



United States  
Department of  
Agriculture

Forest  
Service

Northern  
Research Station

General Technical  
Report NRS-106



# **Evaluating Forest Biomass Utilization in the Appalachians: A Review of Potential Impacts and Guidelines for Management**

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## Abstract

Forests are important economic and ecological resources for both the Appalachian hardwood forest region and the country. Increased demand for woody biomass can be met, at least in part, by improved utilization of these resources. However, concerns exist about the impacts of increased intensity of woody biomass removal on the sustainability of forest ecosystems. Relatively little research has evaluated the impacts of forest biomass harvesting on site productivity, biodiversity, water quality, or other measures of ecosystem productivity, and new information about these and other related topics is not readily available. This report discusses the implications for the sustainability of Appalachian hardwood forests if additional woody biomass is removed for the production of woody biomass-related energy. It includes a summary and synthesis of published literature and ongoing studies to evaluate the possible effects of increased biomass removal on several primary aspects of forest sustainability (i.e., site productivity, water quality, wildlife and biodiversity, wood supply). General management guidelines are proposed that can minimize the impacts of woody biomass utilization on the sustainability of Appalachian hardwood forests. Accompanying the report is an online bibliography, containing references for scientific literature related to woody biomass harvesting and utilization beyond the scope of the Appalachian forest region.

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Manuscript received for publication March 2012

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Published by:  
USDA FOREST SERVICE  
11 CAMPUS BLVD., SUITE 200  
NEWTOWN SQUARE, PA 19073-3294

October 2012

For additional copies:  
USDA Forest Service  
Publications Distribution  
359 Main Road  
Delaware, OH 43015-8640  
Fax: 740-368-0152

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## INTRODUCTION

Renewable energy is projected to increase its share of total energy generation during the next two decades in many countries of the industrialized world (Roos et al. 2000), and woody biomass utilization from forests is expected to be a key element of the renewable portfolio. Many countries have already directed significant resources toward the development of forest biomass to energy conversion facilities, including Sweden, Finland, Denmark, Belgium, Canada, and the United States. For example, Finland utilizes the cogeneration of heat and power and biofuels more extensively than any other nation, and the target of that country's National Action Plan for Renewable Energy Sources is to increase the annual use of woody biomass from forests (Malkki and Virtanen 2003). Sweden is experiencing a rapidly growing demand for commercially traded wood fuel for energy production. Forest biomass, consisting mostly of tops and branches from commercial harvesting operations, comprises 80 percent of the domestic wood fuel resource in Sweden (Bohlin and Roos 2002). The U.S. pulp and paper industry utilizes woody biomass to generate thousands of megawatts of electricity for its own use and for sale to utility companies. China and Turkey have placed high importance on the development of such facilities to create job opportunities and revitalize rural communities in addition to providing alternative energy generation (Cuiping et al. 2004, Demirbas 2004). Turkey, for example, generated 10 percent of its total energy from biomass in the year 1999 compared to 3 percent in the United States (Kaygusuz and Turker 2002, Perlack et al. 2005). Demand for forest biomass as an energy source is already widespread and promises to remain high in the future.

There are two main forces driving the predicted increase in U.S. domestic woody biomass utilization: energy independence and global climate change (Janowiak and Webster 2010). Rising costs of fossil-based energy sources and a greater reliance

on foreign oil are the two most frequently cited energy concerns (Aguilar and Garrett 2009), while increasing greenhouse gas (GHG) concentrations from anthropogenic emissions are considered to be a major contributor to climate change (Apps and Price 1996). The United States has placed the U.S. Forest Service mission within the context of facilitated adaptation to reduce the impacts of climate change and has pursued the development of strategies to mitigate climate change (Barrett 2009). Increasing the utilization of woody biomass for energy production would expand the domestic renewable energy portfolio, which could address both issues of the United States' reliance on foreign energy sources and the need to mitigate greenhouse gas emissions (Bjorhedan et al. 2003, Cuiping et al. 2004, Kumar et al. 2003, Malkki and Virtanen 2003).

Nationally, the Energy Policy Act of 2005 and the Energy Independence and Security Act call for the increased utilization of woody biomass for energy generation, with an emphasis on cellulosic biofuels (Janowiak and Webster 2010). Globally, woody biomass represents about 14 percent of the world's total energy consumption and developing countries utilize three times as much woody biomass relative to industrialized nations (Parikka 2004). Woody biomass contributes to roughly 3 percent of total United States' energy generation, making it the largest source of renewable energy at present (Perlack et al. 2005). However, this represents only a 1.5 percent increase in woody biomass-based energy production over the last three decades (Navickis 1978), and current domestic renewable energy initiatives target substantially greater production. The U.S. Department of Energy estimates that 1.18 billion Mg (1.3 billion tons) of biomass could be produced on an annual basis through relatively small changes in land use and forestry practices. These changes could cut current GHG emissions by up to 10 percent and also replace an equal amount of the nation's petroleum consumption by 2030 (Perlack et al. 2005).

Figure 1 shows the U.S. energy sources, by percentage of consumption for 2010. Wood energy makes up about 25 percent of the renewable energy share, while biofuels (fuel ethanol and biodiesel consumption) and waste (municipal solid waste, landfill gas, sludge, agricultural byproducts, and other biomass) make up another 30 percent of the renewable energy share. Overall, the use of biomass for energy wood appears to be an integral part of addressing the United States' reliance on foreign energy sources and emissions from domestic energy generation.

### Energy Wood in Appalachian Forests

The forests of the Appalachian region, from northern Georgia through southern New York, are already important economic and ecological resources for the region and the nation. Federal emission standards have necessitated the use of biomass for cogeneration with fossil fuel sources such as coal, and biomass will continue to be part of the Appalachian region energy portfolio (ARC 2006). Several bioenergy production facilities in the region already exist and the development of biofuels is a focus of many

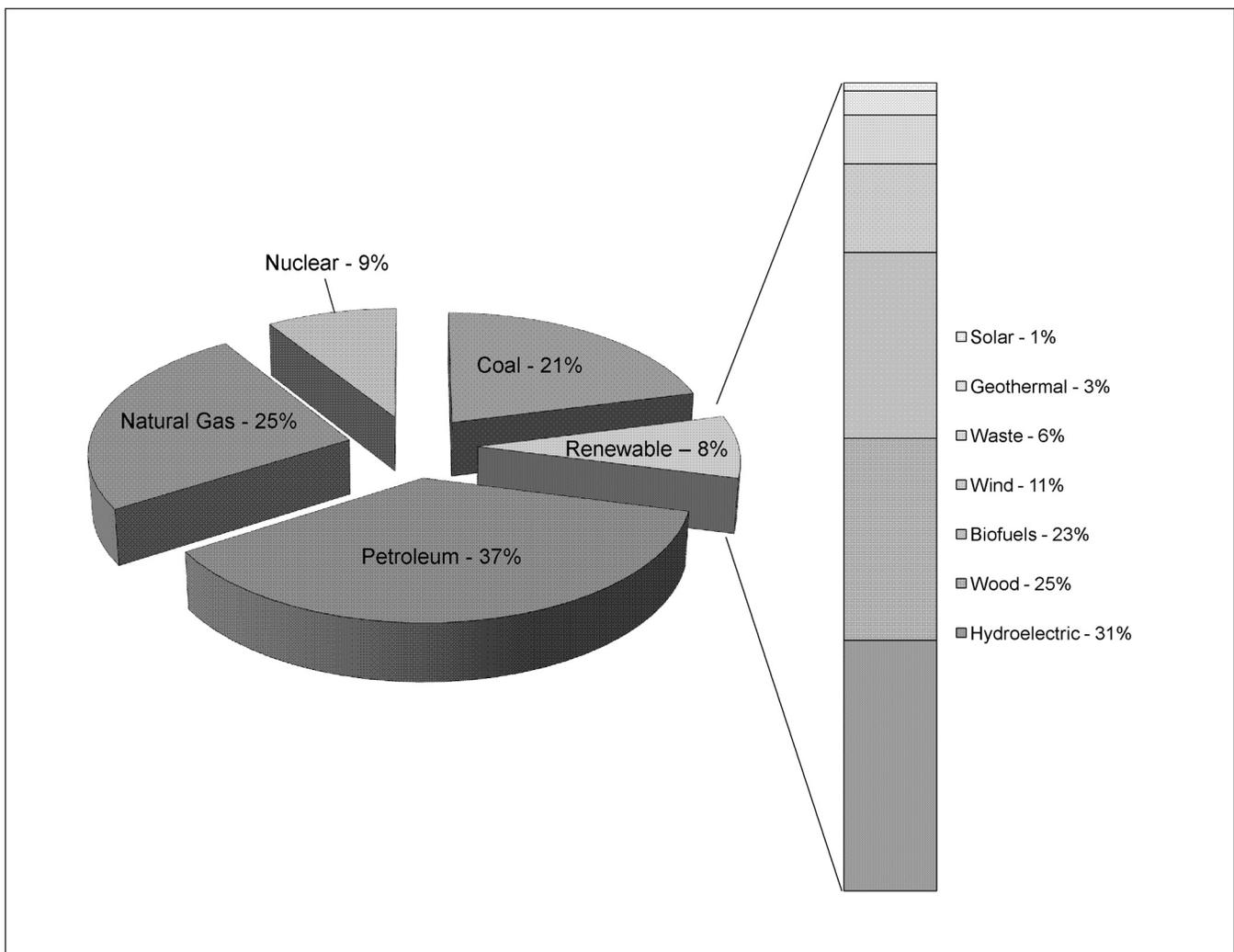


Figure 1.—Renewable energy as a share of total primary energy consumption, 2010 (adapted from EIA 2011).

Appalachian state energy plans (ARC 2006). Examples of policies to promote renewable energy in the Appalachian region include mandates to increase electricity derived from renewable sources to 12.5 percent by 2020 in North Carolina, as well as the requirement for all gasoline to contain 10 percent cellulosic ethanol in Pennsylvania (Aguilar and Garrett 2009). These policies will require biomass as a feedstock and this increase in demand for wood fuel may be met by improved utilization of forest resources (Galik et al. 2009). For example, the utilization of post-harvest residues in the Appalachian forest region has the potential to provide biomass feedstock for energy wood. Average estimates for the dry mass of

harvesting residues in West Virginia range from 18.8 to 23.3 Mg ha<sup>-1</sup> (Fajvan et al. 1998, Grushecky et al. 1998, Grushecky et al. 2006, Wang et al. 2007). However, concerns exist over potential impacts of the heightened intensity of forest biomass removal on the long-term sustainability of forest ecosystems within the Appalachian region. Figure 2 shows production facilities (both existing and planned) in the northeastern United States, which utilize woody biomass that could be used as energy wood. The figure includes wood consumption by energy production facilities as well as traditional forest product industries such as paper, oriented strand board (OSB), medium density fiberboard (MDF), and particleboard (PB).

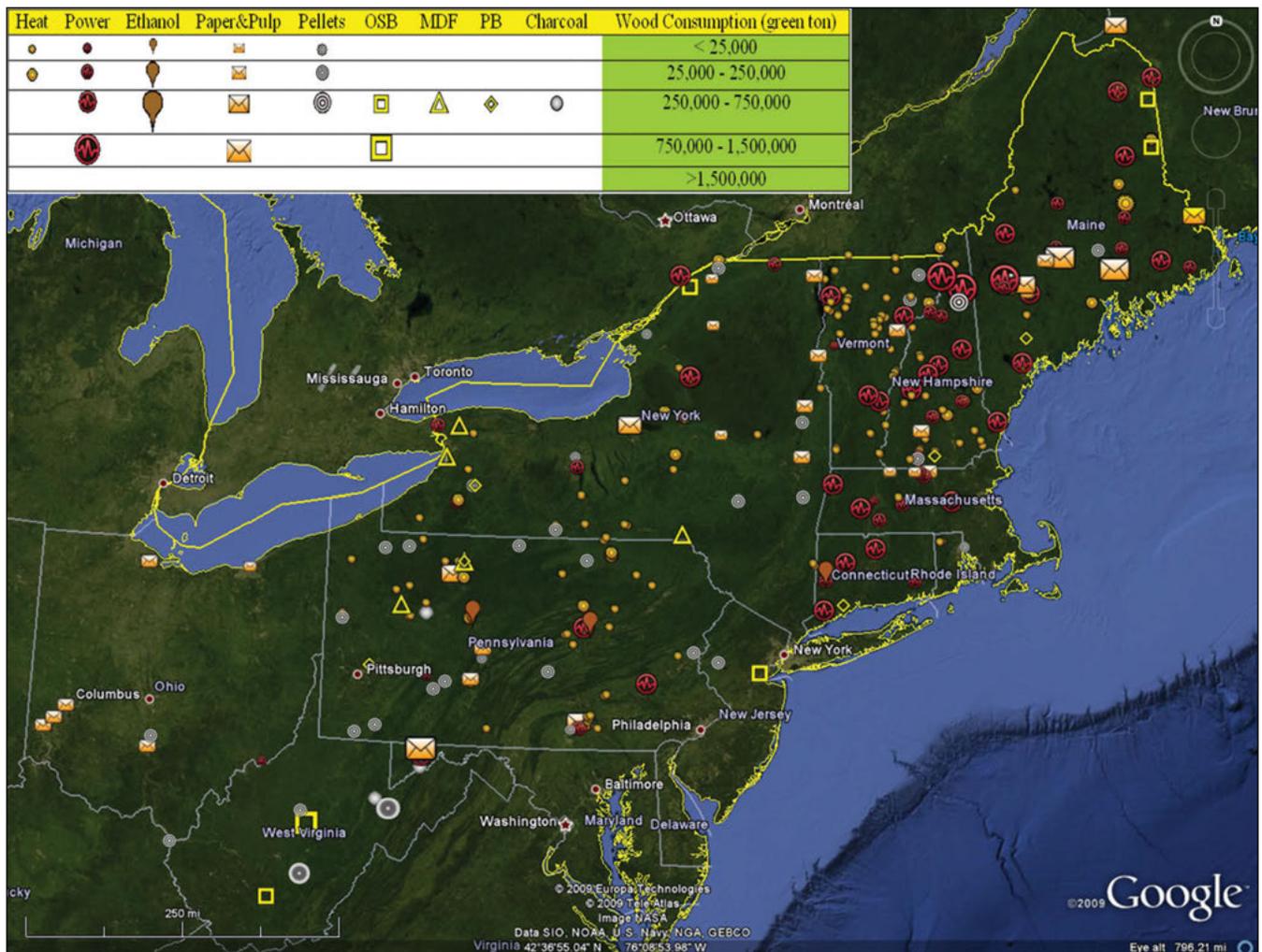


Figure 2.—Biomass use in the northern Appalachian region (from Wiedenbeck et al. 2011).

Aguilar and Garrett (2009) surveyed state foresters, state biomass energy contacts, and National Council of Forestry Association Executives to gain their perspective on defining woody biomass, different renewable energies, and the opportunities and challenges associated with the utilization of woody biomass as a sustainable energy feedstock. More than 90 percent of respondents from the Appalachian region thought woody biomass could encompass tree branches and small-diameter trees from both naturally regenerated and plantation forests on private and public lands, as well as residue from the wood products industry. There was less agreement on the inclusion of forest brush, tree needles, or leaves, and biomass from old growth or late successional forests. Respondents scored the combustion of woody biomass as having the most potential as a sustainable source of energy. However, there was also strong support for wood-based biofuels, gasification, and pyrolysis.

The Aguilar and Garrett (2009) study also measured the relative importance of utilizing woody biomass for energy generation. Within the region containing the Appalachians, the greatest perceived benefits revolved around locally produced energy, job and work opportunities, and improving forest health by increased management opportunities. Furthermore, the study gauged stakeholders' opinions on the challenges facing energy generation from biomass. The single most significant challenge was the cost of harvesting and the transportation of energy wood from the forest to the production facility. Notably, respondents rated the potential negative impacts of forest biomass harvesting on watershed soil conditions, watersheds, and wildlife habitat as some of the least challenging concerns.

## ENERGY WOOD HARVESTING AND WOODY BIOMASS RETENTION

Biomass harvesting consists of the collection and removal of woody biomass from forested sites and may occur as part of a traditional roundwood harvest or as a separate operation following a traditional harvest. In addition to the removal of traditionally marketable products, such as saw logs and pulpwood, biomass harvesting may include the removal of tops and limbs remaining from a roundwood harvest, small diameter trees of both merchantable and non-merchantable species, dead and downed material, and shrub species. Current forest management activities can respond to the increased demand for biomass in at least three general ways, including: 1) the management of forests that may have been previously unmanaged, mismanaged, or underutilized in the past; 2) increased harvest intensity in already managed stands; and 3) the expansion of short-rotation biomass plantations, which may lead to the conversion of some naturally regenerating forest land (Janowiak and Webster 2010). Thus, biomass utilization will likely affect more land area, remove a higher proportion of the vegetation compared to a traditional roundwood harvest only, and also have associated subsequent impacts on a range of factors that influence sustainability. Biomass plantations offer excellent opportunities to produce relatively large amounts of fiber using intensive management, but are outside the scope of this review due to their relative infrequency in the Appalachians and the greater likelihood that natural forests will be the predominant source of woody biomass in the immediate to short term. Therefore, we will limit our discussion to the use of naturally regenerated hardwood forests for energy wood and will only occasionally refer to short-rotation plantations (also known as purpose-grown wood).

Biomass utilization is defined in federal regulations as the harvest, sale, offer, trade, and/or utilization of woody biomass to produce the full range of wood products, including timber, engineered lumber, paper

and pulp, furniture and value-added commodities, and bioenergy and/or bio-based products such as plastics, ethanol, and diesel [48 C.F.R. § 1437.7203; <http://www.gpo.gov/fdsys/pkg/CFR-2010-title48-vol5/pdf/CFR-2010-title48-vol5-chap14.pdf>]. Biomass utilization includes biomass harvesting and encompasses not only the potential environmental impacts of biomass harvesting but also issues pertaining to wood supply and socioeconomics.

A sustainable wood supply is dependent on the greater implementation of smallwood harvesting techniques and the economic feasibility of such techniques, which have been largely absent from the Appalachian hardwood region dominated by higher-valued timber resources, as well as the social acceptance of the process of biomass utilization. In this synthesis, we will evaluate sustainability from a biomass utilization perspective, to include environmental impacts as well as the competition among the markets that rely on the resource. Sustainability guidelines, or best management practices (BMPs), for the Appalachian hardwood region will also be offered for biomass utilization, as it has been found that management objectives, ecology, and economics are all central to forest biomass operations (Evans and Finkral 2009).

While there is a relative abundance of research on the effects of biomass harvesting on soil nutrients (e.g., Johnson et al. 1982, Mann et al. 1988, Powers et al. 2005), only a small portion of that research has been re-evaluated in terms of aboveground vegetative productivity. Furthermore, important factors such as water quality and biodiversity may be affected by heightened demand for biomass, which will necessitate the increased usage of smallwood harvesting practices (e.g., whole-tree removal of traditionally nonmerchantable species) and the improved utilization of traditional harvest residuals. In terms of biomass harvesting, these sustainability factors deserve attention to determine their relative importance beyond traditional saw log and pulpwood harvesting (Bohlin and Roos 2002, Evans and Perschel 2009).

With increasing intensity of biomass removal, a main concern is the removal of woody material that otherwise would be left on site during a conventional harvest. This includes the nutrient-rich branches and tops, stumps, and larger stem pieces, which is a combination of coarse woody debris (small end diameter >7.6 cm, length >1 m), fine woody debris (small end diameter < 7.6 cm), and large woody debris (length >3.7 m) (Evans 2011, Forest Guild Biomass Working Group 2010, Mattson et al. 1987, Rubino and McCarthy 2003, Valett et al. 2002, Webster and Jenkins 2005). These categories of woody debris are commonly classified together as downed woody material (DWM) (Evans 2011). DWM accumulation in forests often follows a U-shaped temporal pattern post-harvest (Figure 3) (Evans 2011, Jones et al. 2009, Sturtevant et al. 1997). Conventional harvest activity causes an initial period of high wood input, followed by a longer period of diminishing input before DWM

accumulation rates increase as trees start to mature and mortality occurs in larger trees. Biomass harvesting that targets DWM can nullify the initial enlargement in input and lead to changes in woody debris dynamics. Forest stands that undergo natural disturbance events will usually have more large snags (standing dead trees) compared to stands that are commercially harvested, but that could vary with the type of management activity (Jones et al. 2009). Generally, the abundance of snags is greater with older stands.

Overall, DWM is an important, and often abundant, component that can impact nutrient availability, nitrogen fixation, wildlife habitat, seedling regeneration, and overland flow of water (Evans 2011). Adams et al. (2003) reported total volumes for DWM ( $69.7 \text{ m}^3 \text{ ha}^{-1}$ ) and snags ( $41.4 \text{ m}^3 \text{ ha}^{-1}$ ) in a mature second-growth central Appalachian hardwood stand. The authors found that the DWM was comprised of 22

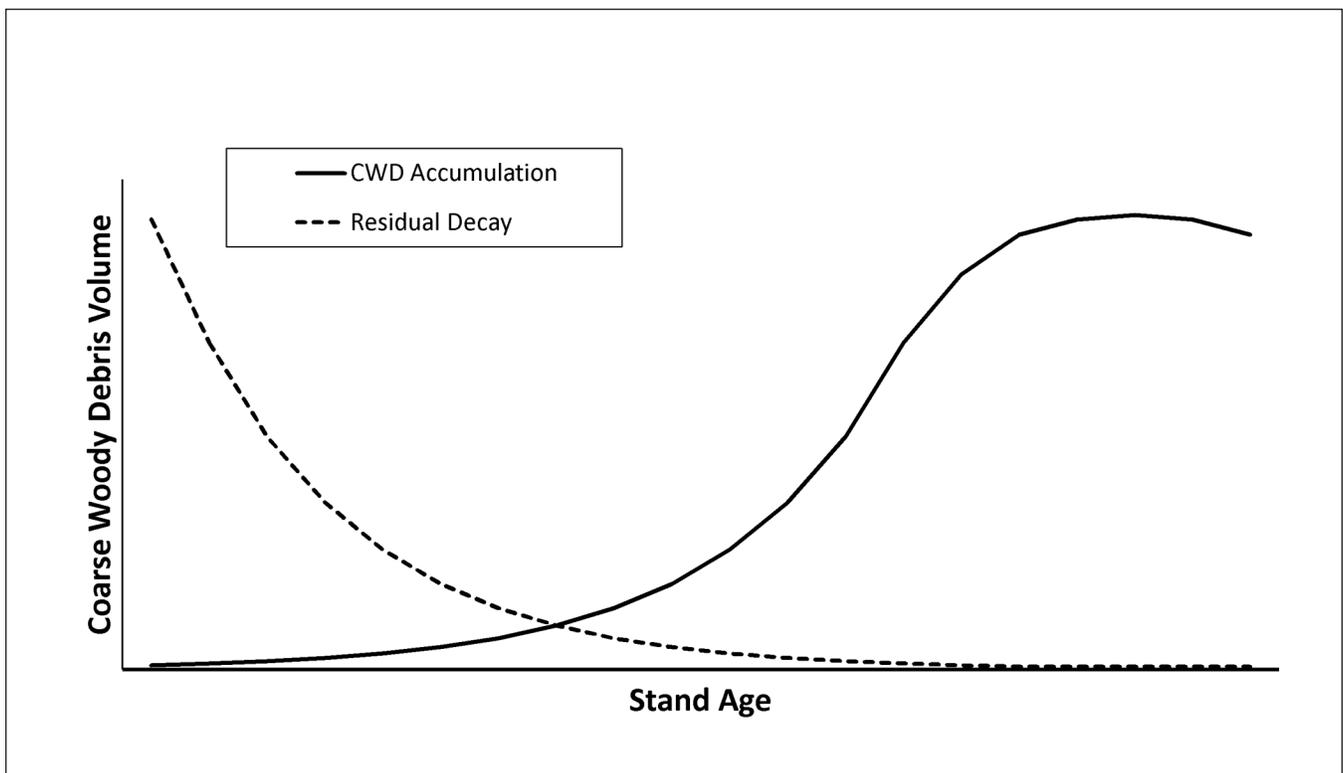


Figure 3.—Post-harvest woody debris dynamics with increasing stand age (adapted from Sturtevant et al. 1997).

tree species, with 27.9, 40.8, and 31.2 percent of the material in decay classes 1, 2, and 3, respectively. (The stage of decay increased with the number of decay class.) A per-hectare average of 48 snags was found, representing 37 percent of the total DWM. The largest diameter of DWM was 96.5 cm, while the largest snag was 107 cm at breast height. Sixty-nine percent of snags had diameters less than 35.6 cm, and 50 percent had diameters less than 20.5 cm. The authors report that the DWM volumes for the stand appeared high compared to other second-growth forests, although other published values for DWM in the region range from 8 to 84 m<sup>3</sup> ha<sup>-1</sup> (Jenkins and Parker 1997, Shifley et al. 1998) and Evans (2011) reports a range of 6.7

to 92 Mg ha<sup>-1</sup> and an average of approximately 30 Mg ha<sup>-1</sup> for four southern Appalachian states. The range of annual DWM accumulation was reported as 0.56 to 15.9 Mg ha<sup>-1</sup>, with an average annual rate of 4 Mg ha<sup>-1</sup> (Evans 2011). The range of DWM in oak-hickory forests has been reported as 13 to 40.4 Mg ha<sup>-1</sup>, while snags ranged from 47 to 108 per hectare or 5 to 15 percent of the basal area. The forests of the southern Appalachians are reported as averaging 57 to 128 snags per hectare greater than 10 cm in diameter at breast height (d.b.h.) and five large snags per hectare greater than 30 cm d.b.h., with an annual accumulation rate of 1.5 snags per hectare (Evans 2011).

## **IMPACTS OF ENERGY WOOD HARVESTING ON FOREST ECOSYSTEMS**

Ecosystem services include maintaining site productivity, providing clean and abundant water supply (i.e., meeting water quality standards), supporting wildlife and biodiversity, and sustaining regional wood supply (Benjamin et al. 2010). Each ecosystem service is affected by factors associated with woody biomass harvesting and utilization, such as the retention of downed woody material and the site impacts due to the harvesting method and silvicultural prescription. For example, the sustainability of forest site productivity is influenced directly by biomass utilization through its impact on nutrient availability and soil compaction. Soil can be compacted by the machinery used within the biomass harvesting system, and nutrient availability can be affected by the type and amount of woody debris and leaf litter, which are a product of post-harvest residual stand conditions.

To a great extent, ecosystem services affected by woody biomass utilization depend on the condition of the residual stand and the harvest system used for management activity. Therefore, to effectively manage a forest for sustainable vegetation growth for future rotations, the planning process must determine a desired harvest system (i.e., type and intensity of silvicultural prescription, and method of forest operations) that will meet the residual stand condition objectives that are necessary for long-term site productivity. Furthermore, decisions that are made in regard to the harvest system to ensure site productivity will also directly affect the ecosystem services of water quality, biodiversity, and wood supply to varying degrees. A management strategy that takes into account the impacts to ecosystem services will help to ensure long-term woody biomass availability for energy wood production.

The body of scientific literature that addresses the impacts of forest harvesting on ecosystem services is large, and some of the research is not specific to the Appalachian forest region. Although such research may be applicable to the Appalachian forest region, much of it is beyond the scope of this publication. However, the authors recognize the value of these publications, and accompanying this report is an online bibliography containing more than 200 references for scientific literature related to woody biomass harvesting, utilization and impacts on forest ecosystem services. The online bibliography can be accessed at the West Virginia University Division of Forestry and Natural Resources – Appalachian Hardwood Center website: [http://ahc.caf.wvu.edu/joomla/index.php?option=com\\_remository&Itemid=148&func=startdown&id=364](http://ahc.caf.wvu.edu/joomla/index.php?option=com_remository&Itemid=148&func=startdown&id=364). The bibliography is maintained as an Adobe Portable Document Format (PDF), and is searchable by keyword, author name, title, publisher, etc. Hyperlinks to publicly available publications are included where appropriate.

In the following sections, the relative importance of woody biomass utilization impacts on ecosystem services in the Appalachian forest region is described in more detail.

### **Maintaining Site Productivity**

The productivity of a site is a function of the local microclimate, organic matter (OM), and available nutrients, and the interactions among those. The Forest Guild Biomass Working Group (2010) suggests that biomass harvesting is unlikely to significantly impact site productivity if sensitive sites (low-nutrient sites) and clearcutting with whole-tree removal are avoided. However, an intensification of biomass harvesting can affect site productivity through several pathways. First, an expansion of the acreage that is harvested may affect site productivity by increasing the area susceptible to erosion and runoff, which results

in removal of important nutrients and OM from individual sites, over a collectively greater area. Also, more vehicle traffic (more passages across a site/area) to access additional biomass can result in greater soil disturbance and compaction which also may affect site productivity. Enlarging the area harvested within a region may result in a greater removal of nutrients and OM, via removal of aboveground biomass on more hectares. Finally, more intense utilization of woody residues may also result in increased nutrient removals as nutrients traditionally left in the woods are removed. Figure 4 depicts nutrient fluxes to and from the forest ecosystem.

Soil disturbance disrupts an orderly process of litter accumulation and decomposition. Although high infiltration capacities of most undisturbed forest soils prevent overland flow (Hewlett and Hibbert 1967), removal of the litter layer and forest floor can increase erosion and affect soil temperature and nutrient cycling. Soil compaction, resulting from multiple passages of heavy equipment and logs over an area, can increase soil bulk density, which results in decreased soil pore space, soil air, and water-holding capacity, and increased surface runoff.

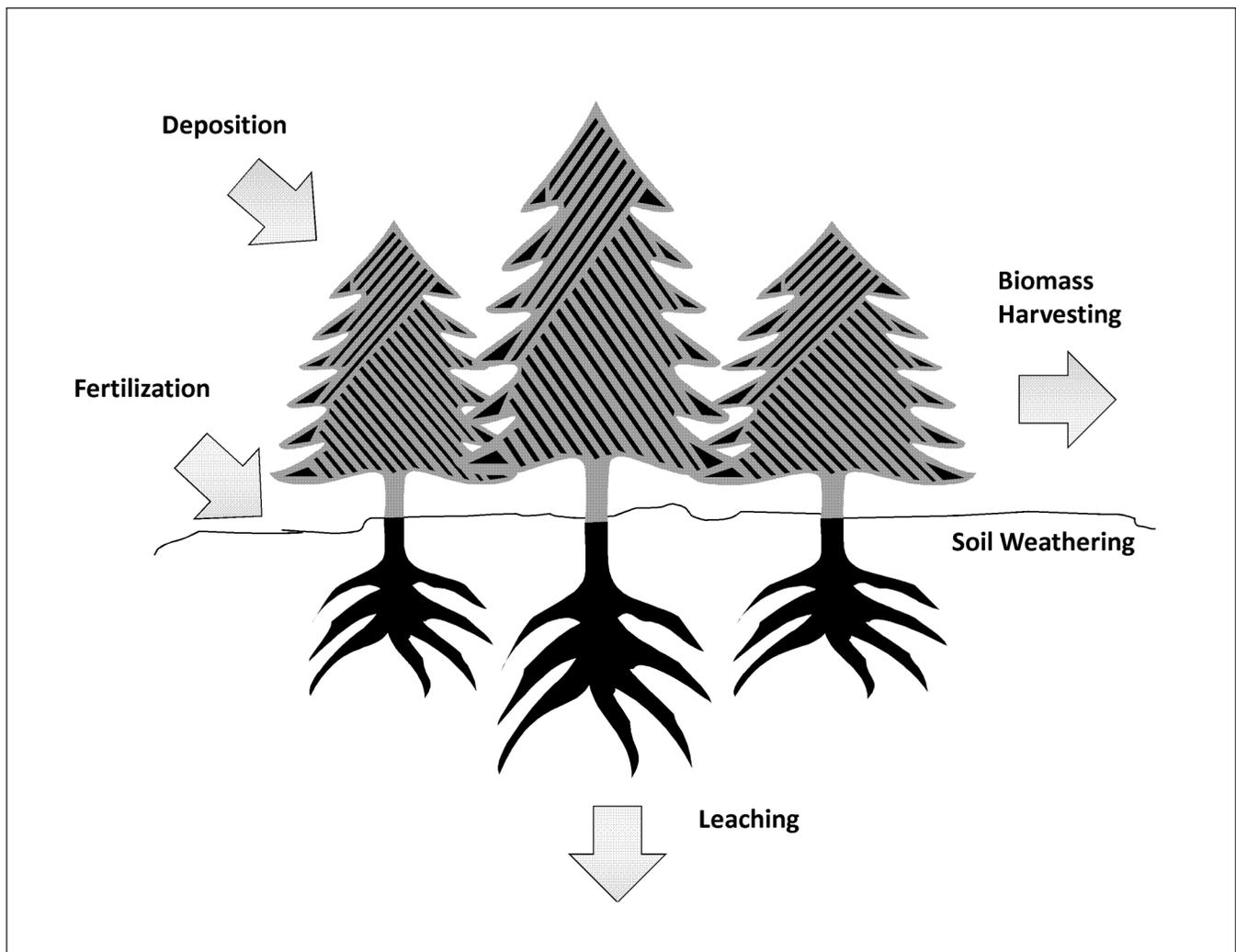


Figure 4.—Nutrient fluxes to and from the forest (adapted from Raulund-Rasmussen et al. 2008).

Water is responsible for most of erosion and sediment movement that occurs in the Appalachian region. Therefore, erosion and sediment impacts from intensified forest management are the result of how surface runoff of water is handled. The risk of erosion and movement of sediment to streams grows as litter and soil disturbance and soil compaction increase. The litter layer protects soil particles from direct impact and detachment by raindrops (Stuart and Edwards 2006) and also plays a major role in maintaining high soil infiltration rates (Patric 1978). Therefore, by retaining litter on the surface and avoiding soil compaction, erosion and sediment transport to streams above natural climate-driven levels can be largely controlled.

Not surprisingly, because of the degree of soil disturbance involved in their construction and use, forest roads and constructed skid trails, not the process of felling timber, are the major source of sediment potentially moving into streams (Megahan 1972, Patric 1976). If water is not controlled properly, it can build up sufficient energy to erode soils and transport soil particles off-site. Much research has shown that when haul roads, skid roads, and landings are properly located and appropriate mitigation measures, such as graveling, are employed, watershed exports of sediment are minimized (Kochenderfer 1970, Patric 1978, Kochenderfer and Helvey 1987, Kochenderfer et al. 1997). As the area exploited for biomass harvesting increases, there may be a concomitant increase in road density, harvesting, and usage of existing roads. Therefore, careful planning and maintenance of roads may mitigate some of the impacts of increased area harvested under an energy wood scenario.

An intensification of biomass harvesting can also lead to greater nutrient losses from an individual site, as well as cumulatively from a region. Timber harvesting removes nutrients from a site in the forest product, and numerous studies have evaluated the effects of harvesting on nutrient pools at the site or stand level

(Johnson et al. 1982, Leaf 1979, Mann et al. 1988, Powers et al 2005). Generally, the amount of nutrient removed is proportional to the biomass removed (Adams 1999). The more intensive a harvest, the more aboveground biomass, and therefore nutrients, are removed from the site. For example, a pulpwood harvest, where all stems 4 inches in diameter and greater were utilized, removed more biomass than a saw log-only harvest, where stems smaller than 8 inches diameter were left on the site (Adams 1999). The greatest removals of biomass and nutrients occur with whole-tree harvesting, where nearly all aboveground woody material is removed from the site, including tops and branches. Tritton et al. (1987) estimated whole-tree harvesting removed 91 percent of aboveground biomass, compared with about 10 percent of the biomass in a commercial thinning operation in central hardwood stands in Connecticut and Tennessee. Estimated removals of nitrogen (N) in whole-tree harvesting in eastern hardwood forests ranged from 143 to 323 kg N ha<sup>-1</sup> (Adams 1999, Tritton et al. 1987), compared to 58 to 162 kg N ha<sup>-1</sup> in saw log only harvests. Yanai (1998) demonstrated that whole-tree harvesting in northern hardwood forests removed five times more phosphorus (P) than bole-only harvests. Removal of calcium (Ca) with whole-tree harvesting was estimated from 300 to 1090 kg Ca ha<sup>-1</sup> (Adams 1999), and also estimated that whole-tree harvesting could result in a decrease of 30 to 50 percent of the Ca pool, assuming no weathering inputs. Note, however, repeated light cuts can remove as much biomass and nutrients over the course of a rotation as one commercial clearcut (Adams et al. 2000, Patric and Smith 1975). Such high levels of removal raise concerns about the availability of these nutrients for the regrowing or remaining forest.

In general, the aboveground nutrient content of the forest stand is relatively small compared to the total nutrient pool of the soil (Adams 1999, Patric and Smith 1975). However, there is a particular concern about nutrients such as Ca and magnesium

(Mg) for which input rates are normally considered low, and which could become limiting in nutrient-poor soils. Adams et al. (2004) reported that, while aboveground N represents 8 percent of the total site N capital, aboveground Ca and Mg represented 85 percent and 60 percent of the estimated site capital, respectively. Using data from Jenkins et al. (1998), where exchangeable Ca levels in West Virginia soils ranged from less than 100 kg ha<sup>-1</sup> to more than 6000 kg ha<sup>-1</sup>, Adams et al. (2000) demonstrated that the lowest levels of harvest removals exceeded the available soil Ca in some of the soils, and the highest levels of removals exceeded available soil Ca levels in all but those soils derived from limestone or other calcium-rich parent materials. However, note that most estimates of soil pools are incomplete because they usually represent only extractable or available nutrients (Schoenholtz et al. 2000). Because mineral weathering rates are poorly quantified in most soils, we generally underestimate total soil levels of nutrients such as Ca and Mg. Also, we base our nutrient budgets on mass-balance models of nutrient supply that are based on static measures that overlook the dynamic nature of chemical equilibria within the soil (Powers, in press).

Significant growth declines following whole-tree harvesting have been documented and attributed to nutrient limitations, but these have been reported mostly in second rotation conifer plantations, located on nutrient poor soils (Egnell and Leijon 1999, Proe et al. 1996, Scott and Dean 2006). These growth declines have often been related in particular to altered organic-matter cycling, and effects on soil N and P. Such problems are less commonly reported in hardwood forests.

However, some hardwood tree species may be more susceptible to the effects of poor nutrition than others (Adams et al. 2000). For example, Johnson and Todd (1998) compared the effects of saw log harvesting and whole-tree harvesting on carbon and nutrient

budgets in a mixed-oak forest near Oak Ridge, TN, immediately after harvesting and again 15 years later. While greater concentrations of Ca, potassium (K), and Mg were found in both foliage and soils of the saw log removal treatment relative to the whole-tree harvested treatment, there were no signs of deficiencies of these nutrients, and no differences in forest growth.

Precipitation that contains high concentrations of N and sulfur (S) can alter nutrient cycling and lead to elevated leaching of base cations, particularly Ca and Mg (Adams et al. 2000, Norton et al. 1997). Annual Ca and Mg leaching losses may represent significant portions of exchangeable soil Ca and Mg pools, although there is wide variability and uncertainty around these estimates (Watmough et al. 2005). Thus, in the central Appalachians, significant losses of Ca and Mg are possible even under a no-harvest scenario due to mobilization of these nutrients by acidic deposition inputs. The Appalachian forest has historically seen high levels of some nutrients in atmospheric deposition, in particular N and S. Sulfur levels have declined significantly during the last 25 years (National Atmospheric Deposition Program, n.d.), but N deposition generally has remained elevated. While often hypothesized, growth declines in hardwood forests related to acidic deposition-induced leaching have not been well documented in the scientific literature (but see Elias et al. 2009).

However there is certainly evidence that leaching of nutrients such as Ca and Mg can be accelerated as a result of elevated nitrogen deposition and availability (Adams et al. 1997, Adams et al. 2006). Nitrogen availability can be increased by atmospheric deposition to the point of N saturation (Adams 1999, Fenn et al. 1998, Gilliam et al. 1996). Concerns associated with N saturation include increased nitrification leading to leaching of soil N, Ca, and Mg to waterways and the effect of the loss of these nutrients on soil productivity (Gilliam and Adams 1999). The effects of increased N levels have been studied extensively over the short

term in Appalachian hardwood forests. Adams and Angradi (1996) found that after 3 years of N and S fertilization, leaf litter decomposition was slower in treated watersheds compared to the control. Adams et al. (1997) found that 5 years of annual N and S fertilization to a young stand increased concentrations and export of N, Ca, and Mg, and that the treated watershed was N-saturated.

Biomass harvesting can further alter the nutrient dynamics in forests affected by acidic deposition (Adams et al. 2000). Gilliam and Adams (1999) studied the effects of harvesting on N dynamics in a N-saturated forest. They found that the already high rates of N mineralization were increased significantly by whole-tree harvest treatments, and the addition of N, Ca, and Mg fertilization with whole-tree harvesting resulted in the highest rates of nitrification. Coates et al. (2008) showed that mechanical thinning-from-below treatments resulted in increases in extractable total inorganic N, net N mineralization, and nitrification during the first post-treatment year. Elevated leaching of Ca and Mg often occurs with increased nitrification. Finzi (2009), however, suggests that the atmospheric N deposition has not yet resulted in the saturation of tree demand for N, nor has it created a limitation of P in the forests of southern New England.

Of equal concern, but less supported by research data, are issues related to changes in nutrient cycling due to altered harvesting regimes in interaction with acidic deposition. Probable effects of proposed wood energy and biomass harvesting activities on nutrient cycling include: increased mineralization of organic material, resulting in increased available nutrients, particularly N; increased nitrification of soil N to nitrate ( $\text{NO}_3$ ), a more mobile form; increased leaching of soil nutrients (N, K, Ca, Mg) as uptake by plants decreases temporarily due to removal of the overstory; and increases in rates of cycling of some nutrients in the upper soil horizons. Increased soil moisture, surface soil temperatures, and increased OM, all of

which have been observed after clearcutting, produce ideal conditions for rapid decomposition of the OM available on the site, resulting in accelerated rates of nutrient cycling. A meta-analysis by Johnson and Curtis (2001) reported that, on average, harvesting had little to no effect on soil nitrogen N and C storage. However, the authors concluded that whole-tree harvesting did cause a slight decrease in soil carbon (C) and N concentrations, while saw log-only harvests resulted in elevated soil nutrient concentrations.

OM is comprised mostly of carbon and is an important contributor to site productivity. Carbon emissions and storage are related to climate change, and since forests play a critical role in mitigating climate change, the consideration of forest biomass harvesting impacts on C cycling in forests deserves attention. In general, we can expect an intensification of harvesting of forest biomass and energy wood to remove more OM from a site, proportional to the forest biomass removed, which can decrease the amount of soil C if OM inputs to the soil are reduced. Carbon can also be lost through the decomposition of OM, releasing carbon dioxide to the atmosphere. However, unless forest land is converted to another land use or degraded in some way, soil C has been mostly observed to not change over decades. Also, changes in soil carbon from biomass harvesting and reforestation may not be realized in the short term, whereas long-term changes in soil C may go undetected. Therefore, the protection of forests from conversion to other land uses is the single most important factor when considering the impacts of forest biomass harvesting on C cycling. The Forest Guild Biomass Working Group (2010) suggests that energy wood harvests may assist in preventing forests from undergoing land-use change by providing additional income to landowners and maintaining the forest industry and its markets. While the utilization of forest biomass for energy may have less of an impact on atmospheric C accumulation, the retention of all sizes of DWM may also be important for the maintenance of forest site productivity (Forest Guild Biomass Working Group 2010).

## Providing Clean and Abundant Water Supply

Potentially the most important impacts of intensified biomass harvesting may be those affecting water availability and particularly water quality. Forest hydrology research has been conducted for many years in the Appalachians (Hornbeck and Kochenderfer 2001), and from multiple studies at Coweeta Hydrologic Laboratory, the Fernow Experimental Forest, Hubbard Brook Experimental Forest, and Robinson Forest in eastern Kentucky, we have learned a great deal about the effects of forest harvesting on water yield. Generally, a minimum removal of about 25 percent of the basal area of a forest is necessary to detect a significant change in annual water yield. While clearcutting can result in increases in annual water yield, generally those changes are short-lived, and flows return to pre-cutting levels within a few years (Arthur et al. 1998, Hornbeck et al. 1993). Because biomass harvesting is likely to be manifested as an increased removal of biomass, annual flows may increase in the short-term in areas where more intensive biomass harvesting and utilization occur. Peak flows during the growing season may increase due to reduced transpiration after tree removal. However, some of these effects will be mitigated by keeping patch/stand size relatively small within a larger watershed, and through the use of BMPs designed to control water flow and protect the stream channels.

The quality of water coming off forested lands is generally very high and maintaining that quality is the focus of national and state regulation. The Clean Water Act of 1972 addresses the need for states to assess damages caused by nonpoint source pollution (Wang and Goff 2008). Indeed, the potential for forest harvesting to impact water quality is the primary driver for most state forest protection laws and BMP guidelines. Most regulations require, or guidelines advise, the implementation of riparian management areas (RMAs) or buffer strips for perennial streams (McClure et al. 2004, Phillips et al.

2000). It is generally acknowledged that water quality is adequately covered by state BMP guidelines (Aust and Blinn 2004, Forest Guild Biomass Working Group 2010), although a review of the potential impacts of biomass harvesting on water quality may be necessary if greater biomass is to be removed during or after traditional timber harvests or if the area of biomass plantations were predicted to increase substantially. Of the many factors that influence water quality, three stand out as paramount: erosion, sedimentation, and stream temperature. Existing state BMPs, regulations, or guidelines may need to be adjusted and revised to encompass these factors.

Erosion is the source of sediment. Increased rates of erosion can be caused by disturbance. Traditional harvesting removes varying degrees of forest canopy and can remove leaf litter and woody debris, which can expose mineral soil on extraction trails and also around tree stems when mechanized felling practices are employed. Biomass harvesting could result in increased erosion due to elevated removal intensity of woody debris. Barrett et al. (2009) documented such increase, demonstrating that average erosion rates across a biomass harvesting site ranged from 7.2 to 19.3 Mg ha<sup>-1</sup> yr<sup>-1</sup>, while rates from a similar traditional harvest ranged from less than 2.2 to 11.2 Mg ha<sup>-1</sup> yr<sup>-1</sup>.

Regardless of biomass removal intensity, the main source of erosion and sedimentation related to forest harvesting is the transportation network of forest roads and skid trails and the control of water leading toward and around the road and trail network (Kochenderfer 1970). Fox et al. (2007) found, over the long term, that treatments which retain some canopy did not reduce soil loss compared to clearcuts because most of the erosion originated from forest roads and skid trails. Erosion rates rapidly declined as vegetation growth increased following each harvest type, but over a 100-year rotation, clearcuts were projected to produce 70 percent less erosion compared to other less intensive treatments because fewer stand entries during a rotation resulted in less road use and disturbance.

The control of precipitation runoff is crucial in the Appalachian hardwood region where steep slopes are not only commonplace, but the norm. However, surface runoff and sheet erosion is rare within forests, except on the exposed soils of skid trails and temporary haul roads.

Increased erosion can increase nutrient removal from forest soils, as particles to which nutrients are absorbed are exported. Also, changes in nutrient cycling, particularly in leaching of nutrients from a site in streamwater, may result from forest harvesting. Bormann and Likens (1979), in an experiment at Hubbard Brook Experimental Forest, New Hampshire, reported that dissolved nutrient levels in streamwater from a clearcut watershed when regrowth of vegetation was prevented for 3 years by use of herbicides were 13 times higher than in an uncut watershed. However, when clearcut watersheds were allowed to naturally regenerate, the export of nutrients was only slightly increased because of rapid uptake by new vegetation, and the effects were temporary (Aubertin and Patric 1972, Galeone 1989, Kochenderfer and Aubertin 1975, Kochenderfer and Edwards 1991). Elevated nitrate in streamwater can be a health concern, but seldom do increases in streamwater N from forest harvesting alone reach such levels (Helvey et al. 1989).

Stream temperature can also be altered by biomass harvesting. Increases in stream temperatures have consequences for cold-water fish, such as trout. Optimum trout production occurs in streams which do not exceed 20 °C, even for short periods of time (Swift and Messer 1971). Swift and Messer (1971) studied the effects of riparian zone harvesting on stream temperatures in the Appalachian region. They found that complete removal of both overstory and understory vegetation increased maximum summer stream temperatures from 19 °C to 23 °C. Where riparian vegetation was left or had regrown along streambanks, summer maximum temperatures remained unchanged from controls of uncut mature hardwood forest. Other more recent research supports these findings: maintaining a greater basal area and

tree heights in riparian zones minimize changes in stream water temperatures following harvesting (Groom et al. 2011).

### **Supporting Wildlife and Biodiversity**

Biodiversity is a measure of the diversity of life in all its forms and at all levels of organization at a specified spatial and temporal scale (Miller et al. 2009), and this definition includes faunal populations as well as vegetation and other organisms such as bacteria. However, we restrict our discussion of biodiversity to plants and traditional terrestrial and aquatic wildlife. Biodiversity has become such a valued ecosystem service that some forest management certification programs such as the Sustainable Forestry Initiative and Forest Stewardship Council have created objectives and guidelines for conserving or increasing biodiversity. As harvesting for energy wood feedstock will likely remove more woody material than traditional harvesting or will do so at shortened time intervals, it follows that it is important to incorporate objectives for the conservation of biodiversity within guidelines for sustainable biomass utilization.

The simplest measure of biodiversity is species richness (S'), which is defined as the number of different species within a specific spatial area. Two indices, Shannon Index (H') and Pielou's Evenness Index (J') are also widely used metrics for biodiversity. Both of these indices relate the number of individual species within a forest system to the total number of all organisms within the same system. Generally, a higher index value represents greater diversity. While these metrics are useful, there is no consensus on what constitutes an appropriate methodology for assessing biodiversity (Guynn et al. 2004, Hagan and Whitman 2006, Lindenmayer et al. 2000, Miller et al. 2009). It is unclear whether metrics concerning biodiversity should be based on forest structure, stakeholder objectives, or ecological objectives. Currently, Miller et al. (2009) suggest that biodiversity should be measured quantitatively by methods that are affordable and simple to understand.

Biomass harvesting may have both positive and negative effects on biodiversity because species respond differently to forest biomass harvesting, and due to differences in how one defines biodiversity and what plant and animal communities are natural or preferred. Wildlife habitat, food sources and browse (e.g., mast production), travel corridors, and population size and density can all be affected by increased harvesting for woody biomass. For example, DWM provides important habitat features for many species of wildlife, and also provides cover for other organisms. Therefore, operations that result in less DWM may affect overall biodiversity of a site because habitat has been affected.

The characteristics of timber harvesting, downed woody material, and snag dynamics have been studied in regard to the abundance and diversity of birds (Jones et al. 2009), small mammals (Bowman et al. 2000, Carey and Johnson 1995, Ecke et al. 2002), large mammals (Brody and Stone 1987, Ford et al. 1997, Ford et al. 1994, Ford et al. 1993), herpetofauna (Butts and McComb 2000) and invertebrates (Gunnarsson et al. 2004). Snags and cull trees are especially important for sensitive and endangered species such as Indiana bats (*Myotis sodalis*) and northern long-eared bats (*Myotis septentrionalis*) (Carter and Feldhamer 2005, Menzel et al. 2002) and northern flying squirrels (*Glaucomys sabrinus*) (Menzel et al. 2004), which make use of tree cavities for nesting and roosting that DWM cannot provide alone. Although generally positively correlated with biodiversity, snags and DWM may not be critical habitat for many wildlife or vegetative species in terms of survival and abundance (Menzel et al. 1999). Further, snag development and enhancement for wildlife concerns must be weighed against safety risks for forest operators, particularly for manual harvesting systems to the region. Regardless, more specific information relating to wildlife and vegetative diversity is provided in the following sections.

## Wildlife

Amphibians are highly abundant and very diverse in the Appalachian region and maintaining that diversity is an important consideration. Research results on the effects of harvesting on salamander populations are equivocal. Petranka et al. (1993) studied the effects of timber harvesting on the abundance and diversity of Appalachian salamander populations. They found that abundance of salamanders within recent clearcuts was five times lower than that of adjacent mature forest and almost all salamander species were adversely affected by timber harvesting. They also suggest that 50 to 70 years would be required for populations to return to preharvest levels. Further research has shown that salamander populations decline initially post-harvest, although without significant differences in abundance between clearcutting and other harvest types (Fox et al. 2007, Knapp et al. 2003, Harpole and Haas 1999). Verschuyt et al. (2011) reported short-term decreases in salamander populations, especially within clearcuts, due to reduced leaf litter, canopy cover, and soil moisture; this same research suggested that thinning treatments can maintain species abundance over time. Ford et al. (2000) suggest no difference in woodland salamander abundance between partial harvest treatments and control stands in the southern Appalachians. Brooks (1999) reported that intermediate thinning to 50-60 percent of residual stand densities to promote upland oak growth had no significant effect on salamander abundance, which was positively correlated with increasing DWM and density of woody stems greater than 1 meter in height. DWM amounts for the study ranged from 6.4 to 8.85 pieces per 100 m<sup>2</sup> (0.854 to 1.406 m<sup>2</sup> per 100 m<sup>2</sup>).

Despite relatively low impacts to salamanders from partial harvesting in some Appalachian forest types, woodland salamander species richness and diversity in Appalachian cove hardwood forests are highest in stands older than 85 years (Ford et al. 2002a). Some salamander populations in isolated cove hardwood stands may be more vulnerable to extirpation or

require longer post-harvest recovery periods (i.e., >50 years) than those in larger coves, and in such cases stand management should incorporate uncut patches, riparian management areas, and DWM retention with harvesting operations (Ford et al. 2002a). Homyack et al. (2011) noted that eastern red-backed salamander (*Plethodon cinereus*) caloric requirements were 33 percent greater in recently harvested areas compared to uncut forest, but no treatment effect on energetic metrics were observed 8-14 years post-harvest. Moseley et al. (2009) found that capture proportion of salamanders in the central Appalachians was greater within 60 m of field edge compared to 60 to 100 m, suggesting that forest habitat adjacent to edge with sufficient DWM can provide suitable habitat. In the central Appalachians, woodland salamanders showed a neutral response to two prescribed fires over a 3-year period; however, post-fire conditions did not mimic repeated stand entry for timber harvesting (Ford et al. 2010). Moseley et al. (2008) sampled *Desmognathus* salamanders in West Virginia headwater streams and found that abundance was impacted negatively with increased timber volume removal, but abundance was positively associated with time since disturbance, with densities 30 percent higher in mature second-growth stands 90 years post-harvest. The authors also suggest that BMP buffer zones of 30.5 m for intermittent/perennial streams and 7.6 m for ephemeral streams are adequate for long-term persistence. Reptile populations can also decline in abundance with timber harvesting, but Verschuyt et al. (2011) reports that impacts vary due to harvest intensity and its effect on solar radiation and thermal cover, with clearcuts being generally detrimental and partial cuts providing a more moderate change in post-harvest conditions.

Bird populations have been found to increase in abundance and diversity following thinning, due to greater vegetation regeneration and development of shrub and understory layers, greater variation in horizontal and vertical forest structure, and a more rapid return to conditions simulating older seral stages

(DeGraff et al. 1991, Verschuyt et al. 2011). Greenberg and Lanham (2001) found that breeding birds in the southern Appalachians had higher densities and species richness in treefall gaps, indicating such gaps as bird activity “hotspots” during breeding season. Tirpak et al. (2006) studied the nest success of ruffed grouse (*Bonasa umbellus*) in Appalachian forests and found that odds of fledgling young improved with increases in stand density, DWM, and deciduous canopy cover, while increased ground cover and distance-to-road or gap lowered the odds. Roads showed no negative impacts on nest success, but to ensure adequate potential nesting sites, the authors suggest retaining at least 20 percent large DWM in residual stands with basal areas less than 25 m<sup>2</sup> ha<sup>-1</sup>.

Ford et al. (2006) found that northern long-eared bats preferred medium-to-large canopy dominant live trees (average d.b.h. = 53.4 cm, average height = 31.5 m), with exfoliating bark, broken limbs, and cavities. Snags used as roosts were smaller than live trees (average d.b.h. = 16.6 cm, average height = 10.3 m). Northern bats also showed a strong preference for black locust (*Robinia pseudoacacia*), both alive and dead. Similarly, northern bats have been found to exploit black locust trees in canopy gaps created by prescribed fires (Johnson et al. 2009). Owen et al. (2002) compared roost trees of northern long-eared bats with randomly selected trees with cavities and exfoliating bark and found that roost trees were taller, smaller in d.b.h., and surrounded by more overstory live trees and snags. These authors also suggest that roost availability is not a limiting factor in intensively managed Appalachian forests.

Verschuyt et al. (2011) reported a positive response to thinning for small mammal abundance, regardless of intensity. Brooks and Healy (1998) reported that intermediate thinnings are compatible with maintaining small mammal composition and relative abundance of dominant species. Kaminski et al. (2007) found that the distribution of terrestrial small mammals

was strongly influenced by leaf litter depth, with the majority of the species analyzed preferring shallow leaf litter (i.e., red-backed voles [*Myodes gapperi*], woodland jumping mice [*Napaeozapus insignis*], white-footed mice [*Peromyscus leucopus*], other deer mice [*Peromyscus* spp.], and eastern chipmunks [*Tamias striatus*]) and responding neutrally or favorably to harvesting activity in terms of abundance (i.e., red-backed vole) and weight (i.e., northern short-tailed shrews [*Blarina brevicauda*], white-footed and deer mice). Ford et al. (2000) reported no difference in the populations of 10 small mammal populations in response to either group selection and two-aged harvests in the southern Appalachians, with the exception of masked shrews (*Sorex cinereus*) whose relative abundance was greater in two-aged harvest treatments compared to group selection and control treatments. Ford et al. (2005) suggest that the complex topography and heterogeneity of forest types in the Appalachian region create a biodiversity “hotspot” for soricids in North America. In the central Appalachians, masked smokey (*Sorex fumeus*), and northern short-tailed shrews showed no difference in relative abundance in response to diameter limit and two-aged regeneration harvests (Ford and Rodrigue 2001). Shrew abundance has not been found to differ among stands representing mature (>60 years), sapling (6-15 years), regeneration (2-5 years), and recent clearcut (<2 years) stages of harvested forest stands (Ford et al. 2002b). Habitat assessment for the endangered Virginia northern flying squirrel (*Glaucomys sabrinus fuscus*) has suggested that occupancy may not be dependent on overstory tree species richness, DWM, tree and shrub density, or on the amount of herbaceous cover and soil OM (Ford et al. 2004). However, Menzel et al. (2004) suggest retaining snags and larger older trees for flying squirrel nesting, and promoting stand-level regeneration of certain species such as yellow birch (*Betula alleghaniensis*) and black birch (*Betula lenta*) and American beech (*Fagus grandifolia*).

Larger animals appear to be impacted similarly to small mammals by forest harvesting. For example, Brody and Stone (1987) concluded that some traditional harvest regimes, depending on the timing and intensity, may actually improve habitat and carrying capacity for black bears (*Ursus americanus*) in Appalachian forests. Other research suggests that clearcut stands provide concentrated and abundant browse favored by white-tailed deer (*Odocoileus virginianus*) in spring and summer months, while increasing the ease of foraging (Ford et al. 1993, Ford et al. 1994). However, there has been no clear indication that clearcutting benefits white-tailed deer in terms of overall weight and antler size (Ford et al. 1997), although nutritional carrying capacity has been reported to be greater following regeneration and thinning treatments compared to uncut stands, and greatest with the addition of prescribed fire (Lashley et al. 2011).

Aquatic biodiversity can also be affected by forest harvesting. Lemly and Hilderbrand (2000) examined the effects of increased amounts of DWM to streams on aquatic insect communities. They reported possible large-scale influences on insect communities, because DWM increases detritus retention and the total area occupied by pools, but noted relatively little effect on insect abundance within pools. In similar research, it was found that the addition of large DWM to streams in the Appalachian region had no overall effect on stream habitat or brook trout (*Salvelinus fontinalis*) populations 6 years post-treatment (Sweka and Hartman 2006, Sweka et al. 2010). The authors reported that, in high-gradient streams, habitat complexity may be governed more by the abundance of boulders, and that large CWD may not be limiting stream habitat for brook trout at study sites.

Leaf litter is a primary nutrient source for aquatic consumers in forested catchments (Solada et al. 1996), and can also affect the population dynamics

of microarthropods (Knoepp et al. 2005). Because intensive biomass harvesting can remove and redistribute the leaf litter layer, there are concerns about effects on aquatic communities. Arthropods have been reported to show a significantly positive response to thinning (Verschuyl et al. 2011). Hollifield and Dimmick (1995) found that abundance and biomass for arthropods (Hymenoptera, Coleoptera, Lepidoptera, Homoptera, and Diptera) was highest on logging roads planted with clover (*Trifolium* spp.) and orchard grass (*Dactylis glomerata*) and in mature hardwoods with herbaceous ground cover, compared to roads not planted with vegetation.

### **Vegetation**

Changes in harvesting regime or frequency can influence vegetative species composition as well as growth. Indeed, silviculture is designed to elicit certain changes in growth or species composition in response to management. In this discussion we limit our discussion to the vegetative response of hardwood forests to biomass harvesting.

Soil disturbance can influence vegetative species composition, growth, and yield. For example, Ponder (2008) concluded that soil disturbance did affect understory development in northern hardwood stands, but resulted in only minor differences in foliar nutrient content concentrations and overall plant species richness after OM removal and soil compaction treatments. Similar findings were reported by Powers et al. (2005). Ponder (2008) also noted that, although treatments did affect stocking levels in some plant groups, the successional trend of forest regeneration was not changed significantly as a result of compaction and/or OM removal.

The long-term soil productivity (LTSP) experiment (Adams et al. 2004, Powers et al. 2005) was designed to evaluate the effects of compaction and OM removal on soil physical properties (e.g., pore space), soil chemical properties (e.g., carbon and nutrient availability), and their influences on soil productivity.

Results from these relatively young, and ongoing, LTSP studies have indicated that complete removal of surface OM can lead to significant declines in soil C and can reduce N availability. However, the effect is thought to be due to the removal of the forest floor, not harvesting residue, and there is little change in the absolute mass of soil C during complete removal of surface OM (Powers et al. 2005). Soil compaction treatments increased bulk density, but the response of forest productivity was dependent on soil texture and the presence of understory vegetation (Powers et al. 2005). Growth rates generally decreased on clayey soils and increased on sandy soils. On sites without an established understory, growth rates were unaffected by severe soil compaction, but the presence of an understory led to decreased production due to increased root competition for soil moisture resources (Powers et al. 2005). In general, compaction can improve productivity in coarse textured soils in drier forests by improving water-holding capacity. However, since much of the Appalachian region is mesic and not usually water-limited, positive impacts from compaction on productivity are limited. Also, since many soils in the Appalachians are coarse and rocky, and most forest traffic is relegated to road systems, compaction may not be a major problem in the region's forests.

Generally, plant species diversity will increase in response to harvesting activity, although duration of response varies with the forest type and thinning intensity. Elliott and Hewitt (1997) evaluated preharvest species diversity in overstory, shrub, and herb layers of a dry, high-elevation Appalachian hardwood forest. The authors found that the overstory layer had relatively high  $H'$  values ranging from 1.62 to 2.50 based on tree density, and values of 0.94 to 2.22 based on basal area. Shrub and herb layer  $H'$  values based on density ranged from 0.64 to 2.33 and 1.72 to 3.02, respectively.  $J'$  was between 0.5 and 0.6 on most sites, and  $S'$  ranged from 51 to 73. Similarly, Adams et al. (2004) assessed preharvest species diversity in a highly productive second-

growth Appalachian hardwood forest and reported tree diversity values of 3.95, 0.95, and 26 for H', J', and S', respectively. Herb layer diversity values were 3.95, 0.91, and 76 for H', J', and S', respectively. Fox et al. (2007) reported that species richness of woody and herbaceous plants in an Appalachian forest was higher in plots that had experienced canopy disturbance within the past year, and that there was little to no loss of herbaceous plants species diversity in response to group selection, shelterwood, leave-tree, and commercial and silvicultural clearcut harvesting techniques. However, the authors found relatively large increases in exotic species richness on harvested sites, some introduced through skid trail revegetation. While the introduction of exotic species may increase the total number of species, exotic plants can also contribute to decreases in plant diversity, ultimately replacing native plant species. Composition and abundance of exotic species is likely to vary with thinning intensity (Verschuyl et al. 2011). Jenkins and Parker (1998) suggested that a mixture of selection harvests and larger clearcuts may be needed for the maintenance of woody species richness and diversity.

Increased energy wood production may have its largest effect on biodiversity under a monoculture or plantation management system (Jones et al. 2009), although any management activity within the forest ecosystem could potentially change the dynamic of biodiversity (Dale et al. 2010). Depending on the type of forest from which energy wood is being harvested (e.g., plantation or naturally regenerated) and the type of silvicultural prescription, increased biomass utilization could provide an opportunity for greater biodiversity of plants and animals. However, silvicultural decisions are many times dependent on ownership philosophy, and decisions related to the loss of natural forest, reduction in snags and DWM, stand structure, and tree characteristics, and economic pressure can result in a subsequent loss of biodiversity within and around associated forest stands (Miller et al. 2009).

## Sustaining Regional Wood Supply

Galik et al. (2009) concluded that biomass supply in Virginia, North Carolina, and South Carolina is a function of current harvest levels, current roundwood prices, and the price elasticity of roundwood supply. However, these will vary and are dependent on factors such as harvesting system and method, site characteristics, stand structure, and species composition (Benjamin et al. 2010). Galik et al. (2009) hypothesized that forest residues would not be sufficient to meet hypothetical national renewable portfolio standards within the region over the long term and that diversion of traditional roundwood resources would be needed to meet renewable demand. This trend would most likely displace those traditional end-users who were marginally profitable prior to the increased in demand for woody biomass. Further, Galik et al. (2009) suggested that to understand the impact of increased demand for wood biomass, further research should focus on: (1) accurate determination of the available resource base; (2) the price and supply implications of rising roundwood demands on traditional markets; and (3) exogenous factors affecting the forest land base (e.g., land use change, carbon offset markets, alternative fuels policy).

A survey conducted by Enrich et al. (2010) found that 60 percent of wood dealers, harvesting contractors, and procurement foresters, as well as 80 percent of forest managers, reported producing or selling energy wood. The breakdown of delivered forest biomass by type was: 38 percent dirty chips, 20 percent unscreened grindings, 18 percent roundwood, and 8 percent clean chips, which suggests that at least some feedstock from traditional markets is already being utilized as energy wood. Fifty-nine percent of respondents made use of conventional harvesting systems (i.e., feller-buncher and rubber-tired skidder), and chipping was handled equally among drum and disk chippers, as well as horizontal grinders. Minimum energy wood harvest yields needed to economically justify operations were reported to be between 29 to

45 Mg ha<sup>-1</sup>. The majority of transportation distances were less than 50 miles, with only 8 percent of respondents transporting biomass greater than 70 miles. Survey participants were split regarding energy wood markets, with 40 percent responding that markets were growing and 38 percent responding that markets were inconsistent, which possibly suggests that much of the market growth is localized.

Increases in forest biomass harvesting will affect overall regional wood supply and those users that rely on forest resources for raw material. A main concern is the competition between the end-users and consumers of roundwood, as it can be used for wood product and paper production, as well as for energy wood feedstock (Benjamin et al. 2010, Galik et al. 2009). If an increase in biomass utilization rate leads to the conversion of small roundwood to energy wood, traditional small roundwood product markets (e.g., pulp, paper, oriented strand board) could face new competition from energy wood feedstock producers. In the end, this increased demand on the forest resource can affect the cost of wood-based products and wood-based energy to the consumer. This would likely be the case when there is a relatively large gap between the cost of fossil-based fuels and energy wood feedstock. Much of the remainder of this section focuses on the challenges of forest biomass harvesting and transportation and a review of innovative techniques and technology used to meet these challenges in an economically feasible fashion.

Biomass harvesting can adversely affect the condition of the residual trees in the stand. Generally, residual stand damage is expected to increase with production intensity (Halbrook and Han 2005, Smith and Miller 1987). This is due to both the size of the extraction equipment needed and operator care and awareness relative to production intensity (Lanford et al. 1991). McIver et al. (2003) showed that woody biomass and stem density reduction treatments of forested stands resulted in a significant visual impact, with about 50 to 75 percent of the residual trees in their study sustaining some level of damage. Similarly, Fajvan et

al. (2002) reported that diameter limit and shelterwood treatments in hardwood stands resulted in significant damage to approximately 50 to 70 percent of residual trees. Although not purposely, the harvesting impacts to the residual standing trees could increase the availability of lower quality wood.

Camp (2002) analyzed four different harvesting systems working in small-diameter forests: (1) cut-to-length (CTL) felling and processing with downhill yarding; (2) feller-buncher and downhill yarding; (3) mechanical felling and uphill yarding; and (4) CTL and downhill forwarding. The results showed that the CTL felling and downhill yarding system yielded the least amount of residual stand damage. The mechanical felling and uphill yarding system and CTL/downhill forwarding system caused more damage to residual trees, and the feller-buncher and downhill yarding system resulted in most residual damage. The study also stressed the importance of silvicultural prescriptions, harvesting technologies, and harvest season in reducing residual stand damage in small-diameter forests.

There are many options for harvesting forest biomass, but challenges remain in establishing efficient harvest systems and processes, transportation and transportation networks, and optimal locations of biomass energy conversion facilities (Moller 2003) to determine the economic feasibility of energy wood harvesting. As with any harvesting system, energy wood harvesting has many associated costs. The economic feasibility of operations is highly dependent on transportation distance, the availability of markets, and the current market prices of harvested material. These factors must be considered as key parts of the cost component toward generating positive net revenue, as small fluctuations in any of these factors could lead to negative revenue streams. Biomass harvesting costs include three factors: felling costs, extraction costs, and the cost of comminution (Mitchell 2005); costs depend on available equipment, piece size, distance to landings, and removal volumes per acre (Kellogg et al. 2006). Comminution is the

process of converting forest materials into consumable products (Pottie and Guimier 1985), and within this synthesis is used as an inclusive phrase for chipping, hogging, tub-grinding, and shredding (Kellogg et al. 2006).

As energy wood harvesting operations become more prevalent in forest management, more economically efficient means for harvesting smaller diameter stems should be developed. Those with a stake in biomass harvesting operations should explore innovative methods by combining technologies and approaching biomass extraction techniques with a more creative outlook than commonly required in traditional forest harvesting. The challenge is to match optimal harvest systems and processes with specific forest conditions to develop biomass harvesting methods that are feasible in terms of both economics and desired silvicultural regimes.

Energy wood production will many times require the harvesting of small roundwood and the costs of harvesting small roundwood with conventional equipment have been shown to increase as tree diameter decreases (Bolding and Lanford 2005, Brown and Kellogg 1996, Kluender et al. 1998, Rummer and Klepac 2002). The harvesting practices associated with the small wood constraints of biomass harvesting are varied and are many times determined based on stand and site characteristics or silvicultural objectives (Hartsough et al. 1995). Furthermore, harvesting forest biomass specifically as feedstock for energy production is a commercial venture and necessitates the generation of positive net revenues. Where energy wood harvesting is conducted concurrently with commercial harvest removals, revenue generated from saw logs has been used to cover expenses of extracting and hauling biomass, resulting in sharing of harvesting costs (Richardson et al. 2002). Therefore, the fusion of traditional forest roundwood removal and energy wood production could be an important step in both protecting forest health and providing an alternative domestic energy source. Until recently, the utilization of forest biomass has rarely been viewed

as an economic opportunity, but under the right circumstances can yield a profit. The following studies provide examples of profitable and non-profitable biomass utilization operations, and provide insight on potential methods to successfully cover the costs of felling, extraction, and comminution.

Li et al. (2006) studied energy wood harvesting economics in Appalachia, and determined that the most productive and cost effective harvesting system was a ground-based feller-buncher/grapple skidder system. The authors also found that small-wood harvesting was about 15 percent less productive and 13 to 29 percent more expensive compared to harvesting mature stands. Fiedler et al. (1999) and McIver et al. (2003) studied both cable yarding and ground-based harvesting systems for forest restoration and fuel reduction in the western United States. Fiedler et al. (1999) reported that in mature stands, favoring larger trees, the ground-based system outperformed the cable yarding system, although both showed positive net revenues. When thinning from below, only the ground-based system resulted in positive net revenue. The McIver et al. (2003) study utilized a single-grip harvester for felling and processing, and logs were extracted for comminution and transportation in chip vans. The authors showed that ground-based harvesting performed better than the yarding system in this study and also realized a net profit. Keegan et al. (2004) also reported promising results in terms of net revenues for fuel reduction activities in Montana. Note that all of these studies made use of mechanized harvesting systems. However, Larson and Mirth (2004) presented a case study on the economics of manually thinning in Arizona. Only logs were merchandized, with limbs and tops being piled for burning, and the system failed to produce positive net revenue.

Research on whole-tree harvesting was conducted by Han et al. (2004), who constructed a case study model of a mechanical harvesting system consisting of a feller-buncher, grapple skidder, processor and loader, and a chain-flail delimiting/debarking chipper. Four product cases were studied: (1) saw log only, (2) saw

log and clean chip, (3) saw log and biomass fuel, and (4) saw log, biomass fuel, and clean chip. Positive net returns were gained through the saw log only option, but all other option showed negative net returns.

Unlike the Appalachian hardwood region to date, in other countries, utilizing forest biomass as a source of energy is a viable business opportunity. The most common system for harvesting forest fuels in Denmark is composed of: (1) the felling and bunching of whole trees; (2) summer drying; (3) on-site comminution with all-terrain chip harvester; (4) extraction of a chipper bin with a forwarder to the landing; (5) transportation to an energy or storage facility; and (6) combustion for energy generation (Talbot and Suadicani 2005). The limiting factor for this type of system has been found to be comminution, based on poor productivity (Suadicani 2003, Talbot and Suadicani 2005).

In Sweden, the productivity of the popular energy wood harvesting system, comprised of manual felling, bunching, and in-woods comminution, has been greatly increased with mechanization (Bjorhedan et al. 2003). Also, innovative machines have provided for better control over fuel consumption and operations have improved through the increased use of information technologies (Berg 2003). Another innovation has allowed for forest biomass to be compressed into composite residue logs (CRL) that can be handled as roundwood for transportation purposes (Berg 2003). It should be noted, however, that innovation in energy wood harvesting may be burgeoning in European and Scandinavian countries due to greater incentives in government subsidies and wood fuel prices in those countries compared to the United States.

Many different harvesting methods can be used for biomass production, and harvest layout options are generally dependent on the terrain and type of system being utilized. Bjorhedan et al. (2003) notes

two effective layouts for energy wood harvesting: the herringbone method and the strip road/secondary passage method. The herringbone method employs strip roads and inserts in a herringbone pattern. The strip roads are harvested by machine, and are later utilized to harvest the inserts. In the second method, strip roads are harvested and then the stands between strips are harvested from the new roads. In Sweden, where these two methods are prominent, the two most promising harvesting systems have been a chipper and forwarder system, and a feller/bundler system (Bjorhedan et al. 2003). The size of the operation is also important to consider in choosing the harvesting system. Van Belle et al. (2003) found that the best harvesting system for large-scale operations was a crane-fed drum chipper mounted on a forwarder, whereas smaller-scale operations may make better use of the same chipper mounted on a tractor, to save equipment investment costs.

Based on the review of current literature on biomass harvesting for energy wood supply, it can be suggested that to create a profit from small-diameter harvesting, it is beneficial to: (1) identify the stand in most need of treatment; (2) refrain from using recovered timber volumes as a driver for restoration treatments; and (3) identify trees usable as products to generate revenue that may aid in supporting the restoration treatment. Four major factors affecting the economic feasibility were discussed: (1) forest harvesting systems must be selected carefully to suit conditions; (2) road accessibility may limit chip vans; (3) hauling distance to manufacturing facilities must be kept as low as possible with a low-value product; and (4) an increase in market prices of thinning materials will make small-diameter harvesting more feasible. Finally, Keegan et al. (2004) noted that the positive impacts of biomass harvesting include the generation of forest product industry jobs and labor income, and that energy wood harvesting for fuels reduction purposes can generate income, but is dependent on market prices.

## EXISTING BEST MANAGEMENT PRACTICES

All states in the United States have developed BMPs to minimize the potential adverse effects of forest management or timber harvesting (Wang and Goff 2008). Some states, including several from Appalachia (Maryland, North Carolina, and Pennsylvania), as well as Canadian provinces, have created BMPs, sustainability guidelines, or initiatives for ensuring the sustainability of increased biomass utilization (Table 1). Currently, the biomass harvesting guidelines for Maryland seem to be the most applicable to the Appalachian forest region as a whole. However, the Maryland guidelines do not consider the impacts of an intensification of biomass harvesting on wood supply or traditional markets that may also use woody

biomass as raw material, which may become more important as biomass harvesting develops.

Evans and Perschel (2009) developed a summary crosswalk table to compare and contrast components of some existing state biomass harvesting guidelines with those from the Forest Stewardship Council. The forest management guidelines (see next section, “Guidelines for sustainable woody biomass management in the Appalachians”) were derived from components of the latest versions of existing state biomass harvesting and utilization standards and guidelines, as well as from the comprehensive review of biomass harvesting and utilization literature and synthesis of information presented in this report. Certainly, there are tradeoffs and many times it may be necessary to balance competing goals.

**Table 1.—Existing biomass utilization and harvesting guidelines**

State, Province, Organization	URL
Maine	<a href="http://www.maine.gov/doc/mfs/pubs/biomass_retention/report/biomass_report_lr.pdf">http://www.maine.gov/doc/mfs/pubs/biomass_retention/report/biomass_report_lr.pdf</a>
Maryland	<a href="http://www.alleghenysaf.org/docs/MD/MD_Biomass_Harv_Guidelines_Final.pdf">http://www.alleghenysaf.org/docs/MD/MD_Biomass_Harv_Guidelines_Final.pdf</a>
Massachusetts	<a href="http://www.manomet.org/sites/manomet.org/files/Manomet_Biomass_Report_Full_LoRez.pdf">http://www.manomet.org/sites/manomet.org/files/Manomet_Biomass_Report_Full_LoRez.pdf</a>
Minnesota	<a href="http://www.frc.state.mn.us/documents/council/site-level/MFRC_forest_BHG_2001-12-01.pdf">http://www.frc.state.mn.us/documents/council/site-level/MFRC_forest_BHG_2001-12-01.pdf</a>
Missouri	<a href="http://mdc4.mdc.mo.gov/Documents/19813.pdf">http://mdc4.mdc.mo.gov/Documents/19813.pdf</a>
North Carolina	<a href="http://www.ces.ncsu.edu/forestry/biomass/pubs/WB005.pdf">http://www.ces.ncsu.edu/forestry/biomass/pubs/WB005.pdf</a>
Pennsylvania	<a href="http://www.dcnr.state.pa.us/PA_Biomass_guidance_final.pdf">http://www.dcnr.state.pa.us/PA_Biomass_guidance_final.pdf</a>
Vermont	<a href="http://www.leg.state.vt.us/workgroups/biomass/BioE_draft_interim_2011_report_for_public_review.pdf">http://www.leg.state.vt.us/workgroups/biomass/BioE_draft_interim_2011_report_for_public_review.pdf</a>
Wisconsin	<a href="http://council.wisconsinforestry.org/biomass/pdf/BHG-FieldManual-lowres090807.pdf">http://council.wisconsinforestry.org/biomass/pdf/BHG-FieldManual-lowres090807.pdf</a>
New Brunswick	<a href="http://www2.gnb.ca/content/dam/gnb/Departments/nr-rn/pdf/en/Publications/FMB0192008.pdf">http://www2.gnb.ca/content/dam/gnb/Departments/nr-rn/pdf/en/Publications/FMB0192008.pdf</a>
Nova Scotia	<a href="http://www.ecologyaction.ca/files/images/file/Wilderness/EACpercent20Forestpercent20Biofuelpercent20Reportpercent20Decpercent2008.pdf">http://www.ecologyaction.ca/files/images/file/Wilderness/EACpercent20Forestpercent20Biofuelpercent20Reportpercent20Decpercent2008.pdf</a>
Council on Sustainable Biomass Production	<a href="http://www.csbp.org/files/survey/CSBP_Provisional_Standard.pdf">http://www.csbp.org/files/survey/CSBP_Provisional_Standard.pdf</a>
Forest Stewardship Council	<a href="http://www.fscus.org/standards_criteria/">http://www.fscus.org/standards_criteria/</a>

## **GUIDELINES FOR SUSTAINABLE WOODY BIOMASS MANAGEMENT IN THE APPALACHIANS**

### **Maintaining Site Productivity**

- Use caution to avoid unnecessary disturbance to the leaf litter and organic matter layers. Dedicated skid trails minimize the area of the forest floor subject to extraction traffic and limit compaction and the exposure of mineral soil.
- Keep preharvest DWM in-forest to ensure the presence of DWM in all stages of decay.
- Leave a percentage of tree tops in-forest for additional contributions to the DWM pool.
- Consider harvesting during leaf-off conditions to allow those nutrients to stay in-forest (applicable where winter weather creates frozen soil conditions or deep snowpack).

### **Providing Clean and Abundant Water Supply**

- Follow existing/established BMPs for traditional harvesting operations.
- Consider a single intense harvest rather than multiple entries at lower intensities.
- Evaluate riparian management area specifications for adequate width and canopy retention levels.

### **Supporting Wildlife & Biodiversity**

- Follow all current regulations concerning threatened and endangered species of flora and fauna.
- Avoid introducing nonnative vegetation of any species. Seed skid trails with grasses native to the region and forest type.
- Leave existing snags and DWM.
- Consider creating additional snags with appropriate attention to safety concerns of forest workers or leaving a proportion of cull trees for cavity nesting species.

### **Sustaining Regional Wood Supply**

- Assess the productivity of the site preharvest in order to plan an operation that keeps the site at or above the level of preharvest productivity.
- Assess the impact of harvesting the site primarily for biomass on local traditional wood markets.
- Develop a long-term (e.g., 100-year) management plan for the site that involves all stakeholders.
- Ensure that the site can sufficiently regenerate naturally or replant with native vegetation if necessary.
- Employ low-impact harvesting techniques and use well trained operators to avoid damage to the residual stand.
- Assess the economics of the proposed operation and alternative utilization opportunities and scenarios.
- Develop a harvesting plan that maximizes the efficiency of the equipment based on the site characteristics and existing infrastructure.

## CONCLUSIONS

Forest biomass and energy wood harvesting are a method of utilizing forest resources as a source of biomass for alternative energy production and many countries are successfully implementing forest biomass harvesting at a commercial scale. The long-term sustainability of forest biomass utilization is subject to the environmental impacts to ecosystem services, as well as the competition among the markets that rely on the forest resource. Based on this review, intensification in the removal of forest biomass from Appalachian forests can be balanced with the maintenance of these other services the forest provides. In general, adopting state Best Management Practices for forest harvesting and retaining appropriate amounts of down woody material, organic matter, live wildlife trees, and snags will adequately address the maintenance of ecosystem services. Adopting technology from our international partners, as well as constructing new bioenergy production facilities, and/or adapting existing facilities for converting biomass to energy could foster a successful energy wood program in the United States. The development of new markets that utilize the small roundwood and woody forest biomass being harvested as a source of energy wood feedstock would create demand and the resulting economic activity that is needed in the Appalachian region. An additional market for small roundwood could potentially create a niche for precommercial and commercial thinning operations in forests that are in need of improvement. The new market could create thousands of jobs (Keegan et al. 2004), revitalize local communities, and turn the timber industry into the largest producer of renewable energy wood. This, in turn, could make the timber industry a supplier of a source of alternative energy that can help reduce U.S. dependence on foreign fossil fuels and assist in the mitigation of climate change.

## ACKNOWLEDGMENTS

The authors would like to thank those who assisted in the completion of this manuscript. Early discussions with Curt Hassler, Shawn Grushecky, and Jan Wiedenbeck were helpful in developing this project. Funding for the Agenda 2020 Technology Alliance project was provided by the National Council for Air and Stream Improvement (NCASI), the U.S. Forest Service, and additional resources were provided by the West Virginia University Appalachian Hardwood Center (AHC). Michael Aust, Curt Hassler, and Jeff Stringer graciously provided reviews of an earlier draft of the manuscript, and their comments greatly improved the overall project. Sheldon Owen also provided valuable insight on wildlife and biodiversity literature pertinent to the Appalachian forest region.

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## GLOSSARY

**Biodiversity:** A measure of the diversity of life in all its forms and at all levels of organization at a specified spatial and temporal scale

**Bioenergy:** Renewable energy made from materials derived from biological sources or biomass

**Biofuel:** Liquid fuel derived from biomass

**Biomass:** Any organic material which has stored sunlight in the form of chemical energy, including wood, wood waste, straw, manure, sugarcane, and many other byproducts from a variety of agricultural sources

**Cogeneration:** The simultaneous generation of both electricity and useful heat

**Comminution:** The process of converting forest materials into consumable products by chipping, hogging, tub-grinding, and shredding

**Downed woody material:** Both coarse and fine woody material within a forest derived from fallen dead trees, branches, bark, and snags

**Ecosystem services:** Sustainable benefits derived from forested ecosystems, including site productivity, reliable and clean water supply, wildlife habitat, biodiversity, and wood and wood fiber supply

**Energy wood:** Feedstock for bioenergy and bioproduct industries derived from forest harvesting and processing residues, along with previously nonmerchantable stems due to poor form, species, or size

**Energy wood harvest:** Extraction of forest biomass for the purpose of energy production

**Feedstock:** Raw material to supply or fuel energy production

**Forest biomass:** Forest harvesting and processing residues, along with previously nonmerchantable stems due to poor form, species, or size

**Forest biomass harvesting:** The collection and removal of woody biomass from forested sites; this may occur as part of a traditional roundwood harvest or as a separate operation following a traditional harvest

**Forest biomass utilization:** The harvest, sale, offer, trade, and/or utilization of woody biomass to produce the full range of wood products, including timber, engineered lumber, paper and pulp, furniture and value-added commodities, and bio-energy and/or bio-based products such as plastics, ethanol and diesel

**Renewable energy:** Energy derived from natural resources such as biomass, sunlight, wind, rain, tides, and geothermal, which are naturally replenished

**Roundwood:** All industrial wood in the rough (saw logs and veneer logs, pulpwood and other industrial roundwood) and, in the case of trade, chips and particles and wood residues

**Snag:** A dead standing tree

**Wood fuel:** Any woody material can be used in the bioenergy or bioproduct industries

**UNITS**

Centimeter (cm)	Unit equivalent to 0.01 meters (.394 inches)
Hectare (Ha)	Unit equivalent to 10,000 square meters (2.47 acres)
Kilogram (kg)	Unit equivalent to 1000 grams (2.2046 pounds)
Megagram (Mg)	Unit equivalent to 1 metric ton (1.1023 short tons)
Meter (m)	Unit equivalent to 100 centimeters (3.2808 feet)

**ABBREVIATIONS**

BMP	Best Management Practice
C	Carbon
Ca	Calcium
CRL	Composite residue log
DWM	Downed woody material
FSC	Forest Stewardship Council
GHG	Greenhouse gas
H'	Shannon Diversity Index
J'	Pielou's Evenness Index
K	Potassium
LTSP	Long-term soil productivity
Mg	Magnesium
N	Nitrogen
NO <sub>3</sub>	Nitrate
OM	Organic matter
P	Phosphorus
RMA	Riparian management area
S	Sulfur
S'	Species richness
SFI	Sustainable Forestry Initiative
USDA	United States Department of Agriculture

Vanderberg, Michael R.; Adams, Mary Beth; Wiseman, Mark S. 2012. **Evaluating Forest Biomass Utilization in the Appalachians: A Review of Potential Impacts and Guidelines for Management**. Gen. Tech. Rep. NRS-106. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 39 p.

Forests are important economic and ecological resources for both the Appalachian hardwood forest region and the country. Increased demand for woody biomass can be met, at least in part, by improved utilization of these resources. However, concerns exist about the impacts of increased intensity of woody biomass removal on the sustainability of forest ecosystems. Relatively little research has evaluated the impacts of forest biomass harvesting on site productivity, biodiversity, water quality, or other measures of ecosystem productivity, and new information about these and other related topics is not readily available. This report discusses the implications for the sustainability of Appalachian hardwood forests if additional woody biomass is removed for the production of woody biomass-related energy. It includes a summary and synthesis of published literature and ongoing studies to evaluate the possible effects of increased biomass removal on several primary aspects of forest sustainability (i.e., site productivity, water quality, wildlife and biodiversity, wood supply). General management guidelines are proposed that can minimize the impacts of woody biomass utilization on the sustainability of Appalachian hardwood forests. Accompanying the report is an online bibliography, containing references for scientific literature related to woody biomass harvesting and utilization beyond the scope of the Appalachian forest region.

KEY WORDS: woody biomass, bioenergy, biomass harvesting, sustainability, biodiversity

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