 1991. Availability. of NH$_4$ _–N to microorganisms and the soil internal N cycle. *Soil Biol. Biochem*. 23:165–169.

Eavis, B.W. 1972. Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sand loam soil. *Plant and Soil*, 36: 613-622.

Ecke, F., O. Lofgren, and D. Sorlin. 2002. Population dynamics of small mammals in relation to forest age and structural habitat factors in northern Sweden. *J. Appl. Ecol.* 39:781-792

Edwards, N.T., and W.F. Harris. 1977. Carbon cycling in a mixed deciduous forest floor. *Ecology* 58: 431-437.

EPA (United States Environmental Protection Agency). 2005. Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture. EPA 430-R-05-006. Office of Atmospheric Programs, Washington DC.

Fassnacht, K.S., and S.T. Gower. 1999. Comparison of the litterfall and forest floor organic matter and nitrogen dynamics of upland forest ecosystems in north central Wisconsin. *Biogeochemistry* 45: 265-284.

Federer, C.A. 1984. Organic matter and nitrogen content of the forest floor in even-aged northern hardwoods. *Can. J. For. Res.* 14: 763-767.

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

Foster, D.R. and D.A. Orwig. 2006. Preemptive and salvage harvesting of New England forests: when doing nothing is a viable alternative. *Conserv. Biol.* 20(4)959-970.

Franklin, J.F., R.J. Mitchell, and B.J. Palik. 2007. Natural disturbance and stand development principles for ecological forestry. USDA For. Serv., N. Res. Stn., GTR NRS-19, 44pp.

Fraver, S., R.G. Wagner, and M. Day. 2002. Dynamics of coarse woody debris following gap harvesting in the Acadian forest of central Maine, U.S.A. *Can. J. For. Res*. 32:2094-2105.

Freedman, B., R. Morash, and A.J. Hanson. 1981. Biomass and nutrient removals by conventional and whole-tree clear-cutting of a red spruce – balsam fir stand in central Nova Scotia. *Can. J. For. Res.* 11(2): 250–258.

Fridman, J. and M. Walheim. 2000. Amount, structure, and dynamics of dead wood on managed forestland in Sweden. *For. Ecol. and Mgmt.* 131: 23-36.

Fujinuma, R., J. Bockheim and N. Balster. 2005. Base-cation cycling by individual tree species in old-growth forests of Upper Michigan, USA. *Biogeochemistry* 74(3): 357-376.

Gerloff, G.C., D.G. Moore, and J.T. Curtis. 1966. Selective absorption of mineral elements by native plants of Wisconsin. *Plant and Soil* 25(3): 393-405.

Germail R. H. and J. F. Munsell. 2005. How much land is needed for the harvest access system on nonindustrial private forestlands dominated by northern hardwoods? *Northern Journal of Applied Forestry*, 22(4): 243-247.

Goodburn, J.M. and C.G. Lorimer. 1998. Cavity trees and coarse woody debris in old-growth and managed northern hardwood forests in Wisconsin and Michigan. *Can. J. For. Res.* 28:427-438

Gosz, J.R., G.E. Likens, and F.H. Bormann. 1972. Nutrient content of litter fall on the Hubbard Brook Experimental Forest, New Hampshire. *Ecology* 53: 769-784.

Gosz, J.R., G.E. Likens, and F.H. Bormann. 1976. Organic matter and nutrient dynamics of the forest and forest floor in the Hubbard Brook Forest. *Oceologia* 22: 305-320.

Gough, C.M., C.S. Vogel, K.H. Harrold, K. George, and P.S. Curtis. 2007. The legacy of harvest and fire on ecosystem carbon storage in a north temperate forest. *Global Change Biology* 13: 1935–1949.

Gower, S.T., A. McKeon-Ruediger, A. Reitter, M. Bradley, D.J. Refkin, T. Tollefson, F.J. Souba Jr., A. Taup, L. Embury-Williams, S. Schiavone, J. Weinbauer, A.C. Janetos, and R. Jarvis. 2006. *Following the paper trail: the impact of magazine and dimensional lumber products on greenhouse gas emissions. A case study*. The H. John Heinz III Center for Science, Economics, and Environment. Washington, DC. 102 p.

Gower, S.T. 2003. Patterns and mechanisms of the forest carbon cycle. *Annu. Rev. Environ. Resour.* 28: 169–204.

Gradowski, T. and S.C. Thomas. 2006. Phosphorus limitation of sugar maple growth in Central Ontario. *For. Ecol. & Mgmt* 226(1-3):104-109.

Gressel, N., J.G. McColl, C.M. Preston, R.H. Newman, and R.F. Powers. 1996. Linkages between phosphorus transformations and carbon decomposition in a forest soil. *Biogeochemistry* 33:97-123.

Grigal, D.A. 2000. Effects of extensive forest mgmt on soil productivity. *For. Ecol. & Mgmt* 128:167-185.

Grigal, D.F., and E.D. Vance. 2000. Influence of soil organic matter on forest productivity. *New Zealand J. For. Sci.* 30:169-205.

Grigal, D.F. 2004. An Update of Forest soils. A Technical Paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota.

Grigal, D.F, and P.C. Bates. 1992. Forest Soils: A Technical Paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota. Online at http://iic.gis.umn.edu/download/geis/documnts.html

Gunnarsson, B., K. Nitterus, and P. Wirdenas. 2004. Effects of logging residue removal on ground-active beetles in temperate forests. *For. Ecol. and Mgmt.* 201:229-239

Hacker, J.J. 2005. *Effects of logging residue removal on forest sites – A literature review.* Report commissioned by West Central Wisconsin Regional Planning Commission, Eau Claire, WI.

Hamburg, SP, Yanai, RD, Arthur, MA, Blum, JD, Siccama, TG. 2003. Biotic Control of Calcium Cycling in Northern Hardwood Forests: Acid Rain and Aging Forests. *Ecosystems* 6: 399–406.

(pdf: http://sambuca.umdl.umich.edu/bitstream/2027.42/42435/1/30060399.pdf)

Hames, R.S., J.D. Lowe, S. B. Swarthout, and K.V. Rosenberg. 2006. Understanding the Risk to Neotropical Migrant Bird Species of Multiple Human-Caused Stressors: Elucidating Processes Behind the Patterns. *Ecology and Society* 11(1): 24. **[online] URL: http://www.ecologyandsociety.org/vol11/iss1/art24**

Hammond, H.E.J., D.W. Langor, and J.R. Spence. 2004. Saproxylic beetles (Coleoptera) using Populus in boreal aspen stands of western Canada: spatiotemporal variation and conservation of assemblages. *Can. J. For. Res.* 34:1-19.

Harmon, M.E., W.K. Ferrell, J.F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247: 699-702.

Howard, E. A., S.T. Gower, J.A. Foley, and C.J. Kucharik. 2004. Effects of logging on carbon dynamics of a jack pine forest in Saskatchewan, Canada. *Global Change Biology* 10: 1267–1284

Hassett, J.E. and D.R. Zak. 2005. Aspen harvest intensity decreases microbial biomass, extracellular enzyme activity, and soil nitrogen cycling. *Soil Sci. Soc. Am J* 69:227-235.

Helms, J.A. (Editor). 1998. *The Dictionary of Forestry*. Society of American Foresters.

Herbeck, L.A. and D.R. Larsen. 1999. Plethodontid salamander response to silvicultural practices in Missouri Ozark forests. *Conserv. Biol.* 13(3):623-632

Holaday, Steve. 1995. *Wisconsin's Forestry Best Management Practices for Water Quality Field Manual for Loggers, Landowners and Land Managers*. Wisconsin Department of Natural Resources, Publication FR-093.

Hole, F.D. 1976. Soils of Wisconsin. University of Wisconsin Press, Madison, WI. 223 p.

Hornbeck, J.W. 1977. Nutrients: A major consideration in intensive forest management. In: Proceedings of the Symposium on Intensive Culture of Northern Forest Types. Gen. Tech. Rep. NE-29. Broomall, PA: U. S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 241-250.

Hornbeck, J.W. 1986. Nutrient cycles and forest productivity. In: Smith, Tattersall C.; Wayne, MC.; Tritton, LM.; [Eds]. Proceedings of the 1986 symposium on the productivity of northern forests following biomass harvesting. Gen. Tech. Rep. NE-115a. Broomall, PA: U. S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 104 p. **Online http://www.treesearch.fs.fed.us/pubs/4162.**

Hornbeck, J.W., C.W. Martin, R.S. Pierce, F.H. Bormann, G.E. Likens, and J.S. Eaton. 1986. Clearcutting Northern Hardwoods: Effects on Hydrologic and Nutrient Ion Budgets. *Forest Sci.* 32(3):667-686.

Hornbeck, J. W., C. W. Martin and C. T. Smith. 1986. Protecting forest streams during whole-tree harvesting. *North. J. Appl. For.* 3: 97-100.

Horsley, S.B., S.W. Bailey, T.E. Ristau, R.P. Long, and R.A. Hallett. 2008. Linking environmental gradients, species composition, and vegetation indicators of sugar maple health in the northeastern United States. Can. J. For. Res. 38, *In press*.

Hura, C.E. and T.R. Crow. 2004. Woody debris as a component of ecological diversity in thinned and unthinned northern hardwood forests. *Nat. Areas. J.* 24:57-64

Hyvonen, R., B. Olsson, H. Lundkvist, and H. Staaf. 2000. Decomposition and nutrient release from *Picea abies* (L.) Karst. and *Pinus sylvestris* L. logging residues. *For. Ecol. and Mgmt*. 126: 97-112.

Hyvarinen, E., J. Kouki, and P. Martikainen. 2006. Fire and green-tree retention in conservation of red-listed and rare deadwood-dependent beetles in Finnish boreal Forests. *Conserv. Biol.* 20(6):1711-1719

Jacobs, K.A. and J.D. MacDonald. 1990. *The effect of low oxygen stress on cork oak and development of phytophthora root rot*. University of California Cooperative Extension, 27(5).

Jentschke, G., and D.L. Godbold. 2000. Metal toxicity and extomycorrhizas. *Physiologia Plantarum* 109: 107-116.

Johnson, D.W., and P.S. Curtis. 2001. Effects of forest management on C and N storage: meta analysis. *For. Ecol. and Mgmt.* 140: 227-238.

Johnson, A.H., A.J. Friedland, E.K. Miller, and T.G. Siccama. 1994. Acid rain and soils of the Adirondacks. III. Rates of soil acidification in a montane spruce–fir forest at Whiteface Mountain, New York. *Can. J. For. Res.* 24(4): 663–669.

Johnson, D.W., G.S. Henderson and D.E. Todd. 1988. Changes in nutrient distribution in forests and soils of Walker Branch watershed, Tennessee, over an eleven-year period. *Biogeochemistry* 5(3): 275-293

Johnson, D.W., J.M. Kelly, W.T. Swank, D.W. Cole, H. Van Miegroet, J.W. Hornbeck, R.S. Pierce and D. Van Lear. 1988. The effects of leaching and whole-tree harvesting on cation budgets of several forests. *J. of Environ. Qual* 17:418-424.
(pdf: http://cwt33.ecology.uga.edu/publications/publications/5th%20group/pdf/756.pdf)

Johnson, D.W. and D.E. Todd. 1987. Nutrient export by leaching and whole-tree harvesting in a loblolly pine and mixed oak forest. *Plant and Soil* 102(1): 99-109.

Johnson, D.W., D.C. West, D.E. Todd and L.K. Mann. 1982. Effects of Sawlog vs. Whole-Tree Harvesting on the Nitrogen, Phosphorus, Potassium, and Calcium Budgets of an Upland Mixed Oak Forest. *Soil Sci. Soc. Am. J.* 46: 1304-1309.

Jorgensen, J.R., C.G. Wells, and L.J. Metz. 1975. The nutrient cycle: key to continuous forest production. *Journal of Forestry* 73: 400-403.

Jurgensen, M.F., R.T. Graham, M.J. Larsen, and A.E. Harvey. 1992. Clear-cutting, woody residue removal, and nonsymbiotic nitrogen fixation in forest soils of the Inland Pacific Northwest. *Can. J. For. Res.* 22: 1172-1178.

Jurgensen, M.F., A.E. Harvey, R.T. Graham, D.S. Page-Dumroese, J.R. Tonn, M.J. Larsen, and T.B. Jain. 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland northwest forests. *For. Sci.* 43: 234-251.

Jurgensen, M.F., and A.L. Leaf. 1965. Soil moisture—fertility interactions related to growth and nutrient uptake of red pine. *Soil Sci. Soc. Am. Proc*. 29: 294-299.

Juice, S.M., T.J. Fahey, T.G. Siccama, C.T. Driscoll, E.G. Denny, C. Eagar, N.L. Cleavitt, R. Minocha, and A.D. Richardson. 2006. Response of sugar maple to calcium addition to northern hardwood forest. *Ecology* 87(5):1267-80.

Karnosky, D.F., J.M. Skelly, K.E. Percy, and A.H. Chappelka. 2007. Perspectives regarding 50 years of research on effects of tropospheric ozone air pollution on US forests. *Environmental Pollution* 147:.489-506.

Kingsbury, B. and J. Gibson. 2002. *Habitat Management Guidelines for Amphibians and Reptiles of the Midwest.* Partners in Amphibian and Reptile Conservation (PARC).

Kim, C., T.L. Sharik, and M.F. Jurgensen. 1996. Canopy cover effects on mass loss, and nitrogen and phosphorus dynamics from decomposing litter in oak and pine stands in northern Lower Michigan. *For. Ecol. and Mgmt*. 80: 13-20.

Klugh, K.R., and J.R. Cumming. 2007. Variations in organic acid exudation and aluminum resistance among arbuscular mycorrhizal species colonizing *Liriodendron tulipifera*. *Tree Phys*. 27: 1103-1112.

Kolka, R.K., D.F. Grigal, and E.A. Nater. 1996. Forest soil mineral weathering rates: use of multiple approaches. *Geoderma* 73:1-21 **(pdf: http://www.ncrs.fs.fed.us/pubs/jrnl/1996/nc_1996_Kolka_001.pdf)**

Komonen, A. 2003. Hotspots of insect diversity in boreal forests. *Conserv. Biol.* 17(4):976-981

Kozlowski, T.T., and S.G. Pallardy. 1997. *Growth control in woody plants.* Academic Press, San Diego, CA. 641 p.

Lichter, J. 1998. Primary succession and forest development on coastal Lake Michigan sand dunes. *Ecological Monographs* 68(4):487-510.

Likens, G.E., F.H. Bormann, R.S. Pierce, and W.A. Reiners. 1978. Recovery of a deforested ecosystem. *Science* 199:492-496.

Lindberg, S.E. and R.C. Harriss. 1981. The role of atmospheric deposition in an Eastern united States deciduous forest. *Water, Air, and Soil Pollution* 16: 13-31.

Lindberg, S.E., G.M. Lovett, D.D. Richter, and D.W. Johnson. 1986. Atmospheric deposition and canopy interactions of major ions in a forest. *Science* 231(4734), pp 141-145.

Lindo, Z., and S. Visser. 2003. Microbial biomass, nitrogen and phosphorus mineralization, and mesofauna in boreal conifer and deciduous forest floors following partial and clear-cut harvesting. *Can. J. For. Res. 33*: 1610-1620.

MacDonald, N.W., A.J. Burton, H.O. Liechty, J.A. Witter, K.S. Pregitzer, G.D. Mroz, and D.D. Richter. 1992. Ion leaching in forest ecosystems along a Great Lakes air pollution gradient. *J. Env. Qual. 21*: 614-623.

MacLean, D.A. and R.W. Wein. 1977. Nutrient accumulation for postfire jack pine and hardwood succession patterns in New Brunswick. *Can. J. For. Res.* 7(4): 562–578.

Mälkönen, E. 1976. Effects of whole tree harvesting on soil fertility. *Silva Fennica* 10:157-164.

Mann, L.K., D.W. Johnson, D.C. West, D.W. Cole, J.W. Hornbeck, C.W. Martin, H. Reikerk, C.T. Smith, W.T. Swank, L.M. Tritton, D.H. Van Lear. 1988. Effects of Whole-Tree and Stem-Only Clearcutting on Postharvest Hydrologic Losses, Nutrient Capital, and Regrowth. *For. Sci.* 34(2):412-428. **(pdf: http://cwt33.ecology.uga.edu/publications/publications/5th%20group/pdf/700.pdf)**

Manning, J.A. and W.D. Edge. 2005. Small mammal responses to fine woody debris and forest fuel reduction in southwest Oregon. *J. Wldl. Mgmt*. 72(3):625-632

Martin, C. W. and J. W. Hornbeck. 1994. Logging in New England need not cause sedimentation of streams. *North. J. Appl. For.* 11(1): 17-23.

McComb, B.C. 2007. Wildlife *habitat management: concepts and applications in forestry.* CRC Press

McGee, G.G., D.J. Leopold, and R.D. Nyland. 1999. Structural characteristics of old-growth, maturing, and partially cut northern hardwood forests. *Ecol. Appl.* 9(4):1316-1329

McInnis, B.G. and M.R. Roberts. 1994. The effects of full-tree and tree-length harvest on natural regeneration. *N. J. Appl. For*. 11(4):131-137.

MFRC. 2005. Sustaining Minnesota Forest Resources: Voluntary Site-Level Forest Management Guidelines for Landowners, Loggers and Resource Managers. Minn. For. Resour. Council. St. Paul, Minnesota

MFRC. 2007. Biomass harvesting on forest management sites in Minnesota. Minn. For. Resour. Council. St. Paul, Minnesota

MIDNR. 2006. Within-stand retention guidance. Michigan Dept. Natl. Resour, For., Min., & For. Mgmt.

Miller, R.W. and D. T. Gardiner. 2001. *Soils in Our Environment*. Prentice Hall.

Morrison, I.K. 1990. Organic matter and mineral distribution in an old-growth *Acer saccharum* forest near the northern limit of its range. *Can. J. For. Res.* 20(9): 1332–1342.

Morrison, I.K., and Foster, N.W. 1979. Biomass and element removal by complete-tree harvesting of medium rotation forest stands. In: A. L. Leaf, ed.Proceedings, Impact of intensive harvesting on forest nutrient cycling; 1979 August 13-16; Syracuse, NY. State University of New York, College of Environmental Science and Forestry. 421 p.

National Atmospheric Deposition Program. *Data Access.* http://nadp.sws.uiuc.edu/ (March 4, 2008).

National Commission on Science for Sustainable Forestry. 2005. Science, biodiversity, and sustainable forestry. National Council for Science and the Environment, Wash. D.C. 52 pp.

National Commission on Science for Sustainable Forestry. 2007. Conserving biodiversity through sustainable forestry. National Council for Science and the Environment, Wash. D.C. 174 pp.

National Council for Air and Stream Improvement, Inc. (NCASI). 2000. *Handbook of control and mitigation measures for silvicultural operations.* Unpublished draft Technical Bulletin. Research Triangle Park, N.C.: National Council for Air and Stream Improvement, Inc.

National Council for Air and Stream Improvement, Inc. (NCASI). 2004. *Effects of heavy equipment on physical properties of soils and on long-term productivity: A review of literature and current research.* Technical Bulletin No. 887.

Niemela, J. 1997. Invertebrates and boreal forest management. *Conserv. Biol*. 11(3):601-610

Norden, B., M. Ryberg, F. Gotmark, and B. Olausson. 2004. Relative importance of coarse and fine woody debris for the diversity of wood-inhabiting fungi in temperate broad-leaf forests. *Biol. Conserv.* 117:1-10

Nyland, R.D. 1996. Silviculture: Concepts and Applications. McGraw-Hill.

Olsson, B.A. and H. Staaf. 1995. Influence of harvesting intensity of logging residues on ground vegetation in coniferous forests. *J. Appl. Ecol.* 32(3):640-654.

OMNR. 2002. Forest management guide for natural disturbance pattern emulation, version 3.1. Ont. Min. Nat. Resour. Queens Printer for Ontario. Toronto

Padley, E.A.. 1989. Associations among glacial landforms, soils, and vegetation in northeastern lower Michigan. Ph.D. Dissertation, Michigan State University. East Lansing, MI. 279 pp.

Pastor, J. 1989. Nutrient cycling in aspen ecosystems. Pages 21-38 in *Aspen Symposium '89*, R.D. Adams, editor. U.S. Forest Service General Technical Report NC-140.

Pastor, J., J.D. Aber, C.A. McClaugherty, and J.M. Melillo. 1984. Aboveground production and N and P cycling along a nitrogen mineralization gradient on Blackhawk Island, Wisconsin. *Ecol.* 65: 256-268.

Pastor, J. and J.G. Bockheim. 1981. Biomass and production of an Aspen-Mixed-Hardwood Spodosol Ecosystem in Northern Wisconsin. *Can J For Res* 11(1):132-138.

Pastor, J. and J.G. Bockheim. 1984. Distribution and Cycling of Nutrients in an Aspen-Mixed-Hardwood Spodosol Ecosystem in Northern Wisconsin. *Ecology* 65(2):339-353.

Patric, J. H. 1976. Soil erosion in the eastern forest. *Journal of Forestry*, 741: 671-676.

Perala, D.A. 1979. Regeneration and productivity of aspen grown on repeated short rotations. USDA Forest Service Research Paper NC-176.

Perala, D.A. and D.H. Alban. 1982. Biomass, Nutrient Distribution and Litterfall in Populus, Pinus and Picea Stands on Two Different Soils in Minnesota. *Plant and Soil* 64(2): 177-192.

Phillipson, J.J. and M.P. Coutts. 1977. The influence of mineral nutrition on the root development of trees. II. The effects of specific nutrient elements on growth of individual roots of Sitka spruce. *Journal of Experimental Botany*, 28: 864-871.

Pierce, F.J., R.H. Dowdy, and D.F. Grigal. 1982. Concentrations of six trace metals in some major Minnesota soil series. *J. Environ. Qual* 11:416-422.

Pierce, R. S., J. W. Hornbeck, C. W. Martin, L. M. Tritton, C. T. Smith, C. A. Federer and H. W. Yawney. 1993. *Whole-tree Clearcutting in New England: Manager's Guide to Impacts on Soils, Streams, and Regeneration* USDA For. Serv., NEFES, GTR NE-172.

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

Pregitzer, K.S., and E.S. Euskirchen. 2004. Carbon cycling and storage in world forests: biome patterns related to forest age. Global *Change Biology* 10: 1–26.

Pregitzer, K.S., D.R. Zak, A.J. Burton, J.A. Ashby, and N.W. MacDonald. 2004. Chronic nitrate additions dramatically increase the export of carbon and nitrogen from northern hardwood ecosystems. *Biogeochemistry* 68: 179-197.

Pritchett, W.L. 1979. *Properties and Management of Forest Soils*. Wiley & Sons. New York, NY. 500 p.

Qualls, R.G., B.L. Haines, and W.T. Swank. 1991. Fluxes of dissolved organic nutrients and humic substances in a deciduous forest. *Ecology* 72: 254-266.

Reich, P.B., D.F. Grigal, J.D. Aber, and S.T. Gower. 1997. Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. *Ecology* 78: 335-347.

Rennie, P.J. 1955. The uptake of nutrients by mature forest growth. *Plant and Soil* 7: 49-95

Rogers, E. and D. Premo. 1997. *Managing for biodiversity.* White Water Associates, Inc., Amasa, MI., 34pp.

Roskoski, JP. 1980. Nitrogen fixation in hardwood forests of the northeastern United States. *Plant and Soil* 54(1): 33-44

Ruark, B.A. and Bockheim, J.G. 1988. Biomass, net primary production, and nutrient distribution for an age sequence of Populus tremuloides ecosystems. *Can. J. For. Res.* 18: 435-43.

Rutkowski , D.R. and R. Stottlemyer. 1993. Composition, biomass and nutrient distribution in mature northern hardwood and boreal forest stands, Michigan. *Am. Midl. Nat.* 130:13-30.

Sager, E.P., and T.C.Hutchinson. 2006. Responses of secondary chemicals in sugar maple (*Acer saccharum*) seedlings to UV-B, springtime warming and nitrogen additions. *Tree Physiol.* 26(10):1351-1361.

Seymour, R.S. and M.L. Hunter Jr. 1999. Principles of ecological forestry. In: Hunter, M.L. Jr. (ed.) Composition in managing forests for biodiversity. Cambridge Univ. Press, NY. pp 22-61.

Scheller, R.M., and D.J. Mladenoff. 2005. A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA. *Global Change Biology* 11:.307–321.

Shetron, S.G., J.A. Sturos, E. Padley, and C. Trettin. 1988. Forest soil compaction: effect of multiple passes and loadings on wheel track surface soil bulk density. *Northern Journal of Applied Forestry*, 5: 120-123.

Silkworth, D.R. and D.F. Grigal. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen. *Soil Sci. Soc. Amer. J.* 46:626-31.

Skog, K.E. and G.A. Nicholson. 2000. Carbon sequestration in wood and paper products. USDA Forest Service Gen. Tech. Rept. RMRS-GTR-59.

Smeltzer, D.L., D.R. Bergdahl, and J.R. Donnelly. 1986. Forest ecosystem responses to artificially induced soil compaction. II. Selected microorganism populations. *Canadian Journal of Forest Research*, 16: 870-872.

Smith, D.M. 1962. *The Practice of Silviculture*, 7th ed. New York: Wiley.

Smith, C.T., M.C. Wayne, L.M. Tritton [Editors]. 1986. Proceedings of the 1986 symposium on the productivity of northern forests following biomass harvesting (Part 1 of 2) Gen. Tech. Rep. NE-115a. Broomall, PA: U. S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 104 p.

Smith, C.T., M.L. McCormack Jr., J.W. Hornbeck, and C.W. Martin. 1986. Nutrient and biomass removals from a red spruce – balsam fir whole-tree harvest. *Can. J. For. Res.* 16(2): 381–388.

St. Clair, S.B., J.E. Carlson, and J.P. Lynch. 2005. Evidence for oxidative stress in sugar maple stands growing on acidic, nutrient imbalanced forest soils. *Oecologia* 145(2): 257-268.

St. Clair, S.B., and J.P. Lynch. 2005. Base cation stimulation of mycorrhization and photosynthesis of sugar maple on acid soils are coupled by foliar nutrient dynamics. *New Phytol.* 165(2):581-90.

Stone, D. M., J. A. Gates and J. D. Elioff. 1999. Are we maintaining aspen productivity on sand soils? In: ZumBahlen, B. and A. R. Ek (comp.) *Improving Forest Productivity for Timber – A Key to Sustainability.* Proceedings of Conference, 1-3 December 1998. Duluth, MN. Department of Forest Resources, University of Minnesota: 177-184.

Swank, W.T. 1984. Atmospheric contributions to forest nutrient cycling. *Water Resources Bulletin* 20(3): 313-321.

Ter-Mikaelian, M.T., and M.D. Korzukhin. 1997. Biomass equations for sixty-five North American tree species. *Forest Ecol. Mgmt.* 97:1-24.

Tew, R.K. 1970. Seasonal Variation in the Nutrient Content of Aspen Foliage. *The Journal of Wildlife Management*, 34(2): 475-478

Thompson, M.A., J.A. Sturos, N.S. Christopherson, and J.B. Sturos. 1995. Performance and impacts of extracting logs on designated trails in an all-age hardwood stand. Presentation at: IUFRO World Congress, August 6 – 12, 1995. Tampere, Finland.

Trettin, C.C., D.W. Jonhson, and D.E. Todd, Jr. 1999. Forest nutrient and carbon pools at Walker Branch Watershed: changes during a 21-year period. *Soil Sci. Soc. Am. J.* 63: 1436-1448.

Tritton, L.M.; C.W. Martin, J.W. Hornbeck, and R.S. Pierce. 1987. Biomass and nutrient removals from commercial thinning and whole-tree clearcutting of central hardwoods. *Environmental Management* 11(5): 659-666.

Tuck, F.M.G., M.G. Verloo, L. Vanmechelen, and E. Van Ranst. 1997. Baseline concentration levels of trace elements as a function of clay and organic carbon contents in soils in Flander (Belgium). *Science of the Total Environment* 201(2):113-123

Tyrrell, L.E. and T.R. Crow. 1994. Dynamics of dead wood in old-growth hemlock-hardwood forests of northern Wisconsin and northern Michigan. *Can. J. For. Res.* 24: 1672-1683

United States Department of Agriculture Forest Service (USDA FS). 2004. Chequamegon-Nicolet National Forests – 2004 land and resource management plan. USDA For Serv. R9-CN-FP

United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS). 2008. Erosion Hazard (off-road, off-trail) Rating Description. http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx.

Vitousek, P.M. and R.W. Howarth. 1991. Nitrogen limitation on land and in the sea: How can it occur? *Biogeochemistry* 13(2): 87–115.

Vitousek, P.M. and W.A. Reiners. 1975. Ecosystem succession and nutrient retention: a hypothesis. *BioScience* 25(6): 376-381.

Wang, J., C. B. LeDoux and P. Edwards. 2007. Changes in soil bulk density resulting from construction and conventional cable skidding using preplanned skid trails. *North. J. Appl. For.* (24)1: 5-8.

Warkentin, B.P. 1971. Effects of compaction on content and transmission of water in soils. In *Compaction of agricultural soils*, ed. Barnes et al, 126 – 153.

Warnken ISE. 2007. Potential for greenhouse gas abatement from waste management and resource recovery activities in Australia. Prepared for SITA Environmental Solutions by Warnken ISE, PO Box 705, Glebe NSW 2037. Review draft March 2007.

WDNR. 1990 (2007). Silviculture Handbook. State of Wisconsin, Dept. Natl. Resour., Hndbk 2431.5

WDNR. 1995. Wildlife and your land. State of Wisconsin, Dept. Natl. Resour., PUBL-WM-216-225.

WDNR. 1995. Wisconsin's biodiversity as a management issue. State of Wisconsin, Dept. Natl. Resour., Pub-RS-915

WDNR. 2003. Wisconsin Forest Management Guidelines. State of Wisconsin, Dept. Natl. Resour., PUB- FR-226.

WDNR. 2004. Wisconsin's statewide forest plan. State of Wisconsin, Dept. Natl. Resour., PUB FR-299.

WDNR. 2006. Old-growth and old forests handbook. State of Wisconsin, Dept. Natl. Resour., Hndbk. 2480.5

WDNR. 2006. Wisconsin's Wildlife Action Plan. State of Wisconsin, Dept. Natl. Resour. (http://dnr.wi.gov/org/land/er/wwap/explore/profiles.asp)

Weetman, G.F. 1998. A forest management perspective on sustained site productivity. *For. Chron*. 74: 75-77.

Weetman, G.F. and D. Algar. 1983. Low-site class black spruce and jack pine nutrient removals after full-tree and tree-length logging. *Can. J. For. Res.* 13(6): 1030–1036.

Weetman, G.F. and B. Webber. 1972. The Influence of Wood Harvesting on the Nutrient Status of Two Spruce Stands. *Can. J. For. Res*. 2(3): 351–369.

Wert, S. and B.R. Smith, 1981. Effects of skid roads on diameter, height and volume growth in Douglas-fir. *Soil Science Society of America Journal*, 45:629-632.

Whalley, W.R., E. Dumitru, and A.R. Dexter. 1995. Biological effects of soil compaction. *Soil and Tillage Research*, 35: 53-68.

White, E.H. 1974. Whole-tree harvesting depletes sofl nutrients. *Can. J. For. Res.* 4:530-535.

White, R. E. 1997. *Principles and Practice of Soil Science: The Soil as a Natural Resource*. Blackwell Science.

Wilkerson, E., J. M. Hagan, D. Siegel and A. A. Whitman. 2006. The effectiveness of different buffer widths for protecting headwater streams in Maine. *Forest Science*. 52(3): 221-231.cf

Wilson, D.M. and D.F. Grigal. 1995. Effects of pine plantations and adjacent deciduous forests on soil calcium. *Soil Science Society America Journal* 59:1755-1761.

Wilson, B.F. and B.C. McComb. 2005. Dynamics of dead wood over 20 years in a New England oak forest. *Can. J. For. Res.* 35:682-692

Woodall, C.W., S.N. Oswalt, and R.S. Morin. 2007. Attributes of down woody materials in hardwood forests of the Eastern United States. USDA For. Serv., SRS, e-GTR-SRS-101, pp. 144-153

Woodley, S.J., G. Johnson, B. Freedman, and D.A. Kirk. 2006. Effects of timber harvesting and plantation development on cavity-nesting burds in New Brunswick. *The Canadian Field Naturalist* 120:298- 306

Yanai et al. 2003. Soil carbon dynamics after forest harvest: an ecosystem paradigm reconsidered. *Ecosystems* 6: 197-212.

Young, H.E., and V.P. Guinn. 1966. Chemical elements in complete mature trees of seven species in Maine. *Tappi* 49(5):190-197.

Zak, D.R., K.S. Pregitzer, and G.E. Host. 1986. Landscape variation in nitrogen mineralization and nitrification. *Can. J. For. Res*. 16: 1258-1263.

Appendix 1: Definitions

Biological Diversity (biodiversity): The spectrum of life forms and ecological processes that support and sustain them. Biological diversity occurs at four interacting levels: genetic, species, community, and ecosystem.

Biological Legacy: An organism, a reproductive portion of an organism, or a biologically derived structure or pattern inherited from a previous ecosystem. Biological legacies often include large trees, snags, and down logs left after harvesting to provide refugia and to structurally enrich the new stand.

Bolewood Utilization: The utilization of trunks, tops and any limbs of trees up to a 4-inch diameter inside bark.

Cavity (den) Tree: A (partially) hollow living tree used by wildlife.

Clearcut: The removal in one operation of essentially all the trees in a stand.

Coarse (down) Woody Debris: Dead woody material, greater than or equal to 4 inches diameter inside bark at small end, on the ground in forest stands or in streams.

Community: An assemblage of plants and animals living together and occupying a given area.

Dry Wash: An incised, often V-shaped, gully that receives precipitation to directly initiate flow or surface runoff to indirectly initiate flow. Little or no water is contributed by seeps or springs. Dry washes often have a coarse rubble or bedrock bed.

Endangered Species (Wisconsin): Any species whose continued existence as a viable component of Wisconsin's wild animals or wild plants is determined by the Department to be in jeopardy on the basis of scientific evidence. These species are protected by state law (see State Statute 29.604 and Administrative Rule NR27). There are additional species that receive protection under the federal Endangered Species Act that are not listed as endangered or threatened by the state of Wisconsin.

Erosion Prone Sites: Sites that are rated "severe" or "very severe" erosion hazard (off-road, off-trail) by the USDA NRCS. A site's erosion hazard rating can be viewed at: http://websoilsurvey.nrcs.usda.gov/app/

Federally-listed Species: Species federally-listed as endangered or threatened (legally protected) and those proposed for federal listing or candidates for federal listing, or their proposed or designated critical habitats. Impacts to federally-listed species are subject to requirements of the U.S. Endangered Species Act.

Fine (down) Woody Debris: Dead woody material, less than 4 inches diameter inside bark at large end, on the ground in forest stands or in streams.

Fine Woody Material: Woody material, living or dead, less than 4 inches diameter inside bark at large end; including fine woody debris and portions of standing living and dead shrubs and trees.

Forest: An ecosystem characterized by a more or less dense and extensive tree cover, often consisting of stands varying in characteristics such as species composition, structure, age class, and associated processes. Typically, tree cover will exceed 50% crown cover, except following a severe disturbance and during stand (re)establishment. Productive forest stands are capable of growing wood volume at an average rate of at least 20 cubic feet per acre per year.

Habitat: The place (environment) where an animal, plant, or population naturally or normally lives and develops.

Logging Residue: The unused portions of trees cut or killed during logging and left in the woods.

Mast: Fruit and nuts consumed as food by wildlife.

Passive Management: A deliberate decision to not manipulate forest vegetation.

Reserve Tree (standard, legacy tree, green tree retention): Living trees, ≥5 inches dbh, retained after the regeneration period under even-aged or two-aged silvicultural systems.

Slash: The residue left on the ground after logging or accumulating as a result of storm, fire, girdling, or delimbing.

Snag: Standing dead tree.

Special Concern Species (Wisconsin): Any species with some problem of abundance or distribution suspected but not proved. The main purpose of this category is to focus attention on certain species before they become endangered or threatened. The Wisconsin Natural Heritage Inventory program maintains a list of species currently tracked by the WDNR. Some species listed as Special Concern are federally-listed and thereby protected under the U.S. Endangered Species Act. In addition, several other state and federal laws may apply to some of these species (see dnr.wi.gov/org/land/er/laws/ for more information).

Species of Greatest Conservation Need (Wisconsin): Animal species identified as at risk or declining in the Wisconsin Wildlife Action Plan (WDNR 2006). They include threatened and endangered species, as well as many other species whose populations are of concern. Designation of a species as SGCN does not, alone, offer legal protection; however, many of the SGCN are either state or federally-listed. In addition, several other state and federal laws may apply to some of these species (see dnr.wi.gov/org/land/er/laws/ for more information).

Sustainable Forest Management (sustainable forestry): 1) WDNR: The practice of managing dynamic forest ecosystems to provide ecological, economic, social, and cultural benefits for present and future generations. 2) SAF – UN: The practice of meeting the forest resource needs and values of the present without compromising the similar capability of future generations. 3) SAF – EU: The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality, and potential to fulfill, now and in the future, relevant ecological, economic, and social functions at local, national, and global levels, and that does not cause damage to other ecosystems.

Threatened Species (Wisconsin): Any species which appears likely, within the foreseeable future, on the basis of scientific evidence. These species are protected by state law (see Statute 29.604 and Administrative Rule NR27). There are additional species that receive protection under the federal Endangered Species Act that are not listed as endangered or threatened by the state of Wisconsin.

Variable Retention Harvest System: An approach to harvesting based on the retention of structural elements or biological legacies from the harvested stand for integration into the new stand to achieve various ecological objectives.

Whole-tree Harvesting: Cutting and removing an entire upper portion of a tree consisting of trunk, branches, and leaves or needles.

Wildlife: All non-domesticated animal life.

Woody Biomass: Wood materials, such as wood, bark, sawdust, timber slash, and mill scraps. **Note: The woody biomass harvesting guidelines refer to woody biomass that comes directly from forestland harvest, i.e. wood, bark, etc. This definition is for the purpose of this document and is not meant to supplant or conflict with the definition of sustainable woody biomass approved by the WI Council on Forestry.**

Appendix 2: Summary of Minnesota's Guidelines

These guidelines are found in Minnesota's Biomass Harvesting Guidelines for Forestlands. Wisconsin is proposing to either adopt, modify or delete these guidelines. The rational for each guideline is provided.

- Avoid biomass harvesting in native plant communities listed in Appendix J.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification and to be consistent with Wisconsin programs and terminology.
WI Guideline: **3B, 4B**

- Avoid biomass harvest with specific sites where plant or animal species listed as endangered or threatened at the state or federal level are know to exist (e.g. sites identified in the DNR Natural Heritage Information System), or where such species are discovered during operations and where biomass harvesting would harm them (unless harvest has been demonstrated to maintain or improve habitat for these species.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification and to be consistent with Wisconsin programs and terminology.
WI Guideline: **1B, 2B**

- Reference M.S. 216B.2424 (Biomass power Mandate) and urge affected utilities to follow the statute as reference.

Status: Delete
Rationale: Refers to specific MN statute. Wisconsin does not have equivalent statutory reference.
WI Guideline: N/A

- Avoid harvest of additional biomass from within RMZs over and above the tops and limbs of trees normally removed in a roundwood harvest under existing timber harvesting guidelines.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification and to be consistent with Wisconsin programs and terminology.
WI Guideline: **9B**

- Avoid additional biomass removal within 25 feet of a dry wash bank expect tops and limbs normally removed in a roundwood harvest under existing timber harvesting guidelines, when managing near a dry wash in southeastern Minnesota.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification and to be consistent with Wisconsin programs and terminology.
WI Guideline: **9B**

- Avoid biomass harvesting (over and above bolewood utilization) on all organic soils deeper than 24 inches that are ombrotrophic.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification and to address nutrient concerns.
WI Guideline: **8B**

- Avoid biomass harvesting (over and above bolewood utilization) on aspen or hardwood cover types on shallow soils (8 inches or less) over bedrock.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification and to address nutrient concerns.
WI Guideline: **6B**

- Do not remove the forest floor, litter layer and/or root systems for utilization as biomass.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification.
WI Guideline: **4A**

- Plan roads, landings and stockpiles to occupy no more than 1-3% of the site.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification and to be consistent with Wisconsin programs and terminology.
WI Guideline: **5A**

- Avoid additional biomass harvest from erosion-prone sites (e.g. those sites on steep slopes of 35% or more) over and above the tops and limbs of trees normally removed in a roundwood harvest under existing timber harvesting guidelines.

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification.
WI Guideline: **9B**

- Ensure that landings or on-site areas used to store biomass are in a condition that favors regeneration and growth of native vegetation and trees after use.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- Install temporary erosion control devices, such as straw bales, mulch or woody debris, to help stabilize soils prior to the establishment of vegetative cover (see Figure ROAD-13 in *Forest Road Construction and Maintenance*, page 32). Take care to avoid introduction of invasive species in bales or mulches.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- For soils with 8-20 inches of soil over bedrock and droughty sands, consider that the recommended retention of one-third or more of fine woody debris (FWD) on the site benefits soil productivity as well as biodiversity. FWD should be distributed relatively evenly throughout the site rather than piled. (See also *Managing and Retaining Wildlife Habitat and Structural Diversity*, pages 27-29).

Status: Adopt with modifications
Rationale: Reword guideline to provide clarification and to address nutrient concerns.
WI Guideline: **3A, 7B**

- Consider that biomass products piled on landings for the majority of one growing season will usually reduce natural regeneration.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- Avoid re-entry into the general harvest area of a site with a second operation for the purpose of harvesting biomass once regeneration has begun or planting has been completed.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- If re-entry is needed once regeneration has begun or planting has been completed, restrict traffic to existing infrastructure.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- Re-establish erosion control measures on roads and landings, including vegetative cover and water diversion devices, after re-entering a site for biomass harvest.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- Avoid re-entry of sites across non-frozen wetlands.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- Retain slash piles that show evidence of use by wildlife. Piles left on site for an extended period may be inhabited by species such as Canada lynx, black bears and other wildlife known to den in slash piles. In addition, consider retaining slash piles that are difficult to access.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations. In addition, Wisconsin does not have Canada lynx and black bear populations are stable or increasing.
WI Guideline: N/A

- Leave all snags possible standing in the harvest areas.

Status: Adopt with modifications.
Rationale: Reword to be consistent with existing Wisconsin programs and terminology.
WI Guideline: **1A**

- Retain and limit disturbances to all pre-existing CWD (except in skid trails or landings).

Status: Adopt with modifications.
Rationale: Reword to be consistent with existing Wisconsin programs and terminology.
WI Guideline: **2A**

- Retain stumps and uprooted stumps.

Status: Adopt with modifications.
Rationale: Reword to provide clarification and to be consistent with existing Wisconsin programs and terminology.
WI Guideline: **4A**

- In filter strips, avoid removal of pre-existing CWD material from the forest floor.

Status:	Adopt with modifications.
Rationale:	Reword to provide clarification and to be consistent with existing Wisconsin programs and terminology.
WI Guideline:	**9B**

- Avoid biomass removal in leave tree clumps, except tops and limbs of trees normally removed in a roundwood harvest under existing *Timber Harvesting* guidelines (see *Timber Harvesting*, pages 33-40).

Status:	Adopt with modifications.
Rationale:	Reword to provide clarification and to be consistent with existing Wisconsin programs and terminology.
WI Guideline:	**1A**

- Avoid biomass harvest form within RMZs, except tops and limbs of trees normally removed in a roundwood harvest under existing *Timber Harvesting* guidelines.

Status:	Adopt with modifications.
Rationale:	Reword to provide clarification and to be consistent with existing Wisconsin programs and terminology.
WI Guideline:	**9B**

- Retain and scatter tops and limbs from 20% of trees harvested in the general harvest area (one “average-sized” tree out of every five trees harvested).

Status:	Adopt with modifications.
Rationale:	Reword to provide clarification.
WI Guideline:	**3A**

- Avoid removing FWD resulting from incidental breakage of tops and limbs in general harvest area.

Status:	Adopt with modifications.
Rationale:	Reword to provide clarification.
WI Guideline:	**3A**

- If harvesting brush and small trees for biomass associated with a timber harvest, leave 20% of this material on the site. This material may be run over or cut, but it should remain on the site.

Status:	Adopt with modifications.
Rationale:	Reword to provide clarification.
WI Guideline:	**3A**

- Retain understory vegetation in several reserve patches that total at least 20% of the harvest area.

Status: Delete.

Rationale: Addressed in other guidelines.
WI Guideline: N/A

- Retain snags greater than 12 inches DBH and down logs where at least one end is greater than 12 inches in diameter and 6 feet in length. Place emphasis on retaining only larger snags and pre-existing CWD, because these larger fuels do not contribute as much to the initial speed and flame length of wildlife.

Status: Delete.
Rationale: Addressed in other guidelines.
WI Guideline: N/A

- Modify management activities to maintain, promote or enhance ETS species (endangered, threatened or special concern) on the site.

Status: Delete.
Rationale: Addressed in other guidelines.
WI Guideline: N/A

- Evaluate the harvest operation and place future adaptations at post-harvest conferences with the logger and landowner.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- Plan for removal of equipment and cut materials from wetland areas at the end of the winter season prior to thawing.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- Avoid removing soil from the general harvest area to rehabilitate roads, landings and skid trails. Use already disturbed soil, if needed, rather than disturbing additional soil.

Status: Delete
Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.
WI Guideline: N/A

- Rehabilitate landings and skid trails, when necessary, to mitigate soil compaction and reduce erosion.

Status: Delete

Rationale: Addressed in existing silvicultural guidelines, forest management guidelines (FMGs) and best management practices (BMPs) that are applicable to all forestry operations.

WI Guideline: N/A

Appendix 3: Nutrient Budgets

Red pine - Calcium budget

Nutrient inputs

	Ca, lb/acre/yr low	 avg	 high
Atmosphere			
wet deposition (1)	1.235	1.712	2.018
dry deposition (est) (2)	1.235	1.712	2.018
Mineral weathering (3)	1.7	3.7	5
Total	4.17	7.124	9.036

Nutrient outputs

Leaching in even-aged systems			
5-yr totals (4)		55.6	

Harvest removal	*Bole+bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Red pine, loamy site, 39 yrs (P&A 1982)	109	193	302
Red pine, sandy site, 41 yrs (P&A 1982)	85	188	273
Avg	97.00	190.50	287.50
lb/acre	**86.52**	169.93	256.45
x 0.66667 (5)		**113.29**	
Amount Ca left in 1/3 of tops/limbs		56.64	
% of total aboveground Ca left		22.08	

Red pine estimate for thinned stand, final harvest at 120 yrs, lb/ac (B 1984) (6)	**350.71**	348.35	
x 0.66667 (5)		**232.24**	
Red pine estimate for thinned stand, final harvest at 60 yrs, lb/ac (B 1984) (6)	**211.77**	179.50	
x 0.66667 (5)		**119.67**	

Nutrient budget calculations

	(Inputs * years) - harvest = nutrient balance
RP - WTH, 40 yr, unthinned (5)	
average	(7.124*40) - 86.5 - 55.6 -113.3 = 30
with high inputs	(9.036*40) - 86.5 - 55.6 -113.3 = 106
with low inputs	(4.170*40) - 86.5 - 55.6 -113.3 = -89
RP - WTH, 120 yr thinned, Ca concentrations from P&A 1982 (5)	
average	(7.124*120) - 350.7 - 232.24 - 55.6 = 216
with high inputs	(9.036*120) - 350.7 - 232.24 - 55.6 = 446
with low inputs	(4.170*120) - 350.7 - 232.24 - 55.6 = -138
RP - WTH, 60 yr thinned, Ca concentrations from P&A 1982 (5)	
average	(7.124*60) - 211.8 - 119.7 - 55.6 = 40
with high inputs	(9.036*60) - 211.8 - 119.7 - 55.6 = 155
with low inputs	(4.170*60) - 211.8 - 119.7 - 55.6 = -137

(1) Data from five NADP stations in Wisconsin, 1997-2006.
(2) Literature estimates that dry deposition is roughly equal to wet deposition. There are no good methods for measuring dry deposition.
(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).
(4) Leaching data from Silkworth and Grigal (1982).
(5) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

(6) Values for thinned red pine with final harvest at 120 yrs estimated using stand data (SI=60) in Bassett (1984) & biomass equations for Upper Great Lakes area (Ter-Mikaelian & Korzukhin 1997), applying concentration data for tree components from 40 yr old stands in Perala & Alban (1982). The red pine plantation was thinned to BA of 90 at ages 30 and 40; to BA of 120 at ages 50, 60, and 70; to BA of 150 at age 90; and final harvest was at 120 yrs.

** Notes: RP stands sampled for nutrient content by Perala & Alban (1982) were relatively young at 39 and 41 yrs, unthinned. Rotation of 120 yrs with thinnings should be sustainable, but biomass harvest at each thinning may not be sustainable for nutrient-poor soils. Some RP sites are nutrient-poor, with low rates of input from mineral weathering.

Appendix 3: Nutrient Budgets

Calculations for red pine biomass and Ca content for thinned plantation with final harvest at 120 yrs (Bassett 1984).

Sample stand is on acre basis and biomass equations are in kg; a conversion from kg/acre to lb/acre (2.204622) is used.

dbh (cm)	# trees, before & after thin	Above-ground total, kg	AB * # trees	Bole wood	B wood * # trees	Bole bark	B bark * # trees	foliage	foliage* # trees	branches w/ bark	branches * # trees	Total
30 yrs												
14.99	798.00	54.11	43180.76	37.55	29966.69	4.04	3224.08	3.28	2615.72	9.24	7374.28	
14.99	464.00	54.11	25107.61	37.55	17424.24	4.04	1874.65	3.28	1520.92	9.24	4287.80	
to lb/ac			95197.26		66065.22		7107.87		5766.68		16257.49	
to lb/ac			55352.79		38413.86		4132.90		3353.06		9452.98	55352.79
lb/ac removed in thinning @ 30			39844.47		27651.36		2974.97		2413.62		6804.51	
Ca content of amt removed, lb/ac					23.59		15.77		7.43		19.79	66.58
40 yrs												
19.30	464.00	99.79	46301.34	68.08	31587.82	6.86	3182.29	7.23	3352.79	17.63	8178.44	
19.30	284.00	99.79	28339.61	68.08	19333.92	6.86	1947.78	7.23	2052.14	17.63	5005.77	
to lb/ac			102076.95		69639.19		7015.75		7391.64		18030.36	
to lb/ac			62478.13		42623.99		4294.12		4524.20		11035.83	62478.13
lb/ac removed in thinning @ 40			39598.82		27015.20		2721.63		2867.45		6994.54	
Ca content of amt removed, lb/ac					23.04		14.42		8.83		20.35	66.64
50 yrs												
24.13	284.00	171.13	48599.87	115.00	32660.27	10.93	3105.15	14.50	4118.70	30.69	8715.75	
24.13	241.00	171.13	41241.44	115.00	27715.23	10.93	2635.00	14.50	3495.10	30.69	7396.11	
to lb/ac			107144.34		72003.54		6845.68		9080.18		19214.94	
to lb/ac			90921.78		61101.60		5809.18		7705.36		16305.64	90921.78
lb/ac removed in thinning @ 50			16222.56		10901.94		1036.49		1374.82		2909.30	
Ca content of amt removed, lb/ac					9.30		5.49		4.23		8.46	27.49
60 yrs												
28.45	241.00	254.76	61396.41	169.31	40803.90	15.42	3717.10	24.25	5843.39	45.78	11032.02	
28.45	175.00	254.76	44582.45	169.31	29629.39	15.42	2699.14	24.25	4243.12	45.78	8010.80	
to lb/ac			135355.87		89957.18		8194.80		12882.46		24321.43	
to lb/ac			98287.46		65321.61		5950.58		9354.48		17660.79	98287.46
lb/ac removed in thinning @ 60			37068.41		24635.58		2244.22		3527.98		6660.64	
Ca content of amt removed, lb/ac					21.01		11.89		10.86		19.38	63.14
70 yrs												

dbh (cm)	# trees, before & after thin	Above-ground total, kg	AB * # trees	Bole wood	B wood * # trees	Bole bark	B bark * # trees	foliage	foliage* # trees	branches w/ bark	branches * # trees	Total
32.77	175.00	358.48	62734.36	235.98	41297.30	20.72	3626.54	37.69	6596.11	64.08	11214.41	
32.77	131.00	358.48	46961.15	235.98	30913.98	20.72	2714.72	37.69	4937.66	64.08	8394.79	
to lb/ac			138305.55		91044.93		7995.14		14541.93		24723.54	
to lb/ac			103531.58		68153.63		5984.94		10885.68		18507.34	103531.58
lb/ac removed in thinning @ 70			34773.97		22891.30		2010.21		3656.26		6216.21	
Ca content of amt removed, lb/ac					19.53		10.65		11.26		18.08	59.52
90 yrs												
40.89	129.00	612.46	79007.73	397.19	51237.72	32.93	4247.93	75.28	9711.56	107.06	13810.52	
40.89	105.00	612.46	64308.62	397.19	41705.12	32.93	3457.62	75.28	7904.76	107.06	11241.12	
to lb/ac			174182.17		112959.80		9365.08		21410.32		30446.97	
to lb/ac			141776.19		91944.02		7622.74		17427.00		24782.42	141776.19
lb/ac removed in thinning @ 90			32405.99		21015.78		1742.34		3983.32		5664.55	
Ca content of amt removed, lb/ac					17.93		9.23		12.26		16.48	55.90
120 yrs, final harvest												
49.02	99.00	949.25	93975.97	608.12	60203.63	48.10	4761.80	132.59	13126.05	160.45	15884.49	
49.02	99.00	949.25	93975.97	608.12	60203.63	48.10	4761.80	132.59	13126.05	160.45	15884.49	
lb/ac removed @ final harvest			207181.48		132726.24		10497.98		28937.98		35019.29	
			207181.48		132726.24		10497.98		28937.98		35019.29	207181.48
Ca content of final harvest, lb/ac					113.22		55.63		89.08		101.87	359.80
Total Ca for all thinnings & final harvest					227.61		123.09		143.95		204.41	699.06
					bole+bark	**350.71**			foliage+branches	**348.35**		

Calculations for red pine biomass and Ca content for thinned plantation with final harvest at 60 yrs (taken from a portion of the stand data in Bassett 1984).

dbh (cm)	# trees, before & after thin	Above-ground total, kg	AB * # trees	Bole wood	B wood * # trees	Bole bark	B bark * # trees	foliage	foliage* # trees	branches w/ bark	branches * # trees	Total
30 yrs												
14.99	798.00	54.11	43180.76	37.55	29966.69	4.04	3224.08	3.28	2615.72	9.24	7374.28	
14.99	464.00	54.11	25107.61	37.55	17424.24	4.04	1874.65	3.28	1520.92	9.24	4287.80	
to lb/ac			95197.26		66065.22		7107.87		5766.68		16257.49	
to lb/ac			55352.79		38413.86		4132.90		3353.06		9452.98	55352.79
lb/ac removed in thinning @ 30			39844.47		27651.36		2974.97		2413.62		6804.51	
Ca content of amt removed, lb/ac					23.59		15.77		7.43		19.79	66.58

dbh (cm)	# trees, before & after thin	Above-ground total, kg	AB * # trees	Bole wood	B wood * # trees	Bole bark	B bark * # trees	foliage	foliage* # trees	branches w/ bark	branches * # trees	Total
40 yrs												
19.30	464.00	99.79	46301.34	68.08	31587.82	6.86	3182.29	7.23	3352.79	17.63	8178.44	
19.30	284.00	99.79	28339.61	68.08	19333.92	6.86	1947.78	7.23	2052.14	17.63	5005.77	
to lb/ac			102076.95		69639.19		7015.75		7391.64		18030.36	
to lb/ac			62478.13		42623.99		4294.12		4524.20		11035.83	62478.13
lb/ac removed in thinning @ 40			39598.82		27015.20		2721.63		2867.45		6994.54	
Ca content of amt removed, lb/ac					23.04		14.42		8.83		20.35	66.64
50 yrs												
24.13	284.00	171.13	48599.87	115.00	32660.27	10.93	3105.15	14.50	4118.70	30.69	8715.75	
24.13	241.00	171.13	41241.44	115.00	27715.23	10.93	2635.00	14.50	3495.10	30.69	7396.11	
to lb/ac			107144.34		72003.54		6845.68		9080.18		19214.94	
to lb/ac			90921.78		61101.60		5809.18		7705.36		16305.64	90921.78
lb/ac removed in thinning @ 50			16222.56		10901.94		1036.49		1374.82		2909.30	
Ca content of amt removed, lb/ac					9.30		5.49		4.23		8.46	27.49
60 yrs												
28.45	241.00	254.76	61396.41	169.31	40803.90	15.42	3717.10	24.25	5843.39	45.78	11032.02	
lb/ac removed in final harvest			135355.87		89957.18		8194.80		12882.46		24321.43	
Ca content of amt removed, lb/ac					76.73		43.43		39.66		70.75	230.57
Sum of Ca in thinnings & final harvest					132.66		79.11		60.14		119.35	391.27
					Bole+bark	**211.77**			Foliage + branches	**179.50**		

Appendix 3: Nutrient Budgets

DRAFT

Jack pine - Calcium budget

Nutrient inputs

	Ca, lb/acre/yr low	avg	high
Atmosphere			
wet deposition (1)	1.235	1.712	2.018
dry deposition (est) (2)	1.235	1.712	2.018
Mineral weathering (3)	1.7	3.7	5
Total	4.17	7.124	9.036

Nutrient outputs

Leaching in even-aged systems			
5-yr totals (4)		55.6	

Harvest removal	*Bole+bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Jack pine (P&A 1982)	131	72	203
Jack pine (P&A 1982)	126	42	168
Jack pine (F,M,H 1981)	40		127
Jack pine (W&A 1983)	180.7	86.4	267.1
Jack pine (M&F 1979)	87	40	127
Avg	112.94	60.10	178.42
lb/acre	**77.60**	35.68	113.28
x 0.66667 (5)		**23.79**	
Amount Ca left in 1/3 of tops/limbs		11.89	
% of total aboveground Ca left		10.50	

Nutrient budget calculations

	(Inputs * years) - harvest = nutrient balance
JP - WTH, 40 yr (5)	
average	(7.124*40) - 78 - 24 - 56 = 128
with high inputs	(9.036*40) - 78 - 24 - 56 = 204
with low inputs	(4.170*40) - 78 - 24 - 56 = 10
JP - WTH, 30 yr (5)	
average	(7.124*30) - 78 - 24 - 56 = 57
with high inputs	(9.036*30) - 78 - 24 - 56 = 114
with low inputs	(4.170*30) - 78 - 24 - 56 = -32

(1) Data from five NADP stations in Wisconsin, 1997-2006.

(2) Literature estimates that dry deposition is roughly equal to wet deposition. There are no good methods for measuring dry deposition.

(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).

(4) Leaching data from Silkworth and Grigal (1982).

(5) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Northern Hardwoods - Potassium budget

Nutrient inputs

	K, lb/acre/yr		
Atmosphere	low	avg	high
wet deposition (1)	0.133	0.179	0.254
dry deposition (est) (2)	0.133	0.179	0.254
Mineral weathering (3)	0.7	1.5	2
Total	0.966	1.858	2.508

Nutrient outputs

Leaching (not included in uneven-aged systems)

Harvest removal	*Bole + bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Mature NH (equations for SM) (R&S 1993)	264.80	159.50	424.30
Sugar maple OG stand (M 1990)	148.40	187.10	335.50
Sugar maple OG stand (M 1990)	87.20	142.20	229.40
NH (SM, AB, YB) (HB)	101.90	119.40	221.30
NH (SM, AB, YB) (HB)	105.20	106.70	211.90
Avg	141.50	142.98	284.48
lb/acre	**126.22**	127.54	253.76
x 0.66667 (4)		**85.03**	
Amount K left in 1/3 of tops/limbs		42.51	
% of total aboveground K left		16.75	

Nutrient budget calculations

	(Inputs * years) - harvest = nutrient balance
NH - WTH, 30 yr equivalent (3 - 10 yr entries; 33% volume removed each entry) (4)	
average	(1.858*30) - 126 - 85 = -156
with high inputs	(2.508*30) - 126 - 85 = -136
with low inputs	(0.966*30) - 126 - 85 = -182
NH - WTH, 40 yr equivalent (4 -10yr entries; 25% volume removed each entry) (4)	
average	(1.858*40) - 126 - 85 = -137
with high inputs	(2.508*40) - 126 - 85 = -111
with low inputs	(0.966*40) - 126 - 85 = -173
NH - WTH, 60 yr equivalent (4 -15yr entries; 25% volume removed each entry) (4)	
average	(1.858*60) - 126 - 85 = -100
with high inputs	(2.508*60) - 126 - 85 = -61
with low inputs	(0.966*60) - 126 - 85 = -153

(1) Data from five NADP stations in Wisconsin, 1997-2006.
(2) Literature estimates that dry deposition is roughly equal to wet deposition. There are no good methods for measuring dry deposition.
(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).
(4) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Northern Hardwoods - Calcium budget

Nutrient inputs

	Ca, lb/acre/yr		
	low	avg	high
Atmosphere			
wet deposition (1)	1.235	1.712	2.018
dry deposition (est) (2)	1.235	1.712	2.018
Mineral weathering (3)	1.7	3.7	5
Total	4.17	7.124	9.036

Nutrient outputs

Leaching (not included in uneven-aged systems)

Harvest removal	*Bole+bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Mature NH (equations for SM) (R&S 1993)	822.03	527.88	1349.80
Sugar maple OG stand (M 1990)	590.00	370.10	960.10
Sugar maple OG stand (M 1990)	689.40	411.90	1101.30
NH (SM, AB, YB) (HB)	303.81	312.87	616.83
NH (SM, AB, YB) (HB)	323.06	288.60	611.87
Avg	545.66	382.27	927.98
lb/acre	**486.73**	340.98	827.76
x 0.66667 (4)		**227.33**	
Amount Ca left in 1/3 of tops/limbs		113.65	
% of total aboveground Ca left		13.73	

Nutrient budget calculations

	(Inputs * years) - harvest = nutrient balance
NH - WTH, 30 yr equivalent (3 - 10 yr entries; 33% volume removed each entry) (4)	
average	(7.124*30) - 487 - 227 = -500
with high inputs	(9.036*30) - 487 - 227 = -443
with low inputs	(4.170*30) - 487 - 227 = -589
NH - WTH, 40 yr equivalent (4 -10 yr entries; 25% volume removed each entry) (4)	
average	(7.124*40) - 487 - 227 = -429
with high inputs	(9.036*40) - 487 - 227 = -353
with low inputs	(4.170*40) - 487 - 227 = -547
NH - WTH, 60 yr equivalent (4 -15yr entries; 25% volume removed each entry) (4)	
average	(7.124*60) - 487 - 227 = -287
with high inputs	(9.036*60) - 487 - 227 = -172
with low inputs	(4.170*60) - 487 - 227 = -464

(1) Data from five NADP stations in Wisconsin, 1997-2006.

(2) Literature estimates that dry deposition is roughly equal to wet deposition. There are no good methods for measuring dry deposition.

(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).

(4) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Northern Hardwoods - Nitrogen budget

Nutrient inputs

	N, lb/acre/yr		
Atmosphere	low	avg	high
wet deposition (1)	7.385	9.14	10.854
dry deposition (est) (2)	7.385	9.14	10.854
Mineral weathering (3)			
Total	14.77	18.28	21.708

Nutrient outputs

Leaching (not included in uneven-aged systems)

Harvest removal	*Bole + bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Mature NH (equations for SM) (R&S 1993)	153.3	222.7	376
Sugar maple OG stand (M 1990)	246.5	268.6	515.1
Sugar maple OG stand (M 1990)	222.8	227.1	449.9
NH (SM, AB, YB) (HB)	228.9	327.4	556.3
NH (SM, AB, YB) (HB)	250.7	308	558.7
average	220.44	270.76	491.20
lbs/acre	**196.63**	241.52	438.15
x 0.66667 (4)		**161.01**	
Amount N left in 1/3 of tops/limbs		80.51	
% of total aboveground N left		18.37	

Nutrient budget calculations

	(Inputs * years) - harvest - leaching = nutrient balance
Northern hardwoods - WTH, 30 yr equivalent (3 - 10 yr entries; 33% volume removed each entry) (4)	
average	(18.28*30) - 196.6 - 161.0 = 491
with high inputs	(21.71*30) - 196.6 - 161.0 = 294
with low inputs	(14.77*30) - 196.6 - 161.0 = 85
Northern hardwoods - WTH, 45 yr equivalent (3 - 15 yr entries; 33% volume removed each entry) (4)	
average	(18.28*45) - 196.6 - 161.0 = 465
with high inputs	(21.71*45) - 196.6 - 161.0 = 619
with low inputs	(14.77*45) - 196.6 - 161.0 = 307

(1) Data from five NADP stations in Wisconsin, 1997-2006.

(2) Literature indicates that dry deposition is estimated as approximately equal to wet deposition. There are no

(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).

(4) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Northern hardwoods - Phosphorus budget

Nutrient inputs

	P, lb/acre/yr		
Atmosphere	low	avg	high
wet deposition (1)	0.05	0.12	0.20
dry deposition (est) (2)	0.05	0.12	0.20
Mineral weathering (3)	0.20	0.60	0.80
Total	0.30	0.84	1.20

Nutrient outputs

Leaching (not included in uneven-aged systems)

Harvest removal	*Bole wood & bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Mature NH (equations for SM) (R&S 1993)	18.50	29.18	47.6830295
Sugar maple OG stand (M 1990)	13.70	15.20	28.9
Sugar maple OG stand (M 1990)	12.40	12.00	24.4
NH (SM, AB, YB) (HB)	17.10	36.50	53.6
NH (SM, AB, YB) (HB)	18.80	31.40	50.2
avg	16.10	24.86	40.96
x 0.66667 (4)		16.57	
lbs/acre	**14.36**	**14.78**	36.53
Amount P left in 1/3 of tops/limbs		10.08	
% of total aboveground P left on site		27.58	

Nutrient budget calculations

	(Inputs * years) - harvest - leaching = nutrient balance
Northern hardwoods - WTH, 30 yr equivalent (3 - 10 yr entries; 33% volume removed each entry) (4)	
average	(0.84*45) - 14.4 - 14.8 = -3.9
with high inputs	(1.2*45) - 14.4 - 14.8 = 6.9
with low inputs	(0.3*45) - 14.4 - 14.8 = -20.1
Northern hardwoods - WTH, 45 yr equivalent (3 - 15 yr entries; 33% volume removed each entry) (4)	
average	(0.84*45) - 14.4 - 14.8 = 8.7
with high inputs	(1.2*45) - 14.4 - 14.8 = 24.9
with low inputs	(0.3*45) - 14.4 - 14.8 = -15.6

(1) Data from five NADP stations in Wisconsin, 1997-2006.

(2) Literature indicates that dry deposition is estimated as approximately equal to wet deposition. There are no good methods for direct measurement of dry deposition.

(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).

(4) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Aspen - Nitrogen budget

Nutrient inputs

	N, lb/acre/yr		
Atmosphere	low	avg	high
wet deposition (1)	7.385	9.14	10.854
dry deposition (est) (2)	7.385	9.14	10.854
Mineral weathering (3)			
Total	14.77	18.28	21.708

Nutrient outputs

Leaching in even-aged systems			
10-yr totals (4)		0	

Harvest removal	*Bole + bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Aspen (P&A 1982)	199	169	368
Aspen (P&A 1982)	173	181	354
Aspen (NH) (A&P 1990)	208	41	249
Aspen (paper birch) (A&P 1990)	181	39	220
Aspen (NH) (A&P 1990)	269	170	439
Aspen over SM (P&B 1984)	183	157	340
average	202.17	126.17	328.33
lbs/acre	**181.00**	112.54	292.87
x 0.66667 (5)		**75.03**	
Amount N left in 1/3 of tops/limbs		37.51	
% of total aboveground N left		12.81	

Nutrient budget calculations

	(Inputs * years) - harvest - leaching = nutrient balance
Aspen - WTH, 40 yr (5)	
average	(18.28*40) - 181 - 75.0 = 475
with high inputs	(21.71*40) - 181 - 75.0 = 612
with low inputs	(14.77*40) - 181 - 75.0 = 335

(1) Data from five NADP stations in Wisconsin, 1997-2006.

(2) Literature indicates that dry deposition is estimated as approximately equal to wet deposition. There are no good methods for direct measurement of dry deposition.

(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).

(4) Leaching data from Silkworth and Grigal (1982).

(5) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Aspen - Calcium budget

Nutrient inputs

	Ca, lb/acre/yr		
	low	avg	high
Atmosphere			
wet deposition (1)	1.235	1.712	2.018
dry deposition (est) (2)	1.235	1.712	2.018
Mineral weathering (3)	1.7	3.7	5
Total	4.17	7.124	9.036

Nutrient outputs

Leaching in even-aged systems			
5-yr totals (4)		55.6	

Harvest removal	*Bole+bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Aspen (P&A 1982)	606	252	858
Aspen (P&A 1982)	612	313	925
Aspen (NH) (A&P 1990)	600	129	729
Aspen (paper birch) (A&P 1990)	571	75	646
Aspen (NH) (A&P 1990)	1106	483	1589
Aspen over SM (P&B 1984)	560	291	851
Aspen (R&B 1988)	188	88	276
Aspen (R&B 1988)	280	133	413
Aspen (S 1980)	1005	387.1	1392.1
Aspen (S 1980)	511	205.4	716.4
Aspen (S 1980)	543	216.5	759.5
Aspen (S 1980)	562	225	787
Aspen (S 1980)	477	199.4	676.4
Aspen (S 1980)	567	248.4	815.4
Aspen (V 1983)	445	236	681
Aspen (R 1974)	278.5	49.41	327.9
Avg	556.97	220.70	777.67
lb/acre	**496.82**	179.03	**693.08**
x 0.66667 (5)		**119.35**	
Amount Ca left in 1/3 of tops/limbs		59.67	
% of total aboveground nutrients left		8.61	

Nutrient budget calculations

	(Inputs * years) - harvest - leaching = nutrient balance
Aspen - WTH, 40 yr (5)	
average	(7.124*40) - 496.8 - 119.4 - 55.6 = -387
with high inputs	(9.036*40) - 496.8 - 119.4 - 55.6 = -310
with low inputs	(4.170*40) - 496.8 - 119.4 - 55.6 = -505
Aspen - WTH, 50 yr (5)	
average	(7.124*50) - 496.8 - 119.4 - 55.6 = -316
with high inputs	(9.036*50) - 496.8 - 119.4 - 55.6 = -220
with low inputs	(4.170*50) - 496.8 - 119.4 - 55.66 = -463

(1) Data from five NADP stations in Wisconsin, 1997-2006.

(2) Literature indicates that dry deposition is estimated as approximately equal to wet deposition. There are no good methods for direct measurement of dry deposition.
(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).
(4) Leaching data from Silkworth and Grigal (1982).
(5) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Aspen - Magnesuim budget

Nutrient inputs

	Mg, lb/acre/yr		
Atmosphere	low	avg	high
wet deposition(1)	0.162	0.226	0.327
dry deposition (est)(2)	0.162	0.226	0.327
Mineral weathering(3)	0.9	1.5	2
Total	1.224	1.952	2.654

Nutrient outputs

Leaching in even-aged systems		29.1	
5-yr totals(4)			

Harvest removal	*Bole wood & bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Aspen (P&A 1982)	39.20	18.40	76
Aspen (P&A 1982)	43.20	28.90	72
Aspen (NH) (A&P 1990)	56.00	6.00	62
Aspen (paper birch) (A&P 1990)	49.00	5.00	54
Aspen (NH) (A&P 1990)	89.00	23.00	112
Aspen over SM (P&B 1984)	42.00	24.40	66.4
avg	53.07	17.62	73.73
lbs/acre	**47.34**	15.71	**65.77**
x 0.66667 (5)		**10.48**	
Amount Mg left in 1/3 of tops/limbs		5.24	
% of total aboveground Mg left on site		7.96	

Nutrient budget calculations

	(Inputs * years) - harvest - leaching = nutrient balance
Aspen - WTH, 40 yr (5)	
average	(1.952*40) - 47.3 - 29.1 - 10.48 = -9
with high inputs	(2.654*40) - 47.3 - 29.1 - 10.48 = 19
with low inputs	(1.224*40) - 47.3 - 29.1 - 10.48 = -38
Aspen - WTH, 50 yr (5)	
average	(1.952*50) - 47.3 - 29.1 - 10.48 = 11
with high inputs	(2.654*50) - 47.3 - 29.1 - 10.48 = 46
with low inputs	(1.224*50) - 47.3 - 29.1 - 10.48 = -26

(1) Data from five NADP stations in Wisconsin, 1997-2006.
(2) Literature indicates that dry deposition is estimated as approximately equal to wet deposition. There are no
(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).
(4) Leaching data from Silkworth and Grigal (1982).
(5) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

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Appendix 3: Nutrient Budgets

Aspen - Potassium budget

Nutrient inputs

	K, lb/acre/yr		
Atmosphere	low	avg	high
wet deposition (1)	0.133	0.179	0.254
dry deposition (est) (2)	0.133	0.179	0.254
Mineral weathering (3)	0.7	1.5	2
Total	0.966	1.858	2.508

Nutrient outputs

Leaching in even-aged systems			
5-yr totals (4)		0.00	

Harvest removal	*Bole wood & bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Aspen (P&A 1982)	198.00	89.00	287
Aspen (P&A 1982)	128.00	92.00	219
Aspen (NH) (A&P 1990)	144.00	35.00	179
Aspen (paper birch) (A&P 1990)	159.00	20.00	179
Aspen (NH) (A&P 1990)	242.00	112.00	354
Aspen over SM (P&B 1984)	273.00	92.00	365
avg	190.67	73.33	263.83
lbs/acre	**170.07**	65.41	235.34
x 0.66667 (5)		**43.61**	
Amount K left in 1/3 of tops/limbs		21.80	
% of total aboveground K left on site		9.27	

Nutrient budget calculations

	(Inputs * years) - harvest - leaching = nutrient balance
Aspen - WTH, 40 yr (5)	
average	(1.858*40) - 170.1 - 43.6 = -139
with high inputs	(2.508*40) - 170.1 - 43.6 = -113
with low inputs	(0.966*40) - 170.1 - 43.6 = -175
Aspen - WTH, 50 yr (5)	
average	(1.858*50) - 170.1 - 43.6 = -121
with high inputs	(2.508*50) - 170.1 - 43.6 = -88
with low inputs	(0.966*50) - 170.1 - 43.6 = -165

(1) Data from five NADP stations in Wisconsin, 1997-2006.
(2) Literature indicates that dry deposition is estimated as approximately equal to wet deposition. There are no good methods for direct measurement of dry deposition.
(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).
(4) Leaching data from Silkworth and Grigal (1982).
(5) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Aspen - Phosphorus budget

Nutrient inputs

	P, lb/acre/yr		
Atmosphere	low	avg	high
wet deposition (1)	0.05	0.12	0.20
dry deposition (est) (2)	0.05	0.12	0.20
Mineral weathering (3)	0.20	0.60	0.80
Total	0.30	0.84	1.20

Nutrient outputs

Leaching in even-aged systems			
5-yr totals (4)		0.00	

Harvest removal	*Bole wood & bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Aspen (P&A 1982)	26.20	20.30	47
Aspen (P&A 1982)	21.40	28.00	49
Aspen (NH) (A&P 1990)	25.00	5.00	30
Aspen (paper birch) (A&P 1990)	24.00	4.00	28
Aspen (NH) (A&P 1990)	35.00	20.00	55
Aspen over SM (P&B 1984)	24.00	22.10	46.1
avg	25.93	16.57	42.52
x 0.66667 (5)		11.05	
lbs/acre	**23.13**	**9.85**	37.92
Amount P left in 1/3 of tops/limbs		4.92	
% of total aboveground P left on site		12.98	

Nutrient budget calculations

	(Inputs * years) - harvest - leaching = nutrient balance
Aspen - WTH, 40 yr (5)	
average	(0.84*40) - 23.1 - 9.85 = 0.6
with high inputs	(1.2*40) - 23.1 - 9.85 = 15.0
with low inputs	(0.3*40) - 23.1 - 9.85 = -21.0
Aspen - WTH, 50 yr (5)	
average	(0.84*50) - 23.1 - 9.85 = 9.0
with high inputs	(1.2*50) - 23.1 - 9.85 = 27.0
with low inputs	(0.3*50) - 23.1 - 9.85 = -18.0

(1) Data from five NADP stations in Wisconsin, 1997-2006.
(2) Literature indicates that dry deposition is estimated as approximately equal to wet deposition. There are no good methods for direct measurement of dry deposition.
(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).
(4) Leaching data from Silkworth and Grigal (1982).
(5) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Aspen - Phosphorus budget

Nutrient inputs

	P, lb/acre/yr		
Atmosphere	low	avg	high
wet deposition (1)	0.05	0.12	0.20
dry deposition (est) (2)	0.05	0.12	0.20
Mineral weathering (3)	0.20	0.60	0.80
Total	0.30	0.84	1.20

Nutrient outputs

Leaching in even-aged systems			
5-yr totals (4)		0.00	

Harvest removal	*Bole wood & bark, kg/ha*	*Foliage, branches, kg/ha*	*Aboveground total, kg/ha*
Aspen (P&A 1982)	26.20	20.30	47
Aspen (P&A 1982)	21.40	28.00	49
Aspen (NH) (A&P 1990)	25.00	5.00	30
Aspen (paper birch) (A&P 1990)	24.00	4.00	28
Aspen (NH) (A&P 1990)	35.00	20.00	55
Aspen over SM (P&B 1984)	24.00	22.10	46.1
avg	25.93	16.57	42.52
x 0.66667 (5)		11.05	
lbs/acre	**23.13**	**9.85**	37.92
Amount P left in 1/3 of tops/limbs		4.92	
% of total aboveground P left on site		12.98	

Nutrient budget calculations

	(Inputs * years) - harvest - leaching = nutrient balance
Aspen - WTH, 40 yr (5)	
average	(0.84*40) - 23.1 - 9.85 = 0.6
with high inputs	(1.2*40) - 23.1 - 9.85 = 15.0
with low inputs	(0.3*40) - 23.1 - 9.85 = -21.0
Aspen - WTH, 50 yr (5)	
average	(0.84*50) - 23.1 - 9.85 = 9.0
with high inputs	(1.2*50) - 23.1 - 9.85 = 27.0
with low inputs	(0.3*50) - 23.1 - 9.85 = -18.0

(1) Data from five NADP stations in Wisconsin, 1997-2006.
(2) Literature indicates that dry deposition is estimated as approximately equal to wet deposition. There are no good methods for direct measurement of dry deposition.
(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996).
(4) Leaching data from Silkworth and Grigal (1982).
(5) WTH harvest assumes removal of 2/3 of nutrient content of foliage and branches.

Appendix 3: Nutrient Budgets

Nutrient inputs from atmospheric deposition and mineral weathering, and outputs through leaching

Deposition and weathering

	Ca, lb/acre/yr			Mg, lb/acre/yr			K, lb/acre/yr			Na, lb/acre/yr			N, lb/acre/yr			P, lb/acre/yr		
	low	avg	high	low	avg	high	low	avg	high	low	avg	high	low	avg	high	low	avg	high
Atmospheric wet deposition(1)	1.235	1.712	2.018	0.162	0.226	0.327	0.133	0.179	0.254	0.162	0.227	0.373	7.385	9.14	10.854	0.05	0.12	0.2
Atmospheric dry deposition (est)(2)	1.235	1.712	2.018	0.162	0.226	0.327	0.133	0.179	0.254	0.162	0.227	0.373	7.385	9.14	10.854	0.05	0.12	0.2
Mineral weathering(3)	1.7	3.7	5	0.9	1.5	2	0.7	1.5	2	1.7	4.7	9.2	0	0	0	0.2	0.6	0.8
Total	4.17	7.124	9.036	1.224	1.952	2.654	0.966	1.858	2.508	2.024	5.154	9.946	14.77	18.28	21.708	0.3	0.84	1.2

Leaching

Leaching in even-aged systems																		
5-yr totals(4)		55.6			29.1			0						0				

(1) Data from five NADP stations in Wisconsin, 1997-2006, except P deposition data from Robertson (1996). High P values are in SE WI.

(2) Literature indicates that dry deposition is estimated to be approximately equal to wet deposition. There are no good methods for direct measurement of dry deposition.

(3) Data for Lake States from Grigal (2004) based on Kolka et al. (1996), except P and Na from Grigal and Bates (1992).

(4) Data from Silkworth and Grigal (1982).

Appendix 3: Nutrient Budgets

Nutrient content of tree components, weight/area basis

Nitrogen

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Aspen	87	82	115	84	199	368	P&A 1982	kg/ha	Pike Bay, MN	vfsl Ca	
Aspen	89	92	96	77	173	354	P&A 1982	kg/ha	Pike Bay, MN	lfs	
Aspen (NH)		41			208	249	A&P 1990	kg/ha	Ottawa NF, MI	clay Ca	Data from Tables 2 & 6. Age 47 yrs
Aspen (paper birch)		39			181	220	A&P 1990	kg/ha	Cloquet, MN	acid fsl	Summer logged 60 yrs
Aspen (NH)		170			269	439	A&P 1990	kg/ha	Pike Bay, MN	vfsl Ca	66 yrs
Aspen over SM	54	103	86	97	183	340	P&B 1984	kg/ha	Vilas Co., WI	sl/fragipan/grs	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	153	131	44	61	105	389	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
White spruce	130	98	44	54	98	326	P&A 1982	kg/ha	Pike Bay	lfs	
Black spruce	65	31	26	45	71	167	M&F 1979	kg/ha	Quebec	avg fert	CitesW&W 1972
Black spruce	63.8	35	11.7	21.2	32.9	131.7	W&A 1983	kg/ha	Quebec	o over bedrock	200 yrs primary forest. To 3" top.
Red spruce-balsam fir					120.1	239.1	F,M,H 1981	kg/ha	central Nova Scotia	stony l	
Red spruce-balsam fir					97	322	S,M,H,M 1986	kg/ha	Weymouth Pt, ME	cs loamy, SPD	2-age stand, 60 yr > spruce budworm. Only spruce-fir values included here (86% of biomass)
Red pine	131	63	44	118	162	434	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Red pine	110	35	42	106	148	293	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine	65	78	34	87	121	264	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Jack pine	64	39	34	59	93	196	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine					98	180	F,M,H 1981	kg/ha	Canada		Cites M&F 1979
Jack pine	36.5	26.2	6	12	18.6	80.7	W&A 1983	kg/ha	Quebec	ms-cs	low site class, dry site, 53 yrs. To 3" top.
Jack pine						161	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds >=40 yr.
Jack pine	50	48	17	65	82	180	M&F 1979	kg/ha	Ontario	sl, low base	glaciofluvial parent material
NH					97	351	H 1986	kg/ha	Hubbard Brook		Bark & bole wood?
NH					142	255	H 1986	kg/ha	Success, NH		Bark & bole wood?
NH (SM,YB,AB)						209	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						257	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						228	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						226	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
NH (SM,YB,AB)						153	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						254	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						220	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						248	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						261	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						329	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						268	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						255	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM, AB, YB						616.83	HB	kg/ha	NH		watershed 6, 2002, ~100 yrs
Mature NH (equations for SM)	58	164.7	63.9	89.4	153.3	376	R&S 1993	lb/ac	Huron Mtns, MI	cl or l, bedrock	Values from biomass equations for SM (TM&K 1997) and concentration from R&S 1993 (likely underestimate).
Sugar maple OG stand	94.5	174.1	117	130	246.5	515.1	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	93.4	133.7	118	105	222.8	449.9	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	
NH (SM, AB, YB)	82.7	244.7	79.7	149	228.9	556.3	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed 6, 2002, all trees>2 cm, ~100 yrs, 5776 trees
NH (SM, AB, YB)	74.7	233.3	90.8	160	250.7	558.7	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed5, 1982, all trees>2 cm, ~80 yrs, 939 trees
Hwd (RM,TA,PC)						201	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds 20-37 yr.
Oaks		97			166	263	T,M,H 1987	kg/ha	Cocksponsett SF, CT	cs loamy till, outcrops	Q. rubra, Prinus, alba, velutina, Carya spp., Acer rubrum
Oaks	60	85			240	385	J,W,T,M 1982	kg/ha	Oak Ridge, TN	cherty cl	Q. prinus, velutina, rubra, alba, tulip pop, Acer rubrum, age 50-120

Phosphorus

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Aspen	9	11.3	16.4	9.8	26.2	47	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Aspen	10.9	17.1	14.4	7	21.4	49	P&A 1982	kg/ha	Pike Bay	lfs	
Aspen (NH)		5			25	30	A&P 1990	kg/ha	Ottawa NF, MI	clay Ca	
Aspen (paper birch)		4			24	28	A&P 1990	kg/ha	Cloquet, MN	acid fsl	
Aspen (NH)		20			35	55	A&P 1990	kg/ha	Pike Bay, MN	vfsl Ca	

Nutrient content, weight/area basis

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Aspen over SM	7	15.1	11	13	24	46.1	P&B 1984	kg/ha	Vilas Co., WI	sl/fragipan/grs	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	27	17.8	8.5	5.2	13.7	59	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
White spruce	18.3	15.1	7.3	4.2	11.5	45	P&A 1982	kg/ha	Pike Bay	lfs	
Black spruce	16			26		42	M&F 1979	kg/ha	Quebec	avg fert	Cites W&W 1972
Black spruce					2.6	19.2	W&A 1983	kg/ha	Quebec	o over bedrock	200 yrs primary forest. To 3" top.
Red spruce-balsam fir					18.2	35.2	F,M,H 1981	kg/ha	central Nova Scotia	stony l	
Red spruce-balsam fir					12	46	S,M,H,M 1986	kg/ha	Weymouth Pt, ME	cs loamy, SPD	2-age stand, 60 yr > spruce budworm. Only spruce-fir values included here (86% of biomass)
Red pine	18.7	8.1	6.7	9.3	16	43	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Red pine	12.5	4.3	5.6	8.3	13.9	31	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine	7.7	7.9	4.8	4.7	9.5	25	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Jack pine	6	4.5	3.4	5.3	8.7	19	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine					10	14	F,M,H 1981	kg/ha	Canada		Cites M&F 1979
Jack pine	3.8	3.6			2.2	9.6	W&A 1983	kg/ha	Quebec	ms-cs	low site class, dry site, 53 yrs. To 3" top.
Jack pine						21.5	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds >=40 yr.
Jack pine	6	4	1	3	4	14	M&F 1979	kg/ha	Ontario	sl, low base	glaciofluvial parent material
Mature NH (equations for SM)	7.8	21.3	5.7	12.8	18.5	47.7	R&S 1993	lb/ac	Huron Mtns, MI	cl or l, bedrock	Values from biomass equations for SM (Ter-Mikaelian 1997) and concentration from R&S 1993 (likely underestimate).
Sugar maple OG stand	4.2	11	4.9	8.8	13.7	28.9	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	4.6	7.4	5.1	7.3	12.4	24.4	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	
NH (SM, AB, YB)	6.6	29.9	4.3	12.8	17.1	53.6	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed 6, 2002, all trees>2 cm, ~100 yrs, 5776 trees
NH (SM, AB, YB)	5.8	25.6	4.9	13.9	18.8	50.2	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed5, 1982, all trees>2 cm, ~80 yrs, 939 trees
NH (SM,YB,AB)						18	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						21	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						18	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
NH (SM,YB,AB)						17	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						13	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						20	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						18	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						18	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						21	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						26	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						21	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						20	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
Hwd (RM,TA,PC)						27	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds 20-37 yr.
Oaks		11			6	17	T,M,H 1987	kg/ha	Cockspongsett SF, CT	cs loamy till, outcrops	Q. rubra, Prinus, alba, velutina, Carya spp., Acer rubrum
Oaks	4	7			16	27	J,W,T,M 1982	kg/ha	Oak Ridge, TN	cherty cl	Q. prinus, velutina, rubra, alba, tulip pop, Acer rubrum, age 50-120

Potassium

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Aspen	47	42	86	112	198	287	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Aspen	35	57	60	68	128	219	P&A 1982	kg/ha	Pike Bay	lfs	
Aspen (NH)		35			144	179	A&P 1990	kg/ha	Ottawa NF, MI	clay Ca	
Aspen (paper birch)		20			159	179	A&P 1990	kg/ha	Cloquet, MN	acid fsl	
Aspen (NH)		112			242	354	A&P 1990	kg/ha	Pike Bay, MN	vfsl Ca	
Aspen over SM	26	66	83	190	273	365	P&B 1984	kg/ha	Vilas Co., WI	sl/fragipan/grs	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	86	83	32	33	65	234	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
White spruce	64	57	25	26	51	172	P&A 1982	kg/ha	Pike Bay	lfs	
Black spruce	30	13	21	20	41	84	M&F 1979	kg/ha	Quebec	avg fert	CitesW&W 1972
Black spruce	50.2	24.1	7.3	28.6	35.9	110.2	W&A 1983	kg/ha	Quebec	o over bedrock	200 yrs primary forest. To 3" top.
Red spruce-balsam fir					76.2	132.6	F,M,H 1981	kg/ha	central Nova Scotia	stony l	
Red spruce-balsam fir					94	191	S,M,H,M 1986	kg/ha	Weymouth Pt, ME	cs loamy, SPD	2-age stand, 60 yr > spruce budworm. Only spruce-fir values included here (86% of biomass)
Red pine	59	33	17	71	88	180	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Red pine	59	19	20	45	65	142	P&A 1982	kg/ha	Pike Bay	lfs	

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Jack pine	20	26	12	41	53	99	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Jack pine	26	19	14	40	54	99	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine					39	89	F,M,H 1981	kg/ha	Canada		Cites M&F 1979
Jack pine	7.2	21.2	3.5	51	54.5	82.9	W&A 1983	kg/ha	Quebec	ms-cs	low site class, dry site, 53 yrs. To 3" top.
Jack pine						78.8	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds >=40 yr.
Jack pine	14	25	7	43	50	89	M&F 1979	kg/ha	Ontario	sl, low base	glaciofluvial parent material
Mature NH				85			R&S 1993	kg/ha	Huron Mtns, cl or l		
Mature NH (equations for SM)	31.1	128.4	34.9	230	264.8	424.3	R&S 1993	lb/ac	Huron Mtns, MI	cl or l, bedrock	Values from biomass equations for SM (Ter-Mikaelian 1997) and concentration from R&S 1993 (likely underestimate).
Sugar maple OG stand	46.5	140.6	66.7	81.7	148.4	335.5	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	41.7	100.5	32.2	55	87.2	229.4	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	
NH (SM, AB, YB)	35.3	84.1	32.1	69.8	101.9	221.3	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed 6, 2002, all trees>2 cm, ~100 yrs, 5776 trees
NH (SM, AB, YB)	31.9	74.8	35.6	69.6	105.2	211.9	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed5, 1982, all trees>2 cm, ~80 yrs, 939 trees
Hwd (RM,TA,PC)						123	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds 20-37 yr.
Oaks		49			111	160	T,M,H 1987	kg/ha	Cocksponsett SF, CT	cs loamy till, outcrops	Q. rubra, Prinus, alba, velutina, Carya spp., Acer rubrum
Oaks	50	35			90	175	J,W,T,M 1982	kg/ha	Oak Ridge, TN	cherty cl	Q. prinus, velutina, rubra, alba, tulip pop, Acer rubrum, age 50-120
Calcium											
	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Aspen	37	215	435	171	606	858	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Aspen	64	249	460	152	612	925	P&A 1982	kg/ha	Pike Bay	lfs	
Aspen (NH)		129			600	729	A&P 1990	kg/ha	Ottawa NF, MI	clay Ca	
Aspen (paper birch)		75			571	646	A&P 1990	kg/ha	Cloquet, MN	acid fsl	
Aspen (NH)		483			1106	1589	A&P 1990	kg/ha	Pike Bay, MN	vfsl Ca	

Nutrient content, weight/area basis

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Aspen over SM	38	253	400	160	560	851	P&B 1984	kg/ha	Vilas Co., WI	sl/fragipan/grs	60% of biomass in TA, 24% SM, 10% BA, 6% RM.
Aspen	10	78			188	276	R&B 1988	kg/ha	NC WI	ls, Rubicon	age 32. Data from Grigal
Aspen	8	125			280	413	R&B 1988	kg/ha	NC WI	ls, Rubicon	age 63. Data from Grigal.
Aspen	38.1	349			1005	1392.1	S 1980	kg/ha	Duluth, MN		Mature stand. Data from Grigal.
Aspen	24.4	181			511	716.4	S 1980	kg/ha	Duluth, MN		Mature stand. Data from Grigal.
Aspen	23.5	193			543	759.5	S 1980	kg/ha	Duluth, MN		Mature stand. Data from Grigal.
Aspen	26	199			562	787	S 1980	kg/ha	Duluth, MN		Mature stand. Data from Grigal.
Aspen	23.4	176			477	676.4	S 1980	kg/ha	Duluth, MN		Mature stand. Data from Grigal.
Aspen	44.4	204			567	815.4	S 1980	kg/ha	Duluth, MN		Mature stand. Data from Grigal.
Aspen	34	202			445	681	V 1983	kg/ha	Alaska		Data from Grigal
Aspen	25.6	23.8			278.5	327.9	R 1974	kg/ha	Maine		Data from Grigal
White spruce	256	224	166	88	254	734	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
White spruce	140	201	182	111	293	634	P&A 1982	kg/ha	Pike Bay	lfs	
Black spruce	73	41	51	112	163	277	M&F 1979	kg/ha	Quebec	avg fert	CitesW&W 1972
Black spruce	68.9	72.6	92.8	63.7	156.5	298	W&A 1983	kg/ha	Quebec	o over bedrock	200 yrs primary forest. To 3" top.
Red spruce-balsam fir					218.9	117.6	F,M,H 1981	kg/ha	central Nova Scotia	stony l	
Red spruce-balsam fir					215	423	S,M,H,M 1986	kg/ha	Weymouth Pt, ME	cs loamy, SPD	2-age stand, 60 yr > spruce budworm. Only spruce-fir values included here (86% of biomass)
Red pine	42	67	73	120	193	302	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Red pine	33	52	70	118	188	273	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine	20	52	57	74	131	203	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Jack pine	15	27	50	76	126	168	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine					40	127	F,M,H 1981	kg/ha	Canada		Cites M&F 1979
Jack pine	15.3	71.1	12.7	168	180.7	267.1	W&A 1983	kg/ha	Quebec	ms-cs	low site class, dry site, 53 yrs. To 3" top.
Jack pine						68.3	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds >=40 yr.
Jack pine	12	28	30	57	87	127	M&F 1979	kg/ha	Ontario	sl, low base	glaciofluvial parent material
Mature NH (equations for SM)	37.8	433.1	465	268	733.3	1204.1	R&S 1993	lb/ac	Huron Mtns, MI	cl or l, bedrock	Component values from biomass equations for SM (Ter-Mikaelian 1997) and concentration from R&S 1993.
Sugar maple OG stand	33	337.1	458	132	590	960.1	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	40.3	371.6	553	136	689.4	1101.3	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
NH (SM, AB, YB)	22.46	290.41	208	95.5	303.81	616.83	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed 6, 2002, all trees>2 cm, ~100 yrs, 5776 trees
NH (SM, AB, YB)	21.25	267.35	223	100	323.06	611.87	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed5, 1982, all trees>2 cm, ~80 yrs, 939 trees
NH (SM,YB,AB)						399	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						338	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						318	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						286	H&K 1983	kg/ha	Berlin, NH	sl	winter harvest
NH (SM,YB,AB)						282	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						271	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						364	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						400	H&K 1983	kg/ha	Berlin, NH	sl	summer cut no leaves
NH (SM,YB,AB)						402	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						374	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						329	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (SM,YB,AB)						365	H&K 1983	kg/ha	Berlin, NH	sl	summer cut + leaves
NH (RM,AB,YB)	24.9	229	193	99.3	292.7	546.6	H 1977	kg/ha	Bartlett Exp For, NH		
Hwd (RM,TA,PC)						126	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds 20-37 yr.
Oaks		98			451	549	T,M,H 1987	kg/ha	Cocksponsett SF, CT	cs loamy till, outcrops	Q. rubra, Prinus, alba, velutina, Carya spp., Acer rubrum
Oaks	40	200			910	1150	J,W,T,M 1982	kg/ha	Oak Ridge, TN	cherty cl	Q. prinus, velutina, rubra, alba, tulip pop, Acer rubrum, age 50-120

Magnesium

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Aspen	6	12.4	20.5	18.7	39.2	76	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Aspen	10.3	18.6	21.4	21.8	43.2	72	P&A 1982	kg/ha	Pike Bay	lfs	
Aspen (NH)		6			56	62	A&P 1990	kg/ha	Ottawa NF, MI	clay Ca	
Aspen (paper birch)		5			49	54	A&P 1990	kg/ha	Cloquet, MN	acid fsl	
Aspen (NH)		23			89	112	A&P 1990	kg/ha	Pike Bay, MN	vfsl Ca	
Aspen over SM	5	19.4	17	25	42	66.4	P&B 1984	kg/ha	Vilas Co., WI	sl/fragipan/grs	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	13.3	13.9	7.5	6.5	14	41	P&A 1982	kg/ha	Pike Bay	vfsl Ca	

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
White spruce	11	15.8	8.6	6.6	15.2	42	P&A 1982	kg/ha	Pike Bay	lfs	
Black spruce	9			18		27	M&F 1979	kg/ha	Quebec	avg fert	CitesW&W 1972
Black spruce					10.5	24.2	W&A 1983	kg/ha	Quebec	o over bedrock	200 yrs primary forest. To 3" top.
Red spruce-balsam fir					20.4	36.9	F,M,H 1981	kg/ha	central Nova Scotia	stony l	
Red spruce-balsam fir					17	44	S,M,H,M 1986	kg/ha	Weymouth Pt, ME	cs loamy, SPD	2-age stand, 60 yr > spruce budworm. Only spruce-fir values included here (86% of biomass)
Red pine	14.4	9.3	8.7	27	35.7	59	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Red pine	11.5	8.1	9.4	23.8	33.2	52	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine	5.6	10.1	5.8	16.9	22.7	38	P&A 1982	kg/ha	Pike Bay	vfsl Ca	
Jack pine	5	5.8	5.9	16.4	22.3	33	P&A 1982	kg/ha	Pike Bay	lfs	
Jack pine					8	20	F,M,H 1981	kg/ha	Canada		Cites M&F 1979
Jack pine	2.2	9.2	1.1	23.4	24.5	35.9	W&A 1983	kg/ha	Quebec	ms-cs	low site class, dry site, 53 yrs. To 3" top.
Jack pine						18.8	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds >=40 yr.
Jack pine	3	4	2	10	12	19	M&F 1979	kg/ha	Ontario	sl, low base	glaciofluvial parent material
Mature NH (equations for SM)	5.4	18.7	7.1	38.3	45.4	69.5	R&S 1993	lb/ac	Huron Mtns, MI	cl or l, bedrock	Values from biomass equations for SM (Ter-Mikaelian 1997) and concentration from R&S 1993 (likely underestimate).
Sugar maple OG stand	5.1	15	8.5	19.4	27.9	48	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	5.9	17.3	11.4	33.3	44.7	67.9	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	
NH (SM, AB, YB)	5.5	20.6	7.1	20	27.1	53.2	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed 6, 2002, all trees>2 cm, ~100 yrs, 5776 trees
NH (SM, AB, YB)	5.2	18.6	8.2	20.9	29.1	52.9	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed5, 1982, all trees>2 cm, ~80 yrs, 939 trees
Hwd (RM,TA,PC)						23	M&W 1977	kg/ha	New Brunswick	in prev paper	Has values for young stands. Here - avg of 4 stds 20-37 yr.
Oaks		12			22	34	T,M,H 1987	kg/ha	Cockspontsett SF, CT	cs loamy till, outcrops	Q. rubra, Prinus, alba, velutina, Carya spp., Acer rubrum
Sulfur											

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Mature NH (equations for SM)	6.3	17.6	9.6	12.8	22.4	46.3	R&S 1993	lb/ac	Huron Mtns, MI	cl or l, bedrock	Values from biomass equations for SM (Ter-Mikaelian 1997) and concentration from R&S 1993 (likely underestimate).
Sugar maple OG stand	9.5	18.1	6.8	11.9	18.7	46.3	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	9	11.9	8.2	15.3	23.5	44.4	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	
NH (SM, AB, YB)	5.6	27.4	7.9	15.6	23.5	56.5	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed 6, 2002, all trees>2 cm, ~100 yrs, 5776 trees
NH (SM, AB, YB)	4.6	26.4	8.9	18	26.9	57.9	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed5, 1982, all trees>2 cm, ~80 yrs, 939 trees
Aspen over SM	5	61.2	8	15	23	89.2	P&B 1984	kg/ha	Vilas Co., WI	sl/fragipan/grs	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Iron											
	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Sugar maple OG stand	0.3	2.5	1	2.4	3.4	6.2	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	0.2	2.4	0.9	2.8	3.7	6.3	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	
Aspen over SM	0.3	0.8	1.2	1	2.2	3.3	P&B 1984	kg/ha	Vilas Co., WI	sl/fragipan/grs	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Manganese											
	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Sugar maple OG stand	3.9	15	12	9.7	21.7	40.6	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Sugar maple OG stand	3.8	9.8	12.3	5.3	17.6	31.2	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	

Zinc

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Sugar maple OG stand	0.3	1.6	1.51	1.77	3.28	5.18	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	0.24	1.09	0.93	1.22	2.15	3.48	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	
NH (SM, AB, YB)	0.28	3.24	0.93	1.72	2.65	6.17	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed 6, 2002, all trees>2 cm, ~100 yrs, 5776 trees
NH (SM, AB, YB)	0.41	3.91	1.56	2.29	3.85	8.17	HB	kg/ha	NH	fsl, Typic & Lithic Haplorthods	watershed5, 1982, all trees>2 cm, ~80 yrs, 939 trees
Aspen over SM	0.2	1.4	2.1	0.2	2.3	3.9	P&B 1984	kg/ha	Vilas Co., WI	sl/fragipan/grs	60% of biomass in TA, 24% SM, 10% BA, 6% RM

Copper

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Soils*	*Notes*
Sugar maple OG stand	0.04	0.19	0.13	0.48	0.61	0.84	M 1990	kg/ha	Norberg, Turkey Lks, Ont	acid till	
Sugar maple OG stand	0.04	0.2	0.14	0.35	0.49	0.73	M 1990	kg/ha	Wishart, Turkey Lks, Ont	acid till	

Appendix 3: Nutrient Budgets

Nutrient concentration of tree components

Nitrogen

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Paper birch	2.027	0.56	0.378	0.12			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	2.21	0.63	0.368	0.06			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	2.6	0.47	0.33	0.07			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. Aspen 65 yrs.	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	0.903	0.593	0.318	0.05			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Balsam fir	1.127	0.447	0.31	0.05			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Tag alder	2.54	0.883	0.956	0.24			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Sugar maple	1.847	0.44	0.452	0.07			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Sugar maple	1.88	0.31	0.48	0.11			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. SM 39-62 yrs	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Eastern hemlock	1.583	0.407	0.282	0.09			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Yellow birch	NR	NR	0.446	0.09			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Red oak	2.167	0.447	0.362	0.14			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Balsam fir	364.1604	26.8	74.9742	69.6189	144.5931	535.53	Y&G 1966	g/tree	Stillwater, ME			Need another article w/ dry weights
Hemlock	259.6944	44.1	61.6224	74.8272	136.4496	440.16	Y&G 1966	g/tree	Stillwater, ME			Need another article w/ dry weights
White pine	158.6	28.4	85.4	134.17	219.57	406.59	Y&G 1966	g/tree	Stillwater, ME			Need another article w/ dry weights
Paper birch	212.43	75.34	219.28	178.2	397.48	685.25	Y&G 1966	g/tree	Stillwater, ME			Need another article w/ dry weights
			note bark to 1/4 "	note wood undefined								

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Red maple	118.38	18.2	173	145.7	318.7	455.3	Y&G 1966	g/tree	Stillwater, ME			Need another article w/ dry weights
Aspen	68.7	15	73	58	131	214.8	Y&G 1966	g/tree	Stillwater, ME			Need another article w/ dry weights

Phosphorus

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Paper birch	0.18	0.067	0.028	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	0.167	0.08	0.038	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	0.27	0.08	0.056	0.01			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. Aspen 65 yrs.	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	0.117	0.087	0.048	0			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Balsam fir	0.14	0.097	0.043	0			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Tag alder	0.133	0.057	0.052	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Sugar maple	0.25	0.057	0.04	0.01			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Sugar maple	0.32	0.036	0.04	0.01			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. SM 39-62 yrs	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Eastern hemlock	0.213	0.05	0.035	0.02			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Yellow birch	NR	NR	0.03	0.01			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Red oak	0.193	0.057	0.02	0			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	

Potassium

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Paper birch	0.743	0.2	0.124	0.05			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Aspen	0.73	0.383	0.28	0.07			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	1.12	0.38	0.35	0.16			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. Aspen 65 yrs.	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	0.437	0.48	0.227	0.03			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Balsam fir	0.473	0.5	0.236	0.14			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Tag alder	0.42	0.17	0.2	0.05			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Sugar maple	0.99	0.343	0.247	0.18			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Sugar maple	1.04	0.29	0.33	0.14			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. SM 39-62 yrs	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Eastern hemlock	0.693	0.173	0.108	0.11			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Yellow birch	NR	NR	0.144	0.08			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Red oak	0.883	0.213	0.122	0.08			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	

Calcium

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Paper birch	1.113	0.63	1.034	0.08			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	1.307	1.843	1.45	0.16			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	1.74	1.12	1.52	0.12			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. Aspen 65 yrs.	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	1.683	0.813	1.652	0.1			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Balsam fir	1.99	0.58	0.927	0.08			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Tag alder	0.863	0.443	1.69	0.09			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Sugar maple	1.203	1.157	3.29	0.21			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Sugar maple	1.47	0.78	2.29	0.14			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. SM 39-62 yrs	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Eastern hemlock	0.827	0.58	0.548	0.1			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Yellow birch	NR	NR	1.22	0.12			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Red oak	0.967	1.14	3.348	0.04			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	

Magnesium

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Paper birch	0.35	0.07	0.044	0.02			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	0.267	0.143	0.088	0.02			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	0.25	0.101	0.076	0.02			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. Aspen 65 yrs.	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	0.087	0.073	0.06	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Balsam fir	0.113	0.07	0.052	0.02			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Tag alder	0.253	0.043	0.048	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Sugar maple	0.173	0.05	0.05	0.03			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Sugar maple	0.19	0.041	0.047	0.021			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. SM 39-62 yrs	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Eastern hemlock	0.11	0.03	0.02	0.02			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Yellow birch	NR	NR	0.054	0.02			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Red oak	0.137	0.077	0.03	0			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Sulfur												
	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Paper birch	0.14	0.04	0.028	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	0.18	0.06	0.05	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Aspen	0.21	0.03	0.03	0.01			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. Aspen 65 yrs.	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
White spruce	0.087	0.057	0.042	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Balsam fir	0.123	0.04	0.037	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Tag alder	0.167	0.05	0.066	0.01			R&S 1993	%	Isle Royale	mature boreal	loamy, nonacid	
Sugar maple	0.2	0.047	0.068	0.01			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Sugar maple	0.2	0.03	0.04	0.01			P&B 1984	% dry	Vilas Co., WI	Aspen over SM. SM 39-62 yrs	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Eastern hemlock	0.143	0.03	0.025	0.01			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Yellow birch	NR	NR	0.038	0.01			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Red oak	0.167	0.04	0.053	0.01			R&S 1993	%	Huron Mtns	mature NH	clay loam & loam	
Iron												
	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Aspen	120	27	38	7.5			P&B 1984	mg/kg dry	Vilas Co., WI	Aspen over SM. Aspen 65 yrs.	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Sugar maple	140	32	95	9.3			P&B 1984	mg/kg dry	Vilas Co., WI	Aspen over SM. SM 39-62 yrs	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM

	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
							Zinc					
	Foliage	*Branches (includes dead)*	*Bole bark*	*Bole wood*	*Bole wood & bark*	*Above-ground total*	*Source*	*Unit*	*Location*	*Veg*	*Soils*	*Notes*
Aspen	170	88	110	17			P&B 1984	mg/kg dry	Vilas Co., WI	Aspen over SM. Aspen 65 yrs.	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM
Sugar maple	23	10	20	5.6			P&B 1984	mg/kg dry	Vilas Co., WI	Aspen over SM. SM 39-62 yrs	sl/fragipan/ gr s	60% of biomass in TA, 24% SM, 10% BA, 6% RM

References

A&P 1990	Alban, DH, and Perala, DA. 1990. Impact of aspen timber harvesting on soils. pp. 377-391. In: Gessel, SP, Lacate, DS, Weetman, GF, Powers, RF, eds. Sustained Productivity of Forest Soils. Proceedings of the 7th North American Forest Soils Conf., Univ. of British Columbia, Vancouver, BC. 525 p.
B 1984	Bassett, J.R. 1984. Red pine plantation management in the Lake States: a review. IFSIM Publication No. 3. University of Michigan, School of Natural Resources. Ann Arbor, MI. 15 p.
F,M,H 1981	B. Freedman, R. Morash, and A. J. Hanson. 1981. Biomass and nutrient removals by conventional and whole-tree clear-cutting of a red spruce – balsam fir stand in central Nova Scotia. Can. J. For. Res. 11(2): 250–258.
H 1977	Hornbeck, JW. 1977. Nutrients: a major consideration in intensive forest management. In: Proceedings. Symposium on intensive culture of northern forest types. Gen. Tech. Rep. NE-129. U. S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.
H 1986	Hornbeck, JW. 1986. Nutrient cycles and forest productivity. In: Smith, Tattersall C.; Wayne, MC.; Tritton, LM.; [Eds]. Proceedings of the 1986 symposium on the productivity of northern forests following biomass harvesting. Gen. Tech. Rep. NE-115a. Broomall, PA: U. S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 104 p. Online http://www.treesearch.fs.fed.us/pubs/4162
HB	Interactive Biomass Program. Online at http://www.hubbardbrook.org/w6_tour/biomass-stop/biomass.htm
H&K 1983	Hornbeck, JW; Kropelin, WK. 1983. Estimating biomass and nutrient removal from a northern hardwood harvest. Journal of Forestry 81(5): 287-288
J,W,T,M 1982	Johnson, DW, D. C. West, D. E. Todd and L. K. Mann. 1982. Effects of Sawlog vs. Whole-Tree Harvesting on the Nitrogen, Phosphorus, Potassium, and Calcium Budgets of an Upland Mixed Oak Forest. Soil Sci. Soc. Am. J. 46: 1304-1309.
M 1990	Morrison, IK. 1990. Organic matter and mineral distribution in an old-growth *Acer saccharum* forest near the northern limit of its range. Can. J. For. Res. 20(9): 1332–1342
M&F 1979	Morrison, IK, and Foster, NW. 1979. Biomass and element removal by complete-tree harvesting of medium rotation forest stands. In: A. L. Leaf, ed.Proceedings, Impact of intensive harvesting on forest nutrient cycling; 1979 August 13-16; Syracuse, NY. State University of New York, College of Environmental Science and Forestry. 421 p.
M&W 1977	David A. MacLean and Ross W. Wein. 1977. Nutrient accumulation for postfire jack pine and hardwood succession patterns in New Brunswick. Can. J. For. Res. 7(4): 562–578.
P&A 1982	Perala, DA, Alban, DH. 1982. Biomass, Nutrient Distribution and Litterfall in Populus, Pinus and Picea Stands on Two Different Soils in Minnesota. Plant and Soil 64(2): 177-192
P&B 1984	Pastor, J, Bockheim, JG. 1984. Distribution and Cycling of Nutrients in an Aspen-Mixed-Hardwood-Spodosol Ecosystem in Northern Wisconsin. Ecology 65(2):339-353
R&S 1993	Rutkowski , D.R.; R. Stottlemyer. 1993. Composition, biomass and nutrient distribution in mature northern hardwood and boreal forest stands, Michigan. Am. Midl. Nat. 130:13-30.
S&G 1982	Silkworth, DR, and DF Grigal. 1982. Determining and evaluting nutrient losses following whole-tree harvesting of aspen. Soil Sci. Soc. Am. J. 46: 626-631.
S,M,H,M 1986	C. T. Smith Jr., M. L. McCormack Jr., J. W. Hornbeck, and C. W. Martin. 1986. Nutrient and biomass removals from a red spruce – balsam fir whole-tree harvest. Can. J. For. Res. 16(2): 381–388.
TM&K 1997	Ter-Mikaelian, M.T., and M.D. Korzukhin. 1997. Biomass equations for sixty-five North American tree species. Forest Ecol. Mgmt. 97:1-24.
T,M,H 1987	Tritton, LM; Martin, CW; Hornbeck, JW; Pierce, RS. 1987. Biomass and nutrient removals from commercial thinning and whole-tree clearcutting of central hardwoods. Environmental Management 11(5): 659-666
W&A 1983	G. F. Weetman and D. Algar.1983. Low-site class black spruce and jack pine nutrient removals after full-tree and tree-length logging. Can. J. For. Res. 13(6): 1030–1036.
Y&G 1966	Young, HE, and Guinn, VP. 1966. Chemical elements in complete mature trees of seven species in Maine. Tappi 49(5):190-197.

Appendix 4: Atmospheric Deposition

Northeast Wisconsin
Station WI-09 Popple River – Florence County

	Total Wet Deposition (kg/ha)									
Year	**Ca**	**Mg**	**K**	**Na**	**NH4**	**NO3**	**Inorganic N**	**Total N**	**CL**	**SO4**
1997	0.87	0.142	0.113	0.153	2.27	7.36	3.43	6.8553	0.33	7.26
1998	1.11	0.144	0.155	0.166	2.33	8.01	3.62	7.2387	0.33	6.82
1999	2.12	0.277	0.156	0.199	2.54	9.12	4.04	8.0725	0.41	7.64
2000	1.77	0.21	0.218	0.202	3.37	10.5	4.99	9.9788	0.44	8.54
2001	1.38	0.185	0.177	0.177	2.76	9.17	4.22	8.4346	0.38	8.42
2002	2.07	0.254	0.186	0.237	4.45	12.05	6.18	12.3575	0.44	9.29
2003	1.41	0.159	0.224	0.124	2.66	7.74	3.82	7.6340	0.3	6.72
2004	1.11	0.157	0.186	0.157	2.73	8.04	3.94	7.8761	0.34	6.47
2005	0.76	0.117	0.182	0.162	2.52	6.43	3.41	6.8193	0.32	6.17
2006	1.28	0.171	0.171	0.243	2.79	7.46	3.86	7.7116	0.46	6.36
kg/ha/yr	**1.388**	**0.182**	**0.177**	**0.182**	**2.842**	**8.588**	**4.151**	**8.298**	**0.375**	**7.369**
lbs/acre/yr	**1.235**	**0.162**	**0.157**	**0.162**	**2.529**	**7.643**	**3.694**	**7.3851**	**0.334**	**6.558**

Northwest Wisconsin
Station WI-37 Spooner – Washburn County

	Total Wet Deposition (kg/ha)									
Year	**Ca**	**Mg**	**K**	**Na**	**NH4**	**NO3**	**Inorganic N**	**Total N**	**CL**	**SO4**
1997	0.86	0.144	0.138	0.24	2.16	5.96	3.02	6.0436	0.43	4.67
1998	1.56	0.221	0.214	0.286	3.84	8.74	4.96	9.9161	0.49	7.69
1999	2.45	0.336	0.36	0.28	4.06	10.61	5.55	11.0994	0.53	8.2
2000	2.23	0.301	0.232	0.301	4.6	11.47	6.17	12.3330	0.55	8.26
2001	2.64	0.347	0.219	0.347	4.56	10.81	5.99	11.9728	0.59	8.99
2002	2.55	0.289	0.222	0.251	5.66	13.2	7.38	14.7569	0.48	10.5
2003	1.38	0.189	0.189	0.12	2.43	6.25	3.3	6.5988	0.25	5.25
2004	3.39	0.433	0.294	0.302	4.01	9.21	5.2	10.3943	0.48	6.77
2005	1.47	0.189	0.158	0.347	3.37	7.6	4.33	8.6636	0.54	6.79
2006	1.49	0.229	0.219	0.141	2.79	7.19	3.79	7.5807	0.31	5.1
kg/ha/yr	**2.002**	**0.268**	**0.225**	**0.262**	**3.748**	**9.104**	**4.969**	**9.936**	**0.465**	**7.222**
lbs/acre/yr	**1.782**	**0.238**	**0.200**	**0.233**	**3.336**	**8.103**	**4.422**	**8.8430**	**0.414**	**6.428**

Central Wisconsin
Station WI-28 Lake DuBay – Portage County

	Total Wet Deposition (kg/ha)									
Year	**Ca**	**Mg**	**K**	**Na**	**NH4**	**NO3**	**Inorganic N**	**Total N**	**CL**	**SO4**
1997	1.13	0.181	0.123	0.222	2.99	9.31	4.43	8.8549	0.45	8.75
1998	1.57	0.202	0.17	0.294	3.01	10.66	4.75	9.4954	0.56	10.67
1999	1.93	0.241	0.143	0.273	2.97	8.54	4.24	8.4754	0.49	8.11
2000	2.07	0.214	0.167	0.238	3.6	9.88	5.03	10.0573	0.46	9.03
2001	1.83	0.232	0.163	0.279	3.94	11.28	5.61	11.2176	0.5	10.64
2002	2.45	0.29	0.167	0.308	4.89	12.56	6.64	13.2744	0.53	11.19
2003	1.37	0.232	0.11	0.116	3.05	8.28	4.24	8.4788	0.33	7
2004	1.43	0.195	0.133	0.223	3.38	7.69	4.36	8.7217	0.39	7.09
2005	1.3	0.192	0.132	0.252	2.91	6.69	3.77	7.5409	0.46	7.03
2006	2.51	0.31	0.183	0.289	4.24	9.49	5.44	10.8762	0.49	8.73
kg/ha/yr	**1.759**	**0.229**	**0.149**	**0.249**	**3.498**	**9.438**	**4.851**	**9.699**	**0.466**	**8.824**
lbs/acre/yr	**1.566**	**0.204**	**0.133**	**0.222**	**3.113**	**8.400**	**4.317**	**8.6323**	**0.415**	**7.853**

Southwest Wisconsin
Station WI-98 Wildcat Mountain – Vernon County

	Total Wet Deposition (kg/ha)									
Year	**Ca**	**Mg**	**K**	**Na**	**NH4**	**NO3**	**Inorganic N**	**Total N**	**CL**	**SO4**
1997	2.04	0.295	0.11	0.274	3.44	10.77	5.1	10.2041	0.55	9.72
1998	2.08	0.3	0.146	0.3	3.43	11.69	5.3	10.6042	0.63	11.04
1999	2.31	0.323	0.134	0.244	3.33	9.81	4.81	9.6118	0.47	8.99
2000	2.69	0.304	0.4	0.296	4.53	12.38	6.32	12.6342	0.56	10.5
2001	3.2	0.391	0.251	0.501	5.32	13.68	7.23	14.4513	0.74	13.22
2002	3.07	0.366	0.203	0.317	4.79	13.33	6.73	13.4607	0.58	11.43
2003	2.78	0.314	0.196	0.183	3.99	9.32	5.21	10.4136	0.39	8.07
2004	2.28	0.309	0.272	0.291	4.37	10.1	5.68	11.3549	0.49	8.94
2005	1.98	0.27	0.148	0.263	3.57	8.16	4.62	9.2354	0.47	8.27
2006	1.89	0.27	0.357	0.23	4.01	8.89	5.13	10.2520	0.42	9.47
kg/ha/yr	**2.432**	**0.314**	**0.222**	**0.290**	**4.078**	**10.813**	**5.613**	**11.222**	**0.530**	**9.965**
lbs/acre/yr	**2.164**	**0.280**	**0.197**	**0.258**	**3.629**	**9.624**	**4.996**	**9.9878**	**0.472**	**8.869**

Southeast Wisconsin
Station WI-99 Lake Geneva – Walworth County

	Total Wet Deposition (kg/ha)									
Year	**Ca**	**Mg**	**K**	**Na**	**NH4**	**NO3**	**Inorganic N**	**Total N**	**CL**	**SO4**
1997	1.92	0.346	0.143	0.346	3.68	12.61	5.71	11.4161	0.71	12.62
1998	2.33	0.449	0.225	0.412	4.59	16.22	7.24	14.4682	0.91	17.71
1999	1.98	0.376	0.188	0.305	3.17	14.64	5.77	11.5387	0.72	15.39
2000	2.87	0.374	0.242	0.594	4.13	16.14	6.85	13.7030	1.12	14.76
2001	2.32	0.38	0.22	0.51	4.77	15.2	7.14	14.2776	0.89	15.6
2002	2.4	0.343	0.195	0.351	3.85	12.19	5.75	11.4932	0.61	11.91
2003	1.99	0.332	0.216	0.317	3.85	10.57	5.38	10.7573	0.68	11.4
2004	1.69	0.286	0.379	0.449	3.43	9.29	4.76	9.5220	0.74	9.21
2005	2.27	0.348	0.249	0.441	3.85	11.43	5.57	11.1416	0.76	12.11
2006	2.9	0.445	0.796	0.464	4.93	13.22	6.82	13.6345	0.88	14.53
kg/ha/yr	2.267	0.3679	0.2853	0.4189	4.025	13.151	6.099	12.1952	0.802	13.524
lbs/acre/yr	**2.018**	**0.327**	**0.254**	**0.373**	**3.582**	**11.704**	**5.428**	**10.8537**	**0.714**	**12.036**

Appendix 5: WI Soil Nutrient Capital Report – Dr. David Grigal

Soil Nutrient Capital
Dr. David Grigal - 27 March 2008

Databases

After some searching, I found that I had three databases that would be helpful. First, I had a database of soil characterization data from the University of Minnesota (*Minnesota Database*). We used those data in the original GEIS (Grigal, D.F. and P.C. Bates. 1992. Forest soils. A technical paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota. Jaakko Poyry Consulting, Inc. Tarrytown, NY. 155 p.). The data were from pedons of representative forest soil series from the Cooperative Soil Survey database that had been developed by the University of Minnesota and the Soil Conservation Service (now NRCS). I wrote a summary program to compute weighted average sand, silt, clay and exchangeable calcium to 100 cm depth. The result was estimates from 175 pedons (I eliminated pedons that had some kind of data problem or did not extend to 100 cm). These pedons were not sampled randomly, but were sampled to be representative. As I said, I only selected soils that are commonly forested for this analysis.

The second database was from a transect of FIA (Forest Inventory and Analysis) plots from the USDA Forest Service (Ohmann, L. F., D. F. Grigal, and S. Brovold. 1989. Physical characteristics of study plots across a Lake States acidic deposition gradient. USDA Forest Service Resource Bulletin RBNC110.47 p.) (*Lake States Transect*). These data represented five cover types (including aspen) over Wisconsin, Michigan, and Minnesota, and were randomly located with the FIA plots. I again wrote a summary program to compute weighted average sand, silt, clay and exchangeable calcium to 100 cm depth. The result was estimates from 149 pedons (I eliminated pedons that had some kind of data problem or did not extend to 100 cm). These pedons were sampled randomly.

The third database was from a study of coexisting pine plantations and adjacent naturally regenerated hardwoods (primarily aspen) (Wilson, D. M. and D.F. Grigal. 1995. Effects of pine plantations and adjacent deciduous forests on soil calcium. Soil Science Society America Journal 59:17551761) (Plantation Pairs). These data were collected in Wisconsin, Michigan, and Minnesota, and were not random in the sense that they were selected to represent adjacent pine 2 and hardwoods. I wrote another summary program to compute weighted average sand, silt, clay and exchangeable calcium to 100 cm depth. The result was estimates from 76 pedons, representing 38 pairs of pine and adjacent hardwoods.

Results – Mineral Soils

Because the sampling criterion for each database differed, the resulting data also differed (Fig. 1)

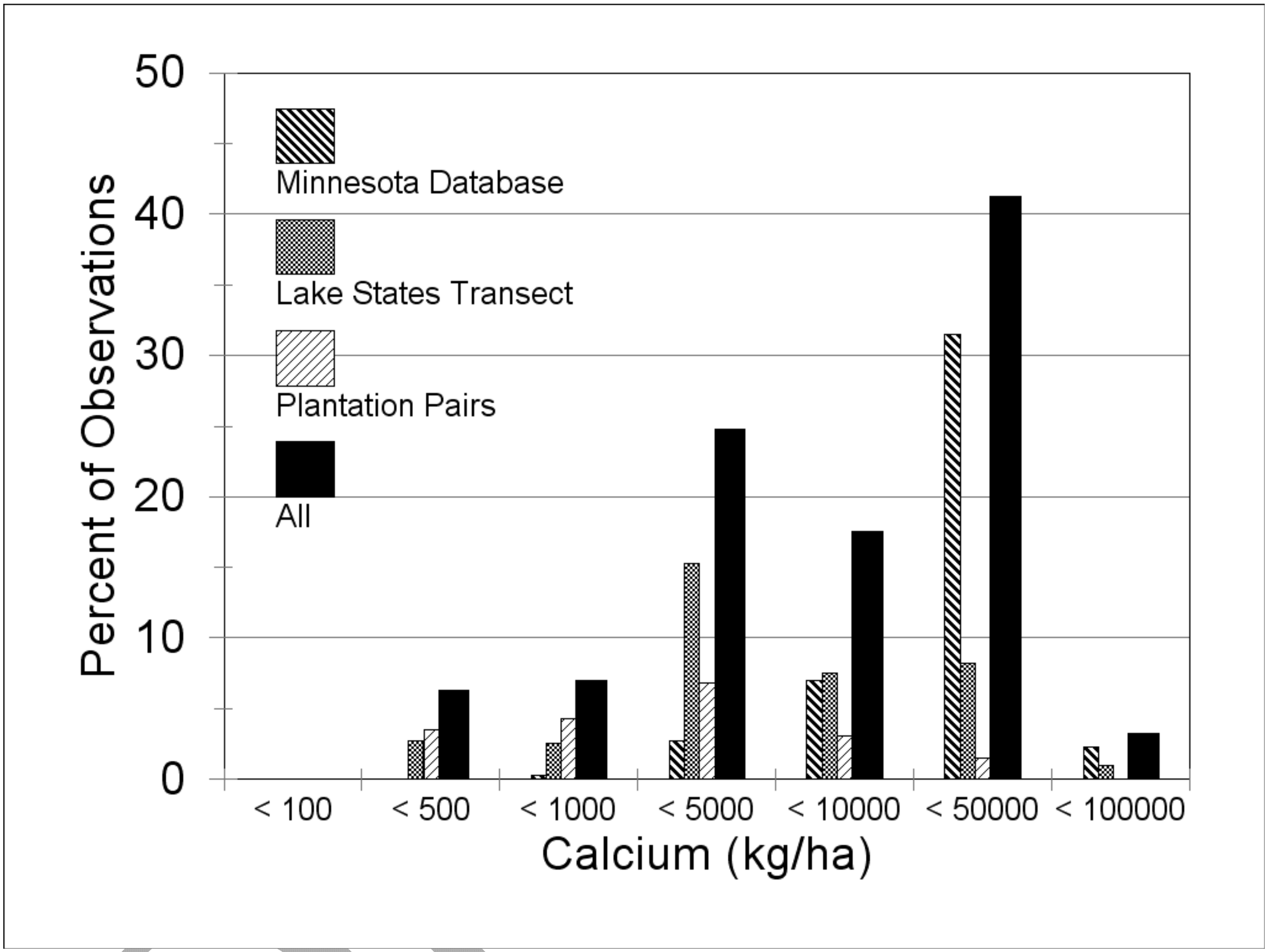

Fig.1. Distribution of exchangeable calcium to 100 cm depth in three different soil databases. "All" is the combined data for all three databases.

The data from the plantation study (*Plantation Pairs*) tend to have the lowest exchangeable calcium of the three databases, and that from the Cooperative Soil Survey database (*Minnesota Database*) tend to be highest in exchangeable calcium (Fig.1). It is likely that the plantations were primarily established on sites suitable for pine (i.e., sandy), while the transect and the Soil Survey databases were more widely distributed.

There is no question that exchangeable calcium to 100 cm is closely related to clay in the same depth (Fig. 2).

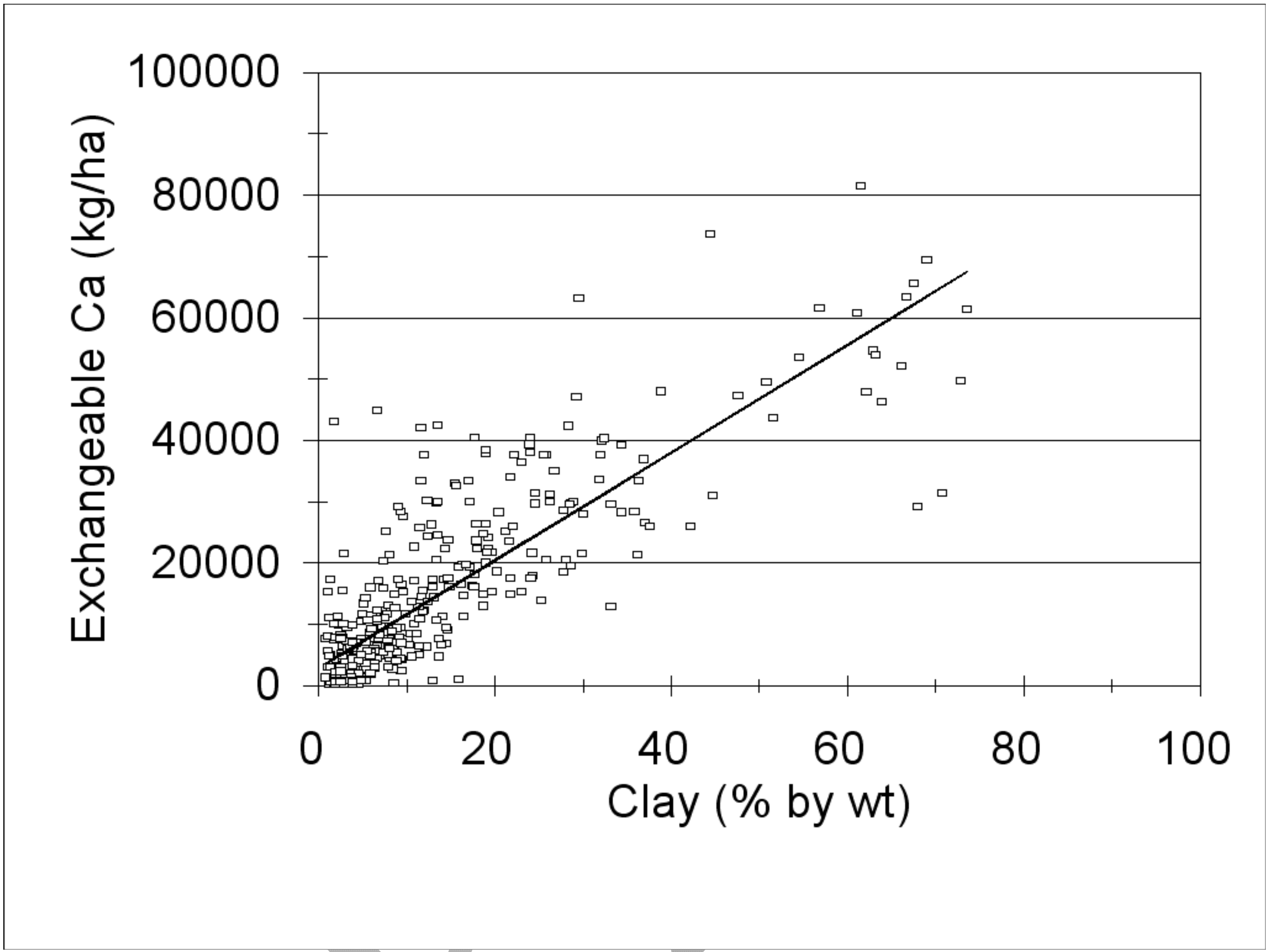

Fig. 2. Scatterplot of relationship between exchangeable calcium and percent clay in upper 100 cm of Lake States' soils. Best fit regression indicated (r2 = 0.71, n = 400, *prob.* = 0).

The best fit regression indicates that exchangeable calcium content in the upper 100 cm of soil increases by 880 kg/ ha for every one percent increase in clay. This variation can have profound effects on any spread sheet type nutrient budget. Certainly other variables, such as characteristics of the parent material and the organic matter content of the soil affect exchangeable calcium, but this regression is remarkable for its simplicity.

As indicated earlier, the databases differed in sampling and in the populations they represent (Fig.1). Because most interest is in soils with low calcium (and clay), a more detailed analysis was conducted of pedons with average clay < 20% dry weight. This value was selected because clay begins to dominate soil physical and chemical properties in soils with more clay, (e.g., sandy clay, clay loam, silty clay loam). This analysis indicated that in this range of clay (0 to 20%), exchangeable calcium increased at the same rate in all databases (i.e., slopes were homogeneous, F (2,319) = 0.25, *prob.* = 0.78), but that the intercept for each database differed (F(3,321) = 110, *prob.* = 0), with *Minnesota Database* highest and *Plantation Pairs* lowest (Fig. 3).

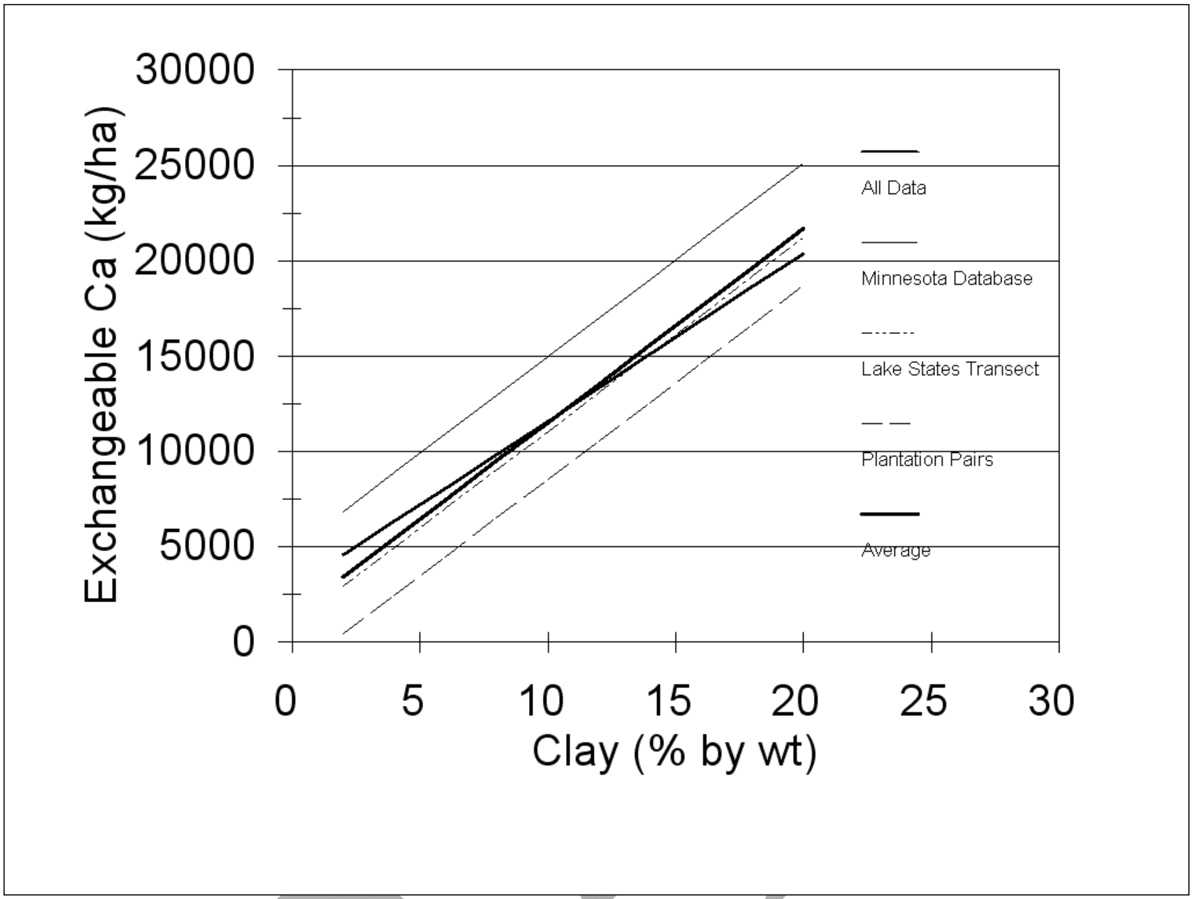

Fig. 3. Results of analysis of covariance, relating exchangeable calcium and percent clay in upper 100cm of Lake States' soils, restricted to soils with less than 20% clay. Overall regression was significant (r2 = 0.71, n = 325, *prob.* = 0). Best-fit for each database indicated. "Average" = average of best fit for the three databases, and "All Data" is best-fit regression for all data, including data with greater than 20% clay (also shown in Fig. 2).

In the case of the analysis of covariance at lower clay contents, the best-fit for the three databases indicates that exchangeable calcium content in the upper 100 cm of soil increases by slightly over 1000 (1015) kg/ha for every one percent increase in clay.

It is clear from these analyses that Lake States' soils are relatively high in exchangeable calcium, even at relatively low clay contents.

Results – Forest Floor

Two of the databases, the *Plantation Pairs* and the *Lake States Transect,* also had forest floor information. In the case of the *Plantation Pairs*, total calcium in forest floor differed between the pine plantation (130 kg/ha) and the hardwoods (155 kg/ha). Forest floor is both a source of nutrition for biomass and is the resultant of biomass accretion over time. The differences noted here, on identical substrates, are presumably the result of the influences of the differing overstories over the time of stand occupancy.

In the *Lake States Transect*, there were also significant differences among cover types in forest floor calcium (F (4,166) = 12.3, *prob*. = 0) (jack pine = 170 kg ha$_1$, red pine = 130 kg ha$_1$, balsam fir = 440 kg ha$_1$, northern hardwoods = 490 kg ha$_1$,and aspen = 365 kg ha$_1$). Forest floor can be a significant reservoir of calcium. In this case, differences in calcium between pine and non-pine types are greater than in the *Plantation Pairs*. In the case of the transect, pine stands were on sandier soils (F (4,143) = 21.1, *prob*. = 0) (jack pine = 92% sand, red pine = 87%, balsam fir = 64%, northern hardwoods = 63%, and aspen = 59%). These data indicate the tendency of aspen to occur on finer textured soils.

Inputs-Outputs

I view all spread sheet approach nutrient budgets with a “grain of salt”. Long-term studies have shown that such paper exercises may not translate into reality. Although they are indicative, they are not absolute. Some values in such budgets are relatively firm (e.g., nutrient capital in soils), but other values (e.g., weathering rates) are highly uncertain. Only long-term studies can provide the real answers. The data from Wilson and Grigal (1995) provide such a taste of reality. As discussed earlier, they examine pairs of adjacent stands, pine plantations and adjacent hardwoods (primarily aspen). The average stand age of the hardwoods (60 yrs) was greater than the pine (46 yrs), perhaps because of immediate occupancy of the site after disturbance by the hardwoods compared to delayed plantation establishment. The calcium inventory indicated no significant differences between pine and hardwoods in soil calcium to 100 cm, yet the total calcium in the sum of overstory, understory, and forest floor in the hardwood stands was much greater than in the pine stands (960 vs. 420 kg/ha, respectively). We can assume that the soils were uniform with respect to calcium before stand establishment (stands were only separated by a property boundary), and measurement indicated that they are now identical with respect to calcium, then the question is the origin of the delta calcium.

Based on an age of 60 years, the delta calcium accumulated at a rate of about 10 kg/ha/yr in the hardwood stands. This is the *delta;* at the same time the pine was accumulating at a rate of over 9 kg/ha/yr over 46 years. To age 60, the hardwoods have accumulated calcium at a rate of 16 kg/ha/yr. Yet the soils did not differ.

These data give support to the observations in the literature (see review p. 20+, Grigal, D.F. 2004. An update of “Forest soils. A technical paper for a generic environmental impact statement on timber harvesting and forest management in Minnesota.” Submitted to Laurentian Energy Agency, Virginia, MN. 32 p.) that find little or no postharvest changes in soil calcium, even though forest regrowth continues, accumulating calcium.

These data surely present a conundrum. Calcium inputs of 16 kg/ha/yr contrast sharply with budgeted inputs of 7.124 lbs/ac/yr. If the former value is valid, then we are faced with much less concern regarding nutrient depletion.

Appendix 6: Research Topics

Soil nutrients

Potentially, research findings could change our understanding of soil nutrient supply or amount of removal in harvest. Guidelines for the harvest of woody biomass could be revised in response to new information.

Some possible research topics include:

- Collect additional data on the nutrient content of tree components, especially for those species that have no reported data, to get better estimates of nutrient content in aboveground biomass.
- Assemble additional soils data from research studies in Wisconsin to better characterize nutrient capital.
- Investigate the supply of micronutrients in Wisconsin soils as it affects tree growth.
- Study the actual amount of woody material, by component, removed in biomass harvests in different forest types, seasons, and sites. Allow for excess removal in some of these harvests to determine limitations imposed by equipment and sites.
- Investigate soil layers lying below 6 feet in deep sands to determine whether calcareous material is present.
- Set up plots for long-term, low-intensity monitoring. Soil tests could be conducted each 10-20 years to determine if changes in available soil nutrients are correlated with the amount of woody material harvested. Wisconsin's CFI plots on state forests may provide suitable locations for long-term monitoring.
- Monitor the weight of the forest floor to determine if it is thinning under guidelines for retention of FWD.
- To quantify amount of WD needed on site, and removal, gaps in data can be filled in with a modeling project that produces such outputs.
- Hotspots of FWD, e.g., tops, will be hotspots for microbes and the functions they provide, because of relatively rapid (compared with CWD) decomposition and availability of C and N. Information is needed on the rate of release at such microsites, responses, and how these sites are distributed across stands.
- Additional work is needed on how the amount and patchiness of nutrient and C availability relates to tree species establishment. This may be keyed to FWD and CWD decomposition patches.
- Research carbon issues, including sequestration in soil, forest floor, and above and below ground biomass, using both budgets and modeling.
- More complete data on nutrient content of tree species is needed by component, age, season, and site types for Wisconsin.
-

Physical Properties of Soil

Better understanding the relationships between soil disturbances and soil productivity will allow development of policies and land management decisions that more accurately the true impacts of these activities.

Research needs include:

- Quantifying the relationship between differing levels of soil compaction and other factors influencing forest productivity.

- Identifying methods to mitigate or repair soil disturbance after they occur in the general harvest area.
- Examining stabilization of skid trails with harvested material.

Water Quality

Additional research on a number of topics could improve our understanding of the relationships between the forest management and the maintenance of water quality. With improved understanding of these topics, the guidelines for woody biomass harvesting could be revised to better reflect increased knowledge.

Research needs include:

- Studying the effects of differing levels of coarse woody debris and fine woody materials, including fine woody debris, on surface water infiltration and runoff.
- Enhancing models to make more informed predictions of erosion from forest lands, including developing erodibility factors for forest soils
- Quantify the effects and costs of different harvest treatments and different BMPs on erosion and water quality

Biodiversity

- Fine woody debris
  - Range of current and historic variation by forest and site types
  - Formation and decomposition rates
  - Different harvest retention levels and patterns
  - Impacts, importance (and causality) on habitat and animal and plant biodiversity
  - Assess the habitat needs of species or other taxonomic groups separately for woody debris and forest floor habitat needs.
- Coarse woody debris
  - Range of current and historic variation by forest and site types
  - Formation and decomposition rates
  - Different harvest retention levels and patterns
  - Impacts (and causality) on animal and plant biodiversity
- Tree and snag retention
  - Different retention levels and patterns
  - Impacts (and causality) on biodiversity
  - Impacts on tree regeneration, and stand growth and yield
- Impacts on deer browsing from removal or retention of tree crowns.
- Determine the amount and type of FWD removed and retained under different harvesting systems:
  - Mechanized CTL
  - Hand CTL
  - Whole tree
  - Pole length