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# Biomass Fuels & Whole Tree Harvesting Impacts on Soil Productivity— Review of Literature

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# **Biomass Fuels & Whole Tree Harvesting Impacts on Soil Productivity— Review of Literature**



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## 1. INTRODUCTION

San Dimas Technology and Development Center (SDTDC) of the Forest Service, U.S. Department of Agriculture, has prepared this literature synthesis to document the general impacts of whole-tree harvesting for biomass fuels on forest soils and soil productivity. The discussion especially focuses on the impacts of whole-tree harvesting on the natural cycling of minerals (nutrients) within the forest ecosystem. The literature synthesis is general and intended to be pertinent to forest ecosystems throughout the United States.

*(Note: Kimmins et al. 1985 compiled an exhaustive bibliography of several thousand references dating up to about 1981. That bibliography is organized into the categories of: nutrient cycling, biomass, nutrient content of biomass, and computer simulation models.)*

Subsequent products expected to be produced by SDTDC in accordance with a proposal submitted to the Technology & Development's Watershed, Soil, and Air Program (by the Hiawatha National Forest) include: (1) a soil sensitivity – risk rating for biomass harvesting in the Northcentral United States (Minnesota and Michigan); (2) a recommendation of practical monitoring methods, measures, and tools that can be used in the field to determine the amounts of down material to be retained or removed on harvested lands; and (3) a recommendation of terms and conditions or special provisions that should appear in a timber sale (or similar) contract to ensure that potential adverse impacts to soils from biomass/whole-tree harvesting are mitigated and monitored.

### 1.A Background



The woody material or debris that fell to the ground after a timber harvest (slash) typically is left on the ground as it is considered not economical to harvest. This downed woody material eventually decomposes and its nutrients are restored to the soil. A new, increased demand to harvest this material for private and commercial energy use and/or to reduce the potential wildfire hazard of slash is becoming an emerging need on several national forests. (See discussion of Forest Service Biomass Utilization Strategy in section 1.B.1).

Forest managers, however, have been concerned for decades that utilizing all parts of the tree (i.e., whole-tree harvesting) has the potential to adversely affect forest sustainability through mechanical impacts to forest soils and by depleting the nutrient reserves of

soil (Boyle et al. 1973; White 1974; Aber et al. 1978; Aber et al. 1979; Leaf 1979; Cleland 1982; Phillips and Van Lear 1984). Recent research associated with the [Long-Term Soil Productivity \(LTSP\) Program](#) is beginning to provide much needed insight on the long-term consequences of soil disturbance on forest productivity and is discussed in detail later in section 3.A.2.

There is a need for a synthesis of recent, published information to answer natural resource management questions such as: what adverse impacts to soil productivity are associated with removal of down woody material (i.e., impacts from depleting soil nutrient reserves and/or mechanical impacts to soil from equipment), how to mitigate adverse impacts, and how to monitor and assure that adverse impacts are minimized. This paper will present natural resource managers with a synthesis of current research to provide practical information addressing some of these issues.

Specifically, this report will address nutrient cycles and soil productivity under natural conditions (section 2) and the nutrient cycles and soil productivity under whole-tree harvested conditions (section 3). In section 3, references are made to guidelines from the Forest Service and other State Forestry agencies of measures to mitigate or prevent adverse impacts of whole-tree harvesting on soil productivity.

### 1.B Similar Nationwide Efforts

In addition to the Long-Term Soil Productivity Program, the Forest Service has developed a Woody Biomass Utilization Strategy to promote the use of woody biomass with forest management activities. Also, through an interagency partnership of the U.S. Department of the Interior and the U.S. Department of Agriculture's Joint Fire Service Program, research on the effects of fire effects on soil productivity on the national forests is investigated. The following is a brief summary of these programs relative to their pertinence with soil productivity issues.

#### 1.B.1 Woody Biomass Utilization Strategy

Biomass is defined as trees and their parts (especially foliage, branches, and limbs of down woody material) that are the byproduct of forest management (harvest) or hazardous fuel treatment. The Forest Service has developed a Woody Biomass Utilization Strategy (see Patton-Mallory [2008] and the [woody biomass Web site](#)) to promote the use of woody biomass on both Federal and private lands. The strategy was developed as a result of a Memorandum of Understanding between the



Departments of Agriculture, Interior, and Energy, that encourages and promotes the use of biomass on public and private lands.

The Woody Biomass Utilization Desk Guide (see page 59) was developed to implement the woody biomass strategy. The guide provides information on: (1) other biomass stakeholders, (2) the viability of offsetting hazardous fuels reduction and forest restoration treatments through biomass utilization, (3) the use of the National Environmental Policy Act to maintain a biomass utilization program, and (4) the use of cost-effective administrative techniques (e.g., site preparation, contract preparation) to promote biomass utilization.

The guide also provides information on the importance of incorporating land management objectives relative to wildlife habitat and forest health and ecology (especially coarse-down-woody and/or nutrient cycling objectives), into any biomass removal project (USDA FS 2007: section 2.13).

### **1.B.2 Joint Fire Science Program**

The Joint Fire Science Program (JFSP) was created by Congress in 1998 as an interagency research, development, and applications partnership between the U.S. Department of the Interior and the U.S. Department of Agriculture ([see JFSP Web site](#)). Funding priorities and policies are set by the JFSP Governing Board, which includes representatives from the Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service, Bureau of Indian Affairs, U.S. Geological Survey, and five representatives from the Forest Service.



One mission of the JFSP is to provide research tailored to the needs of fire and fuel managers. To that end JFSP has funded research dealing with fire effects on natural resources and to support biomass removal as a fuel treatment option.

**Fire effects on soils.** The JFSP has funded more than 300 projects relating to wildfire, prescribed fire, and fuel management activities. Many or portions of these projects examined fire effects on soils. Erickson and White (2008) provides a synopsis of JSFP studies that address season of prescribed burn effects on soil and general fire effects on soil hydrology, soil organisms, soil carbon storage/loss, and soil nutrient availability.

The reader that is interested in other summaries of the research relative to fire effects on nutrient cycling and soil productivity is directed to: Neary et al. (1999); Fisher and Binkley (2000: 241-261); Neary et al. (2005, revised 2008).

**Biomass removal studies.** JFSP has funded several studies to examine the removal of biomass from the forest as a means of hazardous fuels treatment (see [JFSP\\_Focused\\_Research](#)). These studies may be of interest to readers of this report as the JFSP efforts may identify techniques and tools to estimate/calculate biomass quantities in the forest. JFSP would be interested in tools/techniques to determine how much biomass is available for sale to offset hazard fuels treatment (e.g., see Jenkins et al. 2003). Natural resource specialists may be interested in the same tools/techniques to estimate how much biomass is needed to maintain soil productivity.

**Digital photo series.** The Fire and Environmental Research Applications Team has developed a natural fuels photo series that consist of a set of data and photos that display a wide variety of ecosystems throughout the Americas (Ottmar, no date). The [photo series](#) can be accessed as a [Web-based application](#). The photo series and data provide users with a landscape-level appraisal of living and dead woody material, vegetation (fuels), and stand characteristics. While fire managers are the primary target audience, natural resource managers might find useful information relative to down and dead woody material and understory composition and development.

### **2. FOREST ECOSYSTEM NUTRIENT CYCLES & SOIL PRODUCTIVITY UNDER NATURAL CONDITIONS**

To gain a better understanding of the effects of whole-tree harvests on forest soil productivity, one needs to have an understanding of the cycling of the key nutrients under natural (unharvested) conditions. As such, this section focuses on the ecosystem processes that are involved in the cycling of key nutrients that are important to sustained soil productivity of the forest ecosystem.

The information in this section relies heavily on Waring and Running (2007) (especially chapter 4, Mineral Cycles), and it is the source of most of the technical discussion of this section unless otherwise referenced. This discussion focuses on how key nutrients are cycled through the forest ecosystem and where these nutrients are located and stored. (See section 2.B for a discussion of what key nutrients will be discussed in this literature synthesis.)



### 2.A Overview of Forest Ecosystem Nutrient Distribution and Cycling

Waring and Running (2007: 101) begins the discussion of forest ecosystem nutrient cycling with the conceptual diagram below.

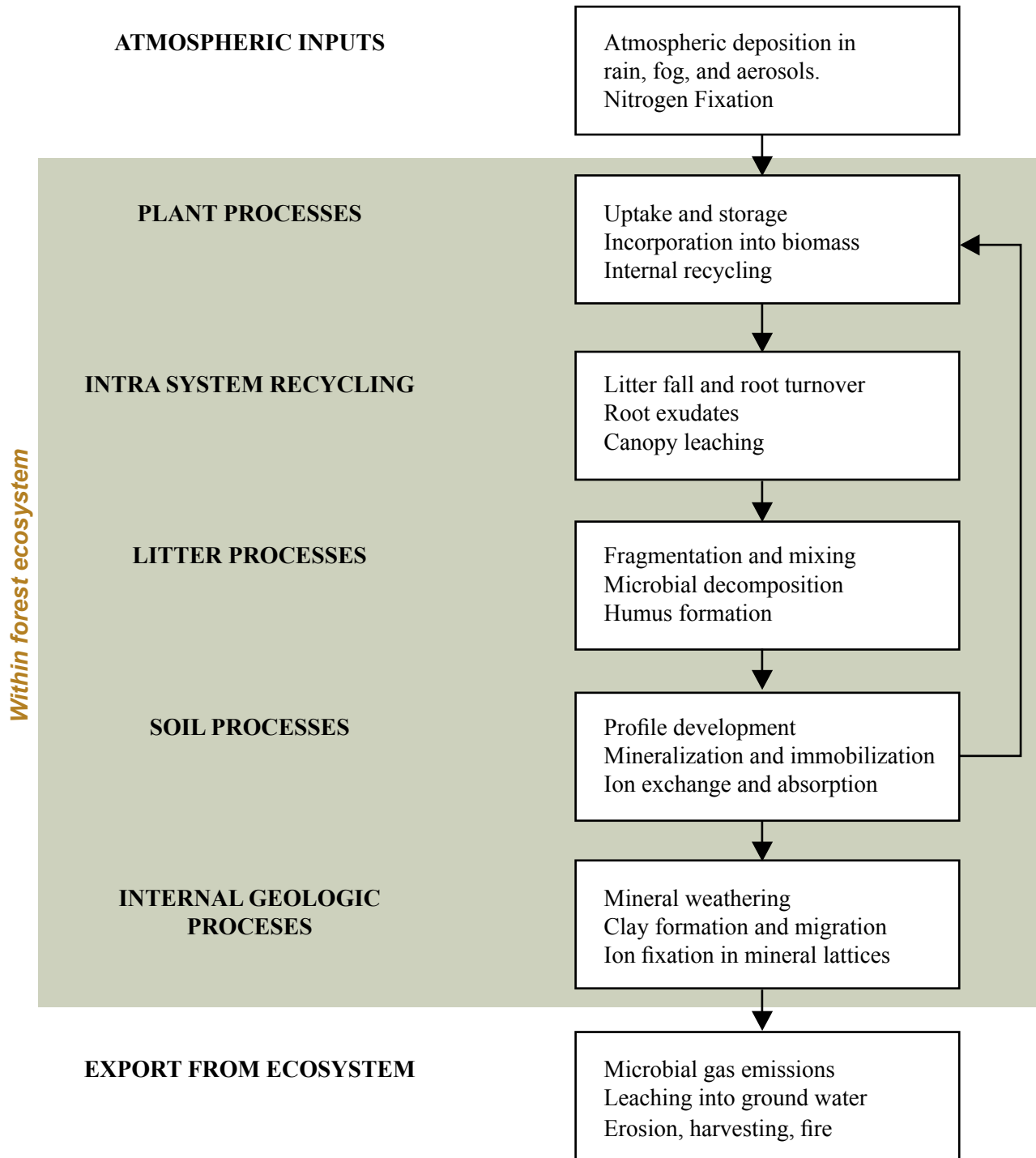


Figure 1. Mineral cycle through the forest ecosystem (from Waring and Running (2007: figure 4.1))

The diagram illustrates the points where nutrients enter (Atmospheric Inputs) and exit (Export from Ecosystem) the forest ecosystem. Within the system nutrients are subjected to several interrelated processes: plant processes, litter processes, soil processes, intrasystem recycling, and internal geologic processes. The following discussion briefly summarizes these processes.

Within the forest ecosystem, nutrients are cycled in two separate but interconnected nutrient reserves or pools: the aboveground plant pool and the belowground soil pool (figure 2). The aboveground plant nutrient pool is created when inorganic nutrients are taken up by trees from the soil and converted into an organic form by plants for metabolism. (Section 2.B provides more discussion of plant nutrient uptake. Section 2.C provides a discussion of organic versus inorganic nutrients and their role in nutrient cycling.)

Once taken up by trees, these nutrients are retained and recycled within the tree (with more-or-less efficiency depending on the species of tree), thereby creating an above-the-ground reservoir of nutrients. The obvious advantage of this strategy is that by recycling/reusing nutrients, the tree reduces its dependency on belowground nutrients that may be in short supply. (Section 2.C provides more discussion of the plant processes that are involved in the recycling of nutrients in the plant pool.)

As the tree discards leaves, branches, bark, or dies, the tree's organic nutrients are returned to the soil where they are eventually converted back to an inorganic form by soil organisms. These nutrients remain in the soil pool for eventual reuse by trees or are leached out of the forest ecosystem. Section 2.D deals primarily with the soil pool and how nutrients are cycled via soil and litter processes. (For a more detailed discussion of the forest nutrient cycle see: Bormann and Likens 1967, Attiwill and Adams 1993, or Likens and Bormann 1995.)



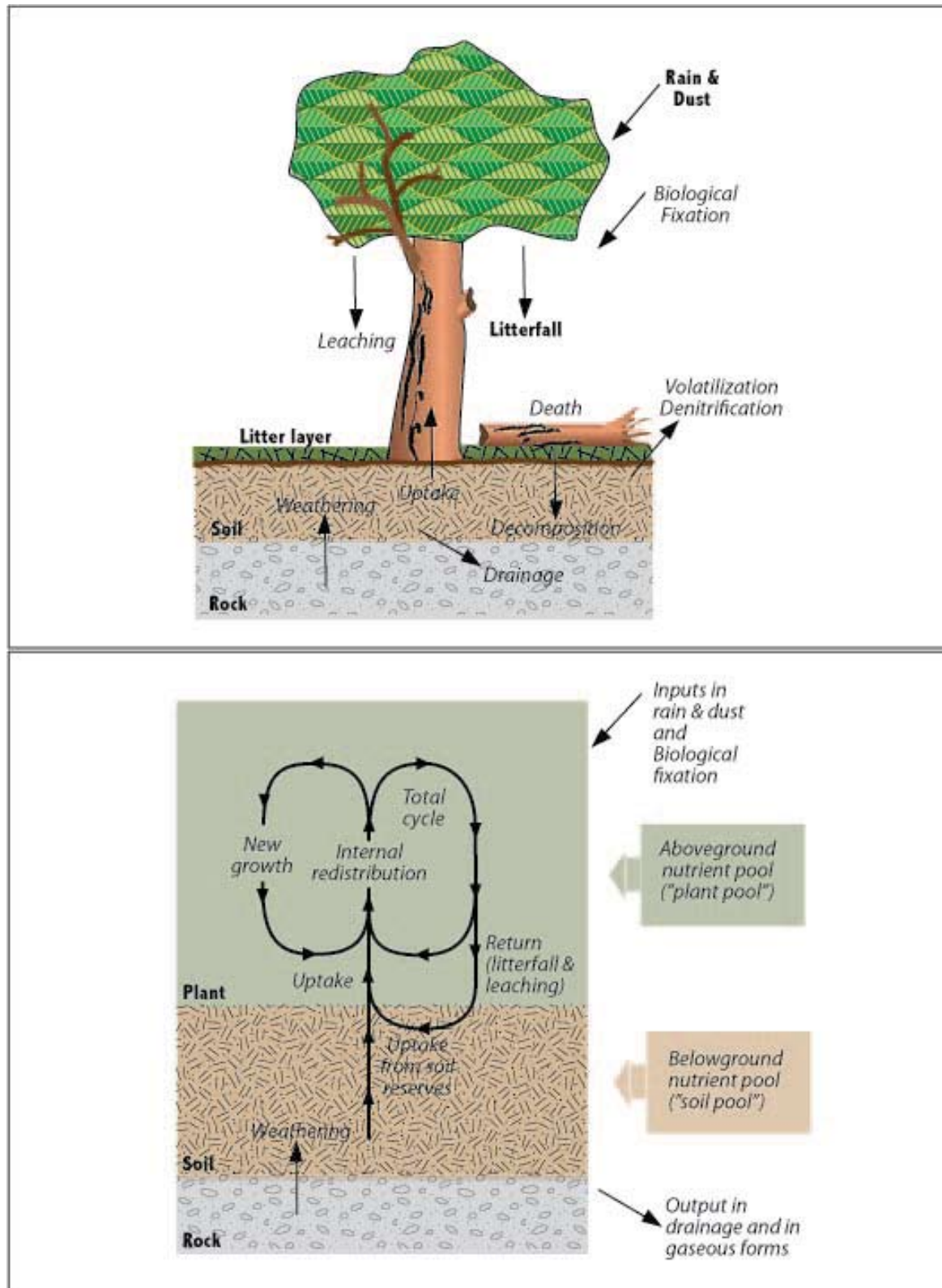


Figure 2. Typical nutrient cycle in the forest ecosystem (modified from Attiwill and Adams 1993: figure 2).

### 2.B Route of Nutrient Entering and Exiting the Ecosystem

#### 2.B.1 Inorganic nutrients entering the soil pool

Plants acquire most of their nutrients from the soil in solution. Depending on the species, they require some nutrients in large quantities (macronutrients) and other nutrients in trace amounts. Most researchers agree that forest ecosystems' sustainability and soil productivity is largely determined by the availability of inorganic (water-soluble) nitrogen (N), phosphorus (P), potassium (K), and calcium (Ca) (e.g., see: Warring and Running 2007: 100; Swank and Waide 1980: 138; Cleland 1982: 4; Boyle et al. 1973: 760.) (Section 2.C contains a more detailed discussion of plant nutrient uptake.)

These macronutrients (i.e., N, P, K, and Ca) will be focus of discussion in this literature synthesis. Other nutrients, such as sulfur (S), and magnesium (Mg) rarely limit forest productivity.

**Atmospheric.** Nearly all of the N (and S) in the forest ecosystem initially enter from the atmosphere. Magnesium, sodium, Ca, and K also enter from the atmosphere, but their primary entrance is by weathering of the underlying mineral rock. All atmospheric elements enter the ecosystem via rain/snow/fog (wetfall) or deposited via gravity (dryfall).

**N<sub>2</sub> fixation.** Nitrogen is a key nutrient that is required in large amounts by plants. Even though N makes up over 78 percent of the atmosphere in the gaseous form, it is unavailable to plants. As such, even though abundant, it is not unusual for N to be in short supply in the soils of most terrestrial ecosystems (Vitousek and Howarth 1991; LeBauer and Treseder 2008). (For more discussion of N, its importance in biological systems, and its potential as a limiting factor, see section 2.E.1.)

Gaseous N only can be made available to plants by the actions of N-fixing soil organisms (i.e., organisms that can fix or incorporate N in a chemical compound that can be used by plants). N-fixing organisms exist in the soil either as free-living or in symbiotic associations of certain forest shrubs and trees with bacteria (Rhizobium) in the root nodules. These soil organisms possess an enzyme that can convert gaseous N<sub>2</sub> into an inorganic form, thereby making it available for plant uptake.

*(Note: N-fixation accounts for only a fraction of the total N in forest ecosystems. Plants acquire most of their nitrogen N from organic material that has been converted into an inorganic form by soil microbes. The organic N comes from decomposed plant material that accumulated in the soil from prior plant growth. This process is discussed in detail in section 2.D.)*

In the forest ecosystem, N-fixation can occur in free-living fungi (e.g., brown rot fungus) that decompose coarse woody debris and in the rhizomes of certain forest plants and shrubs. In the forest, N-fixation is highly variable seasonally and also changes with stand development. For more details on N-fixation and N-fixing vegetation in forests ecosystems see: Davey and Wollum 1979, Vitousek and Howarth 1991, Jurgensen et al. 1991, and Bormann et al. 1993.

**Weathering.** Except for N, most nutrients trace their origin in the forest ecosystem from the mineral composition of the underlying rocks. The forest soil's fertility, texture, and buffering capacity to changes in pH are determined by the type and age of the parent material from which the soil is derived. The soil's parent material, therefore, is the main natural source of most nutrients entering the forest ecosystem (Buol et al. 2003: 122).

As rock is uplifted and exposed near the surface, it undergoes chemical or mechanical weathering. Chemical weathering occurs when minerals in water react with parent rock and release the rock's minerals. Mechanical weathering involves processes that do not change the rock's chemical composition (e.g., heat, freeze/thaw, wind). Since the bulk of the physical structure of soils consist of fragmented and weathered rock, weathering is key to soil formation.

Chemical weathering is the main process by which nutrients are released from rock. Over 80 percent of the original forests ecosystem inputs of Ca, Mg, K, P comes from chemical weathering. (Only in rare, unusual conditions does parent rock contain measurable amounts of N.) As such, the forest soil's fertility (i.e., the amount and type of nutrients in the soil) is largely determined by the type of parent rock material (igneous, sedimentary, or metamorphic) and the rate at which chemical weathering occurs and nutrients are released.



### 2.B.2 Nutrients (organic and inorganic) leaving the forest ecosystem

Most soils of the Northeast, Midwest, and Pacific Northwest are in the tens of thousands of years old and still contain much weatherable materials to supply nutrients. Some soils of the upper coastal plain of the Southeastern United States is much older (by 104 times) and lack weatherable nutrients (Stone 1979: 371).

Garrison and Moore (1998: 4-8) provides a discussion of geochemistry and petrography of rock types and their influence on nutrient availability of soils in the Inland Northwest. Moore et al. (2004a, 2004b) and Shen (2001) demonstrate the role of certain rock types on the forest nutrient environment in the Inland Northwest, especially relative to tree mortality and response to fertilization.

(Also see discussion of nutrient release via chemical weathering in Clayton 1979; Anderson 1988; Kolka 1996; and Waring and Running 2007: 114. For a detailed discussion on the genesis of soils see Buol et al. 2003.)

This paper will not provide a discussion of forest soil types (orders) or the physical properties of soils (i.e., texture, color, bulk density). The reader that is interested in these subjects is referred to chapters 3 and 4 in Fisher and Binkley (2000) and Buol et al. (2003: 169). Soil fertility and productivity is discussed in more detail in section 2.D.2

**Leaching** - Soluble inorganic nutrients are easily leached and often lost to the ecosystem. This is especially true of excessively drained (coarse) soils, which, as a result, tend to be less fertile (productive) than finer soils.

Organic (insoluble) nutrients are less likely to be lost from the soil pool when compared to soluble inorganic nutrients. (See section 2.C.1 for a discussion of organic versus inorganic nutrients.) The exception is organic potassium which is highly soluble.

**Fire** - As this paper focuses on the effects of whole-tree harvesting on soil productivity, a discussion of fire effects on soil nutrients and productivity is considered beyond the scope of discussion. For readers interested in information or a synopsis of fire effects on soils and soil productivity, see references cited in section 1.B.2.

### 2.C Plant Processes

#### 2.C.1 Plant uptake

**Harvesting** - The effects of harvesting, especially whole-tree harvesting on nutrient cycling and loss from the forest ecosystem appear in section 3.

The plant processes: nutrient uptake, nutrient storage, internal nutrient recycling, and return of nutrients to the soil as litter ensure that nutrients essential for forest plant growth and health requirements are met.

A simplistic (arbitrary) definition of an organic compound is one that contains carbon and is synthesized by a living organism. An inorganic compound, in general, is considered a compound that is not generated by a life-force and typically does not contain carbon, especially complex carbon. Organic compounds are, in general, insoluble while many inorganic compounds are soluble.

This is also a key characteristic of organic versus inorganic nutrients. That is, organic nutrients are generally large, insoluble, complex polymers that typically are not taken up by roots. Inorganic nutrients, however, are less complex, soluble compounds that are readily available for plant uptake. The important inorganic nutrients of N, P, K, and Ca are made available to plants largely in solution (i.e., in water).

*(Note: The role of organic nutrients will be discussed in section 2.D. For a discussion of the role that dissolved organic nutrients play in the forest ecosystem see Chapin 1995 and Qualls et al. 1991, 2000, and 2002. Also see the discussion in section 2.D.1 – Mineralization processes relative to recent studies on depolymerized, bioavailable dissolved organic N.)*

Inorganic nutrients are taken into the plant via roots and mycorrhizae (symbiotic fungi that assist roots in nutrient/water uptake). The nutrient demand of the plant depends on its life cycle stage and the species. Older mature trees typically require more nutrients than seedling or saplings.

The primary method of movement of most nutrients into the plant is via mass flow. Nutrients typically enter the plant passively, especially if in sufficient concentration in the soil. However, some plants can actively transport nutrients across root membranes if in lower concentrations.

Figure 3 illustrates the effect of soil pH on the availability of key plant nutrients. Note that in very alkaline soils (pH > 9) Ca and N become insoluble; in acidic soils (pH < 5) P and Ca become insoluble.

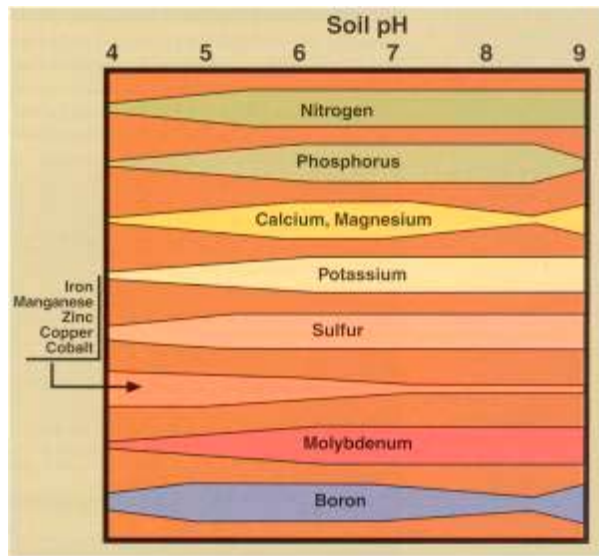


Figure 3. Nutrient availability relative to soil pH. (From [http://www.extension.org/pages/Soil\\_pH\\_and\\_Nutrient\\_Availability](http://www.extension.org/pages/Soil_pH_and_Nutrient_Availability))

The movement of soil water (and therefore critical nutrients) to plants is greatly affected by soil pore size and volume. Most of the water available to plants is in the soil's macropores (i.e., voids > 14 micrometers in radius). There, water is loosely held and is the principal source of water for plants. (Sandy soils have more pore space than clay.) As water is depleted from the macropores, they can become partially recharged from water bound in the more closely packed micropores. However, water can eventually become so thin (depleted) that the water-soil affinity is so great that plants can not extract it from the soil, thereby making it unavailable for plant uptake. From a water/nutrient availability standpoint, any activity that compacts the soil and alters pore size tends to reduce the availability of water and nutrients for plant uptake. This is especially true for clay soils.

*(Note: For a more detailed discussion of soil pore size, nutrient bioavailability, nutrient uptake, and compaction see: Childs et al. 1989, Powers 2002: 72, Shestak and Busse 2005, and Barber 1995. A discussion on which nutrients are most limiting in the forest ecosystem is presented in section 2.E.)*

### 2.C.2 Storage and recycling

**Nutrient Storage.** Once plants have taken in enough nutrients to meet metabolic requirements, they typically take a luxury consumption of nutrients and store the excess in the foliage. For most trees, after leaves, the next highest nutrient concentrations occurs in twigs/small branches, then larger branches, then the bole bark, and finally in the bole wood.

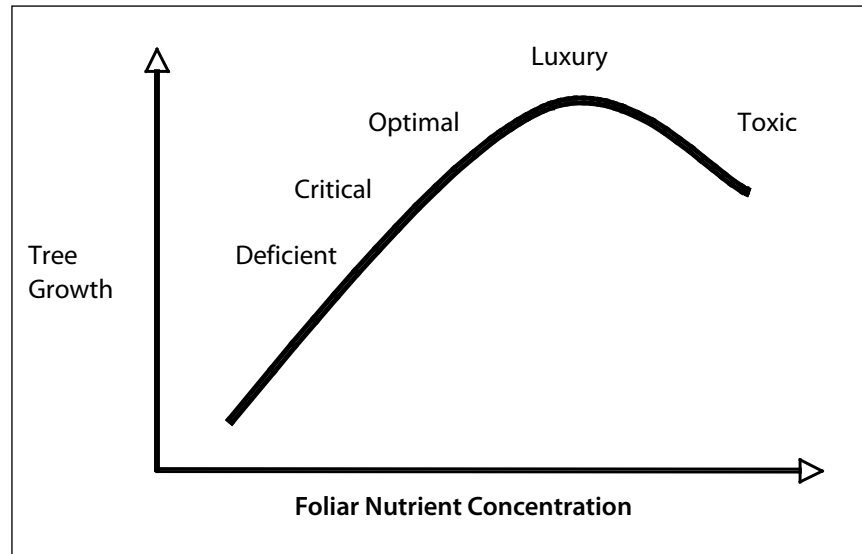


Figure 4. Relationship of tree growth to nutrient concentration in tree foliage (from Edmonds et al. 1989:23, figure 2.3).

Since different tree species and tree tissues can have significantly different nutrient demands, only gross generalizations can be made about where nutrients are stored in tissues while being recycled in the plant nutrient pool. Each species of tree and each part of a tree (leaves, bark, branch, trunk) retains different amounts of nutrients. For example, a review of data from Alban et al. (1978) (and figure 5) shows the complex nature of nutrient distribution (i.e., tree species/tree tissue relationship) for vegetation in a Minnesota forest ecosystem. (Also see Alban et al. 1982: figure 1; and Perala and Alban 1982: tables 2 and 3.)

## Forest Ecosystem Nutrient Cycles & Soil Productivity Under Natural Conditions

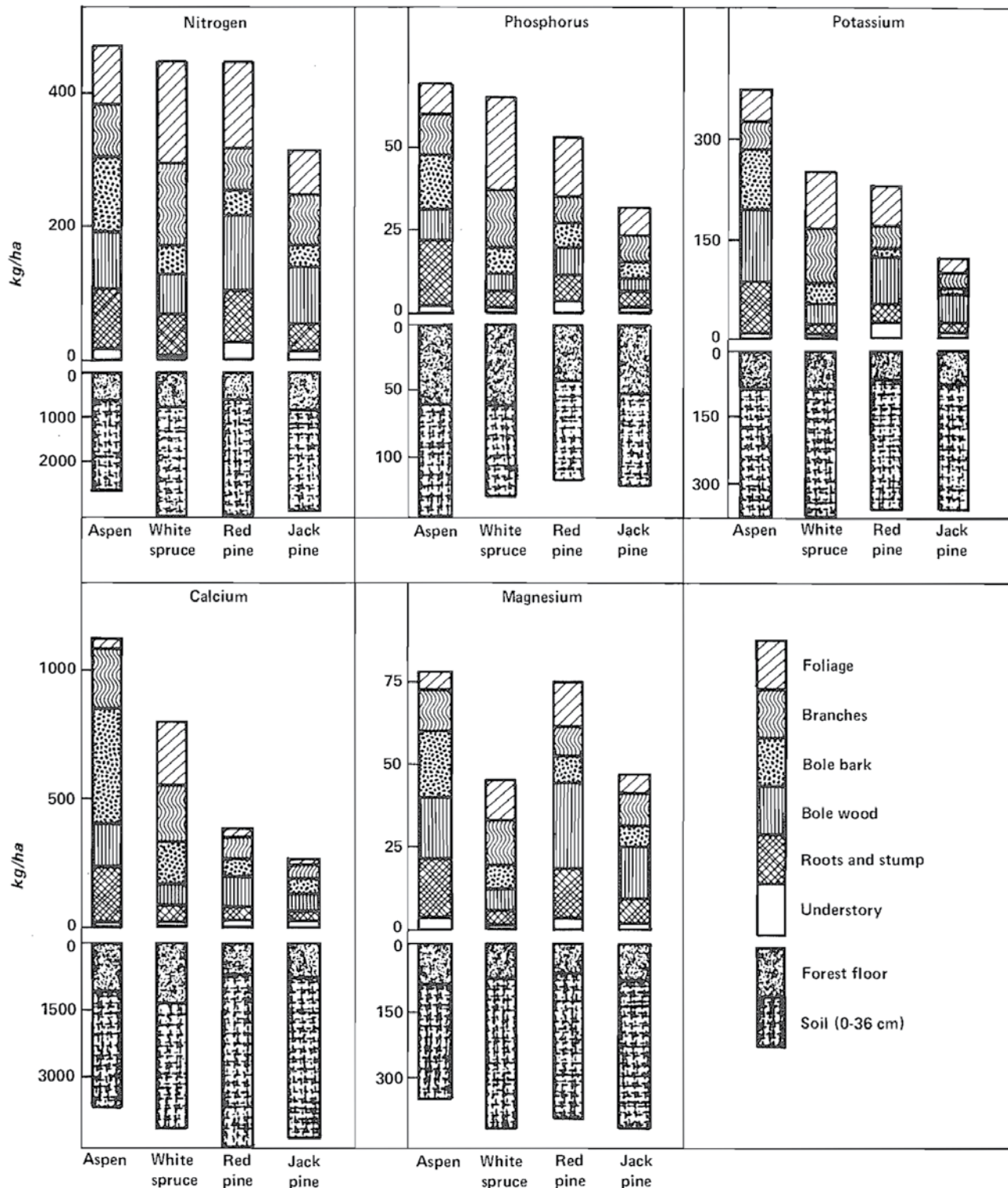


Figure 5. Nutrient distribution in vegetation and soil of a north-central Minnesota forest (from Alban et al. 1978: figure 2). Note the different scales for aboveground versus belowground data.

The distribution of nutrients in western forests shows a similar pattern. Table 1 shows the distribution of nutrients in Douglas-fir as reported by Pang et al. 1987.

*Table 1. Aboveground macronutrient distribution (as percent of mean concentration) in tree components of 34-year old Douglas-fir (from Pang et al. 1987: table 1).*

| <b>Tree Component</b> | <b>Macronutrient concentration (%)</b> |          |           |          |           |
|-----------------------|----------------------------------------|----------|-----------|----------|-----------|
|                       | <b>N</b>                               | <b>P</b> | <b>Ca</b> | <b>K</b> | <b>Mg</b> |
| Current foliage       | 29                                     | 26       | 14        | 29       | 28        |
| Old foliage           | 26                                     | 39       | 29        | 25       | 27        |
| Current twigs         | 21                                     | 17       | 14        | 19       | 20        |
| Branches              | 10                                     | 7        | 17        | 11       | 10        |
| Bark                  | 7                                      | 7        | 10        | 12       | 8         |
| Dead branches         | 6                                      | 3        | 15        | 2        | 6         |
| Wood                  | 2                                      | 1        | 1         | 2        | 1         |

In general, the highest concentration of aboveground nutrients for most species, however, occurs in the foliage and branches and the lowest concentrations occur in the bole wood (also see Pastor and Bockheim 1984: table 1 and Whittaker et al. 1979: table 2).

*(Note: Belowground, large diameter roots of some species can store considerable amounts of nutrients. Nutrients stored in roots typically support root expansion, but can also be mobilized to support leaf expansion.)*

**Nutrient recycling.** Once nutrients are acquired from the soil, plants have evolved a more-or-less (depending on tree species) efficient means to retain and recycle nutrients within the plant (plant pool). Nutrients stored in the leaves and foliage can be distributed to other aboveground organs (especially rapidly elongating shoots) when root uptake is inadequate to meet demands. Prior to seasonal shedding, nutrients from leaves are typically relocated to perennial foliage tissues.

In general, evergreen species (like conifers) have lower nutrient loss rates to the soil pool than deciduous species. This reduced loss appears to be the result of a general low nutrient content and longer lifespan of evergreen tissue compared to deciduous tissue. (There is no evidence that evergreen species are more efficient

at resorption of nutrients from leaves prior to leaf abscission.) Compared to deciduous species, evergreen leaves decompose more slowly and thereby release fewer nutrients to the soil pool (Aerts 1995). Some (Aerts 1995 and 1996 and Hooper et al. 2000) suggest that this results in a positive feedback that keeps evergreen soils relatively infertile, which in turn favors evergreens over deciduous species (Aerts 1995). (Also see discussion in section 2.D.2 relative to aboveground/belowground interactions.)

The nutrient requirement, uptake, and return to the soil are synthesized in table 2.

*Table 2. Nutrient requirement, uptake, and return of deciduous forests versus coniferous forests (modified from Cole and Rapp 1980: 361).*

| Element                    | Process     | Deciduous | Coniferous |
|----------------------------|-------------|-----------|------------|
| <b>Nitrogen (N)</b>        | Requirement | 94        | 39         |
|                            | Uptake      | 70        | 39         |
|                            | Return      | 57        | 30         |
| <b>Potassium (K)</b>       | Requirement | 46        | 22         |
|                            | Uptake      | 48        | 25         |
|                            | Return      | 40        | 20         |
| <b>Calcium (Ca)</b>        | Requirement | 54        | 16         |
|                            | Uptake      | 84        | 35         |
|                            | Return      | 67        | 29         |
| <b>Magnesium (Mg)</b>      | Requirement | 10        | 4          |
|                            | Uptake      | 13        | 6          |
|                            | Return      | 11        | 4          |
| <b>Phosphorus (P)</b>      | Requirement | 7         | 4          |
|                            | Uptake      | 6         | 5          |
|                            | Return      | 4         | 4          |
| All units are in kg/ha/yr. |             |           |            |

(See section 2.E for discussion of evergreen versus deciduous productivity. See section 2.D.1 – Microbial decomposition for a more detailed discussion of the aboveground/belowground feedback mechanism.)

### 2.C.3 Return to litter



### 2.D Soil and Litter Processes

Nitrogen appears to be the most efficiently recycled/retained nutrient prior to season leaf abscission. Several studies indicate that at least  $\frac{1}{2}$  or better of all available N in the ecosystem appears to be located and retained in the plant pool (Helmisaari 1995: 330; Aerts 1996: 603; Whittaker et al. 1979: 218).

The only nutrient that could be considered to be leached easily from living tissues (mostly from leaf's stomatal guard cells) to the soil is potassium, which is highly soluble. The other nutrients are much less prone to leaching loss. The general pattern of loss via leaching appears to be  $K > P > N > Ca$ . (Waring and Running 2007: 106)

For more details on within-plant nutrient demands, storage, recycling/dynamics, and translocation see: Cole and Rapp (1980); Pastor and Bockheim (1984); Swank and Reynolds (1986); Helmisaari (1995); Likens and Bormann (1995).

The major route of plant pool nutrient return to the soil is through litterfall (especially leaves and branches). Annually, significant amounts of leaves, twigs, branches, and fruit fall to the forest floor. If foliage falls to the forest floor early in the season (i.e., before the normal leaf abscission process), a significant nutrient concentration is returned to the soil. Since coarse woody debris (large branches, bole bark) typically has fewer stored nutrients, this component (from dying or diseased trees) accounts for a smaller fraction of nutrients loss from the plant pool.

(In general N, P, and Ca move from the plant pool to the soil pool through litterfall. Potassium enters by throughfall and leaching. Magnesium is intermediate and varies with forest sites [Cole and Rapp 1980].)

Litterfall collects on top of the mineral soil of the forest floor. Chemical, physical, and mechanical processes are necessary to breakdown and decompose the litterfall to a state where nutrients can enter the upper soil layers and become incorporated into the mineral soil.

Once plant material has fallen to the forest floor it can be considered part of the soil nutrient pool. This section discusses the processes that are involved in incorporating and/or transforming former living plant tissue (organic material) so that it becomes a part of the soil nutrient pool.

## 2.D.1 Organic material entering the soil pool

Leaf litter on the forest floor in the O (organic) horizon can often be distinguished as three layers: a top layer of nondecomposed litter, a middle layer of fragmented organic material, and a bottom humus layer. (In the humus the organic litterfall has decomposed into a more inorganic form.) Below the O horizon lies the mineral soil, which sometimes has clearly distinguished A, B, and C horizons (figure 6).

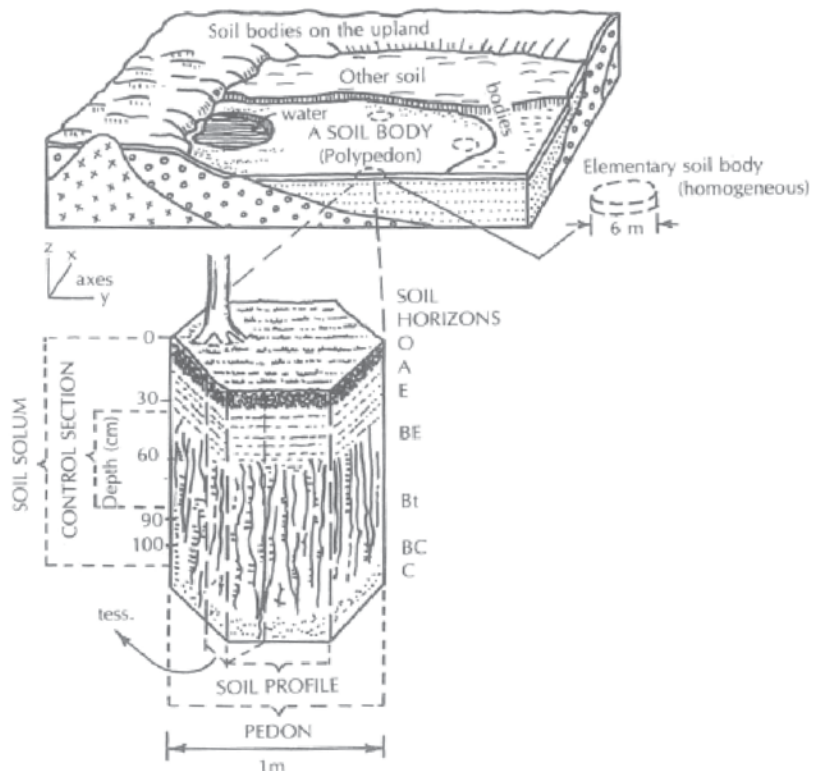


Figure 6. Typical soil profile, pedon, and solum (from Buol et al 2003: figure 2.1)

The A, B, and C horizons have decreasing organic content, as chemical, physical, and biological processes decompose and mineralize the nutrients of litterfall into a soluble, inorganic form.

Most plants get their annual nutrient requirement from the nutrients that are made available through the processes of decomposition and mineralization. The process by which organic material is decomposed, mineralized, and incorporated into the mineral soil is discussed below. (More details on the following subsections are provided in Waring and Running 2007: 122-133.)



**Fragmentation and mixing.** Litterfall is physically cut, fragmented, comminuted, and mixed into lower layers by a wide variety of forest soil invertebrates (e.g., roundworms, insects, microarthropods, segmented worms). They range in size and diversity from microscopic nematodes to large millipedes and earthworms. Temperature and soil pH tend to dictate what species are typically present in the leaf litter. In general, the total biomass of these soil animals increases by a factor of 6 from the boreal to tropical forests.

**Microbial decomposition.** Decomposition describes the process whereby fragmented organic litter is broken down (i.e., consumed) by soil bacterial and fungi. The specific process of mineralization (i.e., the specific hydrolysis and oxidization process whereby carbon is released from organic material and converted into an inorganic, soluble form) will be discussed in the next subsection.

The time that it takes to decompose organic litter (decomposition rates) or the time it takes for nutrients to move through the nutrient pool (mean residence time) are often used to quantify the fate of nutrients in the soil pool.

Soil animals and fungi attack cell walls, cellulose, resins, and lignin of litterfall and break them apart. (Lignin is most resistant to decomposition; only a few fungi can break down this compound.) Since the activity of soil animals and fungi are influenced by temperature and moisture content, decomposition rates typically increase exponentially with increased temperatures. But no simple temperature (or moisture) function provides a reliable predictor of decomposition rates as the chemical composition of the litter also greatly influences decomposition. A synthesis of decomposition rates for general forest types by climate is presented in table 3. (See Olson 1963 and Meetenmeyer 1978 for a more detailed discussion of decomposition rates.)

Another metric used to measure the amount of time nutrients remain in the soil pool is mean residence time (MRT). (MRT is the generic term that is used to determine how long a material, once added to a pool remains in the pool.) In nutrient cycling, MRT is used to determine how long a nutrient remains in the soil pool (i.e., the ratio of the total nutrient pool size to the rate that nutrients are added and removed from the pool over time.)

Table 3. Decomposition rates of foliage and coarse wood by climate from Waring and Running 2007: table 4.7).

| Climate (Biome)       | Forest type | Tissue decomposed (mass lost/yr) |             |
|-----------------------|-------------|----------------------------------|-------------|
|                       |             | Foliage                          | Coarse wood |
| <b>Boreal</b>         | Deciduous   | 0.39 – 0.7                       | 0.02 – 0.3  |
|                       | Evergreen   | 0.22 – 0.45                      | —           |
| <b>Cold temperate</b> | Deciduous   | 0.28 – 0.85                      | —           |
|                       | Evergreen   | 0.14 – 0.69                      | 0.01 – 0.06 |
| <b>Warm temperate</b> | Deciduous   | 0.44 – 2.46                      | 0.03 – 0.27 |
|                       | Evergreen   | 0.16 – 0.75                      | 0.04        |
| <b>Tropical</b>       | Deciduous   | 0.62 – 4.16                      | —           |
|                       | Evergreen   | 0.16 – 2.81                      | 0.12 – 0.46 |

A common estimate of MRT is how long minerals are held as a pool on the forest floor by determining the ratio of all forest floor mass to annual litterfall (assuming the forest floor is in a steady state.) The MRT then is the number of years that nutrients from litterfall are part of the forest floor biomass pool. A general pattern for MRT across biomes is: 20 for boreal forest; 10 for temperate evergreen forests; 4 for temperate deciduous forest; and 2 for tropical deciduous forests (see Waring and Running 2007: figure 4.9; also see Cole and Rapp 1980: 356).

**Mineralization process.** Mineralization describes the specific hydrolysis and oxidization process whereby carbon is released (as CO<sub>2</sub>) from organic material; this results in the conversion of organic nutrients to an inorganic, soluble form that is again available for uptake by plants.

Mineralization typically is the result of soil microbes (especially bacterial) consuming organic material in the soil to extract the carbon for their use. The waste product of the microbe is the inorganic nutrient.

Since the mineralization of nitrogen has been studied extensively, it provides a good example of the mineralization process. Simplistically, the pathway begins with soil microbial consumption of organic N. The microbes use the carbon for their metabolism and excrete N in an inorganic form – ammonium (NH<sub>4</sub><sup>+</sup>). Other microbes can consume ammonium, break it down further, and convert it into inorganic nitrate (NO<sub>3</sub><sup>-</sup>) as shown in figure 7.

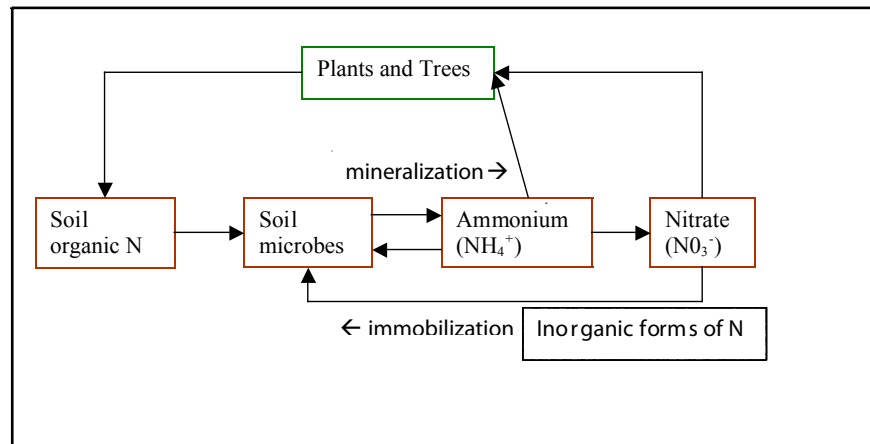


Figure 7. Nitrogen cycle: organic-to-inorganic and mineralization versus immobilization processes.

(A detailed illustration of the dynamic organic/inorganic nitrogen cycle in the soil is provided in Waring and Running [2007: figure 4.12])

The inorganic N excreted by soil microbes is thereby made available for uptake by the roots of aboveground plants. Plants can take up either inorganic form (i.e.,  $\text{NH}_4^+$  or  $\text{NO}_3^-$ ); however, some plants prefer one over the other, and temperature and pH can affect the uptake rates (Barber 1995: 185).

Soil microbes can store organic N and digest it at a later time. In that manner organic N is immobilized until they are released by the microbes. As a result the levels of ammonium and nitrate do not remain constant in the soil.

The soil's organic carbon-to-nitrogen ratio (C:N ratio) is an important metric that is often used to quantify mineralization and immobilization of N. At moderate C:N ratios (20:1) soil organisms are generally most efficient and net mineralization occurs; at high ratios (30:1) immobilization begins.

The rate of mineralization (i.e., how long organic nutrients remain in the soil pool in an organic form) depends on the number of soil organisms and the rate at which they consume organic material (as previously discussed under decomposition rates). As such, mineralization rates and the amount of available inorganic nutrients depend on how favorable soil conditions (i.e., soil chemistry, temperature, moisture, aeration) are for soil biota. For most temperate forests, this causes the soil to accumulate a very large reservoir of organic nutrients (especially N) which can eventually

be mineralized and made available to plants (Cole and Rapp 1981: figure 6.6; Alban et al. 1982: figure 1).

For more details on the mineralization process see Attiwill and Adams (1993: 571). Schimel and Bennett (2004) challenge the old paradigm of the mineralization process (figure 7 above) with a new paradigm, which includes the importance of dissolved organic N uptake by plants.

**Quantity of nutrients in soil pool versus plant pool.** Most of the nutrients within the forest ecosystem are located in the soil pool. The results of several studies indicate that within the forest ecosystem only about 10-20 percent of the total N, Ca, or Mg and about 20-50 percent of P occurs in aboveground vegetation (Alban et al. 1978: table 10 [or figure 2 of this report]; Cole and Rapp 1981: appendix; Pastor and Bockheim 1984: 344; and/or Helmisaari 1995: 330).

Potassium (K) is responsible for a large number of leaf cellular and plant physiological activities, such as photosynthesis, stomatal regulation, phloem transport, enzyme activation, and others (Fisher and Binkley 2000). As such, compared to other macronutrients, it is typically more abundant in the plant pool (as opposed to the soil pool) than other macronutrients.

Alban et al. (1978: 296) shows the relationship of nutrients in the aboveground tree (plant pool) and soil layer (soil pool) for four tree species in Minnesota (table 4). For these tree species, P and K were located primarily in the plant pool.

*(Note: nutrient deficiencies to the forest ecosystem from whole-tree harvests are discussed in section 3.)*

*Table 4. Percentage of nutrients in the aboveground tree versus the soil layer (0-36 cm) (from Alban et al. 1978: 296).*

| Element   | Tree species |              |          |           |
|-----------|--------------|--------------|----------|-----------|
|           | Aspen        | White spruce | Red pine | Jack pine |
| <b>N</b>  | 18           | 15           | 13       | 10        |
| <b>P</b>  | 54           | 84           | 54       | 35        |
| <b>K</b>  | 98           | 77           | 58       | 35        |
| <b>Ca</b> | 32           | 26           | 7        | 5         |
| <b>Mg</b> | 22           | 12           | 18       | 12        |

### 2.D.2 Aboveground/ belowground interactions

Pastor and Bockheim (1984) studied nutrient cycling and distribution in aspen/mixed hardwood forest of Wisconsin and reported nutrient plant pool/soil pool percentages for aspen as somewhat higher for P and Ca and lower for K than Alban et al. (1978).

The role of aboveground quaking aspen trees as a nutrient sink for Ca has emerged over the past few years from several other studies. It has been well documented that aspen take up large amounts of Ca from the soil pool and retain this nutrient in the perennial tissues (plant pool). This distribution of the nutrient capital<sup>1</sup> of Ca in aboveground vegetation has also been reported for white spruce and other deciduous species such as a sugar maple and big-tooth aspen. (See Alban 1982: 858; Silkwood and Grigal 1982; Pastor and Bockheim 1984: 343; Grigal and Bates 1992: 16, Wilson and Grigal 1995; and Trettin et al. 1999: 1443).

Soil organisms have long been known to influence the aboveground plant. Recent research, however, is shedding light on the effect of the aboveground plant on the belowground organisms. Recent studies indicate that plants can create positive feedback relative to nutrient cycling by regulating their uptake of nutrients, by use and loss of nutrients, and by influencing herbivores and belowground soil microbes. These interactions may be functionally important for an ecosystem-level understanding of ecosystem maintenance and stability. Hobbie (1992), Hooper et al. (2000), and Wardle et al. (2004) provide a detailed discussion of the aboveground/belowground interactions. (Also see Haase et al. 2008.)

A general principle that is emerging from this recent research is that plant species adapted to fertile soils tend to be much different than plants adapted to infertile conditions. By the quantity and quality of biomass the plant produces under these conditions, the plant appears to have a significant affect on soil organisms belowground. Plants from infertile soils tend to have slower growth rates, smaller leaves, and fewer nutrients stored in foliage. These characteristics create positive feedbacks that affect belowground soil animals that are involved with nutrient cycling and thereby can further reduce nutrient availability (Hobbie 1992).

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<sup>1</sup> Grigal and Bates (1992:12) define nutrient capital of the soil pool as the nutrients that are available for use by aboveground vegetation depending on internal ecosystem dynamics (i.e., the interchange between sequestered organic nutrients and available inorganic nutrients). The nutrient capital increase when inputs to the system exceed outputs and decreases when outputs exceed inputs.

### 2.E Forest Soil Fertility and Productivity



Conversely, on fertile soils a positive feedback loop is begun when these soils make more nutrients available to the aboveground plant. The result is that the plant produces more biomass and/or stores more nutrients in the aboveground biomass (via luxury consumption). This relatively higher nutrient biomass is returned to the soil as high-nutrient litter, which promotes higher mineralization rates by soil organisms. Also high quality aboveground biomass supports more animal herbivores that can return nutrients in their waste products. This high nutrient litter and animal waste tends to increase mineralization rates in the soil, which in turn, increases the availability of nutrients for plant uptake (i.e., increase soil fertility)—completing the loop (Hobbie 1992; Wardle et al. 2004).

The previous sections dealt, in general, with the mineral cycles and their dynamics within the forest ecosystem. The following discussion will focus on the importance of the key macronutrients to the forest ecosystem. To minimize confusion, the key terms of soil fertility, soil productivity, forest productivity, and forest sustainability are defined below.

Soil fertility is the soil characteristic that allows soil to support abundant plant life. Fertile soil is rich in available, necessary macronutrients (N, K, P, Ca) and has sufficient trace elements (micronutrients). Additionally, the soil texture allows for water retention and drainage to support abundant vegetation. To be fertile, soil also must contain a store of organic material and a relatively neutral pH.

Soil productivity is the capacity of soil, in its normal environment, to support plant growth (MFRC 2005). In the forest, typically it is reflected in the growth of forest vegetation.

Forest productivity is defined by Edmonds et al. (1998: 18) as the amount of biomass (or merchantable wood volume) produced annually. Kimminis (1996: 1644) distinguishes site productivity from forest productivity as a subset of the forest in which the local physical and biological environment has a more pronounced effect. Grigal (2000: 167) discusses the distinction between soil productivity and forest productivity.

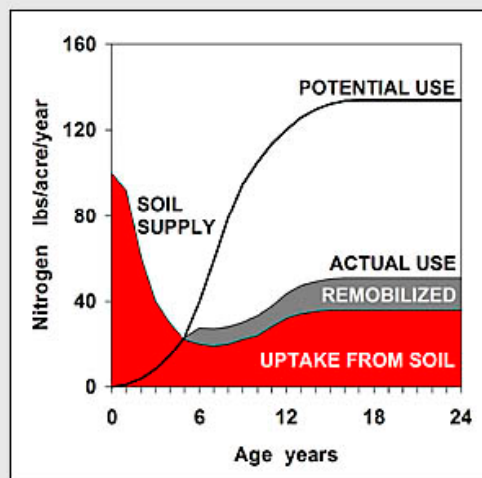
Forest sustainability is a term that is defined differently depending on the eye beholding the forest (Burger and Kelting 1998: 18). However, it is generally agreed that sustainable forest

### 2.E.1 Soil nitrogen

management includes management that is economically feasible, environmentally sound (i.e., maintains forest biodiversity), and socially desirable (i.e., politically acceptable).

Since N is essential to many biological functions of plants and its entry into the ecosystem relies on N-fixing organisms and recycling of organic material within the soil, it is not surprising that it is typically a limiting factor in most terrestrial ecosystems. Globally, N limitation constrains the productivity of most terrestrial ecosystems (Vitousek and Howarth 1991; LeBauer and Treseder 2008). The amount of N required for tree growth is greater than any other mineral nutrient and is, therefore, usually the most limiting nutrient in forest soils—especially in the West (Edmonds et al 1989, Binkley 1991).

The conceptual diagram of Allen et al. (1990: 448) (see figure 8) shows the supply-demand for N over time. In the early stages of stand development (especially after a harvest) crop trees have a modest N demand. But N demand soon overtakes available soil nutrient supply. Intermediate-aged and older stands typically exhibit a deficiency in nutrients, especially nitrogen.



The concept of soil nitrogen supply and a stand's potential and actual use of nitrogen as related to stand development (age).

Figure 8. Concept model of N supply and demand in forest stands over time (from Allen et al. 1990: 448).

One method to determine whether an element is limiting plant productivity is to add it to the soil and document the increased productivity. The discussion below focuses on the responses of forest stands to the addition of nutrients (fertilization) to improve soil fertility.

***Nitrogen in western forest soils.*** Edmonds et al. (1989: 18) consider the absence of N as the major growth-limiting nutrient that limits forest productivity in the Pacific Northwest. Douglas fir is known to consistently respond to N fertilization. Sitka spruce also appears to benefit from increased N. Other Pacific Northwest and Rocky Mountain forest trees have inconsistently responded to N, but have improved productivity when fertilizers included both N + P (Binkley 1991) and N + K or N + S (Garrison et al. 2000).

Kimmins (1996: 1648) discusses the causes for N deficiency in boreal and cool temperate western forests. They include frequent fires, low N mineralization rates caused by low soil temperatures, excessive accumulation of decaying wood (high C/N ratios), and reduced aboveground litter fall from evergreens.

***Nitrogen in eastern forest soils.*** In the Southeast, loblolly and slash pine are known to respond favorably to N and/or a combination of N + P (Allen 1987: 40; Fox et al. 2006: 13; Fox et al. 2007). (Also see [North Carolina State University—Forest Nutrition Cooperative Web site.](#))

In the Northcentral States, jack pine, lodgepole pine, and black spruce are known to respond positively to N and N + P + K combinations (Brockley 2005; Newton and Amponsah 2006).

Many northeastern forests are considered nitrogen rich or at a point of nitrogen saturation. The cause of this excess N in the forest ecosystem is much speculated (e.g., air pollution), as well as its effect (i.e., contributing to forest decline). The reader is referred to Johnson and Taylor (1989); Johnson et al. (1991); Alber et al. (1998); and Fenn et al. (1998) for further discussion on this issue of the cause of N saturation and its affects on northeastern forests.

***Coniferous versus deciduous forest soils.*** As previously mentioned (see section 2.C.2—nutrient recycling) conifers (as well as most evergreen trees) are better adapted to N-deficient soils. Conifers have a lower N requirement (and greater N-use efficiency) than deciduous trees primarily because of their slower growth rates, smaller leaves, and fewer nutrients stored in foliage. As such, conifers can thrive in soils that would not support deciduous forests.

### 2.E.2 Other soil macronutrients

(For more details see: Waring and Franklin 1979: 1385; Cole and Rapp 1980; Aerts 1995; Reich et al. 1997: 344).

Although P, Ca, and K, are not required to the extent of N (see section 2.C.2, table 2), they are nevertheless, important to plant health and vigor. Fisher and Binkley (2000: 224-232) provides discussion of the cycles of these macronutrients and their importance to plant physiology. (For a recent, theoretical discussion that suggests all terrestrial plants require nutrients in similar ratios see Knecht and Goransson 2004.)

**Phosphorous (P).** As mentioned in the section 2.E.1, P typically is added with N as a fertilizer in the Pacific Northwest and Southeast to forest soils. Vitousek and Howarth (1991: 102) discuss in detail the inter-relationships between the N and P cycle, especially how available P can regulate N-fixation.

In the Southeast, P deficiencies in the poorly drained soils of the lower Coastal Plain and certain sites with old, ancient soils (i.e., sites that have weathered in place for several hundred thousand years) in the upper Gulf Coastal Plain are well known (Bengtson 1979; Allen 1987; Huntington et al. 2000; Fox et al. 2007)

**Calcium (Ca).** Ca is seldom a limiting factor for most forest soils. However, since it is disproportionately distributed in the perennial tissue (branches and stems) of certain deciduous tree species (most importantly aspen and to a lesser extent deciduous species like sugar maple, beech, yellow birch, and spruce), Ca is considered susceptible to depletion from the soil under intensive harvesting conditions (Silkwood and Grigal 1982; Federer et al. 1989; Wilson and Grigal 1995; Huntington et al. 2000). The risks associated with whole-tree harvesting of these species will be discussed in greater detail in section 3.

For a detailed discussion of the biogeochemistry of Ca in the forest ecosystem, especially in the northeastern forests, see Likens et al (1998).

**Potassium (K).** Potassium is one of the most common alkali metals and the seventh most abundant element in the earth's crust. It is typically weathered as a soluble cation and readily moves into the soil solution. K is commonly made available in the soil by the weathering of parent material containing potassium feldspar, biotite, and muscovite.

*(Note: Likens et al. 1994 provides a detailed discussion of the biogeochemistry of K at their forest research site in New Hampshire (Hubbard Brook Experimental Forest)).*

As mentioned previously (section 2.C.2—nutrient recycling), even organic K is highly soluble and is readily lost from living plants and dead plant material. Relative to other macronutrients, K can rapidly cycle through the forest ecosystem. Because of this unique property, movement of K in space and time through the forest ecosystem is of general concern in maintaining long-term forest productivity (growth and health). (Also see previous discussion relative to K on pages 18 and 23).

Tripler et al. (2006) provide a detailed review of recent (i.e., past 30 years) literature (from worldwide sources) pertaining to the dynamics of K in the forest ecosystem. The review includes an analysis of the role of K in forest tree growth and plants' responses to K deficiencies. The review also summarizes data on how K moves and is retained within the forest ecosystem. (Their review suggests that the supply and demand of K is similar to that of N and that trees may have similar strategies of acquiring and recycling/retaining K.) Finally, the review acknowledges that there is relatively little information on the role of K in tree growth and its role in overall forest dynamics.

Fertilization studies suggest that many forests respond favorably to increases in K. Potassium concentrations in the foliage of ponderosa pine and Douglas-fir in the Inland Northwest (northern Idaho and Montana) do not change after applications of K fertilizers. However, applications of N + K treatments are believed to decrease tree mortality (by reducing loss to mountain pine beetles and Armillaria root rot) compared to N-only fertilization. N-only fertilization also tends to reduce foliar concentrations of K (Garrison et al. 2000; Garrison-Johnston et al. 2003; Garrison-Johnston et al. 2005; and Mandzak and Moore 1994).

Garrison-Johnston et al. (2007) provides fertilizer recommendations (especially relative to N and K) and nutrient guidelines for northern Idaho and western Montana forestlands based on rock type. These guidelines are based on the knowledge of the affect that parent material has on soil nutrient availability (and soil texture), which in turn affects forest productivity. (See more details on these guidelines in section 3.B.5.)

### 2.F Summary of the Nutrient Cycling Under Natural Conditions

Stone (1979: 368) stated that "[n]o rule of thumb about 'nutrient supply' is useful beyond the grossest generalization." Whittaker et al. (1979: 214) remarked that "[s]tudies of nutrient cycling tend to have an incontinently high ratio of information to interpretation." The following is a list of a few key points discussed in section 2 relative to nutrient cycling within the unharvested forest ecosystem, especially focusing on those issues that are likely to be of concern for the harvested forest. (Note: Hornbeck (1988) also summarized some key considerations relative to nutrient cycling.)

- ❑ Nutrients naturally enter the forest ecosystem from the atmosphere or mineral weathering; nutrients exit primarily by leaching into ground water.
- ❑ The key macronutrients for the forest ecosystem are N, P, K, and Ca.
- ❑ Trees (and all plants) uptake nutrients in mostly soluble, inorganic form from the soil. These inorganic nutrients are converted to an organic form by the plant for metabolism.
- ❑ Most of the tree's nutrients are distributed in the foliage (leaves, twigs, and branches). The bark and wood typically have fewer nutrients than the foliage.
- ❑ Depending on the tree species, nutrients are more or less efficiently recycled within the plant pool.
- ❑ Evergreen trees (especially conifers) require fewer amounts of nutrients than deciduous species, and, as a result, can exist on relatively infertile soils.
- ❑ As the tree discards leaves, branches, bark, or dies, the tree's organic nutrients are returned to the soil.
- ❑ Organic material returned to the soil is decomposed and the nutrients are mineralized (i.e., converted to an inorganic form) by soil organisms depending on the soil's physical conditions (moisture, temperature, aeration, etc...).
- ❑ Within the forest ecosystem, two pools of nutrients exist: a relatively large belowground soil pool and a smaller aboveground plant pool.
- ❑ The soil pool has several orders of magnitude of nutrients more than the plant pool. The soil pool consists mostly of unavailable organic nutrients and, to a much lesser extent, available inorganic nutrients. The total soil nutrient capital is largely unavailable for immediate plant use.

### 3. FOREST ECOSYSTEM NUTRIENT CYCLES & SOIL PRODUCTIVITY UNDER TOTAL TREE HARVEST CONDITIONS

#### 3.A Effects of Whole-Tree Harvesting



##### 3.A.1 Models/nutrient budget predictions of impacts

- ❑ Inorganic (available) nutrients comprise only a small fraction of the total nutrient capital in the soil pool.
- ❑ N is required in large amounts by plants and is typically a limiting nutrient in most terrestrial ecosystems. Phosphorus is sometimes a limiting nutrient, especially in areas of ancient, well weathered soils of the Southeast. K deficiencies are linked to increased tree mortality, especially from mountain pine beetles.
- ❑ Aspen and several eastern broadleaf deciduous species are atypical of most tree species in that they accumulate a high percentage of Ca in the aboveground tissue. Intensive harvest of these species has the potential to result in a significant loss of soil Ca over time.

In this section, studies and analyses of the consequences of whole-tree harvesting on soil productivity are considered in two main categories: (1) studies based on models and/or nutrients budgets which forecast likely effects, and (2) long-term field empirical field studies of the measured loss of soil productivity under actual whole-tree harvesting scenarios.

Also, the following discussion relates primarily to the impacts of whole-tree harvesting on soil productivity per impacts to soil chemistry. The contribution that organic material contributes to the physical properties of soil that affect soil productivity (e.g., water-holding, aeration/drainage, cation exchange) are not emphasized in the following discussion. The reader is encouraged to review Jurgensen et al. (1997) for a detailed discussion of that subject.

The studies cited in this section typically involve investigations whereby the nutrients of aboveground biomass were determined empirically, and the expected impact of intensive harvesting (i.e., nutrient drained) on the ecosystem was calculated or predicted as changes in soil nutrient availability and productivity over time. These analyses typically used nutrient budgets and/or simulation models to forecast changes in nutrient pool sizes (i.e., plant and soil pools) and transfer rates between the pools. These

analyses typically assume that the nutrient pool sizes and transfer rates between nutrient pools are the prime regulator of nutrient availability and forest productivity. Forest harvesting (i.e., nutrient removal) is then used to predict future nutrient availability and soil productivity within the ecosystem.

The major shortcomings of these forecasts and simulations are: (1) few forest ecosystems have been studied in sufficient detail to accurately predict nutrient transfers between pools; and (2) the rates of key ecosystem processes involved in nutrient cycling (e.g., decomposition, weathering, nutrient mobilization/ immobilization) are poorly understood (Alber et al. 1978: 307; Johnson 1983: 157; Dyke and Mees 1990: 182). As a result, the predictions of the consequences of various harvesting regimes may be grossly over- or understated. Nevertheless, up until long-term studies began in the 1990's (see the detailed discussion in section 3.A.2), these forecasts were the best available information that resource specialists had to assess soil productivity impacts from intensive harvesting.

*Note: Dyck and Mees (1990: 173-180) distinguishes the various types of intensive harvest—soil productivity studies as: (1) computer models, (2) site classification systems (used primarily in Europe and New Zealand), and (3) empirical research – which includes studies using the budget method, chronosequence research, retrospective research, and empirical field trials. (See footnote on page 36 regarding chronosequence versus retrospective research.)*

**Nutrient capital and nutrient mining.** The terms nutrient capital and nutrient mining will be used extensively in this discussion of the effects of whole-tree harvesting and are defined below.

Nutrient capital refers to the nutrients in the ecosystem that are available to plants depending on the internal dynamics of the ecosystem. If inputs of nutrients exceed the outputs from the ecosystem, then the nutrient capital is expected to increase (Grigal and Bates 1992: 12). A site's initial nutrient capital is considered the amount of nutrient stored in the soil prior to a disturbance to the ecosystem (Grigal and Bates 1992: 23).

Grigal and Bates (1992: 72) used the term nutrient mining to describe the rate of removal of nutrients that exceeds the rate of replenishments into the forest ecosystem. As stated in section 1.A, for decades there has been concern that whole-tree harvesting

results in significant nutrient mining of the nutrient capital of the forest ecosystem.

**General impacts of whole-tree harvesting.** Waring and Running (2007: 214) provides a brief summary of the impacts of timber harvesting on soil productivity. The following discussion utilizes that summary extensively.

Also, most of the studies and evaluations of the effects of whole-tree harvesting on soil productivity in the United States appear to have been conducted in eastern forest. This may be due to the known impoverished nature of eastern forest soils (due to past agriculture usage) and because the whole-tree harvesting phenomenon first emerged in the eastern forest (see McMillin 1978 and Leaf 1979). The only references to the effects of intensive harvesting on nutrient distribution/cycling in the western forest ecosystem appeared to be: Stark 1980, Stark 1982, Clayton and Kennedy 1985, and Garrison and Moore 1998: 32-38.

*(Note: Several studies and evaluations of the effects of whole-tree harvesting also have been conducted in the United Kingdom and Sweden [see references cited in Walmsley 2009].)*

Since most nutrients of the plant (aboveground) pool are in the branches and foliage, a whole-tree harvest can remove as much as three times the nutrients as compared to a conventional bole-only harvest (Alban et al. 1978; Johnson et al. 1982; Phillips and Van Lear 1984).

However, since the soil nutrient (belowground) pool contains most of the nutrient capital of a forest ecosystem (by several orders of magnitude), in general, the removal of the whole tree during timber harvesting should result in only a small percentage of nutrient loss from the forest ecosystem.

The studies that analyze the consequences of whole-tree harvesting typically specify that impacts to soil chemistry are dependant on the nutrient, the species of tree, and the frequency of harvest (nutrient removal). Johnson et al. (1982) report that K and P in soils of an upland mixed oak forest of eastern Tennessee were sufficient to support one or more additional rotations of bole-only or whole tree harvesting due to the large nutrient capital in the soil. Atmospheric input of N was estimated to replenish the loss of this nutrient in between harvesting.

In general, simulation and nutrient budget studies predict that the longer the interval between rotations, the more likely nutrients lost from whole-tree harvesting are naturally replenished to preharvest conditions (Kimmins 1977: 180; Aber et al. 1978: 311; Swank and Waide 1980: 151).

Mann et al. (1988) compared preharvest and postharvest nutrient budget for bole-only versus whole-tree harvest in sites in eight States (TN, WA, ME, CT, NH, NC, SC, and FL). That analysis concluded that whole-tree harvests remove significantly more nutrients than bole-only harvests from the ecosystem. In general P and Ca (at eastern hardwood sites) are the nutrients most likely lost (mined) if not replaced by natural mineral weathering between rotations. Hornbeck and Kropelin (1982) and Hornbeck et al. (1990) drew similar conclusions for New England forests.

Goulding and Stevens (1998) reported on whole-tree harvesting versus conventional harvesting of Sitka spruce in the United Kingdom (North Wales), especially relative to its effect on K reserves. Their nutrient budget analysis indicated that at their experimental site strong weathering conditions were expected to provide long-term reserves of mica K through many years of harvesting cycles.

Yanai (1998) provided an analysis of whole-tree harvesting effects of phosphorous cycling using nutrient budgets and measurements of uptake of P in vegetation regrowth 2 years after the harvest. Impacts to nutrient supply (i.e., loss of P) within the forest ecosystem were considered small or negligible. Predictions of impacts from future harvest rotations were not made as the author recognized that the rates of key ecosystem processes (e.g., mineralization/immobilizations, decomposition, mineral weathering) which input P to the ecosystem are unknown and difficult to estimate.

***Mining of calcium from the soil pool.*** Of the key macronutrients, Ca is consistently predicted to be susceptible to nutrient mining, as soil Ca levels are typically low (but not typically limiting) at many forest locations and Ca accumulation in the aboveground pool of several tree species tends to be significant.

Nutrient budget and simulation studies from late 1970 thought the late 1980's began to identify Ca as the nutrient most susceptible of being mined from the soil pool of eastern forest soils. As mentioned

previously (section 2.D.1), researches began to document that certain deciduous trees (e.g., aspen, white spruce, sugar maple, beech, yellow birch) stored a significant amount of Ca in its aboveground perennial tissue (especially branches and stems) and, in effect, operated as a nutrient sink for Ca. Even though Ca is seldom a limiting factor for most forest soils, under whole-tree harvesting scenarios, Ca is consistently predicted to be a nutrient that might be mined from the soil pool and lost from the ecosystem. (See Alban 1982: 858; Silkwood and Grigal 1982: 630; Federer et al. 1989: 599; Grigal and Bates 1992: 16; Huntington et al. 2000: 1853).

***Studies that summarize whole-tree harvesting impacts (using simulation models or nutrient budget analyses).*** The following is a list of publications and symposia that provide regional or nationwide summaries of the impacts of whole-tree harvesting on soil productivity:

- ❑ Kimmins (1977) provided one of the earliest general evaluations of the effects of whole-tree harvesting on forest productivity.
- ❑ McMillin (1978) provided one of the earliest proceedings to address the issue of whole-tree harvesting versus soil productivity effects on southern forests.
- ❑ Leaf (1979) provided one of the earliest proceedings to address the issue of whole-tree harvesting versus soil productivity effects on forests nationwide—especially see Stone (1979) and Wells and Jorgensen (1979).
- ❑ VanHook et al. (1982) provided a summary of direct and indirect effects of whole-tree harvesting based on studies at the time of publication.
- ❑ Ballard and Gessel (1983) presents the results of the International Union of Forest Research Organizations (IURFO) "Symposium on Forest Site and Continuous Productivity," which addressed research to date, especially relative to trying to understand changes in forest productivity resulting from management.
- ❑ Smith et al. (1986) provided proceedings of a symposium on the effects of biomass harvesting on northeastern forest productivity.

### 3.A.2 Long-term validation studies of whole-tree harvest effects

- Hornbeck (1988) summarized key considerations to take into account relative to whole-tree harvesting.
- The Minnesota Environmental Quality Board prepared a "Generic Environmental Impact Statement Study (GEIS) on Timber Harvesting and Forest Management in Minnesota" to assess the current, potential and cumulative impacts associated with timber harvesting in the state of Minnesota (Jaakko Poyry Consulting, Inc. 1994). The GEIS contains an appendix prepared by Grigal and Bates (1992) (and updated in Grigal 2004), which is a detailed analysis and prediction of the effects of whole-tree harvesting on soil productivity in Minnesota. The predictions are based on the results of simulations models, which identify the extent of nutrient mining that results from timber harvest in Minnesota – including harvest of the merchantable bole, whole tree, and bole-only (no bark).

By the mid 1980's researchers began to critically examine and question the predictions and forecasts made in the previous decade of intensive harvesting versus soil productivity. Researchers began to notice that the nutrient deficiencies that these studies predicted (which relied on nutrient budgets and model simulations) were not being observed on forest sites. Johnson (1983), in particular, critically questioned the oft-cited generalizations and predictions of nutrient deficiencies made by these previous forecasts.

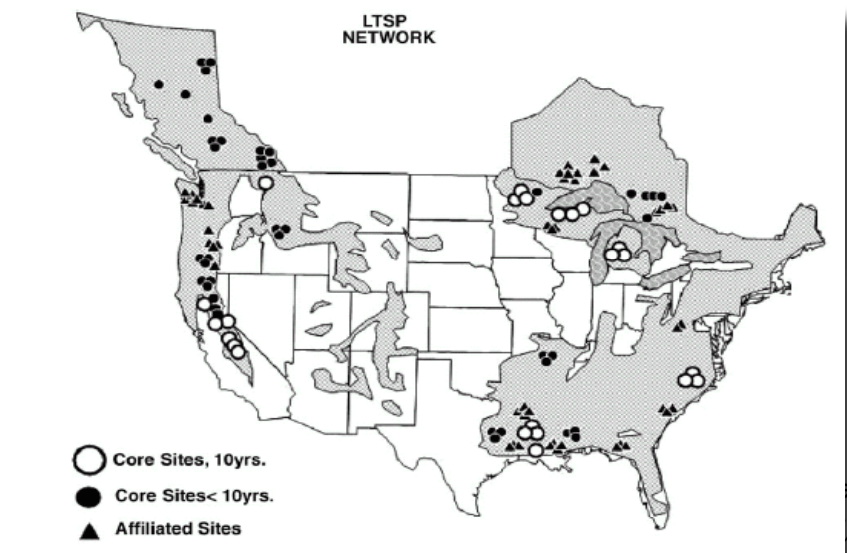
Dyck and Mees (1990: 179) discussed the shortcomings of model simulations and forecasts based on chronosequence and retrospective studies<sup>2</sup>. Even though these studies provided a rapid means of assessing long-term effects of a treatment, a researcher has no control over the previous management practice and has to accept a host of simplifying assumptions (e.g., sites are assumed to have similar slopes, soils, natural pathogens, etc...). Dyck and Mees (1990) stressed that these studies are merely a convenient substitute for a more controlled (and time consuming) long-term empirical study. As such, several researchers (Smith 1986: 35;

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<sup>2</sup> A chronosequence study (e.g., see Turner 1981) involves research on a series of stands of various ages but with all stands having essentially the same treatment. The retrospective research (e.g., see Ballard 1978) involves examining previous treatments of stands and inferring impacts. For more details on chronosequence and retrospective research see Dyck et al. (1994:16-30).

Dyck and Mees 1990: 182; Powers et al. 1990: 68; Dyck and Bow 1992: 174) began to call for long-term empirical validation studies to validate the actual impacts of intensive harvesting on soil and forest productivity. Even though these studies require much more time to obtain definitive results, the researcher has control over key factors such as design and application of the treatments.

**Long-term Soil Productivity (LTSP) Program.** The LTSP program began in 1989 and has developed into a national program for the Forest Service with the goal of examining the long-term consequences of forest harvesting on forest soil productivity. The partnerships and affiliations have expanded into Canada. There are more than 100 LTSP core and affiliated sites (figure 9) that comprise the world's largest coordinated research network addressing applied issues of forest management and sustained productivity.



The LTSP program is described in detail by Powers et al. (2005) and Powers (2006). The following is a brief description of the program based on these references.

The LTSP program is based on the principle that a forest site's net primary productivity is directed by physical, chemical and biological soil processes which are readily affected by forest management practices. The key properties of the soil that are most affected by management are the soil porosity and organic matter of a site. Therefore, the LTSP program targets porosity and organic matter for large-scale, long-term experiments.

The LTSP program has forest types, age classes, and conditions that are likely to come under active forest management. Plots are 0.4 ha in size with comparable soil and stand variability. Sites were sampled to quantify pretreatment standing biomass and nutrient levels in the overstory, understory, and forest floor. The program is planned to extend to include a physical rotation, of about 20 years for tropical forests and as long as 80 years for boreal forests (Powers 2006: 526).

Sites are treated to create extreme ranges in the soil's organic matter and porosity. The treatments are as follows.

| Modification of:              | Symbol          | Description of treatment                                        |
|-------------------------------|-----------------|-----------------------------------------------------------------|
| Organic matter                | OM <sub>0</sub> | Only tree bole removed.                                         |
|                               | OM <sub>1</sub> | Bole and crowns removed.<br>Understory + forest floor retained. |
|                               | OM <sub>2</sub> | Whole-tree removed + all above-ground biomass + forest floor.   |
| Compaction<br>(soil porosity) | C <sub>0</sub>  | No soil compaction.                                             |
|                               | C <sub>1</sub>  | Intermediate bulk density compaction.                           |
|                               | C <sub>2</sub>  | High bulk density compaction.                                   |

This results in a 3 x 3 (organic matter x compaction) combination that produces [nine treatments](#). The first LTSP installation was established in 1990 on the Palustris Experimental Forest of the Louisiana Coastal Plain.

Minimum measurements and intervals consist of the following eight core measurements (Powers 2006: 526).

| Measurement variable                                               | Minimum interval          |
|--------------------------------------------------------------------|---------------------------|
| Climatological data                                                | Continuous                |
| Soil moisture and temperature                                      | Monthly                   |
| Soil bulk density                                                  | Every 5 years             |
| Soil strength                                                      | Seasonally, every 5 years |
| Soil organic matter content and chemical composition               | Every 5 years             |
| Water infiltration and saturated hydraulic conductivity            | Every 5 years             |
| Plant survival, growth, damage from pest, net primary productivity | Every 5 years             |
| Foliar chemistry and standing nutrient capital                     | Every 5 years             |

Powers et al. (2005: 37-48) provides a summary of findings on 26 of the oldest LTSP installations (i.e., 10-years old: 1 from ID Panhandle, 6 from CA Sierra Nevada, 9 from Great Lakes area, and 10 from Southern Coastal Plain). The sites encompassed seven States (CA, ID, LA, MI, MN, MS, and NC) from five different Life Zones and about 1/3 of the current total LTSP installations. The summary discusses results relative to impacts to organic matter and soil compaction. (Note: a list of references of early, site-specific findings (from 1994-1998) are cited; in general, the LTSP program resisted a cross-site comparison until initial growth and soil chemistry oscillations might be dampened by time – so as to reveal potential long-term trends (Powers et al. 2005: 37).

Powers et al. (2005: 47) drew the following conclusions based on analysis of 10-year old LTSP sites:

- ❑ Complete removal of surface organic matter (i.e., from forest floor) leads to significant and universal declines in soil C and reduced availability of N.
- ❑ Loss of soil C and N had no general effect on standing forest biomass, except for aspen stands of the Great Lakes.
- ❑ Soil bulk density was increased by compaction treatments; increases were greater for soils with initial low-to-moderate densities.
- ❑ Forest productivity impacts from compaction depended on soil texture and presence of an understory.

Powers et al. (2005: 48) acknowledges that since only 1/3 of the LTSP installations have reached 10-years of age; it is possible that the abovementioned trends may change as more sites reach the decade age.

**Other Long-term studies (NonLTSP).** The effects of whole-tree versus bole-only harvesting on a mixed oak forest on the Oak Ridge Reservation, near Oak Ridge, TN, was first reported as a 1979 clear-cut in a nutrient budget analysis by Johnson et al. (1982). The study area was reexamined in 1995 by Johnson and Todd (1998). In that analysis, Johnson and Todd (1998) compared the nutrient budget in 1995 with the budget projections of 1979.

The reevaluation found that 15 years after treatment:

- ❑ Soil C was the same for bole-only and whole-tree harvesting.
- ❑ Soil Ca was greater in the bole-only area.
- ❑ Soil C and N increased in both areas over time.
- ❑ Foliar Ca, Mg, and K levels were higher in the bole-only area than the whole-tree harvested area.
- ❑ Foliar N and P levels were not significantly different in both areas.
- ❑ Soil-exchangeable Ca did not decline in whole-tree harvesting as might be expected from predictions. Ca from nonexchangeable reserves (i.e., deep soil reserves or bedrock) probably replenished exchangeable reserves.

Johnson and Todd (1998: 1734) concluded that nutrient budget analyses may have, in general, greatly overestimated the rates at which soil Ca would be depleted and greatly underestimated rates of N accumulation. They suggest that incomplete knowledge of weathering, deep rooting, and N-fixation should cause researchers to be cautious about making long-term predictions without long-term studies.

Johnson et al. (1988) also reported on the changes over an 11-year period of monitoring in nutrient distribution in the forest and soils of another site near Oak Ridge, TN (i.e., Walker Branch watershed). The area, however, was not the subject of an empirical study to validate the effects of intensive harvesting versus soil productivity effects. But the area has been allowed to revert into a forest since 1942 from its previous use as a woodland pasture. (As such, the soils and forests are considered far from having achieved a steady-state condition.) The long-term monitoring provides some insight into the nutrient dynamics of certain forest ecosystems on eastern

### 3.B Guidelines/ Recommendations To Mitigate Whole-tree Harvesting Impacts

forest soils that have been previously disturbed. Over the 11-year period (1972 through 1982) of the monitoring study of vegetation, litter, and soil (surface and subsoil) nutrient content findings, revealed a general decline in fertility, especially for Ca and Mg, in areas of low soil Ca and Mg reserves. The changes in soil C and N of the Walker Branch Watershed over a 32-year period (1972–2004) are reported in Johnson et al. (2007).

Richter et al. (1994) also reported on long-term monitoring of the Calhoun Experimental Forest (Union Co., SC), which has been allowed to revert to forest since about 1957. The previous 150+ years of afforestation for agricultural use of the area is known to have severely affected soil productivity. The long-term (1962–1990) monitoring results of soils, nutrient removals, and nutrient dynamics are similar to Johnson et al. (1988), especially in terms of the declines in soil Ca and Mg in previously afforested eastern forests. (Also see Knoepp and Swank 1994.) Monitoring results suggest that multiple rotations are not sustainable on these impoverished soils (Richter et al 1994:1470).

The Hubbard Brook Experimental Forest (in NH) has been the site of three decades of biogeochemistry study of the flux of water and nutrients through an aggrading northern hardwood forest ecosystem (Likens and Bormann 1995). The experimental forest (established in 1955) comprises 7,810 acres (3,160 ha) of six contiguous watershed ecosystems where studies have been conducted on the interaction of the forest nutrient and hydrologic cycle. Of the hundreds of publications generated from the biogeochemistry studies at the experimental forest, several have monitored the long-term effects of harvesting on specific and general nutrient cycles (e.g., Likens et al. 1978; Hornbeck et al. 1987; Nodvin et al. 1988; Likens et al. 1994; Likens et al. 1998; Likens et al. 2002; Lovett et al. 2005).

The following is a summary of recommendations developed by researchers to mitigate the adverse effects of whole-tree harvesting on soil productivity and guidelines for monitoring soil quality changes that are detrimental to forest soil productivity.

As previously mentioned (in section 1), SDTDC plans to produce a soil sensitivity risk rating for biomass harvesting in the Northcentral United States. SDTDC also intends to make recommendations on practical monitoring methods, measures,

### 3.B.1 Forest Service recommendations and guidance

and tools that can be used in the field to determine the amounts of down material to be retained or removed on harvested forestlands.

**Cleland (1982: 9-11).** This is one of the earliest reviews of the impacts of whole-tree harvesting that provides recommendations to mitigating adverse impacts. The review and the recommendations are largely directed to activities on the Huron-Manistee National Forest.

**Powers et al. 1998.** This describes the soil-quality standards and guidelines (and suggested threshold values) used by the Forest Service to assess the impacts of harvesting (not specifically whole-tree harvesting) on forest productivity and sustainability. The soil-quality guidelines vary by Forest Service region but the sustainability guidelines are uniformly applied regardless of soil or ecosystem properties.

**Page-Demroese et al. (2000).** This study points out the inherent shortcoming of applying uniform soil guidelines and threshold values across Forest Service regions of the Pacific Northwest. The study calls for more site- and soil-specific guidelines to monitor soil to evaluate disturbance effects on soil productivity.

**RMRS's "SoLo" Web site.** The Forest Service's Rocky Mountain Research Station (RMRS) maintains a Web site that has a collection of representative documentation of soil quality monitoring and long-term forest ecosystem sustainability. The collection of literature primarily relates to the Rocky Mountains, especially Forest Service Region 1 (Montana and Idaho Panhandle). The [monitoring](#) page has links to numerous soil quality monitoring reports (especially region 1). The [productivity](#) page has links to numerous references that address long-term forest productivity.

### 3.B.2 State biomass harvesting guidelines

Several States have prepared guidance for forest managers to facilitate informed decisionmaking relative to the harvest of woody biomass on forestlands. The State guidelines are based on the best available information (local and nationally) and intended to serve as a practical, reliable tool that are easy to understand and implement to ensure sustainable harvest of woody biomass. State guidelines are voluntary.

### ***Minnesota Forest Management and Biomass Harvesting***

***Guidelines—(MFRC 2005 and 2007).*** These guidelines were developed to comply with the State of Minnesota's Sustainable Forest Resources Act of 1995. The Act directed the Minnesota Forest Resources Council (MFRC) to develop voluntary, site-level timber harvesting and forest management guidelines. The guidelines are intended to recommend forest management practices that provide for long-term sustainability of Minnesota forestlands.

The objective of the Forest Management Guidelines (MFRC 2005) are to provide consistent, coordinated guidance in sustaining forest functions and values, including cultural resources, soil productivity, riparian areas, visual quality, water quality, and wildlife habitat. The guidelines are general (i.e., common to many forest management activities) and activity-specific (i.e., apply to specific management activities.) General guidelines are further divided into planning activities and operational activities (MFRC, part 3, page 5).

Pertinent to this review, the Forest Management Guidelines provide site-specific rationale for the recommendations relating to the maintaining soil productivity (see MFRC 2005: part 2, Forest Soil Productivity). The Biomass Harvesting Guidelines (MFRC 2007) provides guidance to minimize the impacts of biomass harvesting, including whole-tree harvesting on soil productivity of Minnesota forestlands.

### ***Wisconsin Biomass Harvesting Guidelines (Herrick et al. 2008).***

The guidelines were developed for the Wisconsin Council of Forestry by a technical team of the Wisconsin Department of Natural Resources. The guidelines are divided into general and specific recommendations. General guidelines are applicable to any site within the State where woody material might be harvested. Specific guidelines address specific conditions that are present at all sites.

Site-specific information of nutrient cycling and soil productivity for Wisconsin forestlands (especially relative to the impacts of biomass harvesting) is provided in the rationale (see Herrick et al. 2008: 15).

### ***Northern Idaho and Western Montana Biomass Harvesting***

***Guidelines (Garrison-Johnston et al. 2007).*** These guidelines were developed to assist forest managers determine appropriate nutrient management strategies for stands on various rock types in western Montana and northern Idaho. The nutritional management

guidelines are based on the knowledge of the influence of certain rock types on forest growth in the inland northwest.

The findings of the Intermountain Forest Tree Nutrition Cooperative (IFTNC) indicate that rock type affects the nutrients available in the soil which in turn influences the growth and health of seedlings and young stands. As such, these guidelines emphasize the importance of the underlying rock as the source of most of the important plant nutrients for maintaining forest productivity and sustainability.

The guidelines are provided based on the area's major geologic units (i.e., extrusive and subvolcanic rocks, intrusive rocks, metamorphic rocks, sedimentary rocks, and unconsolidated deposits). Furthermore, the guidelines are limited to rock types in which the IFTNC has empirical information relative to the effect of the rock type on forest growth and fertilization response.

***Oregon—Environmental effects of forest biomass removal (Oregon Department of Forestry 2008)*** This report was prepared to comply with the State of Oregon's Senate Bill 1072. The Bill requires the State Forester to actively manage forest to reduce wildfire fuels and to promote the health of forests and rural economies. One of the key requirements of the bill directs the preparation of a report (every 3 years) that specifies the effects harvesting of woody biomass on the forest environment.

The report contains a literature review of environmental effects of woody biomass harvesting (associated primarily with thinning operations), a discussion of current resource protections (Federal and State) for biomass removal, recommendations to encourage biomass harvesting, and methods of how to avoid negative impacts of biomass harvesting on the State's forestlands.

Note that the emphasis of the literature search is primarily on the effects on the forest ecosystem from thinning of stands and the removal of nonmerchantable woody biomass. Almost none of the discussion relates to the specific impacts of whole-tree harvesting.

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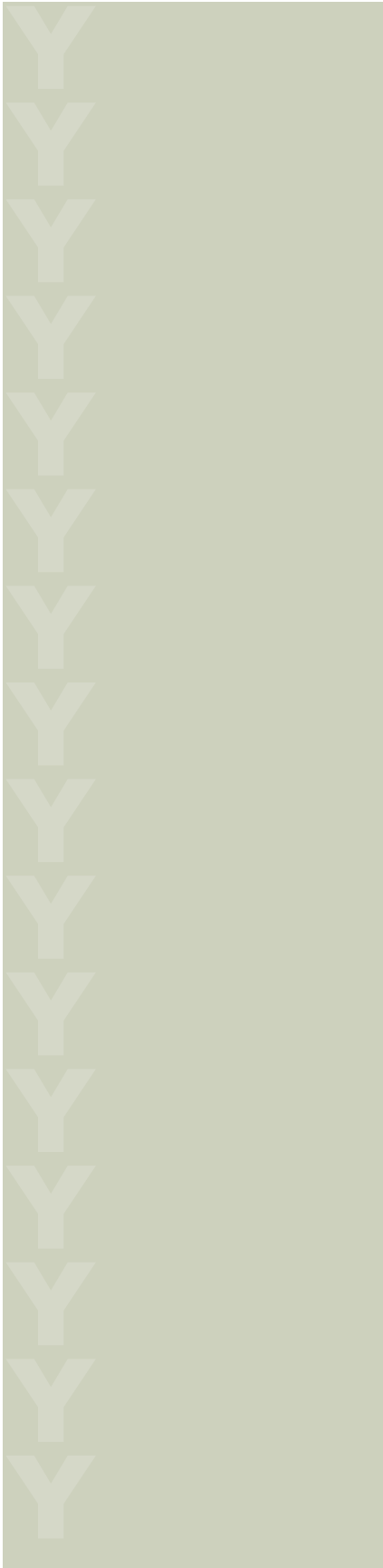
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