Promoting Ecological Sustainability in Woody Biomass Harvesting

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ABSTRACT

Enthusiasm for the use of forest biomass as an energy resource is growing as a result of increased energy costs and a desire to reduce the greenhouse gas emissions responsible for climate change. Although the opportunity exists for forests to have a significant role in the development and use of bioenergy technologies, justifiable concerns regarding the long-term sustainability of using forest-based energy feedstocks have emerged. In this article, we review the state of our knowledge regarding the impacts of intensive forestry with respect to issues relevant to bioenergy production, including soil and site productivity, hydrologic quality, and biodiversity. We then present guiding principles intended to aid with sustainable forest management decisions.

Keywords: bioenergy, biomass harvesting, forest productivity, forest residues, sustainable forest management

Recent concerns regarding climate change and rising energy costs have dramatically increased interest in the use of renewable and alternative energies. Biomass—material derived from plants and animals—has long been used as an energy source but is undergoing widespread reevaluation as a viable resource for the large-scale production of bioenergy. The creation of electricity, heat, and transportation fuel from biomass has great potential to yield environmental and social benefits, including reduced greenhouse gas emissions (Volk et al. 2004, Malmsheimer et al. 2008), a greater supply of energy from domestic sources (Perlack et al. 2005), and strengthened rural and local economies (Domac et al. 2005). The opportunity exists for forests to have a significant role in the development and use of bioenergy technologies. In the context of climate change and greenhouse gas mitigation, wood-based bioenergy often compares favorably with fossil fuels and several renewable energies because of a relatively low amount of fossil fuel inputs and a smaller "carbon footprint" (Hill et al. 2006, Malmsheimer et al. 2008). In a broader context, this energy can effectively complement efforts to reduce overall energy consumption and diversify energy resource portfolios.

Although energy consumption from wood sources in the United States is currently greater than it was during much of the 20th century (Figure 1), the overall contribution of wood to the nation's energy portfolio is small. In 2006, wood and wood-derived fuels supplied 2% (2.2 quadrillion British thermal unit [Btu]) of total energy and 32% of renewable energy consumed in the United States (Energy Information Administration 2007). However, wood sources are expected to contribute a greater portion of energy in the future. For example, national efforts to increase alternative energy use, such as the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007, aim to boost woody biomass use for energy, particularly in regard to cellulosic ethanol production. Recently, the US Departments of Energy and Agriculture determined that US forestlands have the potential to sustainably produce enough biomass in 2030 to supply energy and products equivalent to 10% of the nation's current level of petroleum consumption (Figure 2; Perlack et al. 2005). This analysis suggests that much of the feedstock would come from the improved use of woody materials remaining in the forest after harvest (e.g., tops, woody debris, stumps, and other logging residues), nonmerchantable biomass (e.g., small trees and noncommercial species), and waste from the creation or disposal of wood products (e.g., mill residues and municipal wood waste). Additional material may also come from short-rotation woody crops of trees grown specifically for bioenergy.

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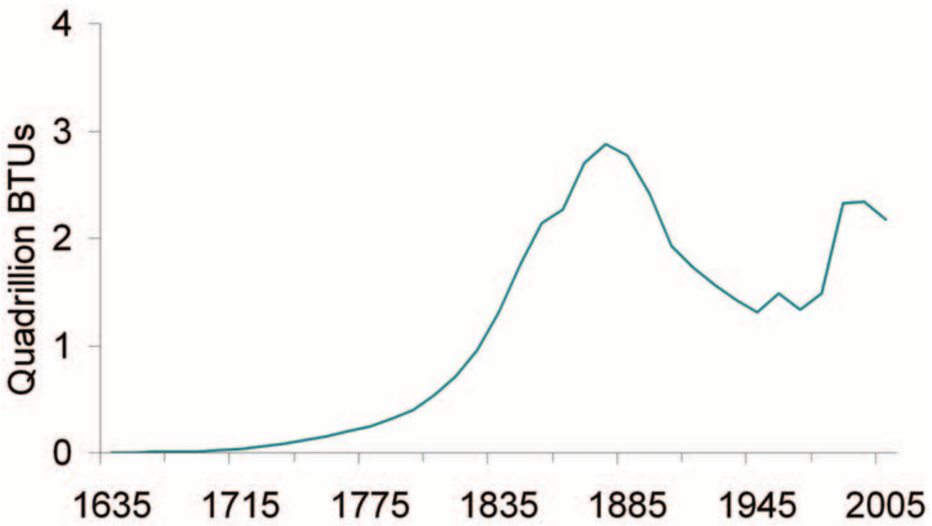

Figure 1. Historical use of wood and wood products for energy in the United States, in quadrillion British thermal units (Btu) per year. Data through 1945 represent fuelwood only and data after 1945 include energy from wood and wood-derived fuels. (Data source: Energy Information Administration 2007.)

Because of the wide variety of biomass sources, increased bioenergy use and greater demand for woody feedstocks may directly affect forest management practices in at least three ways: (1) increased demand for small diameter, poor quality, or otherwise previously noncommercial biomass leading to implementation of management activities in stands that have been unmanaged, inappropriately managed, or underused in the past because of low market prices; (2) intensification of harvesting in managed forests through increased residue removal (from materials such as tops, dead wood, or brush) and/or decreased time between harvests and rotations; and (3) expansion of short-rotation energy crops in which their management will more closely parallel agricultural crops than contemporary forest products (Figure 3).

Ensuring the long-term integrity of forestlands and natural ecosystems is essential to maintaining ecosystem function and services as well as providing for current and future use of forest products. Sustainable forest management, defined as "the practice of meeting the forest resource needs and values of the present without compromising the similar capability of future generations" (Helms 1998), is a vital component of socially acceptable and environmentally responsible forest management. Consequently, although woody biomass is rapidly moving to the forefront as a renewable source of energy, it is crucial that forest managers look past the "boosterism" and consider the safeguards needed to ensure that this feedstock is sustainably managed rather than exploited. Here, we review the state of our knowledge regarding the impacts of intensive forestry with an emphasis on issues relevant to bioenergy production. Because the forests from which biomass is harvested for energy are likely to represent a continuum of management intensities and production systems, our review includes, but is not limited to, literature on whole-tree harvesting, increased residue removal, and woody crop production. Based on this review, we then present guiding principles for sustainable production of woody biomass intended to aid with decisions related to soils, site productivity, hydrology, and biodiversity.

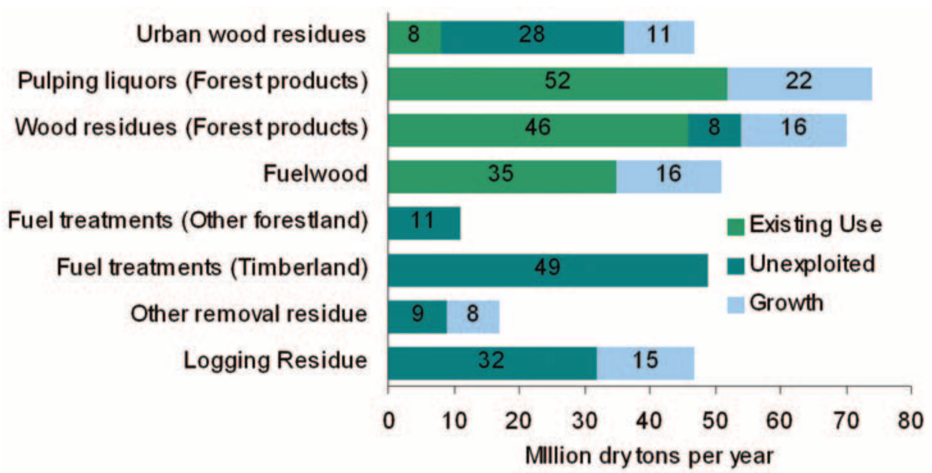

Figure 2. Estimate of potentially available biomass resources from US forestlands by source in 2030. (Redrawn from Perlack et al. 2005.)

Potential Effects of Forest Biomass Harvests

Soils and Site Productivity

Forest or stand productivity can be estimated by the amount of biomass produced per unit of land as a function of time (Powers et al. 1990, Burger 2002). Many factors contribute to forest productivity, including site conditions, soil characteristics, vegetative cover, and management history (Fisher and Binkley 2000, Grigal 2000). Soils are uniquely important, because soils are positively or negatively impacted by management, and soils perform functions necessary for tree growth and site productivity, including serving as the substrate for plant growth, absorbing rainfall and providing water to trees, house microorganisms essential to decomposition and nutrient cycling, and retaining and supplying nutrients to tree roots (Burger 2002).

Research regarding the sustainability of forest productivity emphasizes the importance of preserving soil quality by maintaining organic matter and soil nutrients (Vance 2000, Burger 2002). Soil organic matter is essential for tree growth, because it provides food for soil organisms, maintains the ability of soil to hold adequate amounts of water and air, supplies nutrients necessary for growth, and moderates soil temperatures (Fisher and Binkley 2000). In agricultural systems, long-term experiments and observations show a direct association between organic matter and crop productivity (Vance 2000). Levels of soil organic matter are largely tied to the quantity of materials available as inputs to the soil, as well as management activities that disturb the forest floor. Consequently, the degree of organic matter loss from disturbance is highly variable because of site and management factors (Vance 2000). A review (Johnson 1992) and meta-analysis (Johnson and Curtis 2001) determined that, although studies varied widely in terms of both site conditions and research methodologies, no overall alteration of soil carbon was evident as a result of forest harvesting except when there was intense burning, mechanical disturbance, or soil tillage. Whole-tree harvesting resulted in slight decreases of soil carbon in the A horizon, while the effects of stem-only harvesting varied by species composition (Johnson and Curtis 2001). More intensive actions, such as substantially shortening rotations, removing coarse woody debris, and/or harvesting of submerchantable trees and brush, would be more likely to reduce soil carbon and organic matter. Increased carbon accumulation was observed after reforestation of formerly agricultural lands as well as through nitrogen fertilization or fixation, which affects organic matter content by increasing primary production and generating greater inputs to the soil from leaf fall and root turnover (Johnson 1992, Johnson and Curtis 2001).

Figure 3. Short-rotation woody crops, such as this willow stand, have potential to serve as feedstock for bioenergy while maintaining or enhancing ecosystem services on former agricultural or degraded lands. (Photograph courtesy of USDE National Renewable Energy Laboratory.)

Soil nutrients, such as nitrogen, phosphorus, calcium, magnesium, and potassium, are also essential for plant growth and development. For this reason, greater removals of wood biomass for bioenergy or other uses frequently raises concerns about whether adequate levels of nutrients can be maintained to protect site productivity. In general, many tree components that comprise a small amount of biomass, such as leaves, cambium, and root tips, contain disproportionately large quantities of nutrients when compared with tree wood (Hakkila 2002, Powers et al. 2005). Models of forest nutrient budgets suggest that intensive, whole-tree harvesting has the potential to remove enough nutrients to cause long-term productivity declines (e.g., Boyle et al. 1973, Paré et al. 2002), although actual evidence is rare and frequently confounded by other factors, such as site or management differences (Powers et al. 1990, Morris and Miller 1994). Reviews of research investigating stem-only and whole-tree harvesting systems have found few long-term impacts on soil nutrients or future biomass production under more intensive management (Morris and Miller 1994, Fox 2000, Hakkila 2002). Johnson and Curtis (2001) found that mineral soil nitrogen levels increased after sawlog harvest and decreased only slightly as a result of whole-tree harvest. Examination of nutrient budgets in the eastern United States have suggested that calcium is the most likely nutrient to become depleted in the long term (Boyle et al. 1973, Mann et al. 1988, Federer et al. 1989). Evidence of whole-tree harvest resulting in nutrient deficiency and subsequent decline in growth has been suggested by some studies (Sverdrup and Rosen 1998, Joki-Heiskala et al. 2003), although the current evidence is limited by both a lack of long-term studies and an uncertainty associated with the impact of harvesting relative to nitrogen deposition (Grigal 2000). Continued monitoring and research is required given possible individual and combined effects from harvesting practices and atmospheric deposition on forest nutrients and site productivity (Adams et al. 2000, McLaughlin and Phillips 2006) and potential alterations in forest composition from interactions between nitrogen and other key nutrients (Bigelow and Canham 2007, Zaccherio and Finzi 2007). In addition, more information is needed to evaluate the effects of management activities that will be altered as a result of increased biomass use, such as changes in rotation length or seasonality of harvest.

Tree species, density, and vigor can also be strongly correlated with soil fertility and have a role in site-specific nutrient dynamics. Site-species specific productivity relationships are also important factors in evaluating the impact of bioenergy harvesting on soil productivity. For example, sites that have inherently low soil fertility are more likely to experience nutritional deficiencies (Burger 2002). Paré et al. (2002) found greater nutrient demands by trembling aspen (*Populus tremuloides*) and balsam fir (*Abies balsamea*) in eastern Canada when compared with paper birch (*Betula papyrifera*), jack pine (*Pinus banksiana*), and black spruce (*Picea glauca*); as a result, they suggested avoiding whole-tree harvesting on thin soils and on sandy outwash sands when these species are present. In some situations, and where economically viable, amelioration through fertilization, liming, or ash recycling could be used where soil nutrient depletion from bioenergy harvesting is of concern (Burger 2002). Where these practices occur, the preservation of organic matter and other soil properties are necessary to maintain soil quality and productivity.

Harvesting can also cause soil displacement and erosion, as well as compaction and other structural changes. Soil compaction increases bulk density and decreases pore space (Fisher and Binkley 2000, Grigal 2000), and the degree to which these effects occur is related to initial soil characteristics (Kozlowski 1999, Powers et al. 2005). The risk of these impacts on soil productivity may be exacerbated by greater removal of forest biomass for energy and associated increases in machinery use for the collection of woody residues (Burger 2002). Soil compaction is often caused by the first few passes of machinery (Shetron et al. 1988, Williamson and Neilson 2000); consequently, if traffic patterns for biomass harvest resemble those of conventional harvest, biomass harvesting may not cause substantial increases in soil compaction relative to conventional harvests. More research is needed to evaluate changes in soil physical properties resulting from intensive timber harvesting operations and emerging biomass harvesting systems.

Results from agricultural studies indicate that maintenance of long-term soil productivity may be possible in short rotation, intensively managed forest systems (Vance 2000). Plantations of short-rotation woody crops have been shown to improve soils that have been previously tilled; studies of agricultural lands converted to short-rotation woody crops showed increased soil organic matter and reduced soil compaction from equipment use (Mann and Tolbert 2000). Although nutrient runoff and soil erosion levels are similar to agricultural crops during the 1st year after woody crops are planted, these effects generally decline in subsequent years after perennial woody crops have become established (Mann and Tolbert 2000, Volk et al. 2004). Nevertheless, it is less clear whether these same benefits would occur if woody crops were established on already forested lands, and potentially irreversible changes could occur.

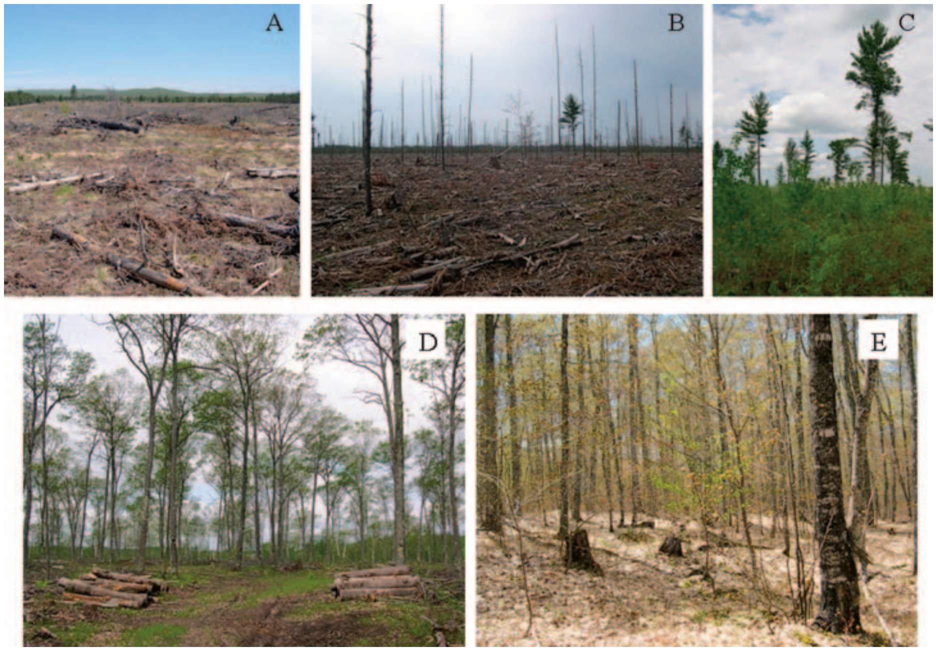

Figure 4. Increasing level of complexity in retention of biological legacies after harvesting: (A) traditional clearcut, (B) clearcut with snag retention, (C) clearcut with green-tree retention, (D) two-aged management, and (E) uneven-aged management of northern hardwoods.

Hydrology

Water is an essential ecosystem component, where both water quality and quantity serve as indicators of ecological function. Disturbances from forest management can subsequently affect natural processes, including hydrologic flows and physical, chemical, and biological properties of waterways (Brown and Binkley 1994, Neary 2002). Timber harvesting activities are often associated with disturbance to the soil surface and compaction, especially along skid trails, which can lead to increased erosion and sedimentation that negatively affects water quality. Road construction is usually the greatest contributor to erosion of the nutrient-rich soil surface layers (Grigal 2000), and stream sediment from forest roads and landings can have serious effects on aquatic habitats. Logging often results in higher soil moisture levels and runoff, which can alter soil nutrient flows, increase streamflow levels, and impact fish and other aquatic organisms (Neary and Hornbeck 1994, Grigal 2000). Nitrate-nitrogen concentration, often used as an indicator of water quality, generally does not increase after harvest but is more likely to increase after fire or when nitrogen fertilizers are used (Neary and Hornbeck 1994, Neary 2002). Harvesting significant amounts of vegetation adjacent to waterways raises the likelihood of increased water temperature, altered chemistry, and reduced clarity that can impair biological communities and ecological processes. Overall, the effects of harvesting on forest hydrology are highly variable among sites and from year to year; however, harvest impacts are generally greatest immediately after harvest and recover to preharvest conditions within 2–5 years (Aust and Blinn 2004).

Although typically voluntary, best management practices (BMP) for water quality have been established in all 50 states to serve as guidelines to prevent nonpoint source water pollution from activities associated with forest management (Shepard 2006). These recommendations focus on maintaining water quality through (1) careful planning and construction of roads, (2) minimization of exposed soil, (3) quick revegetation, and (4) maintenance of buffers adjacent to streams (Aust and Blinn 2004). Existing BMPs should largely be applicable to biomass removal in conventional forestry systems, although increased fertilizer use under more intensive management may be a concern (Shepard 2006). Regional guidelines that specifically address greater forest biomass removals for bioenergy can be developed (e.g., Minnesota Forest Resources Council [MFRC] 2007, Pennsylvania Department of Conservation and Natural Resources [PA DCNR] 2008) to address hydrologic, as well as many other, potential concerns associated with intensified harvest (Evans and Perschel 2009). Furthermore, biomass production using short-rotation woody crops may require expanded BMPs to address increased site preparation, greater use of fertilizers, and more permanent road systems (Shepard 2006). It may also be prudent to consider development of BMPs for hydrologically sensitive areas not covered by most contemporary BMPs (e.g., vernal pools, ephemeral streams, and wetlands).

Biodiversity and Forest Habitats

Sustainable forest management seeks to maintain or enhance ecosystem function and sustainability by emulating natural stand dynamics and disturbance regimes (Figure 4). Such practices often include an objective of preserving biodiversity, as biodiversity losses can reduce forest productivity and damage the ability of forest ecosystems to provide habitat for associated wildlife and plant species as well as other valuable ecosys-

Figure 5. Deadwood provides an important substrate for regeneration as well as habitat for a multitude of forest plants and animals.

tem services (e.g., Naeem et al. 1994). The extraction of additional biomass from the forest for energy may have detrimental effects on some species where essential habitat is degraded or removed beyond the range of natural variability. Consequently, decisions on how to balance biomass harvesting with maintaining forest biodiversity will require a system-level assessment of tradeoffs.

Species diversity in forest ecosystems is closely tied to habitat patch size and structural diversity, both of which may be influenced positively or negatively by intensive forest management (Fischer et al. 2006, Flaspohler et al. 2009). Strong species-area relationships have been observed in many ecological systems, with larger habitat patches containing more species (Brown and Lomolino 1998). Consequently, the production of bioenergy feedstocks using short-rotation woody crops may provide an opportunity to increase biodiversity, depending on previous land use, if the end result is an increase in the amount and/or connectivity of forest habitat. Biodiversity gains are most likely following conversion of agricultural fields to woody crops, which may occur more frequently in the future as a result of programs such as the 2008 Farm Bill Biomass Crop Assistance Program, while the effects on biodiversity would likely be negative after conversion of native forest or open-land vegetation (Cook and Beyea 2000, Lindenmayer and Hobbs 2004, Flaspohler et al. 2009). Although short-rotation woody crops often provide a more desirable habitat for forest species than agricultural fields, especially when these new stands have a diversity of tree species, ages, and growth habits (Cook and Beyea 2000), plantation forests generally do not support the same level of diversity present in natural forests (Lindenmayer and Hobbs 2004). For example, research by Volk et al. (2004) has indicated that although bird diversity is higher in short-rotation willow plantations in the northeastern United States than on agricultural lands, it is not as high as levels found in natural forests. Similarly, although often overlooked, soil organisms are expected to benefit from reduced tillage under perennial energy crops (Mann and Tolbert 2000), which usually need fewer pesticide and fertilizer applications than traditional agricultural crops (Cook and Beyea 2000, Mann and Tolbert 2000).

Age-class diversity and mixed species plantings can be used to enhance structural heterogeneity at a variety of spatial scales relevant to wildlife (Kerr 1999, Cook and Beyea 2000, Hartley 2002). Retention of biological legacies during harvest operations in both native forests and plantations can enhance structural heterogeneity in developing stands (Figure 4; Hartley 2002). For example, the retention of legacy trees has been shown to yield important benefits for the conservation of wildlife diversity in intensively managed forests (Mazurek and Zielinski 2004). Consequently, many of the potential impacts to wildlife will depend on the level and pattern of harvesting and the nature and number of biological legacies retained after regeneration cuts (Kerr 1999, Fischer et al. 2006).

In addition to living biological legacies, deadwood and other forest residues may be disproportionally impacted by biomass harvesting and increased use of cull trees and logging residues. Deadwood, in the form of both standing dead trees and down wood, is an essential structural component for biodiversity in forest systems (Figure 5; Harmon et al. 1986, Hunter 1990). In terrestrial systems, this material provides habitat for a host of arthropod (Jabin et al. 2004), amphibian (Butts and McComb 2000), mammal (McCay and Komoroski 2004), and bird species (Rosenberg et al. 1988). Its quantity and quality are related to management intensity (Goodburn and Lorimer 1998, Jenkins et al. 2004, Webster and Jenkins 2005), with the quantity of deadwood in managed forests ranging from 2 to 30% of the amount present in unmanaged forests (Fridman and Walheim 2000). Increased harvesting/recovery of forest residues (material that otherwise would recruit into the coarse woody debris pool) will likely reduce or possibly eliminate this component from forests intensively managed for bioenergy. Research on slash harvesting in Sweden has shown a significant negative effect on species composition and richness of bryophyte and liverwort communities (Astrom et al. 2005). Slash removal has also been found to reduce beetle abundance and species richness

Table 1. General level of concern regarding long-term sustainability for intensive removal of tree and forest ecosystem components as a result of increased use of woody biomass based on a review of the contemporary literature.

Harvested component	Level of concern	Comments
Forest floor	High	The forest floor retains organic matter, nutrients, and moisture required for tree growth and habitat for soil organisms vital for nutrient cycling. Maintaining the forest floor reduces soil erosion, compaction, and other impacts associated with harvest.
Dead down wood	High	Dead down wood provides habitat and structure necessary for biodiversity and provides substrate for growth of some tree and plant species.
Standing dead trees	Low when management component	Bioenergy harvest may be appropriate and sustainable when used as a part of a silvicultural plan or to mitigate the impacts of a disturbance, such as severe blow down or pest outbreak; a minimum number of standing dead trees should be retained (number varies by forest type and management) for habitat, regeneration, or other purposes.
Live trees (stem)	Low	Long-term research on harvesting of the merchantable tree bole shows minimal environmental impact when part of a sustainable forest management system.
Live trees (branches and foliage)	Medium	There is little evidence of whole-tree use removing enough nutrients to reduce tree growth, although some sites may be at greater risk. Sites that are nutrient poor or managed intensively on short rotations may require fertilization or may not be sustainable if whole-tree harvest is performed. A portion of crown material should be retained for value as down deadwood.
Live trees (stump and roots)	High	Extracting the stump and coarse roots of trees will disturb the soil, likely leading to greater amounts of soil erosion and sedimentation, and may remove structure and substrate necessary for biodiversity. Stump removal may be possible when part of site preparation in some silvicultural systems.

within the first year after harvest and prompt longer-term shifts toward generalist nonforest species (Gunnarsson et al. 2004, Nitterus et al. 2007). Consequently, provisions will be needed for the creation, retention, and preservation of deadwood in forests intensively managed for bioenergy.

Guiding Principles

Similar to any other forest management practice, ensuring the sustainability of biomass harvesting for energy will require attention to individual site conditions and consideration of multiple management objectives. Based on our review of the literature, we offer the following guiding principles that can be incorporated into biomass management activities:

• *Increase extent of forested land where feasible.* Afforestation of agricultural, abandoned, and degraded lands can produce many ecological benefits while also providing more forestland for production of wood products and/or energy. The benefits derived from the establishment of both conventionally planted forests and short-rotation woody crops will likely vary as a result of prior land use, landscape context, species composition of the planting, and rotation length. Short-rotation woody crops in particular may help to shift intensive forest management away from natural forests while enhancing biodiversity and soil and water quality relative to past land uses (Cook and Beyea 2000, Volk et al. 2004)

• *Adapt management to site conditions.* Although it is widely recognized that forest management objectives and activities need to be matched to existing site conditions, the probable intensification of harvesting to obtain woody biomass for energy underscores this fundamental adage. For example, old forests and areas of high conservation priority have inherent value because they provide essential services for biodiversity, ecosystem health, and carbon sequestration. Biomass harvesting is not suitable for many of these sites because the benefits that would be obtained from woody feedstocks are dwarfed by the ecological and social needs to manage for other ecosystem functions and services. In areas where biomass harvest is a possible management objective, the occurrence and intensity of biomass removal should consider and address potential limitations due to site productivity, soil physical properties (e.g., potential for compaction and/or erosion), presence of valuable habitat, or conflicts with other management goals.

• *Use management guidelines*. A multitude of guidelines have been developed for specific aspects of forest management, such as BMPs for water quality, which contain information to prevent or minimize the effects of most harvesting activities on water resources. Recognizing the value of BMPs, additional guidelines specific to biomass harvest have been created (e.g., MFRC 2007, PA DCNR 2008) or are in the process of being written in many states to complement existing recommendations for forest management. Where available, these guidelines should be used to better understand the challenges of biomass harvesting specific to a geographic location, as well as actions that can be taken to promote sustainability (Evans and Perschel 2009).

• *Retain organic legacies for soil productivity*. Long-term impacts on site productivity will be largely reduced by keeping a portion of forest biomass on site. Preserving existing sources of organic matter, such as deadwood and the forest floor, and retaining some slash from harvesting will help to maintain adequate levels of organic matter and nutrients in the soil and to minimize compaction, rutting, and erosion (see Table 1). For example, deciduous trees can be harvested during leaf-off to allow for greater cycling of nutrients and organic matter into the forest floor. Transpiration drying—a process where trees are cut and left on site for several months to dry—can be used to keep needles of coniferous trees and small branches on site after harvesting but needs to be balanced with threats to forest health from fire or pests (Hakkila 2002). Piling slash in windrows can also decrease productivity by concentrating the forest floor and nutrient-rich, surface mineral soil layer on a small portion of the site (Morris and Miller 1994). Dispersed slash will redistribute organic matter and nutrients and provide more uniform productivity.

• *Retain deadwood and structural heterogeneity for biodiversity*. Objectives for biodiversity can be included in management and harvest planning to minimize adverse impacts. Managers will need to determine the critical threshold for key habitat features (Angelstam et al. 2002), especially snags and down deadwood. To the greatest extent possible, management should strive to promote and maintain deadwood (including standing and fallen trees), structural heterogeneity, native plants, and a healthy forest floor (Figure 4). For short-rotation woody crops, planting a variety of age classes and species will increase diversity of other plant and animal species.

• *Evaluate role of fertilization and wood ash recycling*. Site-specific fertilization may be beneficial or necessary in some intensive bioenergy systems. Increased primary productivity from fertilization causes greater inputs of organic matter to soil, which can improve soil nutrient and water availability and make soil less susceptible to compaction. State and regional guidelines, including but not limited to BMPs, provide information and guidance on the use of specific site preparation and fertilization techniques. Wood ash generated as a byproduct of energy production can serve as a fertilizer for calcium, magnesium, and potassium. Although ash fertilization rates >10 tons per hectare normally will replace these cations removed during whole-tree harvesting (Vance 1996), caution is necessary to prevent negative environmental effects that could occur from ash fertilization, such as high concentrations of heavy metals and large alkaline pulses. For example, ash application rates of >5 tons per hectare have been shown to have detrimental impacts on moss and lichen communities (Pitman 2006).

• *Use biomass harvest as a tool for ecosystem restoration*. Biomass harvesting may have the most positive effect on forest management if it effectively advances activities that promote forest health and function (Evans 2008). The development of a strong biomass industry may enhance the economic and operational viability of many management operations by increasing the value of the wood resource as well as increasing the availability of harvesting and transportation machinery specifically suited to conditions typical of biomass harvest (i.e., removal of small diameter trees and brush). Although the opportunities for ecosystem restoration are wide ranging, applications include fuels reduction in overstocked stands or in the wildland–urban interface, thinnings to improve tree growth and stand vigor, and invasive species removals (e.g., Neary and Zieroth 2007, Evans 2008).

Literature Cited

Adams, M.B., J.A. Burger, A.B. Jenkins, and L. Zelazny. 2000. Impact of harvesting and atmospheric pollution on nutrient depletion of eastern US hardwood forests. *For. Ecol. Manag.* 138(1–3):301–319.

Angelstam, P., G. Mikusinski, and M. Breuss. 2002. Biodiveristy and forest habitats. P. 216–243 in *Bioenergy from sustainable forestry: Guiding principles and practice*, Richardson, J., R. Björheden, P. Hakkila, A.T. Lowe, and C.T. Smith (eds.). Klewer Academic Publishers, Dordrecht.

Astrom, M., M. Dynesius, K. Hylander, and C. Nilsson. 2005. Effects of slash harvest on bryophytes and vascular plants in southern boreal forest clear-cuts. *J. Appl. Ecol.* 42(6):1194–1202.

Aust, W.M., and C.R. Blinn. 2004. Forestry best management practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years (1982–2002). *Water Air Soil Pollut. Focus* 4(1):5–36.

Bigelow, S.W., and C.D. Canham. 2007. Nutrient limitation of juvenile trees in a northern hardwood forest: Calcium and nitrate are preeminent. *For. Ecol. Manag.* 243(2–3):310–319.

Boyle, J.R., J.J. Phillips, and A.R. Ek. 1973. Whole-tree harvesting: Nutrient budget evaluation. *J. For.* 71(12):760–762.

Brown, J.K., and M.V. Lomolino. 1998. *Biogeography*, 2nd Ed. Sinauer Associates, Sunderland, MA. 560 p.

Brown, T.C., and D. Binkley. 1994. *Effect of management on water quality in North American forests*. US For. Serv. Gen. Tech. Rep. RM-248. 29 p.

Burger, J.A. 2002. Soil and long-term site productivity values. P. 165–189 in *Bioenergy from sustainable forestry: Guiding principles and practice*, Richardson, J., R. Björheden, P. Hakkila, A.T. Lowe, and C.T. Smith (eds.). Klewer Academic Publishers, Dordrecht.

Butts, S.R., and W.C. McComb. 2000. Association of forest-floor vertebrates with coarse woody debris in managed forests of western Oregon. *J. Wildl. Manag.* 64:95–104.

Cook, J., and J. Beyea. 2000. Bioenergy in the United States: Progress and possibilities. *Biomass Bioenergy* 18(6):441–455.

Domac, J., K. Richards, and S. Risovic. 2005. Socio-economic drivers in implementing bioenergy projects. *Biomass Bioenergy* 28(2):97–106.

Energy Information Administration (EIA). 2007. *Annual energy review 2006.* Available online at www.eia.doe.gov/aer/; last accessed June 7, 2009.

Evans, A.M. 2008. *Synthesis of knowledge from biomass removal case studies.* Available online at www.forestguild.org/publications/research/2008/Biomass_Case_Studies_Report.pdf; last accessed June 7, 2009.

Evans, A.M., and R.T. Perschel. 2009. *An assessment of biomass harvesting guidelines.* Available online at www.forestguild.org/publications/research/2009/biomass_guidelines.pdf; last accessed June 7, 2009.

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

Fischer, J., D.B. Lindenmayer, and A.D. Manning. 2006. Biodiversity, ecosystem function, and resilience: Ten guiding principles for commodity production landscapes. *Front. Ecol. Environ.* 4(2):80–86.

Fisher, R.F., and D. Binkley. 2000. *Ecology and management of forest soils*. John Wiley and Sons, Inc., New York. 489 p.

Flaspohler, D.J., R.E. Froese, and C.R. Webster. 2009. Bioenergy, biomass and biodiversity. P. 33–162 in *Renewable energy from forest resources in the United States*, Solomon, B.D., and V.A. Luzadis (eds.). Routledge, New York. 330 p.

Fox, T.R. 2000. Sustained productivity in intensively managed forest plantations. *For. Ecol. Manag.* 138(1–3):187–202.

Fridman, J., and M. Walheim. 2000. Amount, structure, and dynamics of dead wood on managed forestland in Sweden. *For. Ecol. Manag.* 131(1–3):23–36.

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

Grigal, D.F. 2000. Effects of extensive forest management on soil productivity. *For. Ecol. Manag.* 138(1–3):167–185.

Gunnarsson, B., K. Nitterus, and P. Wirdenas. 2004. Effects of logging residue removal on ground-active beetles in temperate forests. *For. Ecol. Manag.* 201(2–3):229–239.

Hakkila, P. 2002. Operations with reduced environmental impact. P. 244–261 in *Bioenergy from sustainable forestry: Guiding principles and practice*, Richardson, J., R. Björheden, P. Hakkila, A.T. Lowe, and C.T. Smith (eds.). Klewer Academic Publishers, Dordrecht.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, A.N. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, Jr., and K.W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res.* 15:133–302.

Hartley, M.J. 2002. Rationale and methods for conserving biodiversity in plantation forests. *For. Ecol. Manag.* 155:81–95.

Helms, J.A. 1998. *The dictionary of forestry*. Society of American Foresters, Bethesda, MD. 224 p.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. U.S.A.* 103(30):11206–11210.

Hunter, M.L., Jr. 1990. *Wildlife, forests, and forestry: Principles of managing forests for biological diversity*. Prentice-Hall, Inc., Upper Saddle River, NJ. 370 p.

Jabin, M., D. Mohr, H. Kappes, and W. Topp. 2004. Influence of deadwood on density of soil macro-arthropods in a managed oak–beech forest. *For. Ecol. Manag.* 194:61–69.

Jenkins, M.A., C.R. Webster, G.R. Parker, and M.A. Spetich. 2004. Coarse woody debris in managed central hardwood forests of Indiana, USA. *For. Sci.* 50:781–792.

Johnson, D.W. 1992. Effects of forest management on soil carbon storage. *Water Air Soil Pollut.* 64(1–2):83–120.

Johnson, D.W., and P.S. Curtis. 2004. Effects of forest management on soil C and N storage: Meta analysis. *For. Ecol. Manag.* 140(2–3): 227–238.

Joki-Heiskala, P., M. Johansson, M. Holmberg, T. Mattsson, M. Forsius, P. Kortelainen, and L. Hallin. 2003. Long-term base cation balances of forest mineral soils in Finland. *Water Air Soil Pollut.* 150(1–4): 255–273.

Kerr, G. 1999. The use of silvicultural systems to enhance the biological diversity of plantation forests in Britain. *Forestry* 72:191–205.

Kozlowski, T.T. 1999. Soil compaction and growth of woody plants. *Scand. J. For. Res.* 14: 596–619.

Lindenmayer, D.B., and R.J. Hobbs. 2004. Fauna conservation in Australian plantation forests a review. *Biol. Conserv.* 119:151–168.

Malmsheimer, R.W., P. Heffernan, S. Brink, D. Crandall, F. Deneke, C. Galik, E. Gee, J.A. Helms, N. McClure, M. Mortimer, S. Ruddell, M. Smith, and J. Stewart. 2008. Forest management solutions for mitigating climate change in the United States. *J. For.* 106(3):115–117.

Mann, L.K., D.W. Johnson, D.C. West, D.W. Cole, J.W. Hornbeck, C.W. Martin, H. Riekerk, C.T. Smith, W.T. Swank, L.M. Tritton, and D.H. Vanlear. 1988. Effects of whole-tree and stem-only clearcutting on post-harvest hydrologic losses, nutrient capital, and regrowth. *For. Sci.* 34(2):412–428.

Mann, L., and V. Tolbert. 2000. Soil sustainability in renewable biomass plantings. *Ambio* 29(8):492–498.

Mazurek, M.J., and W.J. Zielinski. 2004. Individual legacy trees influence vertebrate wildlife diversity in commercial forests. *For. Ecol. Manag.* 193:321–334.

McCay, T.S., and M.J. Komoroski. 2004. Demographic responses of shrews to removal of coarse woody debris in a managed pine forest. *For. Ecol. Manag.* 189:387–395.

McLaughlin, J.W., and S.A. Phillips. 2006. Soil carbon, nitrogen, and base cation cycling 17 years after whole-tree harvesting in a low-elevation red spruce (*Picea rubens*)–balsam fir (*Abies balsamea*) forested watershed in central Maine, USA. *For. Ecol. Manag.* 222(13):234–253.

Minnesota Forest Resources Council (MFRC). 2007. *Biomass harvesting guidelines for forestlands, brushlands, and open lands*. Available online at www.frc.state.mn.us/Info/MFRCdocs/forest%20biomass%20harvesting.pdf; last accessed June 7, 2009.

Morris, L.A., and R.E. Miller. 1994. Evidence for long-term productivity change as provided by field trials. P. 41–80 in *Impacts of forest harvesting on long-term site productivity*, Dyck, W.J., D.W. Cole, and N.B. Comerford (eds.). Chapman and Hall, London.

Naeem, S., L.J. Thompson, S.P. Lawler, J.H. Lawton, and R.M. Woodfin. 1994. Declining biodiversity can alter the performance of ecosystems. *Nature* 368(6473):734–737.

Neary, D.G. 2002. Hydrologic values. P. 190–215 in *Bioenergy from sustainable forestry: Guiding principles and practice*, Richardson, J., R. Björheden, P. Hakkila, A.T. Lowe, and C.T. Smith (eds.). Klewer Academic Publishers, Dordrecht.

Neary, D.G., and J.W. Hornbeck. 1994. Impacts of harvesting and associated impacts on off-site environmental quality. P. 81–118 in *Impacts of forest harvesting on long-term site productivity*, Dyck, W.J., D.W. Cole, and N.B. Comerford (eds.). Chapman and Hall, London.

Neary, D.G., and E.J. Zieroth. 2007. Forest bioenergy system to reduce the hazard of wildfires: White Mountains, Arizona. *Biomass Bioenergy* 31:638–645.

Nitterus, K., M. Astrom, and B. Gunnarsson. 2007. Commercial harvest of logging residue in clear-cuts affects the diversity and community composition of ground beetles (Coleoptera: Carabidae). *Scand. J. For. Res.* 22(3): 231–240.

Paré, D., P. Rochon, and S. Brais. 2002. Assessing the geochemical balance of managed boreal forests. *Ecol. Indic.* 1(4):293–311.

Department of Conservation and Natural Resources (PA DCNR). 2008. *Guidance on harvesting woody biomass for energy in Pennsylvania*. Available online at www.dcnr.state.pa.us/PA_Biomass_guidance_final.pdf; last accessed June 7, 2009.

Perlack, R.D., L.L. Wright, A. Turhollow, R. Graham, B. Stokes, and D. Erbach. 2005. *Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billionton annual supply*. Oak Ridge Natl. Lab. Tech. Rep. ORNL/TM-2006/66. 60 p.

Pitman, R.M. 2006. Wood ash use in forestry—A review of the environmental impacts. *Forestry* 79(5):563–588.

Powers, R.F., D.H. Alban, R.E. Miller, A.E. Tiarks, C.G. Wells, P.E. Avers, R.G. Cline, R.O. Fitzgerald, N.S. Loftus Jr. 1990. Sustaining site productivity in North American forests: Problems and prospects. P 49–79 in *Sustained productivity of forest soils. Proc. of the 7th North American Forest Soils Conference*. Gessel, S.P., D.S. Lacate, G.F. Weetman, and R.F. Powers (eds.). University of British Columbia, Faculty of Forestry Publication, Vancouver, BC. 525 p.

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

Rosenberg, D.K., J.D. Fraser, and D.F. Stauffer. 1988. Use and characteristics of snags in young and old forest stands in southwest Virginia. *For. Sci.* 34(1):224–228.

Shepard, J.P. 2006. Water quality protection in bioenergy production: The US system of forestry Best Management Practices. *Biomass Bioenergy* 30(4):378–384.

Shetron, S.G., J.A. Sturos, E. Padley, and C. Trettin. 1988. Forest soil compaction: Effect of multiple passes and loadings on wheel track surface soil bulk density. *North. J. Appl. For.* 5:120–123.

Sverdrup, H., and K. Rosen. 1998. Long-term base cation mass balances for Swedish forests and the concept of sustainability. *For. Ecol. Manag.* 110(1–3):221–236.

Vance, E.D. 1996. Land application of wood-fired and combination boiler ashes: An overview. *J. Environ. Qual.* 25(5):937–944.

Vance, E.D. 2000. Agricultural site productivity: principles derived from long-term experiments and their implications for intensively managed forests. *For. Ecol. Manag.* 138(1–3): 369–396.

Volk, T.A., T. Verwijst, P.J. Tharakan, L.P. Abrahamson, and E.H. White. 2004. Growing fuel: A sustainability assessment of willow biomass crops. *Front. Ecol. Environ.* 2(8):411–418.

Webster, C.R., and M.A. Jenkins. 2005. Coarse woody debris dynamics in the southern Appalachians as affected by topographic position and anthropogenic disturbance history. *For. Ecol. Manag.* 217:319–330.

Williamson, J.R., and W.A. Neilson. 2000. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. *Can. J. For. Res.* 30:1196–1205.

Zaccherio, M.T., and A.C. Finzi. 2007. Atmospheric deposition may affect northern hardwood forest composition by altering soil nutrient supply. *Ecol. Applic.* 17(7):1929–1941.