Forest fuel harvesting: a review of environmental risks, criteria and indicators and certification standards for environmental sustainability

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Summary. Biomass from sustainably managed forests can contribute to the energy profile of the United States by providing a homegrown and renewable energy source that off-sets fossil fuel use, reducing overall carbon emissions. Forest bioenergy feedstocks production and harvesting systems range from small-scale fuelwood gathering to large-scale industrial plantations and removals of virtually all above-and-below ground biomass from intensively managed forests. Across this wide range of options for production and extraction, there is an equally wide range of potential impacts. It is therefore critical that forest biomass procurement systems do not adversely impact forests or the environment; therefore, effective standards and planning tools, based on the best available scientific knowledge, must be in place prevent these impacts being realized, and hence ensure a sustainable industry. Sustainable forest management (SFM) certification schemes are one mechanism for applying measurable environmental standards (in the form of criteria and indicators, or C&I) to forest management systems. We will examine how existing SFM certification schemes and frameworks, such as C&I and Adaptive Forest Management, can be used to help guide sustainable biomass operations. We first present a basic introduction to the potential impacts of biomass production and harvesting on soil and water resources, site productivity and biodiversity in the forest, as well as issues related to greenhouse gas balances and global and supply-chain impacts. We then propose a number of principles and example criteria (from a complete set by Lattimore et al. (2009) for sustainable biomass production to address these potential impacts. Finally, we will briefly introduce current SFM certification standards and discuss how these might be adjusted for forest fuel production and harvesting, using an adaptive forest management framework, to help ensure the sustainability of the emerging forest bioenergy sector.

Keywords. *Biomass Harvesting,Sustainability Criteria*

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Introduction

Biomass from sustainably managed forests can contribute to the energy profile of the United States by providing a homegrown, renewable energy source that off-sets fossil fuel consumption. If forest bioenergy is to be publicly accepted as a sustainable, renewable resource, however, it is critical that forest fuel production and harvesting systems do not adversely impact forests or the environment. A number of potential impacts on soils, water, biodiversity and greenhouse gas balances can occur during biomass production and harvesting processes and along the bioenergy supply-chain. Understanding and mitigating these impacts through the use of effective standards and planning tools will be necessary if sustainable practices are to be achieved. Policy-makers and forest managers must be able to understand and predict these impacts, and prevent them through the application of appropriate standards, planning tools and practices, if sustainability is to be achieved. Sustainable forest management frameworks such as criteria and indicators (C&I), sustainable forest management certification schemes and Adaptive Forest Management (AFM) can work together to structure and inform the design, implementation and continual adaptation of low-impact forest biomass production systems.

Our objective is to provide guidance on creating a sustainable industry for policy-makers, forest managers and any other stakeholders interested in forest biomass production for bioenergy in the United States. Although we focus on environmental sustainability during feedstock production and harvesting, it is imperative that environmental impacts be considered along the entire bioenergy supply chain, from stump to consumer to waste disposal, and that social and economic impacts also be taken into account when seeking to create a truly sustainable industry.

Gathering and synthesizing the best available scientific knowledge to discern how a practice might affect a particular forest ecosystem, and identifying management techniques to minimize negative effects, is the first step in creating sustainable feedstock supply systems. We therefore begin with a brief overview of the potential environmental impacts of biomass production and harvesting processes across a range of forest types, and possible mitigations techniques, based on a review of current literature (after Lattimore et al., 2008). Using this synthesized knowledge of potential impacts as a foundation, we then present some examples of principles and criteria for sustainable forest biomass production (from a complete set of principles, criteria, indicators and verifiers proposed by Lattimore et al., 2009). We then discuss sustainable forest management (SFM) certification schemes and their applicability to forest fuel production and harvesting systems (after Stupak et al., 2009). SFM certification schemes are voluntary mechanisms for governing sustainable forest management; through the use of C&I, they provide both standards and monitoring mechanisms for forest management, thereby ensuring continual learning and adaptation. It is important to recognize that knowledge is always changing, based on new research and experience; forest management, research and the formulation of standards must take place within an Adaptive Forest Management (AFM) framework, which allows for the continual improvement of systems to ensure long-term sustainability. We therefore end with a brief discussion of the importance of apply an AFM framework to sustainable forest fuel production and harvesting. (For more in-depth exploration of these topics, see recent review papers by Lattimore et al. (2009) and Stupak et al. (2009), upon which this paper is based).

Environmental risks of forest fuel production and harvesting

Forest fuel production can be integrated into conventional forest management activities (e.g., residue removal as part of forest harvesting or pre-commercial thinning), or can be the primary focus of forest management (e.g., dedicated energy plantations). The production and use of forest fuels can have a number of environmental benefits, including: off-setting fossil fuel use, with consequent greenhouse gas reductions; fuel load reduction; and improved forest ecosystem health through rehabilitation of degraded stands. On the other hand, environmental risks can increase if forest bioenergy production systems entail more intensive forest management and utilization of biomass - often over shorter rotations - than conventional forest management (e.g., for timber, pulp).

A range of possible environmental risks from forest fuel production and harvesting was identified through an examination of current literature (notably key review papers) and tabulated under six headings (Lattimore et al., 2009):

1) Soils (Table 1)
2) Hydrology and water quality (Table 2)
3) Site productivity (Table 3)
4) Forest biodiversity (Table 4)
5) Greenhouse gas balances (Table 5)
6) Global and supply-chain impacts of bioenergy production (Table 6)

Each table contains a list of ecosystem attributes that may be affected by forest fuel production systems, followed by specific issues related to these attributes and the forest management activities that may contribute to such issues. References to key papers that discuss these issues in more depth are also included. It is important to note that potential impacts will vary regionally and differ according to local ecological conditions and management practices. Site-specific soil surveys, climate data and knowledge of local conditions and best management practices will therefore determine which issues are most critical at different sites.

The following sub-sections will provide a bit more detail to some of the key considerations that fall under each of the six categories listed above. This coverage is by no means exhaustive; for a more in-depth review, please consult Lattimore et al. (2009), and the key scientific papers referred to in Tables 1-6 and throughout the text.

Potential effects of forest fuel production systems on soils

Soils (Table 1) are of particular concern with relation to forest fuel production systems because practices can involve more intensive removal of organic matter from forest ecosystems than timber harvesting, and can include whole-tree harvesting (WTH)

Table 1. Potential environmental impacts of forest fuel production systems on soils.

Physical properties (moisture, structure, temperature, erodability) (Grigal 2000, Burger 2002, Powers et al. 2005, Fleming et al. 2006, Greacen et al. 1980, Merino et al. 1998, Sabourin et al. 1992, Smith et al. 1997, Borjesson et al. 2000, Masman et al. 2006, Ravindranath et al. 1995)

Issues

- Exposure of soil surface → drying of surface layers, soil temperature extremes, wind and water erosion
- Compaction → decreased soil oxygen and soil porosity → decreased water infiltration → waterlogged ruts
- Rise of water table and saturation of soil due to loss of evapotranspiration after clearcutting
- Stump removal can cause instability and erosion, especially on sloping terrain, and bring up undesirable lower horizons (e.g., calcareous or low nutritional materials, or heavily textured soils)

Contributing activities

- Exposure of soil through removal of protective litter layer, dead wood, downed wood or slash
- Removal of slash and resultant loss of protective roadbed for machinery
- Time of year and soil conditions during operations (e.g., harvesting when soil is wet)
- Whole-tree harvesting, especially clearcutting
- Biomass removal that requires more frequent and/or intensive entries than needed for conventional harvesting (e.g., slash left to dry until foliage abscises, multiple-pass harvesting)
- Building of additional roads/leaving roads open longer for biomass harvesting
- Stump harvesting

Chemical properties (SOM and soil carbon storage, nutrients, toxic substances, pH and salinity) (Grigal 2000, Burger 2002, Dyck & Mees 1990, Binkley & Brown 1993, Dyck & Maclaren 1994, Gustafsson 1993, Lundborg 1993, Sabourin et al. 1992, Morris & Fleming 2006, Briggs et al. 2000, Man et al. 1988, McLaughlin & Phillips 2006.)

Issues

- Reductions in soil organic matter and soil carbon storage
- Reduction in total capital and availability of nutrients (especially N, Ca, P and K)
- Increased nutrient leaching from the soil
- Base cation depletion leading to changes in pH
- Salinity changes due to water table modifications
- Accumulation of toxic substances

Contributing activities

- Removal of biomass during and/or at the end of the rotation (e.g., whole-tree harvesting, removal of dead wood, thinnings)
- Rotation length and species chosen (e.g., lack of time for root turnover, litter fall, natural mortality)
- Conversion of native grasslands to short-rotation woody crop plantations
- Improper use of herbicides, pesticides and fertilizers and recycled wood ash
- Vegetation removal, groundwater extraction and irrigation leading to changes in the water table
- Use of harvesting machinery (e.g., leaking of lubricants and hydraulic fluids)

Biological properties (soil biota, soil regenerative capacity) (Burger 2002, Binkley & Brown 1993, Dyck & Maclaren 1994, Lundborg 1993 Sabourin et al. 1992, Marshall 2000)

Issues

- Soil biota is decreased through: Compaction; drying; waterlogging; accumulation of toxic elements; temperature extremes
- Compaction, moisture imbalance and nutrient loss decreases regenerative capacity of site

Contributing activities

- Exposure of mineral soil through removal of dead wood, downed wood or slash
- Improper use of machinery when harvesting
- Improper use of herbicides, pesticides, fertilizers and recycled wood ash

Desertification

Issue

- Severe degradation in soil quality can lead to expanses of denuded soils that are inhospitable to plant establishment and vulnerable to erosion

Contributing activity

- Improper fuelwood and industrial feedstock harvesting practices (see activities under Attributes 1, 2 and 3)

with residue removal, or even stump extraction (as practiced in some Nordic countries). Concern over the impacts of increased interventions and soil organic matter removals on soil productivity have led to a number of long-term site productivity experiments and other studies to determine the effects of different harvesting intensities on soil chemical, biological and physical properties (Grigal 2000, Burger 2002, Powers et al. 2005, Scott et al. 2004, Olsson et al. 1996).

Soil chemical and biological properties

Impacts of intensive biomass removals on soil chemical and biological properties can include: reduced levels of soil organic matter and soil carbon storage; and reduced soil nutrients and base cation depletion.

Reduced levels of soil organic matter and soil carbon storage

Adequate amounts of soil organic matter (SOM) are important for maintaining nutrient cycling, soil moisture levels, soil structure and soil microbial communities (Burger 2002, Powers et al. 2005, Scott et al. 2004). Studies from North America show varying effects on SOM and soil carbon storage from intensive management, ranging from reduced levels of SOM to a depth of 20 cm after intensive harvesting (Grigal 2000), to negligible effects on most sites after 15 years (Johnson 1992). Despite such variations in results, Powers et al. (2005) hypothesize that changes in site organic matter will lead to changes in productivity in the longer term, after a number of rotations. Site preparation techniques, length of rotation, and timing of harvest and residue removals all play a role in determining the severity of effects, and should be taken into account during management planning. (See Table 7 for potential mitigations techniques).

Changes in substrate and micro-climate for soil microorganisms

Removals of surface organic matter and downed woody debris (DWD) can disrupt soil microbial communities (Grigal 2000); studies show, however, that these communities are very resilient to changes and there is currently no evidence of lasting impacts from WTH or other intensive management activities (Grigal 2000). As a precautionary measure, retaining adequate DWD and residues can help to mitigate potential impacts. (See Table 7 for other mitigations techniques).

Reduced soil nutrients and base cation depletion

The loss of key nutrients such as nitrogen (N), phosphorous (P) and calcium (Ca) because of the intensive removal of biomass is of primary concern, while there have been a few long-term studies (Briggs et al. 2000; Mann et al.1988, McLaughlin & Phillips 2006), not all ecosystems have been equally represented; however, the following generalizations indicate how forest fuel production systems might impact nutrient pools (Burger 2002):

- WTH removes a greater amount of nutrients than stem-only harvesting, because of the high concentrations of nutrients in leaves, branches and bark;

- shorter rotations will result in the greatest loss of nutrients because young trees have higher relative proportions of nutrient-rich biomass;
- site preparation activities involving the removal of slash, litter and topsoil will result in reduced nutrient pools and influence the rate of decomposition, leading to decreased levels of soil organic matter (SOM).

WTH and residue removal can decrease amounts of soil N and sulfur (S) in soils (Powers et al. 2005), though end losses are often negligible when inputs from atmospheric deposition are taken into account (Grigal 2000, Burger 2002). Residue handling (e.g., slash piling) may be as important as harvesting method in determining N concentrations (Rosen 1986). Compensatory fertilization, encouraging plant diversity, intercropping with leguminous shrubs, and leaving biomass to dry on-site can all help to combat N losses (Burger 2002, Hakkila 2002). Losses of P and K may be of greater concern, because they are not easily replenished (through weathering or atmospheric deposition). Studies show decreases in exchangeable pools of P, K, Mg and Ca in soil after WTH, which increases the susceptibility of these soils to acidification (Olsson et al. 1996, Burger, 2002). Concern is greatest on sites with naturally low levels of Ca (e.g., the Southeastern US) and areas with base cation depletion because of atmospheric deposition (e.g., Northeastern US (Jeziorski et al. 2008). Effects of intensive biomass removal on nutrient levels are entirely site-specific, and therefore site-specific soil surveys should precede any management interventions; once issues are identified, practices can be designed to mitigate nutrient losses (Hakkila et al. 2002) (Table 7).

Soil physical properties

Increased machine traffic into the forest for biomass harvesting, removal of protective mats of harvesting residues for energy, and changes in soil moisture and organic matter can lead to negative impacts on soil physical properties. For example, studies have shown productivity losses of 10% on intensively managed sites that are directly linked to physical damage (esp. erosion) (Grigal 2000). Machinery used in forest fuel production can also increase soil bulk density and strength, reducing aeration, water infiltration and root growth. Most compaction occurs within the first few passes, but results may be irreversible (Grigal 2000). Vulnerability to physical damage varies from site to site (e.g., compaction is more of an issue on wetter soils), and therefore sites should be assessed individually before management decisions are made (see Table 7 for mitigations techniques).

Potential effects of forest fuel production systems on hydrology and water quality

Forest fuel production systems can have a range of impacts on hydrological processes and water quality (Table 2). Main concerns for groundwater and adjacent aquatic ecosystems include: changes in water yield and peak flow; changes to stream temperature and light infiltration; increased turbidity and sedimentation; increased concentrations of N and other nutrients; and accumulation of toxic substances (Olsson et al.1996, Dyck & Mees 1990, Keim & Shoenholtz 1999, Neary 2002). The removal of streamside vegetation for energy wood, for example, can lead to increased runoff and changes to temperature and light infiltration, adversely affecting aquatic organisms (Jordan 2006, Holopainen & Huttunen 1992). Intensive harvesting and/or wood ash fertilization can also increase nitrate concentrations in adjacent aquatic ecosystems, though studies thus far have shown this to be rare (Neary 2002). On weathered geological formations, the combination of atmospheric deposition and harvesting effects can depleted soil base cations, reduce calcium in the water, and change aquatic biodiversity (Jeziorski et al. 2008)but the extent to which this is exacerbated by biomass harvesting is not yet known. Knowledge of watershed characteristics, use of appropriate planning, and the incorporation of streamside management zones can all help to mitigate negative impacts to local hydrology (for more suggestions, see Table 7).

Table 2. Potential environmental impacts of forest fuel production systems on hydrology and water quality.

Ecosystem hydrologic flux (infiltration, groundwater recharge, interception and transpiration) (Neary 2002, Greacen & Sands 1980, Van Der Salm et al. 2006, Eigenbrod & Kaluza 1999.)

Issues

- Compaction creating impermeable soils and waterlogged depressions
- Decreased leaf and slash surface area after harvesting → decreased interception and transpiration
- Increased leaf area from plantations → increased interception → decreased infiltration to water table
- Changes to water tables

Contributing activities

- Removal of slash and resultant loss of protective roadbed for extraction machinery
- Removal of vegetation and alteration of soil properties
- Whole-tree harvesting, especially with clearcutting
- Plantation establishment
- Irrigation of short-rotation woody crop plantations

Physical properties (turbidity, temperature, light infiltration) (Keim & Shoenholtz 1999, Neary 2002, Jordan 2006, Holopainen & Huttunen 1992, Wilkerson et al. 2006, Moore 1999; Rice et al. 2001)

Issues

- Soil exposure → increased overland flow → erosion and sedimentation → increased turbidity, decreased light availability
- Loss of streamside canopy cover → increased light infiltration → temporary temperature changes in water bodies adjacent to heavily harvested areas
- Effectiveness of streamside management zones (SMZs) (e.g., water temperature)

Contributing activities

- Harvesting intensity (i.e., both silvicultural system used and proportion of biomass removed)
- Time of year and soil condition during operations (e.g., harvesting when soil is wet)
- Selection and use of forwarding and transporting equipment
- Design, location and construction of roads and stream crossings
- Harvesting in riparian areas

Chemical properties (nutrients, toxic compounds, pH) (Neary 2002, Egnell et al. 2006, Egnell et al. 1998, Moore 1999, Jug et al. 1999, Vuori et al. 2003, Röser et al. 2007.)

Issues

- Transport of topsoil into watercourses
- Subsurface and lateral flow of herbicides and fertilizers to adjacent water bodies
- Changes in the buffering capacity of the soil → lake acidification and mobilization of toxic

elements (e.g., Al)
- Eutrophication of aquatic ecosystems

Contributing activities
- Exposure of soils due to gathering of downed woody debris, stumps and roots → lateral transport of nutrients via wind and rain
- Management activities that result in excessive leaching of nutrients, especially N and P
- Plantations upstream of, or adjacent to, waterbodies
- Improper use of herbicides, pesticides, fertilizers and recycled wood ash

Biological properties **(**Neary 2002, Holopainen & Huttunen 1992.)

Issues
- Increased turbidity, temperature changes and changes in pH in water bodies adjacent to harvested areas can have negative ecological consequences, including disruption of spawning grounds and fish kills
- Toxic compound accumulation can affect aquatic life

Contributing activities
- See activities under Attributes 6 and 7

Potential effects of forest fuel production systems on site productivity

The potential impacts of forest fuel production and harvesting on site productivity (Table 3), as indicated by tree growth response, depend on site conditions (e.g., nutrients, moisture, light, temperature, wind) (Scott et al. 2004, Smith et al. 2001). Therefore, site specific conditions, along with reforestation practices, can lead to a range of responses after forest fuel harvesting, from decreased productivity (Egnell et al. 2003), to no difference (Sanchez et al. 2006), to even increased tree growth (Proe et al. 2001). Long-term effects can be difficult to predict, even after 20 years of observation, however, so caution must be used when interpreting possible impacts in the longer term (Egnell et al. 2003). It is also important to realize that soil quality and site productivity are not necessarily synonymous; improved genetic stock and site-specific reforestation techniques may appear to improve productivity, even as soil quality decreases. C&I for soils should therefore be used in conjunction with those for site productivity.

Table 3. Potential environmental impacts of forest fuel production systems on site productivity.

Regeneration **(**Lundborg 1993, Morris & Fleming 2006.)

Issues

- Lack of suitable micro-sites for seedling establishment because of extreme soil microclimatic conditions
- Reduction in nurse logs and organic woody substrates for seedling establishment
- Reduction in habitat for seed-dispersing birds and mammals

Contributing activities

- Removal of deadwood, downed wood and slash

Soil quality [see references for Attributes 1-4]

Issues

- Reduced soil organic matter, nutrient capital and nutrient availability
- Reduced soil biota activity (biodiversity, population size, function) → reduced nutrient cycling rates and soil aeration
- Reduction in plant growth rates
- Decreased vigor → increased susceptibility to insects, disease, climate change, etc.

Contributing activities

- See Table 2 for activities impacting soil physical, chemical and biological properties

Potential effects of forest fuel production systems on biodiversity

Forest fuel production can have both positive and negative effects on species biodiversity (Table 4). These effects can include (Angelstam et al. 2002; Christian et al. 1998, Dyck & Maclaren 1994, Egnell et al. 1998, UN-E 2007, Jonsell 2008, Gustafsson 1993, Lundborg 1993, Paine et al. 1996):

- habitat loss or gain from landscape and ecosystem changes (e.g., loss through deforestation of forestlands, or gain through afforestation of agricultural lands);
- removal of niche habitats (e.g., dead and downed wood);
- disturbances to wildlife from increased forest access;
- encroachment into protected areas;
- proliferation of invasive species (e.g., through disturbance and stockpiling);
- trapping and removal of rare insects in residues stored on site; and
- overall changes in ecosystem health.

Table 4. Potential environmental impacts of forest fuel production systems on forest biodiversity.

Landscapes **(**Angelstam et al. 2002, Christian et al. 1998, Dyck & Maclaren 1994, Gustafsson 1993, Paine et al. 1996, Albrecht 1991.)

Issues

- Decrease in area and diversity of forest cover
- Decrease in overall forest health → increased susceptibility to insects and disease
- Decrease in habitat connectivity at both the landscape and stand levels (e.g., forest patches, migration corridors, connected networks of DWD)
- Inadequate protected areas
- Land use change
- Land tenure

Contributing activities

- Demand for energy feedstock and household fuelwoods → uncontrolled harvesting
- Mechanical damage to residual trees from intensive harvesting, lack of care, and multiple interventions over the rotation
- Road building to access previously unmerchantable fibre; roads open longer for two-pass harvesting
- Excessive gathering of dead and downed wood
- Design of protected areas (e.g., patch size and shape, edge effects)
- Encroachment on protected areas and high conservation value forests for forest fuel, due to:
  - Lack of alternatives when conventional forest fuel supply is low
  - Lack of monitoring and enforcement
  - Energy issues receiving higher political priority than environmental issues
- Afforestation of farmland or degraded lands (+ for biodiversity)
- Conversion of native forests into plantations
- Intensive management of forests
- Lack of secure land tenure → lack of coordination amongst user groups → unsustainable harvesting

Ecosystems **(**Dyck & Mees 1990, Angelstam et al. 2002, Gustafsson 1993.)

Issues

- Loss of ecosystems due to land conversion (e.g., natural grasslands, native forests)
- Reduction in ecosystem functions and services
- Adjacent and downstream effects of forest operations and plantations on aquatic ecosystems (e.g., erosion and sedimentation, wood ash recycling, chemical fertilizers and herbicides)

Contributing activities

- Market and policy pressure to convert native ecosystems to energy plantations

Habitats (Christian et al. 1998, Dyck & Maclaren 1994, Gustafsson 1993, Albrecht 1991, Ehnstrom 2001, Clarkson & Mills 1994.)

Issues

- Loss of DWD and dead wood needed for the survival of some species of mosses, fungi,

insects, small mammals and cavity nesting birds
- Overall reduction in quantity and quality of forest and adjacent aquatic habitats

Contributing activities
- Increased thinning with removal of biomass
- Excessive gathering from the forest floor
- Conversion of natural forests
- Unsustainable production processes and absence of appropriate guidelines

Species (Angelstam et al. 2002, Dyck & Maclaren 1994, Gustafsson 1993, Clarkson & Mills 1994, Edman et al. 2004, Norden et al 2004.)

Issues
- Changes in forest composition
- Species loss due to habitat degradation (see Attribute 13)
- Proliferation of invasive species and species that prefer disturbance landscapes
- Conflicts between humans and wildlife increase as forest access and intensity of management increases, causing danger to humans, increased poaching of bushmeat and other illegal wildlife harvesting activities
- Inadequate maintenance of trophic levels

Contributing activities
- Encouragement of naturally occurring fast-growing species (e.g., willow, poplar, eucalyptus)
- Replacement of natural forests with mono-specific plantations or short-rotation woody crops for fuel production
- Extensive clearing
- Open corridors and increasing traffic into forests
- Encroachment further into the forest to gather fuel wood

Genes (Angelstam et al. 2002, Christian et al. 1998, Dyck & Maclaren 1994, Gustafsson 1993.)

Issues
- Decrease in genetic diversity of native tree species
- Maintenance of critical breeding populations of all organisms

Contributing activities
- Clonal forestry
- Use of genetically modified organisms
- Mono-specific plantations
- Selective tree breeding
- Harvesting without proper guidelines and attention to species' requirements

A range of scales must be considered when planning for biodiversity protection, from landscapes, ecosystems, habitats and species to genes. The following broad approaches can help to ensure the conservation of biodiversity in and around forest fuel production sites (Angelstam et al. 2002, Franklin 1993):

- assessing and maintaining biodiversity at a landscape level;
- avoiding harvesting where sensitive species are present;
- using the "umbrella species" concept to ensure the protection of as many species as possible (i.e., focusing protective measures on the needs of certain species requiring large areas of habitat and assuming that other species will gain protection from this as well; for more information on this technique, see Angelstam et al. 2002 for more information);
- incorporating wildlife provisions into the managed landscape; and
- insuring an Adaptive Management system with adequate monitoring.

(See Table 7 for more potential mitigations techniques).

Potential effects of forest fuel production systems on greenhouse gas balances

Potential impacts of forest fuel production on greenhouse gas balances are summarized in Table 5. When forest bioenergy is sustainably produced and used to replace fossil fuels, there are net reductions in CO_2 emissions over the course of the next rotation, because the CO_2 emitted during fuel burning is captured in the next growing crop of trees. When assessing the full impact of individual bioenergy production systems on carbon and greenhouse gas budgets, however, there are a number of additional factors that must be considered. These include (Heller et al. 2003, Marland & Shlamadinger 1995, Marland & Schlamadinger 1997, Marland & Marland 1992):

- changes in carbon stored in soil, litter and trees, resulting from land-use changes and management systems;
- fossil fuels used in production, transport, conversion and waste disposal;
- temporal variations in carbon stocks and fluxes; and
- complete life-cycle analyses of products and systems.

Planning should incorporate the most energy-efficient methods at each stage of production, and consider how land use changes will affect overall carbon balances (see also Table 7). (For more information on greenhouse gas balances of bioenergy systems, see the work of IEA Bioenergy Task 38 (2008))

Table 5. Potential environmental impacts of forest fuel production systems on GHG balances.

Net carbon sequestration (soil carbon, carbon stored in living and dead biomass or in wood products) (Marland & Schlamadinger 1997; Markewitz 2006; Marland & Marland 1992; IEA 2007; Massman et al. 2006; Albrecht 1991.)

Issues

- Carbon removed through harvesting exceeds that which will be sequestered over the next rotation
- Changes in carbon fluxes throughout the ecosystem (e.g., decomposition, dissolved organic carbon, methane production) caused by removal of biomass
- Permanent loss of vegetation (e.g., loss of forest productivity, desertification) leading to reduced carbon sequestration in the forest
- Most of the carbon in soil is stored in SOM, and recruitment of SOM is reduced when biomass is removed from the system

Contributing activities

- Land use change
- Harvest utilization practices
- Unsustainable forest practices to extract energy feedstock, as described in above tables
- Harvesting for bioenergy beyond the productive capacity of the forest site
- Forest fires and prescribed burning
- Mechanical site preparation

Non-carbon greenhouse gases (IEA 2007.)

Issue

- Flux of non-carbon greenhouse gases may be increased (e.g., N_2O)

Contributing activity

- Unsustainable biomass feedstock production systems

Global and supply-chain issues

Imported biomass from other countries can also help to meet US bioenergy feedstock demands. While forest biomass production for export can provide positive economic opportunities in developing countries, it can also create negative impacts along the bioenergy supply chain in the absence of fair trading regulations and effective domestic policies (e.g., the rapid expansion of palm oil plantations in Southeast Asia have led to tropical deforestation; Danielsen et al. 2008). The adoption of standardized C&I for sustainable biomass feedstock and bioenergy production (e.g., those put forth by the Roundtable on Sustainable Palm (RSPO, 2008) and the Netherlands (Cramer et al., 2006)) would help to encourage sustainable feedstock production in developing countries. (See also IEA Bioenergy Task 40 website (2008), and the Roundtable on Sustainable Biofuels (RSB, 2008)).

Because the focus of this paper is at the forest management level, there are no criteria or mitigations techniques provided to deal with issues further along the supply-chain. However, some relevant issues are included in Table 6 to stress the importance of a supply-chain assessment.

Table 6. Global and supply-chain impacts of bioenergy production**.**

Environmental sustainability of the supply chain (Forsberg 2000, Jungmeier 1998, Lewandowski & Faaij 2006.)

Issues

- Air pollution
- Waste
- Distribution of production systems globally (e.g., distances between system components, allocation of operations to areas with low environmental standards)

Contributing activities

- Global demand for bioenergy
- Design and selection of harvesting machinery
- Design of milling and bio-refinery facilities
- Emissions controls on combustion equipment
- Waste management and resource recycling
- Water use in production processes
- Distance of processing facilities from harvesting sites
- Distance of markets from processing facilities

Global environmental health (Lewandowski & Faaij 2006.)

Issues

- Unequal distribution of impacts worldwide (e.g., exporting impacts, national policy variations)
- Inefficiencies associated with exporting feedstock (e.g., fossil fuel use in transport)

Contributing activities

- International trade systems
- Gaps in national policies and enforcement

Table 7. Examples of operational techniques to mitigate ecological damage

Environmental attribute	Possible mitigations techniques
Soils	• Develop site-specific nutrient management regimes • Utilize best management practices for road building, where available • When using pesticides and fertilizers, follow available guidelines • Apply recycled wood ash or fertilizers where needed, according to available guidelines • Minimize interventions by practicing one-pass harvesting • Restrict interventions to seasons when soil moisture is low • In applicable regions, harvest deciduous trees in winter, after leaves have fallen • Orient skid trails and site preparations along slope contours • Maintain protective slash and litter layer on forest floor • Retain nutrient-rich crown biomass on site (e.g., needles, bark, branches, tops) • Avoid windrowing/root raking that results in soil organic matter depletion • Use specialized equipment such as high flotation tires and boom-forwarding • Ameliorate soil compaction through ripping and cultivation
Hydrology	• Follow regional Best Management Practices (BMPs) for maintaining water quality, if available • Maintain buffer zones in riparian areas • Manage for healthy soils (see Table 2) • Avoid short-rotation woody cropping systems where irrigation causes deleterious changes in groundwater levels • Apply chemicals (e.g., pesticides, herbicides, fertilizers) according to guidelines
Productivity	• Mitigating practices for negative impacts to site productivity are similar to those listed in Tables 1 and 2 for soils and hydrology, respectively
Biodiversity	• Incorporate wildlife management guidelines into biomass production systems • Use landscape analysis techniques to assess landscape-level features of the site (e.g., patch size and shape, connectivity) • Ensure habitat quality and connectivity through: patch design; attention to species requirements; incorporation of corridors

	• Create buffer zones around habitats of threatened or endangered species • Maintain adequate buffer zones for species requiring “interior” forest habitat • Manage stands for structural diversity (e.g., structural retention at the time of harvest; long rotation periods) • Create suitable habitat within managed stands (e.g., nest boxes) Control weeds appropriately
Greenhouse gas balances	• Mitigate loss of site productivity (e.g., examples in Tables 2-4) • Mitigate loss of soil organic carbon (e.g., examples in Table 2) • Ensure adequate replacement replanting (e.g., time frame, number of trees planted, regeneration success) • Design landscape use and operations to maximize carbon storage and minimize carbon losses through production
Supply chain impacts	• Mitigating negative impacts along the supply chain can be accomplished through assessing alternatives using life-cycle analyses, including such factors as: changes in land use and impacts on biodiversity and ecosystem services; carbon storage in forests; fertilization and other input requirements; fossil fuel use in feedstock production and transport; feedstock conversion efficiency; carbon and other pollutants emitted during transport of energy to consumer; waste recycling and disposal.

Criteria and indicators for sustainable forest fuel production and harvesting

Sustainable forest management criteria and indicators (C&I) can provide a framework for conceptualizing, applying, and monitoring sustainable forest management for forest fuel production. Various sustainable forest management C&I sets have been developed by intergovernmental processes and international organizations over the past few decades, usually to address the needs of specific continents or regions, though some are broader in scope (e.g., the Montreal Process, which provides a model for North American standards as well as those of a number of other regions) (NRCAN, 2008; Montreal Process, 2008). These systems are often used to guide policy development and the design of C&I at more local levels, through government endeavors or certification schemes. (For more on existing SFM C&I sets, see Stupak et al. (2009)).

Translating the attributes, issues and contributing activities presented in this paper (Tables 1-6) into sustainable forest management C&I would allow these issues to be addressed through sustainable forest management certification systems and other governance mechanisms (e.g., policy, guidelines). Lattimore et al. (2009) have adapted existing certification systems and international processes and devised a set of principles, criteria, indicators and verifiers (PCI&V)

to address the potential concerns from forest fuel production and harvesting. (See Lattimore et al. (2009) for the complete set of PCI&V).

Principles, criteria, indicators and verifiers form a hierarchical system of standards and monitoring mechanisms, increasing in specificity as they move from principles (most general) to verifiers (most specific). A principle rests at the broadest level and refers to "a fundamental truth or law as the basis of reasoning or action" (CIFOR 1999). Principles are used to justify the chosen criteria, indicators and verifiers. Criteria follow principles, and are used to enhance their meaning and operability; they do not, however, measure performance. Performance is measured by indicators (which provide concrete, measurable information about a criterion), and verifiers (the highest level of quantitative specificity, used to add detail to indicators). This type of structure provides goals and standards (through principles and criteria), and tools for measuring progress (through indicators and verifiers). Table 8 gives a list of the five principles provided by Lattimore et al. (2009), along with an example of one criterion and one indicator for each, and a column linking the principles with the environmental issues that they address (from Tables 1-6).

In the United States, most sustainable forest management C&I currently available have been developed and implemented by forest certification schemes, including the international Forest Stewardship Council (FSC) (FSC 2008), North America's Sustainable Forestry Initiative (SFI) (SFI 2008), the Canadian Standards Association (CSA 2008), and the American Tree Farm System (ATFS 2008). SFI, CSA and ATFS are all regional schemes endorsed by the Programme for the Endorsement of Forest Certification (PEFC), an international umbrella organization that currently supports 26 independent certification schemes (PEFC 2008). These schemes are designed to cover conventional forest management activities (e.g., for timber, pulp and paper) as well as non-timber forest product activities. Many issues that arise from conventional production

Table 8. Principles for sustainable forest fuel harvesting (Lattimore et al. 2009)

Principle	Sample criterion and indicator	Relevant environmental impacts
P1. There exists the institutional capacity to effectively protect resources from ecologically unsustainable biomass production systems.	C1.1 Existence of an economic and policy framework to guide sustainable bioenergy production systems. ➢ I1.1.1 Provision of economic incentives for environmental protection.	Relevance to all issues addressed in Tables 1-6.
P2: Biomass availability and amounts extracted for households, charcoal production and industrial bioenergy feedstocks are quantified and taken into consideration in forest management plans.	C2.1 Volumes of wood extracted for households, charcoal production and industrial bioenergy feedstocks are monitored and recorded. ➢ I1.2.5 Accessible programs to teach rural populations about the importance of sustainable forest management.	Relevance to most issues listed in Tables 1-6.

P3: The productive capacities of ecosystems and landscapes are maintained.	C3.1 Harvest levels must not exceed a rate whereby they can be maintained over the long term. ➢ I3.1.1 Existence of national and/or local guidelines regarding sustainable residue extraction levels.	Relevance to potential impacts on soils (Table 1), hydrology and water quality (Table 2), and site productivity (Table 3).
P4: Ecological and biological diversity at the landscape level will be maintained or improved.	C4.3 There is no degradation of sensitive or valuable ecosystems, high conservation value forests, or protected areas. ➢ I4.3.1 Amount and distribution of organic matter present on forest floor.	Relevance to potential impacts on biological diversity (Table 4).
P5: Forest management and supply chain systems will, over a rotation, lead to a net reduction in non-renewable greenhouse gas (GHG) emissions compared to conventional fossil fuel systems needed to produce the same amount of energy.	C5.1 Full life-cycle carbon analysis along the entire supply chain will be used to select among system alternatives.	Potential impacts on greenhouse gas balances (Tables 5 and 6).

and harvesting processes are the same or similar to those that arise from biomass production and harvesting for bioenergy, but there are still great opportunities for adapting existing sustainable forest management certification schemes through the addition of new criteria (e.g., some of those suggested by Lattimore et al. (2009)) and the modification of existing criteria to ensure that they address issues unique to forest biomass production and harvesting for energy (Lewandowski & Faaij 2006, Stupak et al. 2009).

Applying SFM certification schemes to forest fuel production and harvesting

Consumers need to feel assured that forest biomas production is sustainable if forest bioenergy is to become a widely accepted and supported source of energy in the United States. In light of the potential environmental impacts introduced in this paper, it is evident that clear standards and monitoring regimes are required to govern this emerging industry. Increasing attention is being given to the role that sustainable forest management certification might play in helping to fulfill a governing role. Thirteen percent of American forests are currently certified under either FSC, SFI, CSA or ATFS; this number is likely to increase significantly in coming years (Georgia-Pacific 2007). Sustainable forest management certification is a voluntary, market-driven mechanism for ensuring sustainability that provides standards in the form of C&I, and requires a third-party audit to ensure that standards are met. If forest biomass production and harvesting were certified under SFM certification schemes, these could also form part of a wider labeling system for the entire bioenergy supply chain (e.g., green energy labeling) by providing assurance that energy feedstocks were produced in a sustainable manner.

Current SFM certification schemes offer a range of C&I to address the basic protection of ecosystem values, including soils, water, site productivity and biodiversity. While this is a good starting point, it is also important that such schemes include explicit C&I for forest fuel production and harvesting if forest certification is to play a major role in ensuring sustainability of this industry. By cross-checking the C&I from current systems with C&I designed to specifically address forest fuel production and harvesting (e.g., the PCI&V provided by Lattimore et al. (2009)), systems could be adapted to cover a wider range of forest management activities. In addition to adding specific new criteria and indicators to existing systems, more general improvements can be made to SFM certification schemes to make them more applicable to forest fuel production and harvesting.

Stupak et al. (2009) conducted a very thorough review of current international processes and SFM certification systems as they relate to forest fuel production and harvesting. They uncovered the following shortcomings in the ability of current SFM certification systems to ensure sustainable forest management for forest fuel production and harvesting (Stupak et al. 2009):

- Many SFM certification schemes *fail to explicitly mention forest fuels as a product*, and it is often unclear whether they are classified as a timber or non-timber resource. Explicit definitions would make it easier to address relevant issues directly in SFM standards.
- Current schemes *do not address potential trade-offs between ecological, social and economic criteria*, which may lead to confusion and decreased transparency when managing for forest fuel production and harvesting. A number of trade-offs between criteria may be necessary when managing for forest fuel production and harvesting (e.g., criteria requiring that most residues are left in the forest for ecological reasons conflicts with criteria encouraging residue removal to optimize economic value). Appropriate references should be made to these trade-offs in all relevant criteria, with mutual referencing among them;
- Existing SFM certification schemes *do not require that any forest fuel production or harvesting activities be included in forest management plans*. Addressing fuel wood production along with other forest management activities through appropriate planning is key to sustainability.
- *Current SFM certification systems do not specifically discuss energy plantations (e.g. PEFC) or positions are unclear (e.g. FSC).* Short-rotation systems on former agricultural lands are likely to increase in importance as sources of forest fuel North America and Europe (COM 2005; USDOE 2008). Energy plantations can be used to reclaim and manage degraded lands and abandoned farmland, and can take pressure off of natural forests to produce forest fuels, however standards are needed to ensure that these plantations form part of a sustainable forest landscape.
- *Synergetic cooperation between SFM certification and other governance means needs to be stronger*. Ideally, certification and other governance mechanisms (e.g., policies, guidelines, environmental conventions) should mutually support one another to ensure the highest level of sustainability possible. Currently, many States do not have policies, guidelines, or other standards in place that explicitly address forest fuels.
- *Strong partnerships between SFM certification schemes and energy labeling schemes (e.g., Green-e (2008); EcoLogo (2008)) do not yet exist.* In order to ensure that bioenergy is a sustainable product on a landscape scale and throughout its lifecycle, certification at the

feedstock production and procurement level should form just one part of certification along the entire supply-chain (i.e., green energy labeling); the stronger the links between the two, the greater the level of sustainability that can be achieved.

- *Strong partnerships between FSM certification schemes and other schemes for sustainable land use.* In order to ensure that bioenergy production is sustainable on a landscape scale and that competition between land uses is addressed.

In light of these concerns, if SFM certification systems are to effectively ensure sustainable forest fuel production and processing effectively, then they first need to be adapted to (Stupak et al., 2009):

- clearly define and explicitly address forest fuels in SFM standards;
- address potential trade-offs under different conditions (e.g., quantify what is meant by leaving an "adequate" amount of residues in the forest for ecological functions versus removing these residues for fuel wood); appropriate references should be made to these trade-offs in all relevant criteria, with mutual referencing among them;
- require that forest fuel production and harvesting is included in management plans;
- define standards for establishing and managing energy plantations within a sustainably managed landscape, or where to exclude them;
- cooperate and work synergistically with other governance mechanisms (e.g., international conventions, policy, guidelines) to ensure sustainable production and harvesting of forest fuels; and
- address the sustainable production and harvesting of forest fuels as it relates to sustainability at the landscape level and along the whole wood energy supply chain.

Although adaptations for SFM certification schemes would help ensure sustainable forest fuel production and harvesting in the United States, they provide solid and well-established frameworks as starting points. Through the use of C&I and regular third-party auditing, and requirements on regular revision of the standards, SFM certification schemes also facilitate an Adaptive Forest Management framework, which is critical for making improvements to the long-term sustainability of systems.

Adaptive Forest Management

Large-scale forest fuel production and harvesting is relatively new in the United States, and there is still much to learn about the effects of these types of management systems on forest ecosystems. Because there is still a great deal of learning to be done, it is important that management systems and standards are built around a dynamic Adaptive Forest Management (AFM) framework, to encourage learning through experience and new scientific knowledge. AFM is "a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs", therefore encouraging learning through experience (BC Ministry of Forests and Range 2006). An Adaptive Forest Management Framework (Figure 1) acknowledges the dynamic nature of sustainable forest management, and encourages constant improvement through stakeholder input and the continual incorporation of new science and knowledge (Raison 2002).

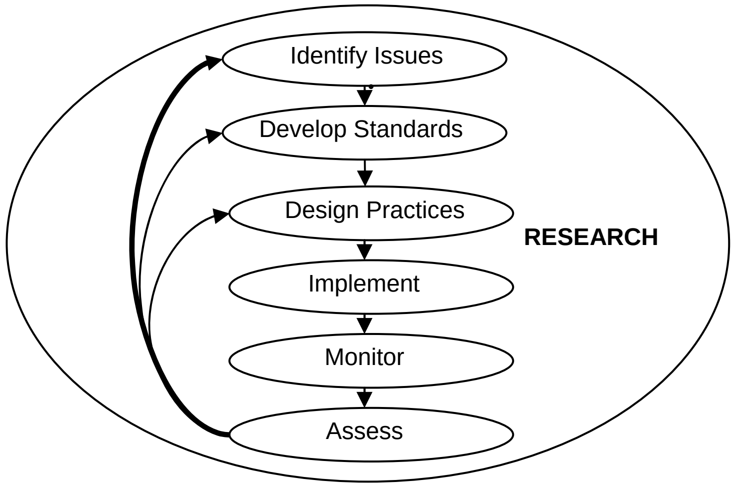

Figure 1. Adaptive Forest Management framework

The first step in an AFM framework is using the best available knowledge to assess potential impacts (e.g., Tables 1-6, Lattimore et al. (2009)). This knowledge informs the next step, the design of practices, which involves the setting of appropriate targets and indicators (e.g., C&I sets, PCI&V from Lattimore et al (2009)). Local adaptation of C&I and the establishment of any additional guidelines also occur at this stage, along with the creation of management plans. During the implementation phase, forest management proceeds in accordance with the agreed upon guidelines (e.g., Table 7) and C&I. Monitoring is the next step, and is critical in an AFM approach; monitoring must continually assess compliance with and the effectiveness of standards and management plans. Outcomes are then compared to the goals and indicators developed earlier; if outcomes are not satisfactory, if capacity changes or if new information becomes available, then plans, standards and guidelines are adjusted accordingly.

Adaptive Forest Management is an efficient means for systematically improving the effectiveness of management systems whn applied to newly emerging practices, such as forest fuel production and harvesting; AFM cycles may be rather short as we adapt to a rapidly changing base of knowledge (e.g., Sweden updated its 2001 recommendations for forest fuel extraction and harvesting just seven years after they were formulated, in 2008 (Scogsstyrelsen 2001)). Some jurisdictions have a legal requirement that AFM be applied to biomass regulations over cycles lasting a specified number of years (e.g., five years in the case of Ontario, Canada).

Conclusions and recommendations

Renewable sources of energy could play an important role in satisfying the energy demand of the United States, and contribute to decreased greenhouse gas emissions and increased energy security. Sustainable management of America's abundant forest resources could contribute to the production of significant amounts of bioenergy feedstocks as well as contribute to rural economic development and realization of ecological services provided by forest ecosystems. Environmental sustainability can be achieved by developing environmental management systems that combine reliable scientific knowledge, adequate standards and guidelines, and a flexible and adaptive approach to continual learning and improvement. Sustainable forest management frameworks and tools like criteria and indicators, Adaptive Forest Management and certification schemes can help to structure knowledge and make it available to policies, standards and operations.

In this paper, we presented a variety of potential impacts that forest fuel production and harvesting can have on forest ecosystems and the environment. We then introduced a number of principles for sustainable forest fuel production and harvesting (from Lattimore et al. 2009), and discussed how these and corresponding criteria, indicators and verifiers (or other C&I for forest fuel production and harvesting) could be applied through sustainable forest management certification schemes and using an Adaptive Forest Management approach, to ensure an industry that will be environmentally sustainable in the long term. Existing sustainable forest management schemes operating in the United States, such as FSC, SFI, CSA and ATFS, can provide effective tools for encouraging and monitoring sustainable forest fuel production and harvesting systems. However, to do so they must be modified to explicitly address the unique concerns associated with this emerging industry and should operate in the presence of effective policies and guidelines.

Based on our research, we recommend the following steps (for governments, certifying organizations, forest managers and other stakeholders) to help make the transition towards a sustainable forest bioenergy industry:

- Fund and promote long-term research trials into the effects of intensive forest management for energy production on forest landscapes and environments, as well as lifecycle analyses of bioenergy systems;
- Encourage states to develop standards and management guidelines for forest fuel production and harvesting, based on the most current knowledge;
- Adapt sustainable forest management certification schemes to explicitly address forest fuel production and harvesting alongside timber and pulp production;
- Strengthen linkages between sustainable forest management certification schemes and green energy certification schemes, to ensure sustainability along the whole supply chain;
- Structure knowledge gathering, standard development and forest management around an Adaptive Forest Management framework, so that knowledge and systems will continue to improve concurrently; and
- Create regional programs to educate forest managers and other stakeholders about issues and opportunities in forest bioenergy production.

In the presence of a strong framework of knowledge, standards, adaptability and awareness, sustainable forest management for bioenergy production in the United States can provide an exciting, environmentally sound opportunity in both forestry and energy production.

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