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Forest Biomass Harvesting: Best Practices and Ecological Issues in the Canadian Boreal Forest

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1. Introduction

In spite of the recent increase in interest, the use of forest biomass for energy production is not a new phenomenon. In fact, wood has always been used for this purpose and it was the primary source of energy until the industrial revolution, when fossil fuels came to the fore (Kerr 2010).

1.1. What is forest biomass?

Biomass is, by definition, living mass. It can be derived from forestry and agriculture products as well as from waste (European Environment Agency 2006). For circumboreal countries like Canada, forest biomass, because of its abundance, represents an especially promising energy source.

Energy for industrial, commercial and domestic use can be derived from forests by converting woody biomass into solid, liquid or gaseous fuels (Hall 2002). The expression “forest biomass” encompasses (i) primary residues from conventional forestry operations such as site preparation, salvage harvesting, thinning and final cutting, (ii) secondary residues from industrial wood processing, (iii) tertiary residues from construction, renovation and demolition, and (iv) traditional firewood (Figure 1) (Röser et al. 2008). Primary residues currently are the main source of biomass for bioenergy obtained from temperate and boreal forests. In particular, harvest residues from the final cutting (often a clearcut) constitute the most accessible and economical source of forest biomass. More concretely, these residues consist of tree crowns and branches from harvested stems destined for processing. It is this category of forest biomass that will mainly be discussed in this guide.

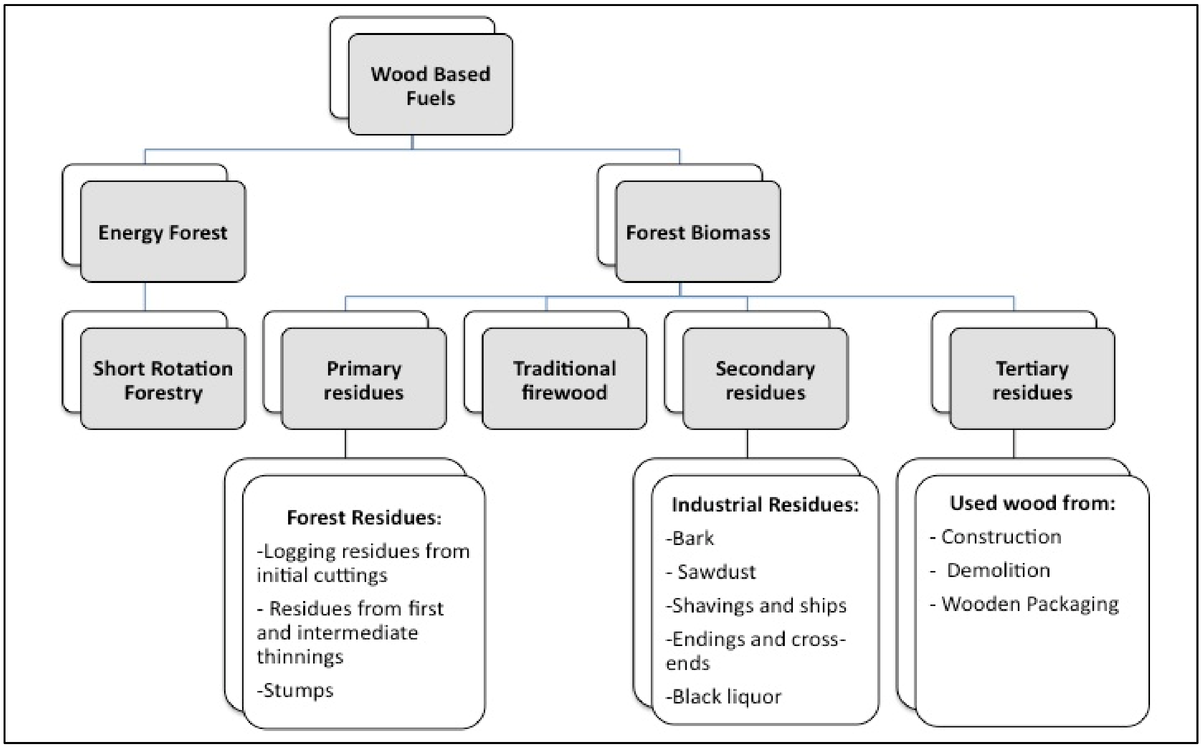

Figure 1. Classification of fuels derived from wood (from Röser et al. 2008).

1.2. Why use forest biomass?

The use of forest biomass has multiple advantages. Biomass is an attractive option in view of the rising price of fossil fuels and environmental concerns related to their use, as well as considerations regarding the security and diversification of the energy supply (van Dam et al. 2008).

One of the key benefits of using forest biomass is that it can replace fossil fuels in energy production, thereby reducing greenhouse gas emissions and mitigating climate change. This benefit has been recognized by the International Panel on Climate Change (IPCC) (Nabuurs et al. 2007). Bioenergy derived from the forest is renewable. It is often described as "carbon neutral" because as forest trees grow they sequester atmospheric carbon. The stored carbon is released when the wood is harvested and converted into bioenergy, and sequestered once again by the regeneration that grows on the logged sites. However, the term "carbon neutral" is not accurate, as the literature on the subject shows (Haberl et al. 2012). Nevertheless, carbon budget models that take forest emissions dynamics into account show that eventually, forest biomass provides benefits in terms of reductions of CO_2 emissions relative to fossil fuels. Those benefits are greater and appear faster when harvest residues are used for energy production. It would thus be more accurate to talk about a form of energy with low carbon emissions. Nonetheless, this is a very important advantage of using forest biomass for bioenergy compared with fossil fuels.

1.3. Why the need for caution in forest biomass harvesting?

In North America, three factors have historically hindered the use of forest residues for energy production: inefficient combustion technologies, problems related to residue harvesting operations, and knowledge gaps related to site impacts of residue removal, particularly its effects on biodiversity, soil productivity and forest health (Hacker 2005).

Furthermore, growing demand for woody biomass and therefore increased forest biomass removal can lead to conflicts with other forest functions and values. For example, for a given site, harvest residues can either be left on site to protect the soil against rutting and maintain nutrient stocks, which is not possible when they are harvested for bioenergy use. This situation indicates that an analysis of trade-offs is necessary in order to strike a balance among the different uses (Stupak et al. 2007; Benjamin 2010).

1.4. The guide

This guide summarizes the knowledge currently available concerning the potential impacts of forest biomass harvesting, especially the removal of residues from clearcut harvesting (branches and crowns) on the forest ecosystem. The information is presented in relation to the primary ecological issues associated with these practices in the boreal forest. It also examines the guidelines developed by different jurisdictions to address these impacts. Finally, recommendations are provided with a view to ensuring sustainable harvesting of forest biomass in Quebec and Canada.

2. Biomass harvesting issues

The five main issues related to forest biomass harvesting are biodiversity, water and riparian zones, soil productivity, stand productivity, and CO_2 emissions (carbon budget). Each of these issues is related to the potential impacts of harvesting forest residues that can be expressed as sensitivity indices. Thus, the sensitivity of biodiversity (e.g., the abundance and diversity of birds and invertebrates) mainly depends on the quantity, quality and spatial distribution of dead wood left in the forest, while the sensitivity of soil productivity depends primarily on soil texture, organic matter content, its capacity to provide phosphorus and its mineral base cations content. The sensitivity of stand productivity is related to the physiology of the species, climate and the microclimate of the site. Biomass harvesting also affects water and riparian areas through its effects on sedimentation, nutrient concentration, stream temperatures and water availability; however, the limited availability of information on this subject has prevented the development of sensitivity indices for this issue. Lastly, biomass harvesting results in CO_2 emissions resulting primarily from various harvesting, transport and storage operations and the combustion of forest biomass. This issue is measured by the amount of carbon (C) emitted into the atmosphere.

The issues related to forest biomass harvesting can be classified into five categories: biodiversity, water and riparian zones, soil productivity, stand productivity, and carbon emissions (CO_2) (Figure 2). It should be noted, however, that this is not a strict classification. For example, soil protection issues, such as erosion, also influence water quality aspects.

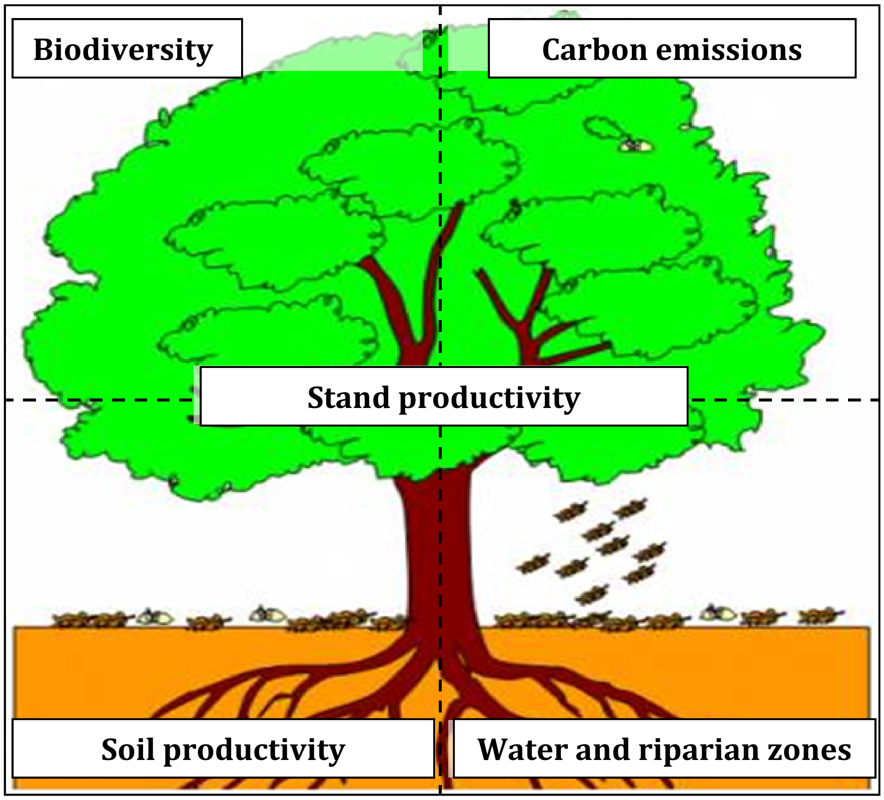

Figure 2: Issues related to forest biomass harvesting.

In this section, the scientific literature available is reviewed and the potential impacts of biomass harvesting are identified for each issue. In addition, the information is summarized in a way that highlights *site sensitivity to forest biomass harvesting*, i.e., the characteristics of forest sites for which biomass harvesting exerts additional pressure beyond that associated with conventional stem-only harvesting (Figure 3).

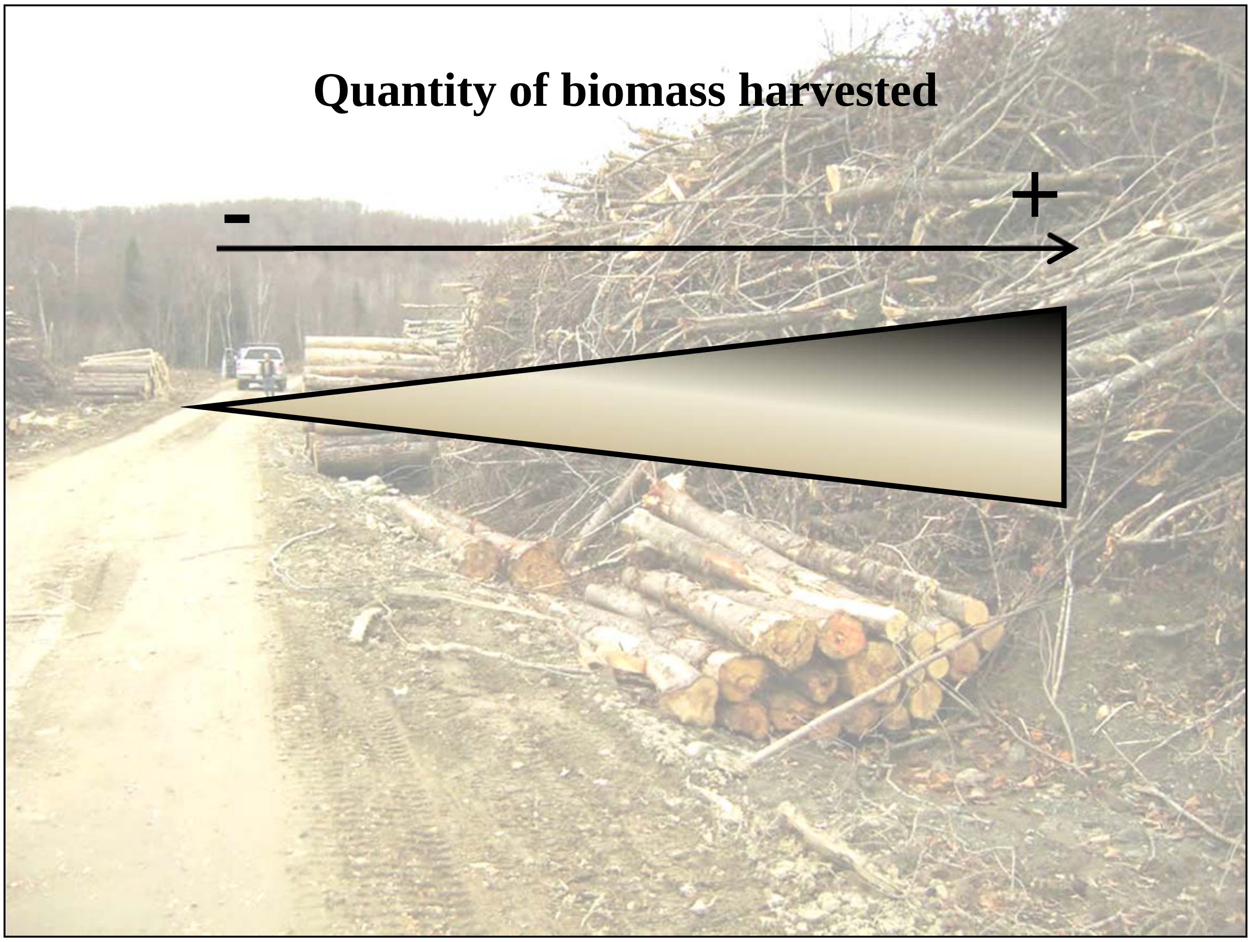

Figure 3. Sensitivity index of forest sites to biomass harvesting.

2.1. Biodiversity

Current scientific knowledge of the impacts of forest biomass removal on biodiversity is fragmentary compared with the vast literature that generally exists on the topic of biological diversity (Stewart et al. 2010). Few studies focus specifically on the impact of forest residue removal. Europe has a longer history of intensive forest management than North America; therefore, it has a greater number of studies on the impact of biomass removal on biodiversity (Berch et al. 2011). However, due to this more intensive management, research results may not be applicable to the Canadian context since the initial state and level of forest biodiversity differ.

Dead wood is a typical component and key factor in terms of species richness in natural forests (Schuck et al. 2004). Woody debris are essential for maintaining the basic functions of a variety of organisms, including breeding, feeding and shelter (Riffell et al. 2011). Thus, American researchers have conducted a meta-analysis on the impact that large-scale removal of coarse woody debris has on biodiversity (Riffell et al. 2011). By compiling the results of 26 studies on the topic, they discovered that bird and invertebrate diversity and abundance are lower in treatments where less coarse woody debris or fewer snags are left on site (Figure 4). However, a study conducted in Quebec in a mature balsam fir stand in the boreal forest showed that in the short-term (1 year), the cut itself, regardless of harvesting intensity and the amount of debris left on the ground, was the main factor behind the abundance of beetles (Work et al. 2013). A few differences were noted in species composition between stem-only harvesting and the more intensive whole-tree harvesting, but the real impact of these differences on the functioning of the ecosystem has yet to be determined. In addition, there is no clear evidence that mammals, reptiles and amphibians are affected by the removal of coarse woody debris and snags (Riffell et al. 2011).

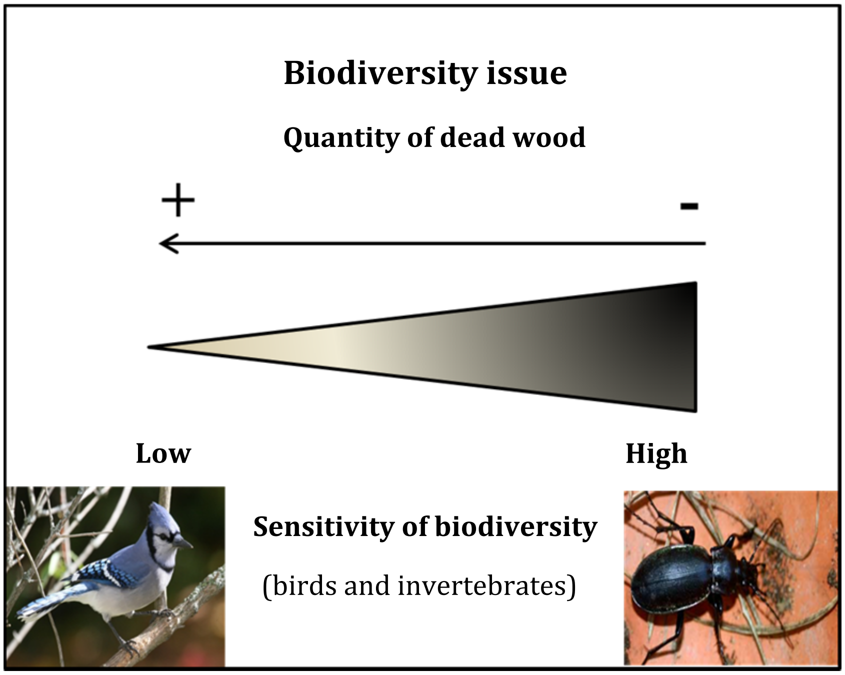

Figure 4. Sensitivity index of biodiversity (birds and invertebrates).

Furthermore, polypore fungi use wood as a host for their own development. Thus, a reduction in the quantity and quality of woody debris can have an adverse effect on their abundance and diversity (Figure 5). In the long term, this could lead to the disappearance of endangered species that play a fundamental role in the preservation of forest ecosystems (e.g., Toivanen et al. 2012). For example, a study conducted on trembling aspen forests (*Populus tremuloides*) in Minnesota found that polypore fungi occurred more frequently in the presence of dead wood with a diameter of less than 5 cm (Brazee et al. 2012). Given this fact, it is necessary to take both coarse woody debris and fine woody debris into consideration during biomass removal (Juutilainen et al. 2011).

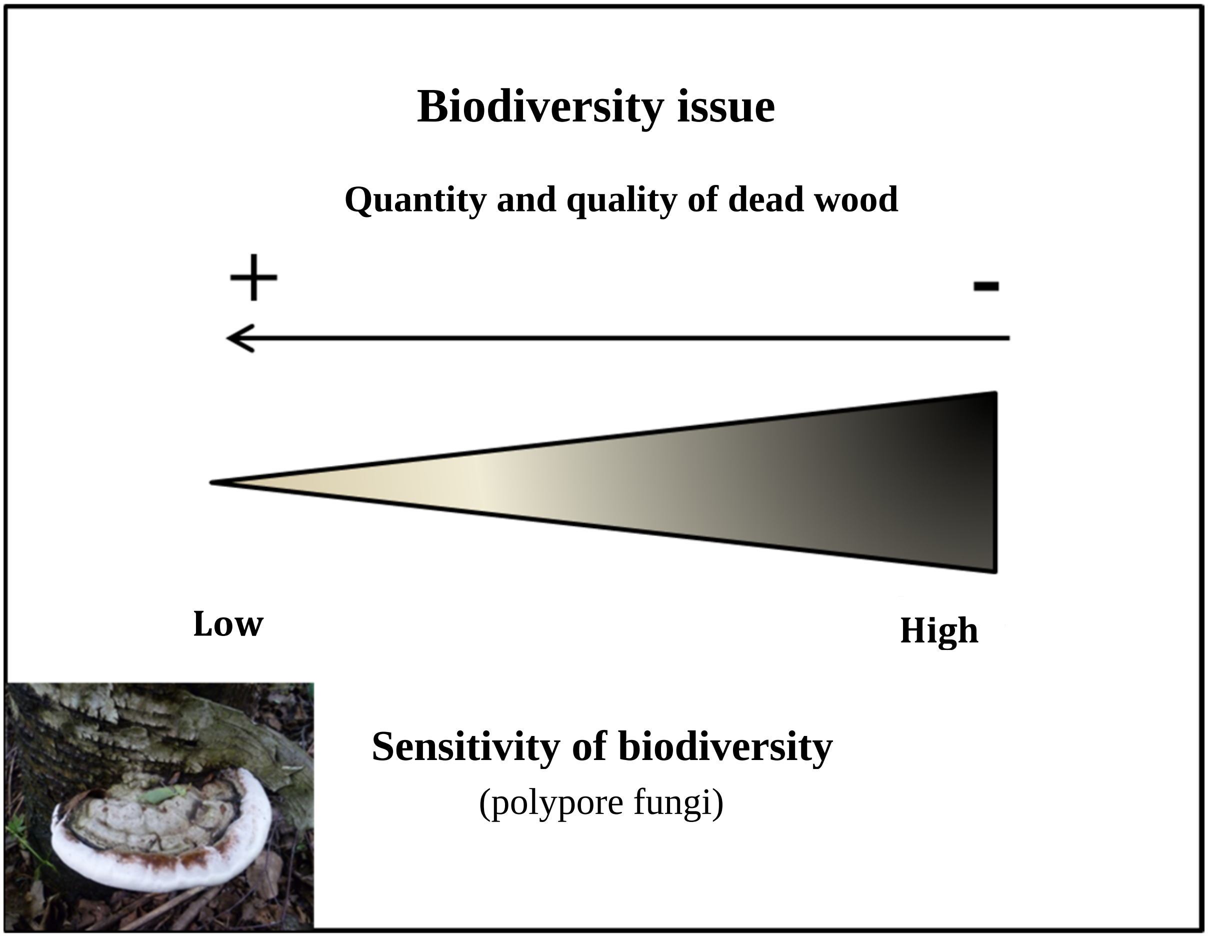

Figure 5. Sensitivity index of biodiversity (polypore fungi).

To date, very little research has been able to establish dead wood retention targets for forest harvesting with a view to maintain biodiversity. A few studies have proposed specific targets consisting of quantities of dead wood to be retained during timber harvesting. However, they do not make specific recommendations relating to the spatial arrangement of woody debris, tree species or rate of decay; those elements are nonetheless identified in the studies as being just as important for maintaining ecological diversity (Stewart et al. 2010).

2.2. Water and riparian zones

Given the close links between soil and surface water, forest operations conducted in terrestrial ecosystems can have consequences on aquatic ecosystems, particularly on stream quality and ecology (Laudon et al. 2011). Forest management-induced disturbances can affect water flow as well as the physical, chemical and biological properties of streams (Janowiak and Webster 2010). Although the impacts of forestry activities on this resource have been the focus of many research projects over the years, few of them have focussed on the specific effects of removing logging residues. Therefore, the effects of this practice on water quality at the landscape level are still poorly understood (Laudon et al. 2011); however, they are generally considered to be similar to the impacts of other intensive forest harvesting activities (Stewart et al. 2010).

Stewart et al. (2010) identify four types of potential biomass harvesting impacts on water resources: sedimentation, nutrient concentrations, stream temperature, and water availability.

"Hydrological Implications of Forest Biomass Use", a report by Buttle and Murray (2011), provides additional information on the subject. According to their research, the removal of harvest residues would have little impact on soil moisture content in sites where clearcutting has been performed. In fact, biomass would intercept rainfall, which would decrease net precipitation on the ground surface. On the other hand, the presence of residues would prevent an increase in soil temperature by diminishing solar radiation and wind velocity, which together reduce evaporation at the soil surface. Field studies also show that the effect of residues on the amount of water in the soil is often minor or non-existent (e.g., Zabowski et al. 2000; Trottier-Picard et al. 2014).

The presence of residues can have an impact on the amount of snow present on a site, as well as its melting rate in the spring. The presence of biomass helps to retain more snow on sites, and thus increases the amount of water (infiltration, runoff) during the melting period in spring. In addition, residues could contribute to an increase in the melting rate of snow. Overall, the combined effect of higher amounts of snow and a more rapid spring melt could cause greater water infiltration into the soil and thus increased availability of water to streams (Buttle and Murray 2011). In this sense, biomass harvesting would contribute to the regulation of stream flows.

In addition, the presence of forest biomass on a harvested site could slow surface runoff and thus reduce the erosion of mineral soil, which would reduce sediment transport from slopes to streams (Buttle and Murray 2011; Stewart et al. 2010).

Also, the shade cast on streams by woody debris could help to moderate sharp increases in average water temperature (Jackson et al. 2001). When woody residues are removed from areas where riparian buffers are not maintained, stream turbidity may increase (Hornbeck et al. 1986). Similarly, biomass removal can interfere with the role that dead wood and logging residues normally play in regulating flow and filtering water when left in place (European Environment Agency 2006).

In summary, harvesting logging residues carries potential risks for water quality and riparian areas. However, very few empirical studies confirm these risks. Therefore, we are still largely at the hypothesis stage with regard to the real impacts of biomass harvesting on water and riparian areas.

2.3. Soil productivity

Forest biomass harvesting can have an impact on soil productivity. One of the theoretical effects of forest biomass harvesting on soil is a reduction in organic matter content and nutrients, namely nitrogen (N), phosphorus (P), and base cations (potassium (K), calcium (Ca), and magnesium (Mg)). This impact can be explained by the fact that biomass removal means that less organic material is returned to the soil than in the case of conventional stem-only harvesting.

However, the mechanisms through which biomass harvesting influences soil fertility seem more complex than the simple export of organic matter and nutrients (Thiffault et al. 2011).

2.3.1. Organic matter

The organic matter content of soil affects its capacity to retain water and nutrients. Although biomass removal deprives the soil of a source of organic material, field studies have shown that biomass removal has little to no effect on soil carbon (e.g., Brandtberg and Olsson 2012; Klockow et al. 2013), except on very sandy, coarse soils that contain little organic matter to begin with (Thiffault et al. 2011). Sandy, coarse-textured soils or soils with low levels of organic matter are thus considered sensitive to biomass harvesting (Page-Dumroese et al. 2010) (Figure 6).

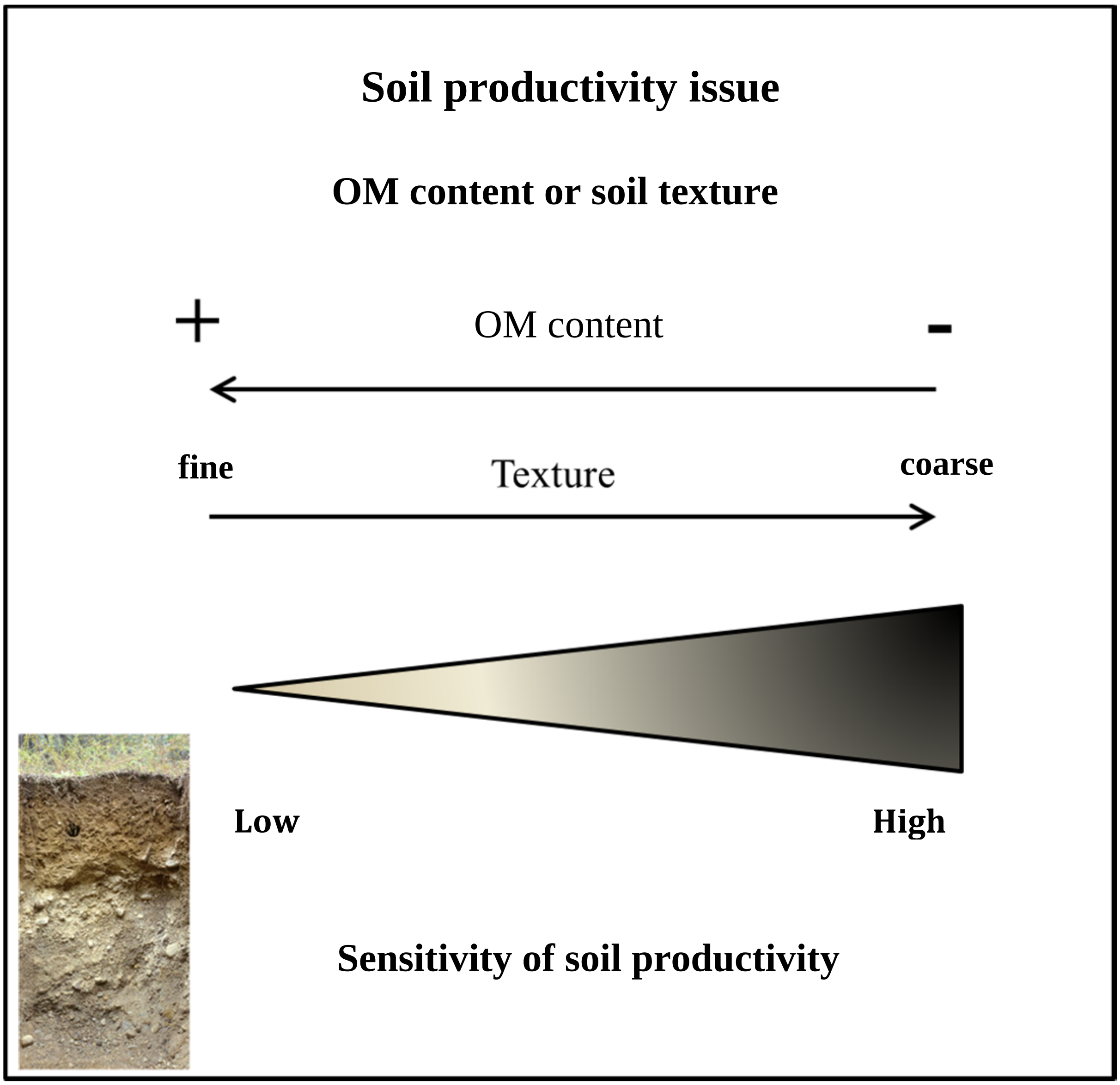

Figure 6. Sensitivity index based on soil organic matter (OM) content or soil texture.

2.3.2. Nitrogen

As with carbon, the effect that forest residue removal has on soil nitrogen reserves does not show a clear trend (e.g., Brandtberg and Olsson 2012; Klockow et al. 2013). Although the effect of reduced nitrogen stocks in the soil has not been clearly demonstrated, it seems that residue removal could affect nitrogen cycling mechanisms between soil and vegetation, thus impairing the nitrogen nutrition of trees (Thiffault et al. 2011) and the ability of forest sites to fix atmospheric nitrogen. For example, a study by Wilhelm et al. (2013) suggests that the removal of woody debris in stands dominated by oaks on sandy soils in Wisconsin causes a decrease in the rate of nitrogen accumulation in soils. However, due to the fragmented nature of the scientific information available, it is not possible to establish a site sensitivity index in relation to nitrogen in the soil.

2.3.3. Phosphorus

Forest biomass harvesting can have a significant effect on soil phosphorus reserves. For example, logging residue removal from pine stands growing on highly altered soils in the southern United States caused a reduction in phosphorus and a decrease in tree growth (Scott et al. 2004; Scott and Dean 2006). However, this risk is probably limited to geographic regions where soils have particularly low phosphorus concentrations (e.g., in the southern United States) or to specific sites such as abandoned farmlands (Figure 7).

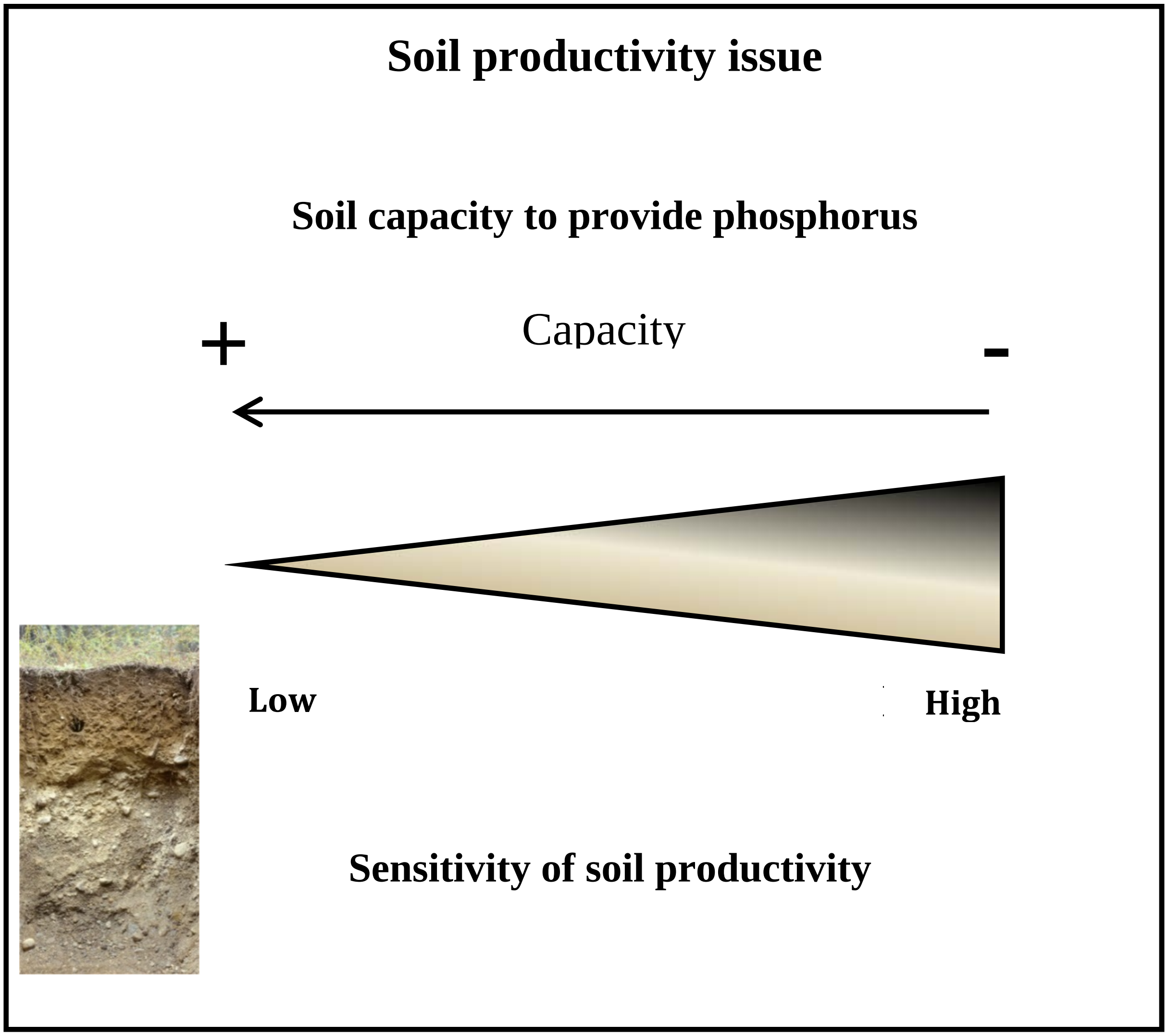

Figure 7. Sensitivity index based on the soil's capacity to provide phosphorus.

2.3.4. Base cations

Forest biomass harvesting also influences base cation reserves in the soil (Ca, Mg, K). This practice can contribute to a reduction in the availability of base cations, particularly in poor soils with low base cation levels in their mineral composition. While this seldom leads to reduced tree growth, it may decrease tree vigour and increase their susceptibility to environmental stresses such as drought or frost (Figure 8) (McLaughlin and Wimmer 1999; De Hayes et al. 1999; Schaberg et al. 2001).

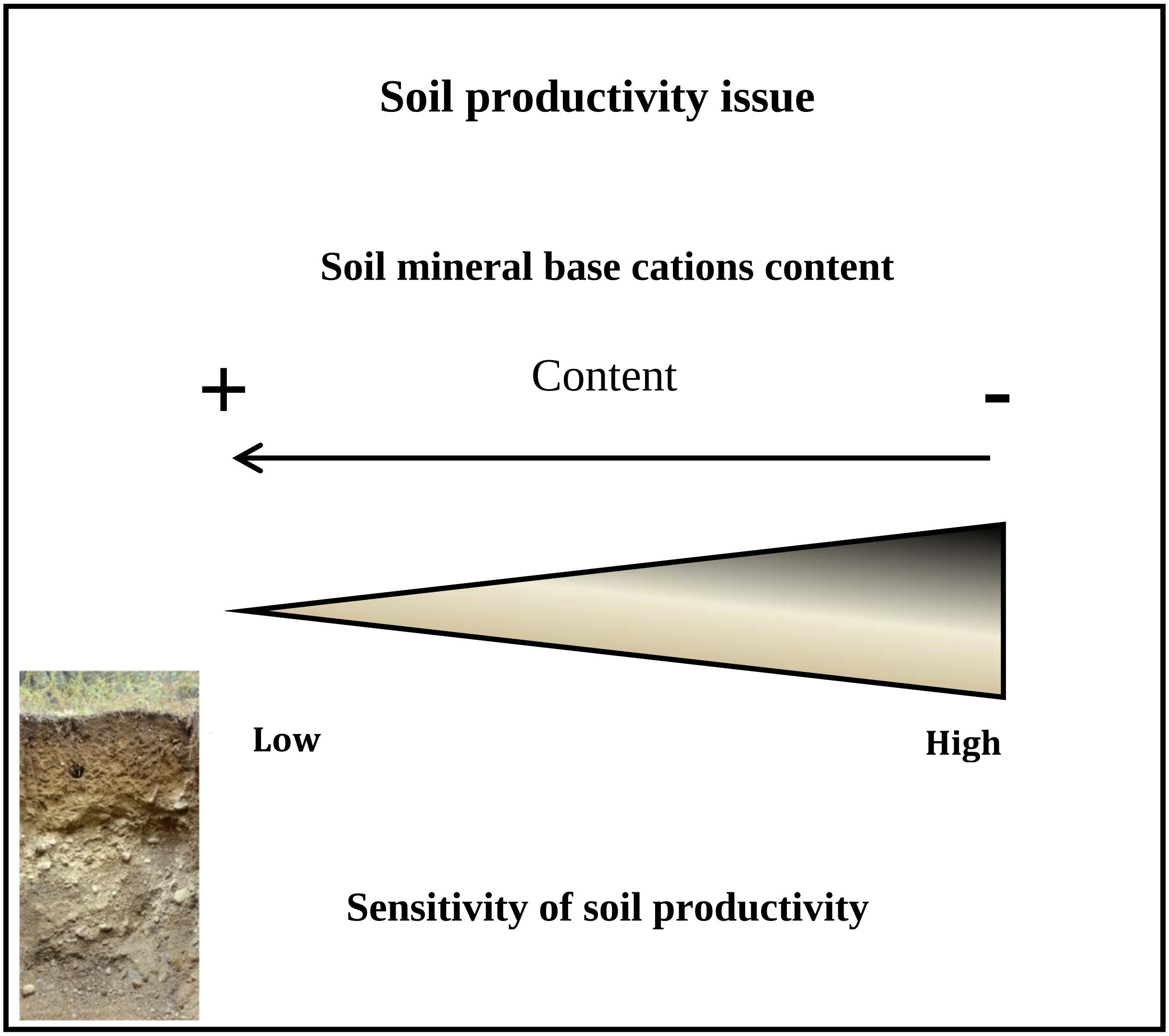

Figure 8. Sensitivity index based on soil mineral base cations content.

Forest growth causes natural acidification of soils because it entails the removal of more cations than anions by trees, which results in the release of H+ into the soil solution through their roots (Nilsson et al. 1982; van Breemen et al. 1983). However, forest harvesting prevents the natural replenishment of base cation reserves because it permanently deprives the soil of a large amount of base cations taken up by the vegetation since these concentrations are not returned to the soil through decomposition of organic matter. This phenomenon could potentially be of concern in regions affected by high acid rain precipitation, as shown by theoretical soil acidification models, since they already are vulnerable. However, field studies have shown that, in reality, the acidifying effect of biomass harvesting is less than that predicted by theoretical models (Staaf and Olsson 1991).

2.4. Stand productivity

The effects of residue removal on tree growth and stand productivity are very complex. Residues affect the microclimate, nutrient levels, water availability and vegetation, all of which can play significant roles in stand productivity (Figure 9). Limiting factors for tree growth are also highly dependent on site conditions (macroclimate, topography, soil type) and species characteristics, two factors that can change over time as the stand evolves. That is why studies show widely varying results for tree growth response to harvesting treatments (Thiffault et al. 2011).

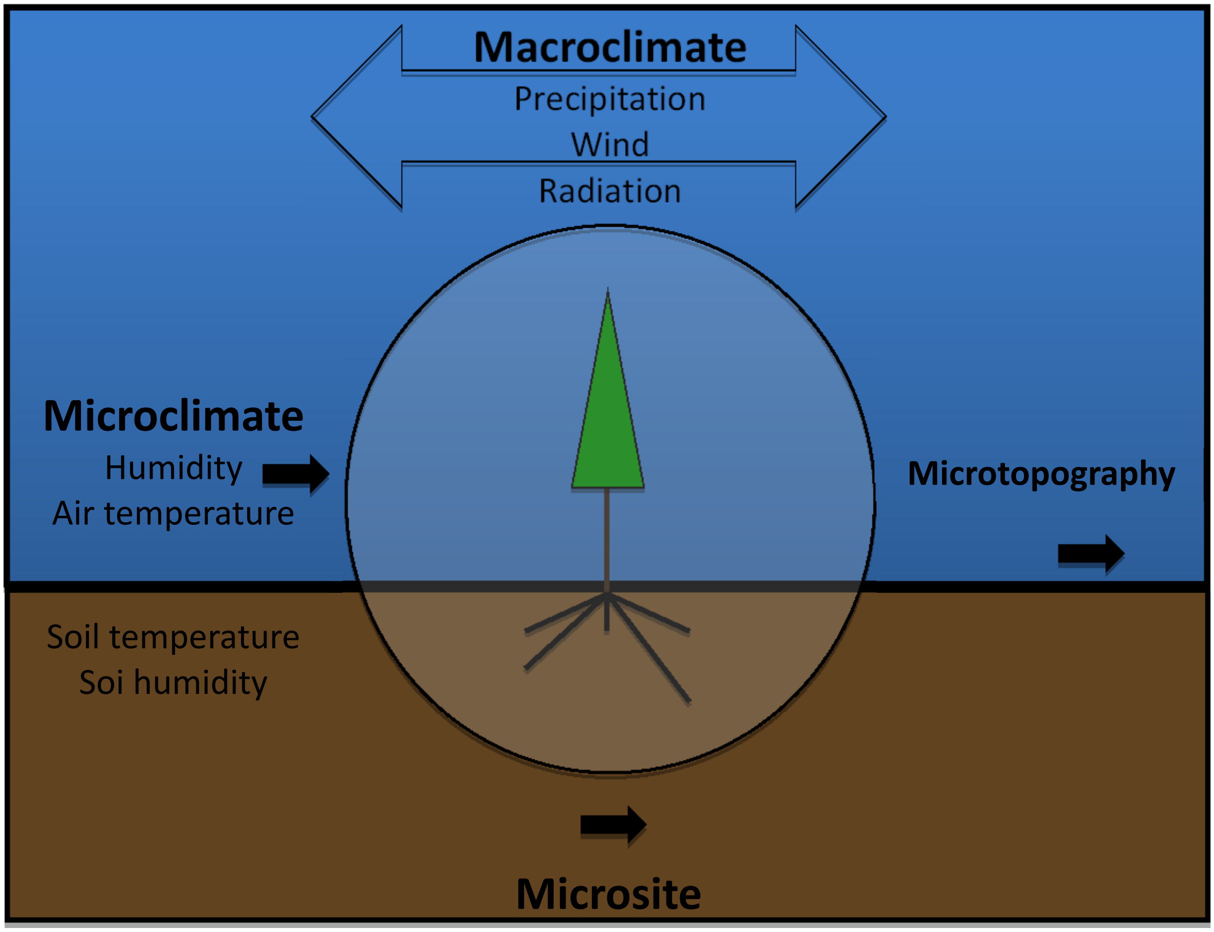

Figure 9. Microsite of a plant.

The various effects of residue harvesting on tree growth and stand productivity are linked, on the one hand, to the microclimate conditions created by this practice and, on the other hand, to its effect on nutrient availability (Thiffault et al. 2011). In the initial years after biomass harvesting, microclimate conditions and vegetation competition are the factors that have the biggest influence on tree growth and stand productivity (Proe et al. 1999). However, as stands approach the canopy closure stage, the trees develop greater needs for water and nutrients, hence the idea that soil fertility would become the predominant factor impairing their growth (Thiffault et al. 2011).

Logging residue removal affects the microclimate and competing vegetation in a number of ways, which in turn affect tree growth and site productivity. This practice causes soil disturbance and soil mixing, which may favour the establishment of natural regeneration, create better conditions for reforestation (Mann 1984; Hendrickson 1988; McInnis and Roberts 1994; Waters et al. 2004; Fleming et al. 2006), and increase the survival and growth of young seedlings (Morris and Miller 1994). In addition, in the absence of residues on the ground, the soil surface receives more solar radiation as well as a greater quantity of rain since biomass does not intercept water. Consequently, the soil warms up earlier in the spring, which makes for a longer growing season, an effect that could be particularly beneficial in cold regions (Figure 10) (Proe et al. 1994; Zabowski et al. 2000).

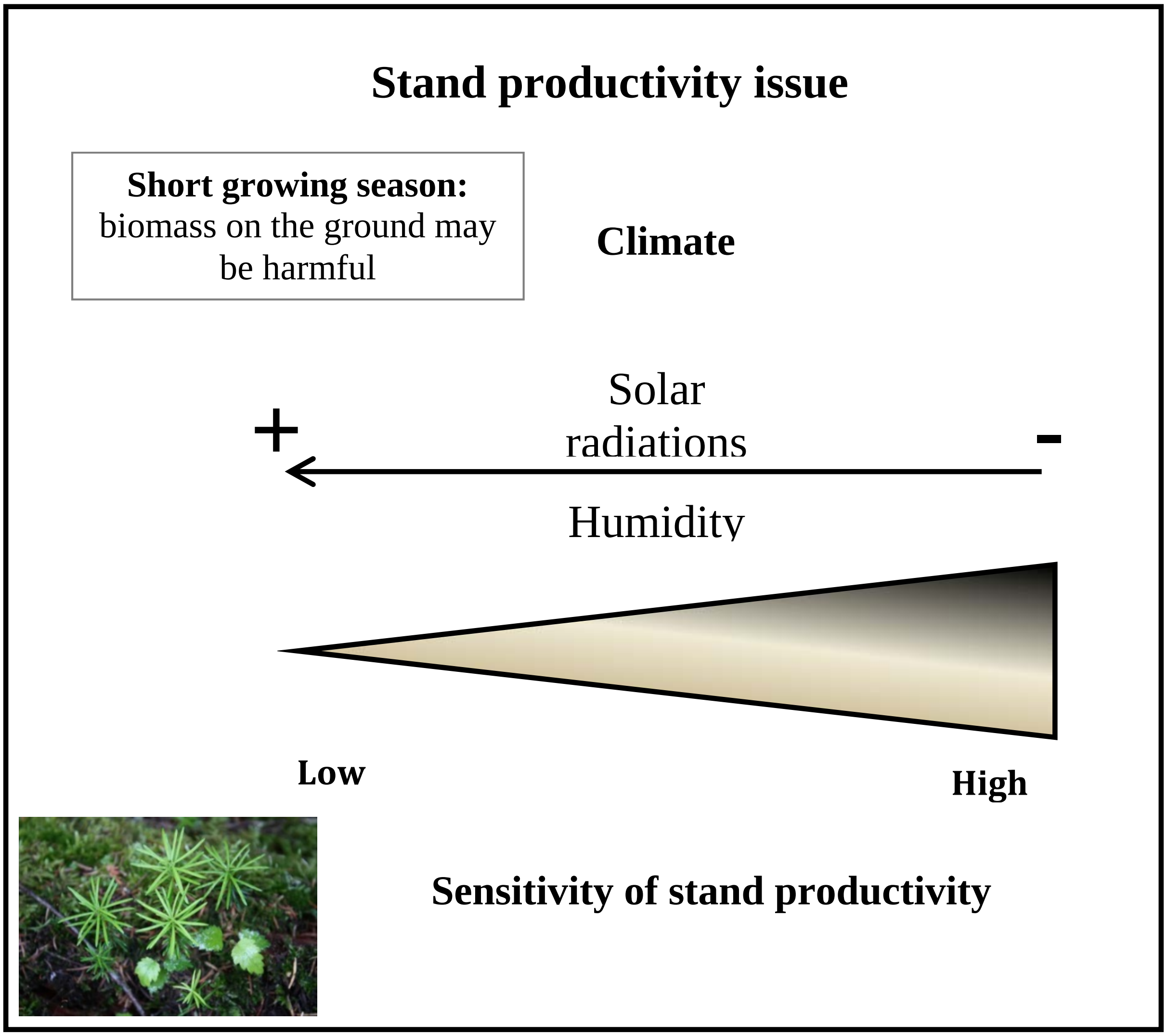

Figure 10. Sensitivity index based on climate.

In contrast, on certain sites, the presence of logging residues may enhance seedling growth by providing shelter and reducing wind speed on largely exposed microsites (Proe et al. 1994). Retention of residues may reduce soil surface temperatures and moisture loss caused by evaporation and evapotranspiration, particularly on dry and less productive sites (Robert et al. 2005). Residues may protect seedlings in microsites that are prone to frost (Fleming et al. 2006) (Figure 11).

Finally, residues left on site can reduce competition by preventing the establishment of competing vegetation (Stevens and Hornung 1990; Fahey et al. 1991; Proe et al. 1994; Trottier-Picard et al. 2014). The study by Trottier-Picard et al. (2014) is the only one performed in Quebec's boreal forest; it concludes that in the short term (2 years after cutting), harvesting residues alter the microenvironment of seedlings by reducing soil temperature and competing vegetation cover, but this does not translate into an effect on tree growth.

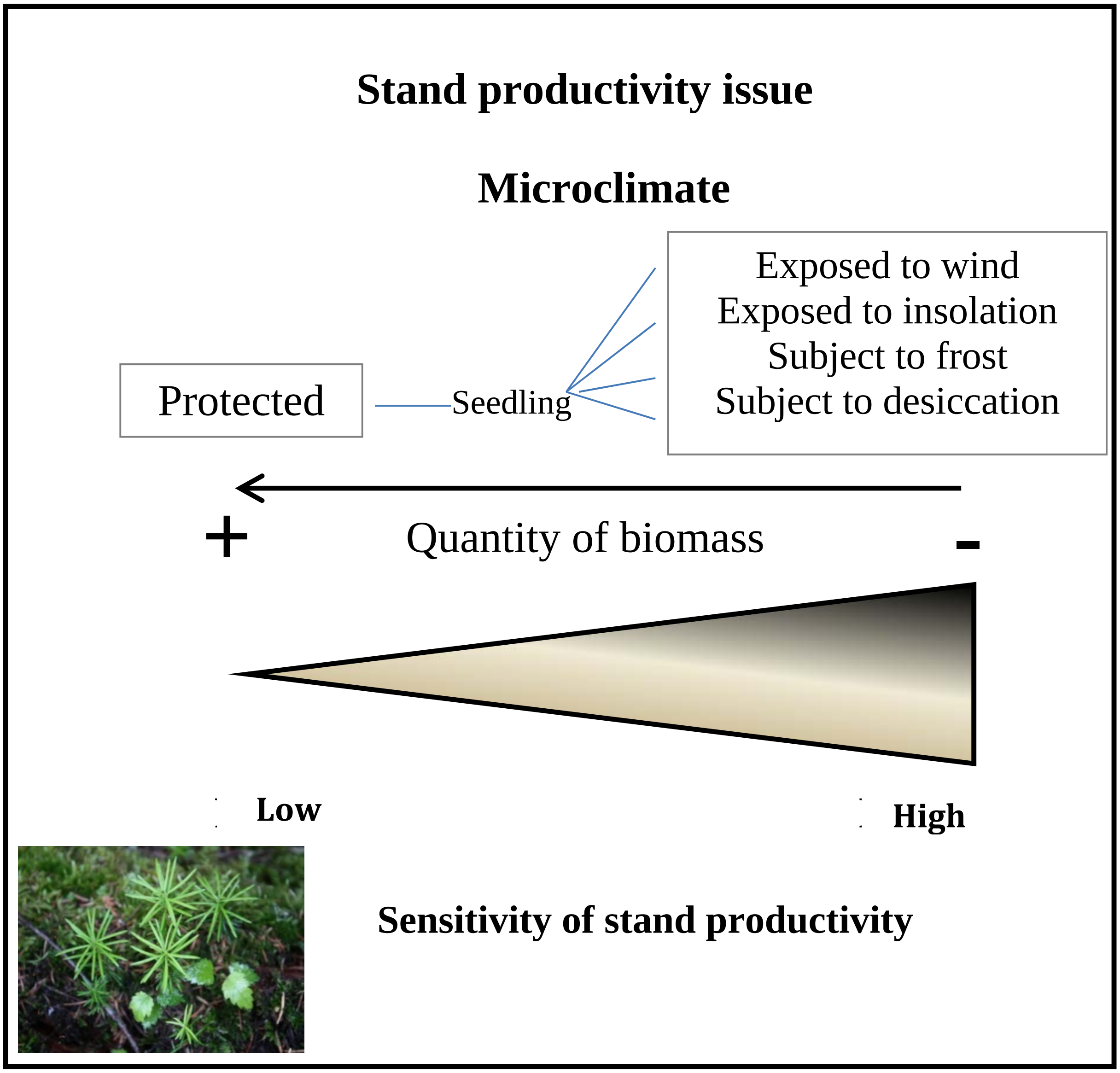

Figure 11. Sensitivity index based on microclimate.

Some research projects have focused on the optimal amount of logging residues to be left on site in order to provide a maximum of microclimate-related silvicultural benefits. For example, Lieffers and Van Rees (2000) developed a residual tree retention index for biomass harvesting in trembling aspen stands on the Canadian Prairies. Since this species' regeneration is linked to suckering, it is important to promote favourable insolation levels and suitable soil temperatures by controlling the amount of residues left on site. Residual trees were classified according to the size of slash piles (Table 1) and recommendations concerning regeneration were made. For example, to promote trembling aspen regeneration, it is important to avoid creating large piles of slash in winter and medium-sized piles in summer (Duinker 2003).

Table 1. Classification of slash piles by size.

Slash pile size	Volume (tonnes/hectare)
Small	< 200
Medium	200 to 400
Large	> 400

Later on during stand rotation, growth and productivity are also dependent on nutrient availability, a factor that is affected by the type of harvesting done. In this case, the species that regenerates after harvesting has an influence on stand growth and productivity responses to biomass removal. In fact, different species may show a different response to harvesting operations (Thiffault et al. 2011). For example, 15- to 20-year-old jack pine stands that regenerated on sites without logging residues showed poorer foliar nutrition than stands established on sites with residues. However, black spruce established on the same sites as jack pine showed no difference between the harvesting treatments (Thiffault et al. 2006). This can be explained by the difference in species' sensitivity to changes in nutrient availability in the soil, particularly nitrogen (Figure 12). Some species (e.g., black spruce) appear to have strategies enabling them to maintain fairly stable nutrition and growth no matter what the soil conditions are; this is often typical of end of succession species that are more shade tolerant and have slow to moderate juvenile growth. On the other hand, in other species, notably those typical of beginning of succession that establish quickly after disturbance or have a fast juvenile growth (e.g., jack pine, trembling aspen), nutrition and growth may be more sensitive to differences in soil nutrient availability (Thiffault et al. 2011); for these so-called "responsive" species, biomass harvesting may thus have a marked negative effect.

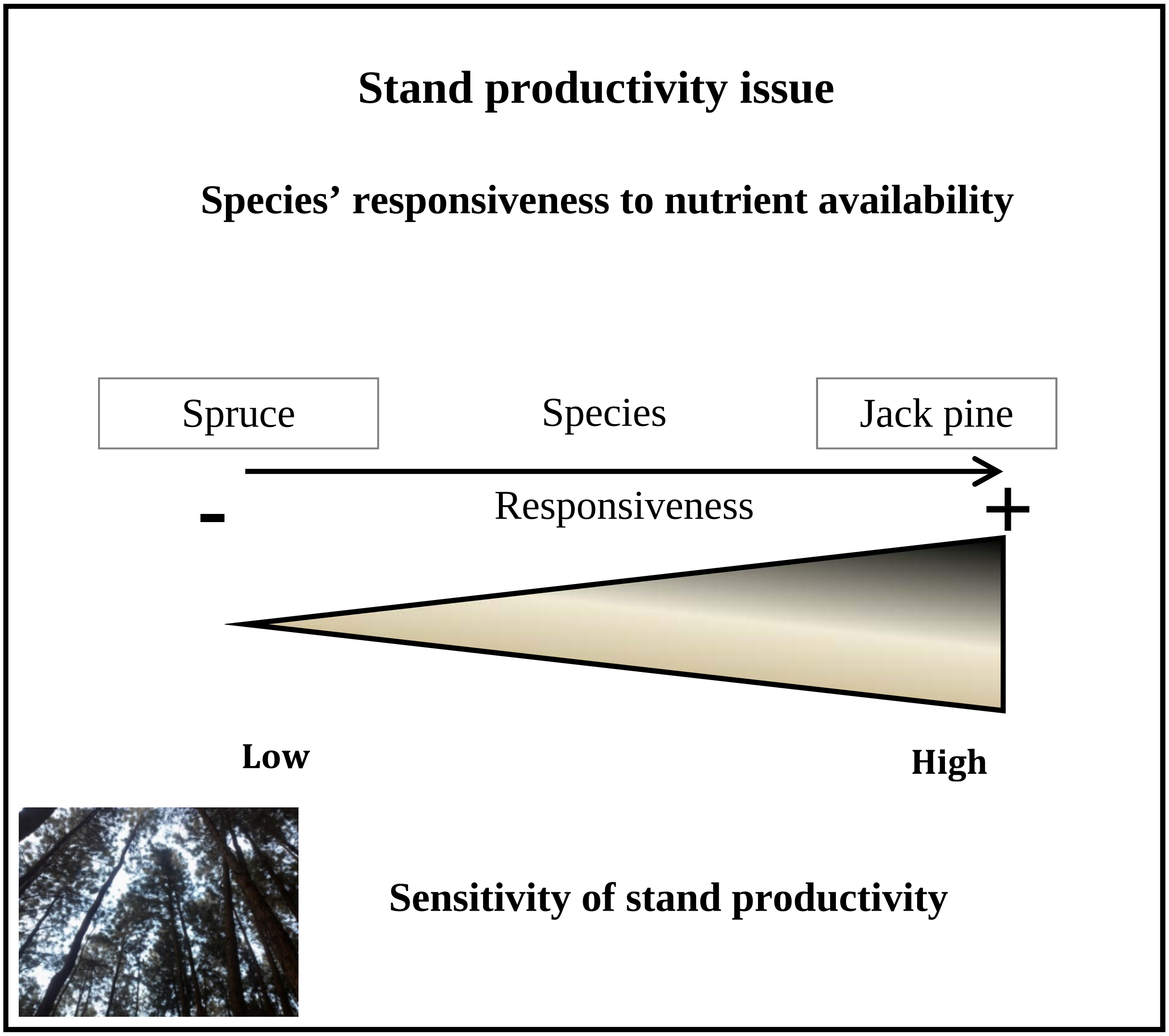

Figure 12. Sensitivity index of species' sensitivity to nutrient availability.

2.5. CO_2 emissions

Forests can be considered as carbon sinks (the process of removing CO_2 from the atmosphere) when they sequester more CO_2 and other greenhouse gases (GHGs[1]) than they emit in a given period, or as carbon sources when they emit more CO_2 than they sequester. These exchanges are determined by natural processes (e.g., decomposition of organic matter), but also by anthropogenic processes resulting from forest management such as timber harvesting, tree planting, natural disturbance control practices (fires, outbreaks), etc. One of the methods recognized by the Intergovernmental Panel on Climate Change (IPCC) to mitigate climate change in the forestry sector is the use of forest biomass for the production of bioenergy to

[1] The principal GHGs that exist in the atmosphere are, in decreasing order (from most polluting to less polluting): carbon dioxide (CO_2 ~ 38 Gt $C0_2$.year^{-1}), methane (CH_4 ~ 7.5 Gt CO_2. year^{-1}) and nitrous oxide ($N0_2$ ~ 3.5 Gt CO_2. year^{-1}). These data correspond to the year 2004 (Intergovernmental Panel on Climate Change (IPCC) 2007).

replace fossil fuels (Comité sur la contribution du secteur forestier à la lutte contre les changements climatiques 2012).

The forest biomass supply chain for bioenergy production results in CO_2 emissions. These emissions occur at each stage of the process to obtain bioenergy: harvesting, transport, storage, conditioning and combustion (Figure 13). In return, the forest acts as a carbon sink by sequestering CO_2, but this capacity varies depending on several factors, including forest type (e.g., old or managed, young or mature), the type of species present (e.g., softwoods or hardwoods, trees, shrubs or grass), and climate (e.g., slower growth in cold climates). Because of this, there is a preconceived notion that all biomass projects for the production of energy are "carbon neutral" (Johnson 2009; McKechnie et al. 2011). The CO_2 emitted into the atmosphere during the production of energy would be captured by the forest through photosynthesis. However, in practice, the CO_2 emitted during the production of bioenergy is not immediately recaptured by the forest; recapture occurs over a more or less longer period.

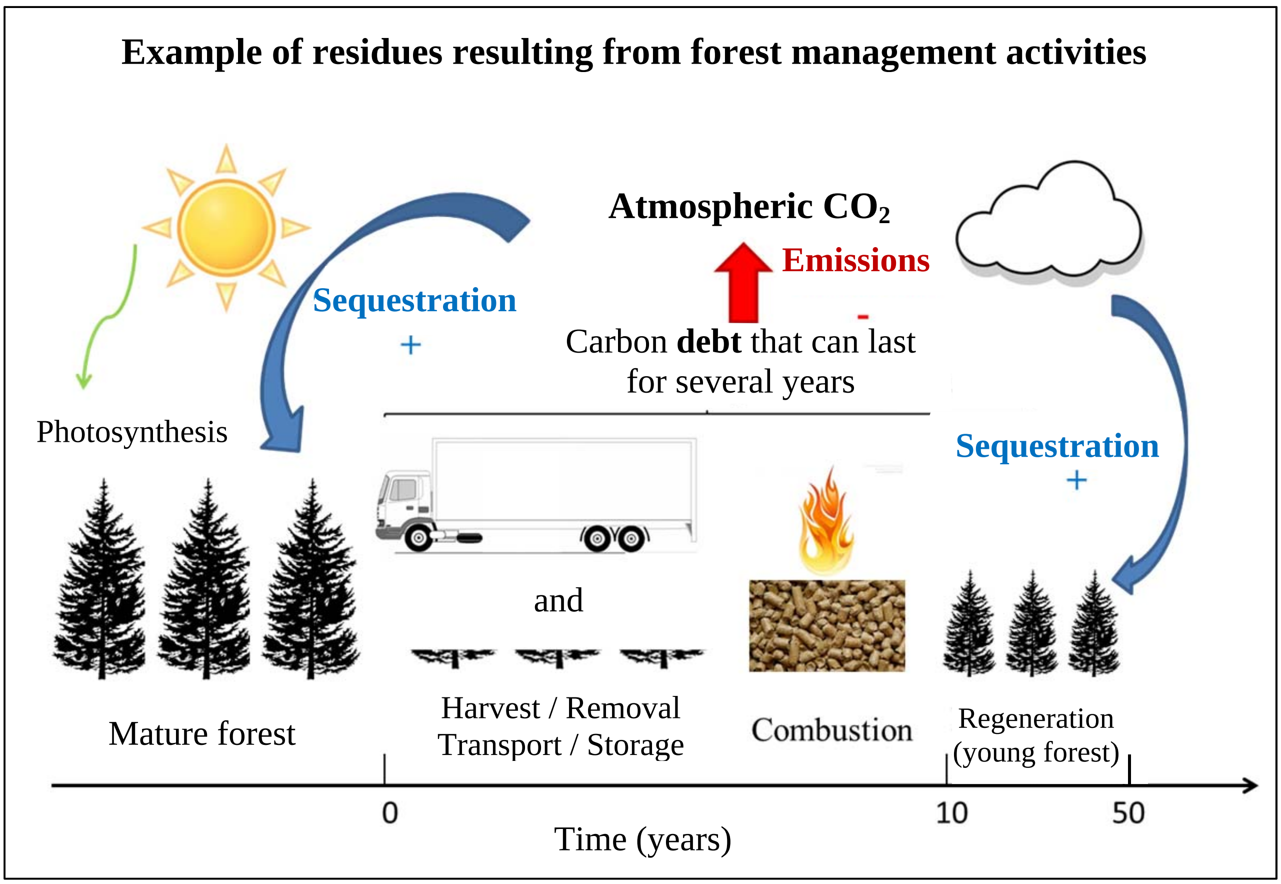

Figure 13. Simplified diagram of the carbon balance in the forest sector (carbon life cycle).

Typically, CO_2 emissions from forest biomass are higher per unit of energy than those from fossil fuels because:

– biomass is less energy dense and emits more CO_2 per unit of energy than fossil fuels;
– biomass is often burned with a lower conversion efficiency than fossil fuels.

This is recognized by international scientific literature and is not a subject of controversy (Bird et al. 2011).

Bioenergy does not physically reduce CO_2 stack emissions. However, the recapture of CO_2 as vegetation regrows results in the use of bioenergy having a beneficial effect on GHG concentrations in the atmosphere over the medium to long term.

Evaluating the contribution of forest biomass to reducing CO_2 emissions in a view to replace fossil fuels is done by comparing the emissions scenario in which biomass is the resource used to produce energy, i.e., the “Bioenergy” scenario, with emissions in the baseline scenario. The baseline scenario is the scenario that would normally occur if the biomass project had not existed. Specifically, all of the activities of a biomass project are determined in the “Bioenergy” scenario, and the overall sinks and total emissions associated with the use of biomass or fossil fuels to produce a given amount of energy are compared.

In some cases, the baseline scenario is easy to establish and comparison with the “Bioenergy” scenario is simple. This is particularly true when the biomass used comes from a site managed to produce additional biomass. For example, a project to establish energy plantations on old abandoned farmlands provides immediate benefits in terms of reducing GHG emissions. It creates additional biomass and therefore additional CO_2 absorption beyond that which would be absorbed in the baseline scenario without conversion into bioenergy.

This is also the case when bioenergy production uses logging residues, post-consumer wood waste or other forms of residual biomass that would otherwise decompose and emit CO_2 into the atmosphere in a short amount of time. In these cases, the contribution of forest biomass to reducing CO_2 emissions is rapid and certain.

The benefits in terms of emissions reduction are more far-off, uncertain or difficult to predict with biomass sources such as green trees. In the baseline scenario, the trees would likely have continued to sequester carbon for some time. This loss of fixation creates a “carbon debt” in the “Bioenergy” scenario, which is repaid gradually as the trees grow back and recapture the carbon emitted from tree burning. However, it is possible that in the baseline scenario, the trees undergo natural disturbances or are harvested to make other products. There are many hypotheses, which makes the prediction of actual benefits to the atmosphere uncertain.

It is also recognized that the conversion of natural forests into energy plantations causes negative effects on the climate. The substitution of a mature forest by an energy plantation results in significant CO_2 emissions at the time of conversion due to the reduction in carbon stocks. The carbon debt related to conversion often takes a very long time to repay, despite the reduced amount of fossil fuels being used (Righelato and Spracklen 2007).

Other sources of biomass lie between these two extremes, from sources of biomass with rapid and certain benefits to those with far-off and more uncertain benefits.

All things being equal, the sources of biomass that provide certain and **short-term** benefits are (Figure 14):

– post-consumer waste;
– industrial waste;
– logging residues and other forest management residues that decompose rapidly (e.g., young trees originating from precommercial thinning);
– biomass from short-rotation plantations in afforestation.

Sources of biomass that provide **medium-term** benefits are (Figure 14):

– wood salvaged following natural disturbances;
– forest management residues that decompose more slowly (large trees that are cut but have no commercial value);
– wood from live trees with no commercial use that are left standing after clearcutting and are liable to die quickly.

Sources of biomass that provide more uncertain and **long-term** benefits are (Figure 14):

– wood of standing live trees directly used for bioenergy;
– plantation biomass originating from the conversion of mature forests.

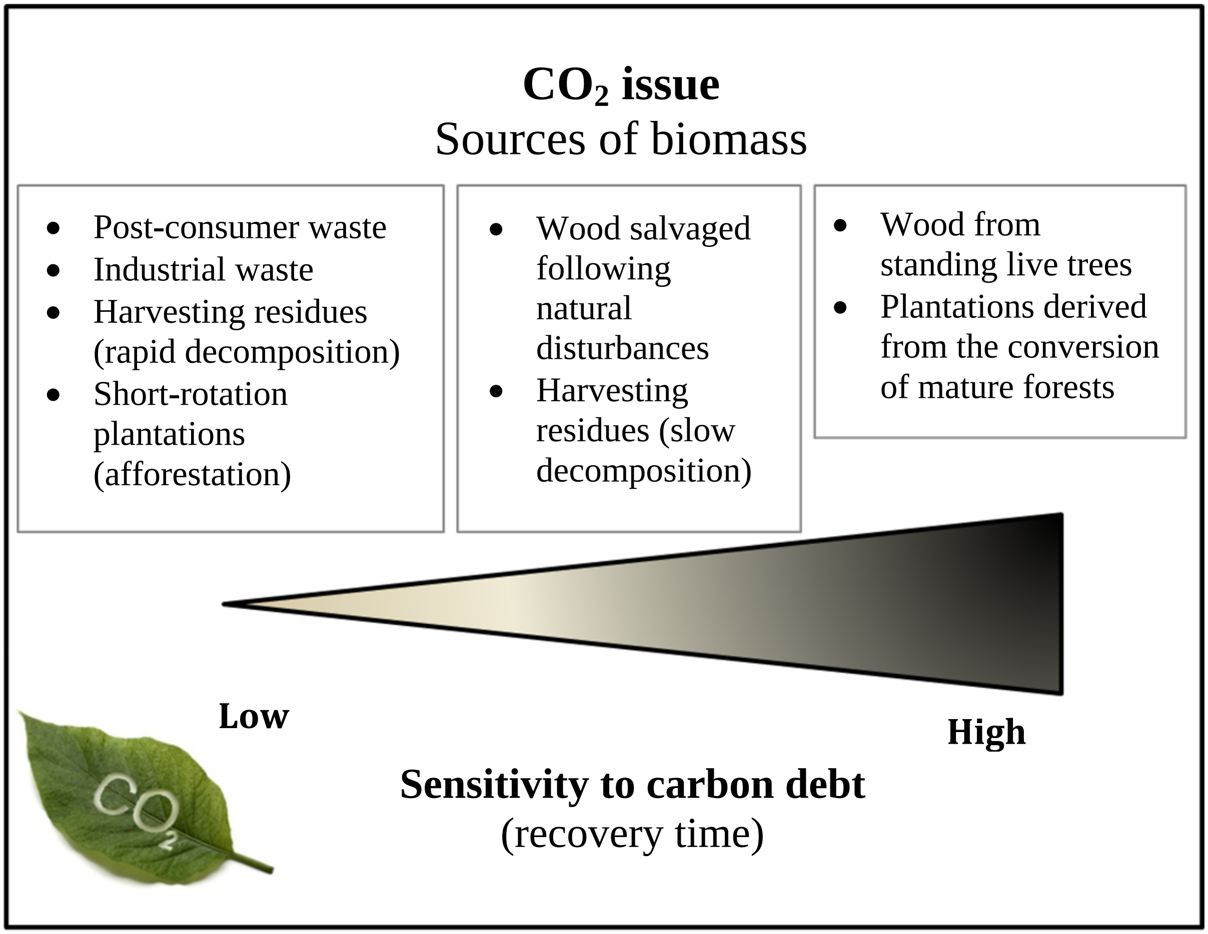

Figure 14. Sensitivity index based on the short-, medium-, and long-term benefits of biomass sources.

The timing and certainty of benefits arising from the use of forest bioenergy therefore depend on the source of forest biomass used. Other parameters also cause these benefits to vary: the method used to convert biomass into energy (efficiency of energy production) and the type of fossil fuel replaced.

The amount of useful energy produced from forest biomass depends on the conversion method used. For example, the efficiency rate of conversion solely for the production of electricity by conventional thermal power plants is 35% to 45%, while the rates for heating boilers alone and for co-generation (combined heat and power) increase on average to 90% and 85%, respectively (European Environment Agency 2010). Therefore, based on that order, the conversion methods that should be given priority, starting with the most advantageous, are (Figure 15):

1. heat and co-generation;
2. electricity;
3. biofuel.

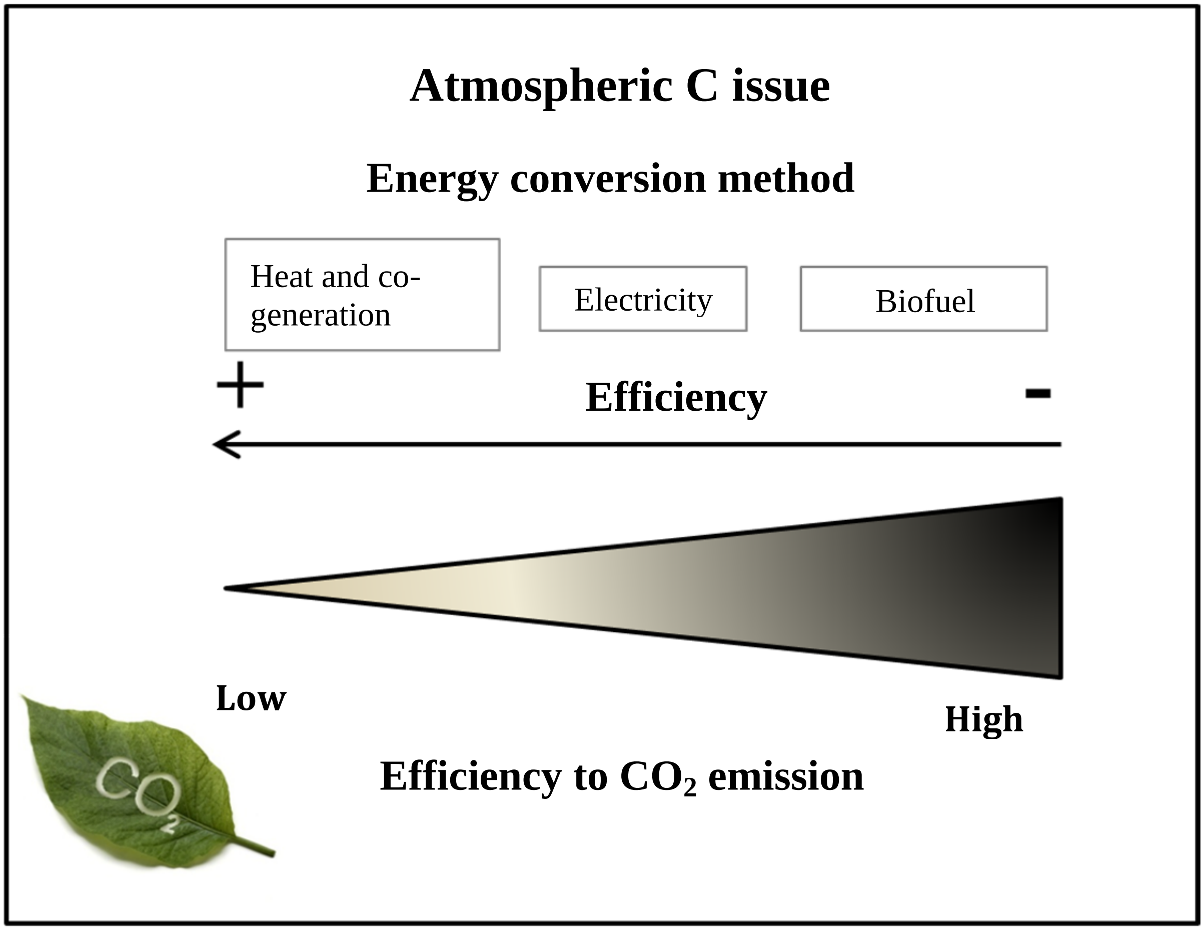

Figure 15. Sensitivity index based on the method used to convert biomass into energy

Some fossil fuels emit more CO_2 per unit of energy than others, and their priority replacement increases the generation swiftness and scope of benefits generated by a bioenergy project for climate. Fossil fuels can be classified in decreasing order of CO_2 emissions per unit of energy produced (kg/GJ), with the first thus presenting the best opportunity for substitution by biomass (Comité sur la contribution du secteur forestier à la lutte contre les changements climatiques 2012):

1. Coal 92,385 kg CO_2/GJ;
2. Heavy fuel oil 74,032 kg CO_2/GJ;
3. Light fuel oil, diesel 70,483/72,125 kg CO_2/GJ;
4. Gasoline 68,145/73,156 kg CO_2/GJ;
5. Natural gas 50,198 kg CO_2/GJ.

In addition, pre-consumer emissions, which are linked to the extraction of fossil fuels, are generally very high. In fact, all oil extraction methods generate significant pre-consumer emissions, much higher than those related to forest biomass. These emissions can be particularly high in the case of oil extraction by steam injection or when natural gas is burned as waste from oil extraction, as is is practiced in some operations not served by gas pipelines. Refining also causes significant emissions due to the combustion of gas waste from the fractional distillation process, among other things. All of these emission sources combined reach an average of 25% of stack emissions (Air Resources Board 2009; Manomet Center for Conservation Sciences 2010).

In summary, the source of biomass, the conversion method and the type of fossil fuel replaced are key factors in the selection of biomass projects that will maximize benefits to the atmosphere. Over time, any biomass project inevitably generates a reduction in CO_2 emissions compared with a scenario based on the use of fossil fuels. When analyzing a biomass project, the challenge is not to demonstrate that a benefit exists, but rather to determine when it will occur and to what extent.

The timing and extent of the benefit to the atmosphere can vary greatly from one project to another. The carbon debt of a project using logging residues can be repaid after 6 years and generates perpetual profits thereafter (Table 2) (Comité sur la contribution du secteur forestier à la lutte contre les changements climatiques 2012). However, the debt can take almost 100 years to be repaid if green trees are harvested from natural forests to produce energy. The faster the debt is repaid, the faster benefits are generated, which reduces the impact on global warming. Table 2 illustrates the high sensitivity of the duration of carbon debt repayment (from 4 to more than 100 years) compared with the parameters of a project that uses forest biomass for energy production by presenting some examples taken from the scientific literature.

Table 2. Examples of carbon debt repayment times associated with main project parameters (analytical methods may vary between projects).

Debt (years)	Type of forest biomass used	Conversion method (Energy produced)	Fossil fuel replaced	Reference
4	Branches	Heat	Natural gas	Repo et al. 2011
6	Logging residues[1]	Heat	Fuel oil	Bernier and Paré, in press, GCB Bioenergy
22	Stumps	Heat	Natural gas	Repo et al. 2011
70-75	Merchantable stems[2]	Heat (residential and urban heating)	Fuel oil	Manuilova and Johnston 2011
74	Logging residues	Ethanol	Gasoline (E85 Fuel)	McKechnie et al. 2011
90	Whole trees[3]	Heat	Fuel oil	Bernier and Paré, personal communication
> 100	Whole trees	Ethanol	Gasoline (E85 Fuel)	McKechnie et al. 2011

1. Logging residues: non-merchantable parts of the tree, generally the branches and sometimes the thin end of the stem.
2. Stem: Main stem of the tree, between the trunk and the top.
3. Whole tree: Entire aerial portion of the tree, including the stem and branches

Source: Comité sur la contribution du secteur forestier à la lutte contre les changements climatiques (2012).

3. Biomass harvesting guidelines around the world

Several jurisdictions in Europe and North America have developed guidelines, regulatory or otherwise, that take the environmental and social impacts of forest biomass harvesting into consideration. These jurisdictions have the option to retain only the guidelines that apply to conventional forestry practices, to adapt them, or to develop new guidelines that apply specifically to forest biomass harvesting. The guidelines may take on the form of general recommendations or more prescriptive indexes that include specific thresholds to be met. They are built based on knowledge acquired by scientists as well as local experts. The impacts of biomass harvesting are often deducted from the impacts associated with other types of forestry operations. Therefore, issues related to the removal of forest residues are often already partially covered by a set of best management practices and by legislation governing traditional forestry practices. Lastly, certification systems specifically ensuring sustainable forest biomass production are currently being developed.

If biomass harvesting is to be integrated with conventional forestry activities, the different jurisdictions involved need to develop guidelines that take into account the effects of this new practice, at different levels, on the environment and on communities (Fernholtz et al. 2009). To date, a number of European jurisdictions (European Community, Denmark, Finland, France, United Kingdom, Scandinavia, Sweden) and North American ones (United States: Maine, Missouri, Minnesota, Pennsylvania, Wisconsin, Michigan, Massachusetts, Maryland, Vermont and California; Canada: New Brunswick, Nova Scotia, Ontario, Quebec and British Columbia) (Stewart et al. 2010, 2011) have tackled this issue. Since forest regimes vary from jurisdiction to jurisdiction, it should be noted that some of the guidelines have regulatory force, meaning that they are legally binding, whereas others are merely recommendations on the best practices to be applied.

3.1. Guidelines

Guidelines are developed using different approaches. In some cases, existing guidelines for conventional forestry practices are considered adequate to cover biomass harvesting activities and therefore no additional action is required. However, when those guidelines are considered insufficient, some jurisdictions prefer to develop a distinct set of guidelines governing biomass harvesting or to adapt the existing legislation (Evans et al. 2010).

3.1.1. Adaptive forest management

Guideline development is a process that varies widely and involves a diversity of actors. Ideally, the process is carried out according to an adaptive forest management process. (Thiffault et al. 2010). First, the new legislation must be based on the existing scientific literature concerning the effects of forest biomass harvesting. Second, the participation of representatives of the different jurisdictions is essential in order to identify all of the potential impacts of forest biomass removal. Third, the guidelines must be revised as new information becomes available from monitoring and research efforts (Figure 16).

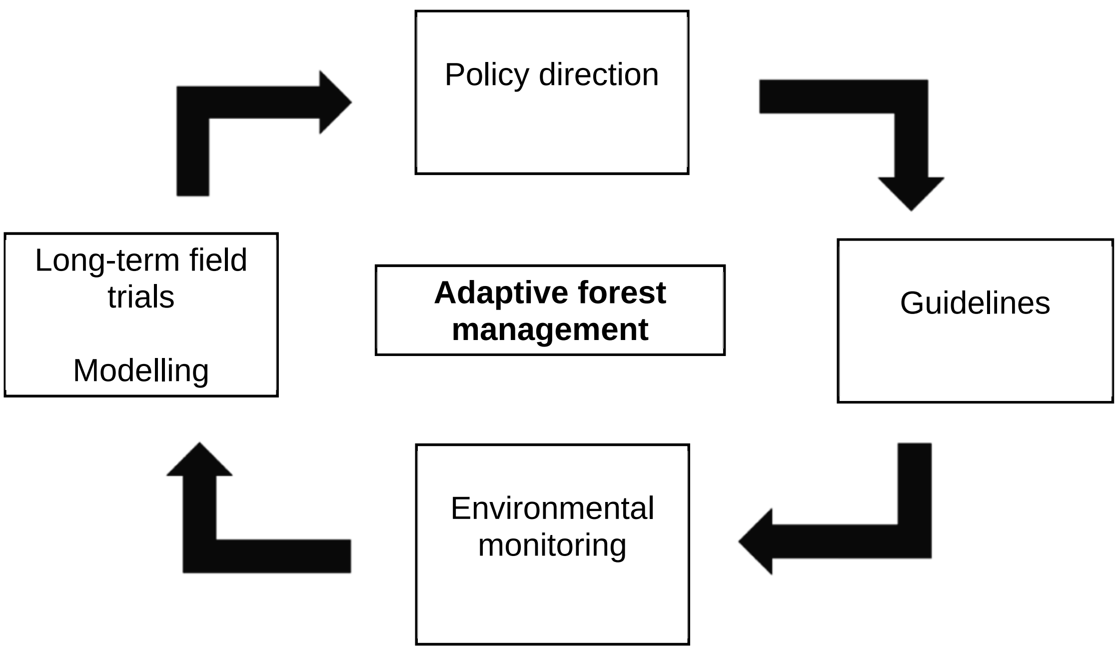

Figure 16. Adaptive forest management.

Several jurisdictions have adhered to some of these essential prerequisites in their guideline development approach, including Wisconsin, Ontario and Sweden. In Wisconsin, the existing guidelines are subject to periodic review based on the best scientific information available. The guidelines are assessed by expert groups and stakeholders, and undergo public consultation (Wisconsin Department of Natural Resources 2008).

In Ontario, the guideline development process is likewise based on the principle of adaptive management, which entails research efforts, increased surveys, monitoring of the impacts of biomass removal practices, and regulation amendment as new information becomes available. Consequently, new knowledge acquired by scientists is transferred to decision makers, who in turn incorporate it into the existing legislation. Collaboration among the different levels of government (federal, provincial) and academic institutions is also encouraged (Puddister et al. 2011).

Lastly, since 1986, the Swedish Forest Agency has developed a set of recommendations and best practices for forest biomass harvesting. These guidelines were updated between 1993 and 1998 using information from various research initiatives undertaken to gain a better understanding of the ecological impacts of this practice. In 2002, the recommendations were codified in the *Swedish Forestry Act*. This new legislation was subjected to an evaluation process involving various stakeholders (academic institutions, forest industry, non-governmental agencies, etc.) who were asked to provide suggestions for improvements. The most recent revision of the guidelines on logging residues removal practices dates back to 2008 (Levin and Eriksson 2010).

3.1.2. Recommendations and sensitivity indices

In general, guidelines are recommendations made to prevent the negative impacts of biomass harvesting on ecosystems. They may also be prescriptive, meaning that they establish an index of site conditions for which the environmental risk presented by biomass harvesting is low, moderate or high. Sensitivity indices concern a site's level of sensitivity or the environmental risk to a site, which varies according to a given factor. For example, the coarser the soil texture, the greater is the site's sensitivity and its risk of being negatively affected. The type of harvesting permitted on a given site is inversely proportional to the level of sensitivity or risk. Thus, on low-sensitivity sites, biomass harvesting is permitted with few or no restrictions. However, the higher the sensitivity level, the greater the restrictions placed on harvesting logging residues, up to prohibition. To this end, forest sites are often classified according to specific thresholds in order to provide a framework for biomass harvesting practices. Therefore, depending on the characteristics of the forest site, its level of sensitivity may be considered high (harvesting prohibited), moderate (conditional harvesting) or low (harvesting permitted) (Figure 17).

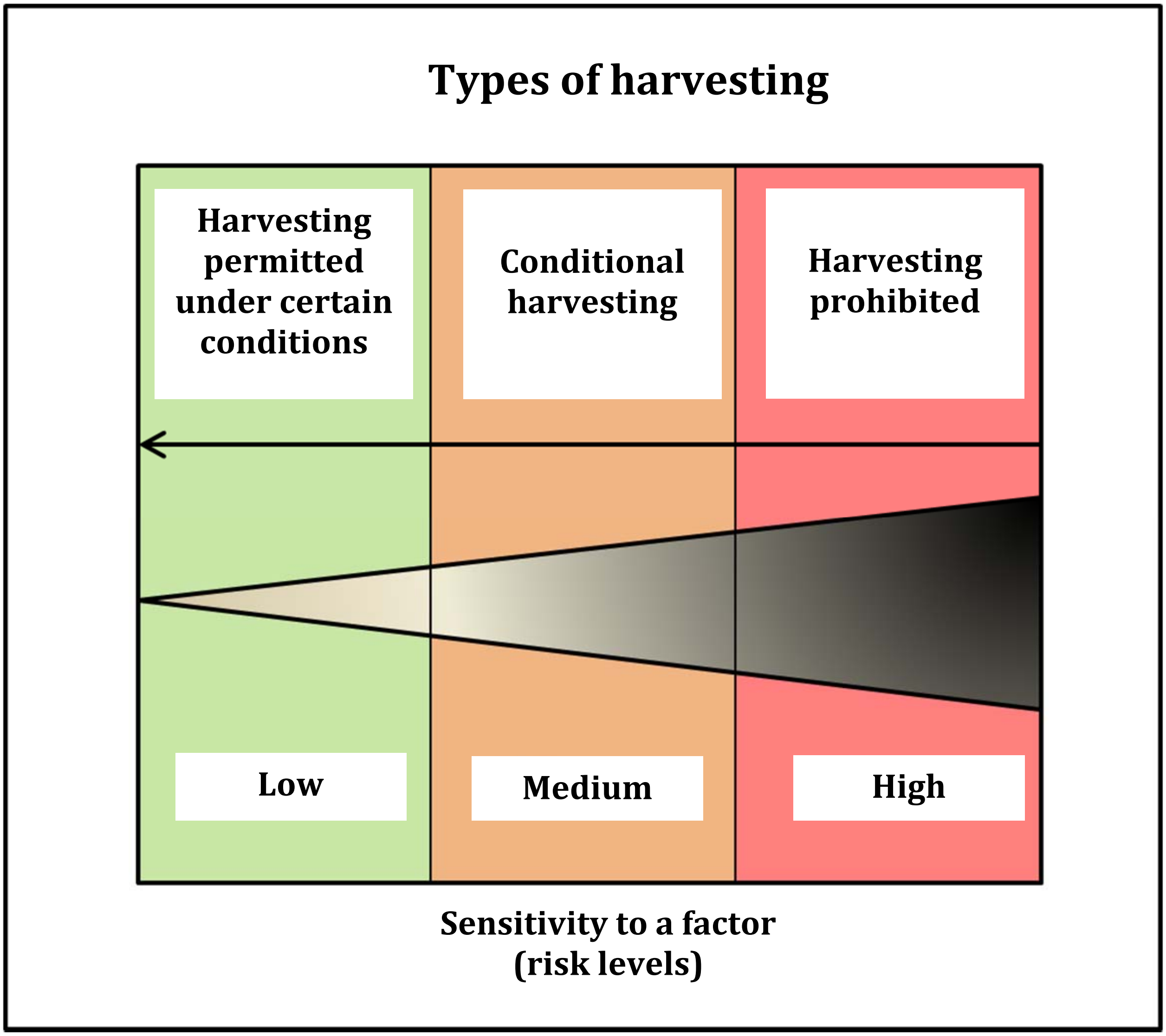

Figure 17. Sensitivity index and types of harvesting.

Guidelines in the form of recommendations are presented in Appendix 1. The different jurisdictions deal with the issue of soil productivity through the use of sensitivity levels linked to different degrees of risk. This issue is presented in Appendix 2.

In general, the forest biomass harvesting guidelines developed by different jurisdictions are based on scientific knowledge and input provided by local experts. Consequently, the expected environmental impacts of forest biomass harvesting are often predicted or deduced from the known impacts of other forestry operations.

Similarly, the precise thresholds identified in the documents consulted are not usually taken directly from the scientific literature. For example, the dead wood retention targets set out in U.S. guidelines are more or less supported by references to the scientific literature (Stewart et al. 2010). Most of these thresholds were established based on experts' advice and local knowledge.

In many jurisdictions, several biomass harvesting issues such as water protection or biodiversity are already covered by best management practices or by existing legislation governing forestry operations at large (Evans et al. 2010). Nonetheless, most forest residues removal guidelines include complementary recommendations to address the additional pressure that this practice could place on ecosystems.

The information currently presented in the scientific literature and that of future studies could help to create more elaborate, accurate and efficient guidelines with regard to biomass harvesting practices that respect various environmental issues. To this end, research initiatives should focus to a greater extent on identifying thresholds associated with levels of environmental risk.

3.2 Recommendations and sensitivity indices according to issue

3.2.1. Biodiversity

Based on the guidelines assembled in Appendix 1, the most common recommendations aimed at reducing the negative effects of biomass harvesting on biodiversity are to:

- retain dead wood (coarse woody debris, fine woody debris, logs and snags);
- retain wildlife trees (seed trees, live trees, cavity trees, etc.);
- retain forest floor (humus), stumps and roots;
- avoid biomass removal on sites with significant conservation value; and
- avoid biomass removal near habitats used by threatened or endangered species.

The importance of most of these recommendations for biodiversity conservation is widely recognized. Most of them have already been taken into consideration in the legislation administered by a number of jurisdictions. However, few jurisdictions have set specific targets for harvest residue retention on sites. For example, to preserve the richness of polypore communities, Brazee et al. (2012) recommend retaining a certain proportion of fine woody debris (<5 cm diameter), but they do not indicate the volume to be left on site. Table 3 shows some retention guidelines depending on the type of structure.

Table 3. General guidelines for forest structure retention.

Structure	Minimum target (per acre[1])		Considerations
	Number	Basal area (foot²)	
Declining live trees (12-18 inches[3] DBH)	**4**	**4**	In locations where the trees designated for retention are not present and where the targets cannot be met due to species or site conditions, leave the largest trees on site.
Declining live trees (> 18 inches DBH)	**1**	**1**	
Snags (> 10 inches DBH)	**5**	**5**	Worker safety is a priority. Retain as many snags as possible, but if individual snags must be felled for safety reasons, they should be left in the forest.

1. Measurement unit: 1 acre = 0.40 ha.
2. Measurement unit: 1 foot = 30.48 cm.
3. Measurement unit: 1 inch = 25.4 mm.

These guidelines do not have to be applied in all circumstances. They are methods that can be implemented in a stand, a harvest block or a private lot (Forest Guild Biomass Working Group 2010).

In addition, there are objectives based on forest type for the quantity of woody debris (snags and dead wood) to be left on site during biomass harvesting (Table 4).

Table 4. Objectives for forest structures.

Type of forests	Snags	Dead wood
Southern Appalachians hardwood	At least 17 snags per acre > 4 inches DBH	At least 3 tonnes per acre
Uplands hardwood and pine-hardwood mixed forests	At least 11 snags per acre > 4 inches DBH	At least 3 tonnes per acre
Lowlands hardwood	At least 6 snags per acre > 10 inches DBH	At least 3 tonnes per acre
Piedmont and pine coastal plain	At least 5 snags per acre > 4 inches DBH	At least 1 tonne per acre

Source: Forest Guild Southeast Biomass Working Group (2012).

3.2.2. Water and riparian zones

In Appendix 1, we can identify the following recommendations for maintaining water quality:

- plan and build roads carefully;
- minimize soil exposure;
- promote rapid recovery of vegetation;
- maintain buffer zones adjacent to streams;
- retain some logging residues and standing trees; and
- select harvesting equipment that minimizes soil disturbance.

In most cases, regulations governing forestry practices already contain provisions for the protection of water resources and riparian zones. These best practices could ensure the protection of water resources within the context of biomass harvesting, provided that certain elements specific to this new practice, such as fertilization, are taken into account (Shepard 2006).

3.2.3. Soil productivity

Many jurisdictions have soil productivity guidelines that are based on site sensitivity indices. These indices are presented in Appendix 2. It should be noted that the different soil characteristics used in different jurisdictions likely refer to the same concepts of soil sensitivity. For example, most jurisdictions consider poor soils to be at risk. However, since the range of soil conditions differs from country to country, what is considered poor soil in one jurisdiction may not be considered poor in another. For example, podzols are considered poor, and therefore sensitive, in the United Kingdom’s soil fertility classification scheme, whereas in Finland (whose boreal stands grow mainly on podzols), very dry, coarse and lichen-dominated soils are considered poor and sensitive.

In addition to establishing sensitivity indices, most jurisdictions have formulated complementary recommendations related to soil productivity (Appendix 1). The key recommendations in this regard are to:

- retain the forest floor (humus), stumps and root systems on the site;
- retain a proportion of logging residues on the site;
- limit disturbances associated with road or landing construction;
- minimize soil disturbance, including compaction, rutting and erosion; and
- fertilize certain sites with wood ash.

It should be noted that, as with the protection of water and riparian zones, soil productivity is often addressed in the different jurisdictions’ legislation pertaining to forestry practices. For example, in Michigan, the *Sustainable Soil and Water Quality Practices on Forest Land Manual* (IC 4011) sets out specific guidelines that cover soil protection (Stewart et al. 2010).

The guidelines relate mainly to the physical disturbance of the soil (compaction, erosion, rutting, etc.) due to more frequent machinery traffic and the removal of part of the ground cover that normally acts as a carpet to reduce the impact of this traffic. However, the aspects aimed at preserving soil chemistry (level of acidity, nutrient reserves, etc.) are less often covered in the recommendations.

Recommendations for the protection of soil productivity specific to forest conditions in Quebec, based on the knowledge and recommendations made elsewhere, are found in Appendix 2.

3.2.4. Stand productivity

Guidelines concerning stand productivity have been developed by several U.S. states (Appendix 1). The most commonly encountered recommendations in the U.S. guidelines are to:

- avoid converting natural forests into plantations;
- limit the number of entries into stands;
- avoid selective cutting; and
- use biomass harvesting to achieve various management objectives: salvage and stand sanitation operations, aesthetics, reduction in forest fuel loads, control of invasive plant species, etc.

Most of the recommendations established by U.S. states are not aimed at forest biomass production *per se*. Residue harvesting is rather viewed as a silvicultural tool for attaining desirable stand conditions (Stewart et al. 2010). Consequently, most of the recommendations are aimed at exploiting the benefits associated with biomass harvesting in order to achieve these favourable conditions rather than addressing the potential negative effects of this practice on site productivity.

Reduction in forest fire risk is one of the management objectives most often associated with forest biomass harvesting. This management approach makes it possible to create stand structures that are more fire resistant by reducing forest fuel loads (small-diameter trees, slash on the ground, etc.) (Stewart et al. 2010). Managing and collecting these fuel materials through biomass removal may help to reduce fire risk by reducing fire intensity, by promoting measures to control this disturbance, and by reducing its effects on other issues. In addition, since fuel management entails frequent and costly interventions, combining this practice with the removal of forest residues for bioenergy production could be a way to make these operations profitable (Landmann et al. 2009).

3.2.5. CO_2 emissions

In general, existing guidelines on forest biomass harvesting do not include recommendations on the carbon issue. However, some U.S. states, namely California, Oregon and Washington, address the subject of carbon (North East State Foresters Association (NEFA) 2012). For example, in Oregon, one of the recommendations is to use the resource efficiently and, specifically, to promote co-generation (Oregon Forest Biomass Working Group (OFBWG) 2011).

However, in the northeastern United States, recommendations for the CO_2 issue by the Forest Guild Biomass Working Group (2010) often address forest management as a whole:

- Prevent conversion of forests to other land-use systems. Forest biomass harvesting can reduce the urge to convert forests because it offers a new source of income to forest owners and maintains supplies for the forest industry and markets.
- Prioritize uneven-aged forest structures over even-aged ones. Silvicultural methods that favour the development of complex structures (uneven-aged forests) sequester more carbon than silviculture aimed at recreating homogeneous conditions. When even-aged structures are recommended, favour advanced regeneration or retain the residual components of the initial stand. When it comes to shade-tolerant or moderately shade-tolerant species, favour uneven-aged plantations as this increases carbon sequestration.
- Retain trees or delay their removal. Lengthen rotation periods.
- Prioritize the use of woody debris for energy production over green trees. Woody debris decompose and emit carbon whereas green trees continue to sequester atmospheric carbon and other GHGs.
- Prioritize the harvesting of diseased or short-lived trees over healthy trees (longer lifespan and faster carbon sequestration). In addition, they can produce higher quality products, so that their carbon sequestration capacity is much longer compared with products with a shorter life cycle (e.g., paper).

Lastly, one of the aspects mentioned, fire prevention through biomass harvesting, also applies to the issue of carbon sequestration. In fact, by reducing the risk of fire, biomass harvesting also reduces CO_2 emissions (Stewart et al. 2011).

However, these guidelines do not include recommendations on the volume of forest biomass to remove in order to minimize the "carbon debt". This volume can only be determined by modelling carbon flow over time (Forest Guild Biomass Working Group 2010) and must be specific to site conditions. In addition, these recommendations are not always realistic mainly because of technical and economic constraints arising from the diversity of sites. It is therefore important to adapt the recommendations to the specific characteristics of the site.

In Quebec, in order maximize reductions of GHG emissions in the short term (2020), the *Comité sur la contribution du secteur forestier à la lutte contre les changements climatiques* (2012) recommends prioritizing projects characterized by:

- the use of residual biomass (logging residues, post-consumer wood) which emissions related to production, transportation and preparation are low or nil;
- the production of heat and co-generation;
- the replacement of coal and petroleum products; and
- the analysis of the complete life cycle of the biomass project (GHG distribution over time).

3.3. Certification

The development of certification systems that provide a framework for biomass harvesting for energy production addresses concerns regarding the sustainability of these harvesting practices. The increase in biomass production and marketing has environmental, economic and social consequences. Therefore, certification appears to be a means of ensuring the sustainability of biomass production by minimizing the negative impacts that are associated with it (van Dam 2008).

In the forestry context, certification is an independent third-party attestation that forest products are generated from sustainably managed lands (Hall 2002; Van Dam 2009). Certification is based on a set of principles, criteria and indicators specifically designed to assess the sustainable management of forests (Lattimore et al. 2009). The principles are the fundamental statements about a desired outcome, the criteria are the necessary and sufficient conditions that need to be met to comply with a principle, and the indicators enable the assessment of whether or not a criterion has been met (Business and Biodiversity Offsets Program (BBOP) 2012).

At present, there is no specific certification system for sustainable production of forest solid biomass. However, efforts are under way at the international level to establish criteria and indicators that can be used as the basis for a future biomass harvesting certification system (Stewart et al. 2010). In addition, this process will be able to draw on existing certification systems for other energy-related products (van Dam 2009).

Forest certification systems take into account a wide range of forest cover types, tenures, and harvesting objectives and treatments (Stewart el al. 2010). Although they do not set out criteria and indicators specifically related to biomass harvesting for bioenergy, some aspects of these systems may be applicable. One approach for ensuring forest biomass certification would be to incorporate information related to this practice into existing criteria and indicators for sustainable forest management (Lattimore et al. 2009). These sustainable forest management certification programs are compatible with those related to bioenergy, although they do not take GHG emissions, air quality, food safety, and several segments of the forest biomass supply chain into account (Gan and Cashore 2013).

Thus, the Forest Stewardship Council (FSC) International and the Programme for the Endorsement of Forest Certification (PEFC) International are the main international umbrella organizations for forest certification. They review and endorse national certification standards that comply with their own sustainability standards (Stewart et al. 2010). These standards have a hierarchical structure articulated around principles, criteria and indicators that are used to assess the participants’ practices from an environmental, social and economic standpoint (Stupak 2007; Lattimore et al. 2009). The Sustainable Forestry Initiative (SFI) and the Canadian Standards Association (CSA) are two examples of national forest certification systems endorsed by the PEFC (Stewart et al. 2010). The SFI does not include specific requirements on GHG emissions, air quality or local food safety, but the SFI program (2010-2014) contains elements on bioenergy production using forest biomass, carbon sequestration and climate change (Gan and Cashore 2013). The CSA has a criterion that directly addresses biomass, Criterion 2, which recommends the development of guidelines for sustainable biomass harvesting when an agency has an interest in biomass removal for bioenergy production (Stewart et al. 2011).

More globally, the Roundtable on Sustainable Biofuels (RSB), coordinated by the École Polytechnique Fédérale de Lausanne (Switzerland), has developed a certification standard with 12 principles and 37 criteria applicable to four types of operators: forest biomass producers, forest biomass processors, biofuel producers, and blenders (Stewart et al. 2011). These principles were developed by a multidisciplinary team including bioenergy companies, biomass producers, research organizations, governments and NGOs. "Version 2", which became effective in January 2011 (Gan and Cashore 2013), covers biofuels (e.g., bioethanol, biodiesel) and solid biomass products (e.g., wood chips, pellets). The principles and certification criteria relate to the majority of the issues presented in this guide. For example, aspects related to conservation (biodiversity, ecosystems, etc.), water, and soil are considered. Aspects related to GHG emissions and air quality are also covered. Similarly, the social aspect (community well-being and development) and ongoing improvement are strongly emphasized in this standard that may function as a certification system (Roundtable on Sustainable Biofuels 2011).

Another bioenergy certification system is the International Sustainability and Carbon Certification (ISCC), which has 6 principles and 92 criteria for biofuels and solid biomass products (International Sustainability and Carbon Certification (ISCC) 2011). As with the RSB, it was developed by various stakeholders in the bioenergy supply chain as well as NGOs. The principles include restrictions on the production of biomass on lands with high conservation value or high carbon stock, soil, water and air protection, and the adoption of good agricultural practices. Similarly, the social aspect is also addressed (International Sustainability and Carbon Certification (ISCC) 2011).

Because the same principles and criteria are found in sustainable forest management certification systems and those related to bioenergy production, Gan and Cashore (2013) suggest combining the two certification systems. This could prevent the duplication of information and reduce certification costs. In addition, the experience acquired in sustainable forest management certification systems could accelerate the implementation of bioenergy certification programs. Moreover, barriers such as the practice of prescribed burning – often permitted during forest operations for the production of commercial timber but banned during forest residue harvesting – constrain the harmonization of the two certification systems.

Internationally, the Food and Agriculture Organization (FAO) of the United Nations runs the Sustainable Wood Energy System (SWLS) program, which focuses on bioenergy production from biomass (FAO 2010). The Bioenergy and Food Security Criteria and Indicators (BEFSCI) project aims to develop principles, criteria and indicators for the sustainable production of bioenergy while maintaining food safety (Stewart et al. 2011). Other international organizations working on sustainable bioenergy production are:

- Global Bioenergy Partnership (www.globalbioenergy.org);
- European Commission: Directive on renewable energy and EU Biomass Action Plan (http://ec.europa.eu/energy/renewables/bioenergy/bioenergy_en.htm);
- International Energy Agency (IEA) – Bioenergy (http://www.ieabioenergy.com/).

Thus, in Europe, the fact that the import of forest biomass is continually increasing and that there is a risk this biomass may be produced unsustainably, the principal European biomass- importing countries have begun to establish national sustainability requirements for bioenergy. This has led to the emergence of certification systems (voluntary and mandatory) (European Commission (EC) 2010). For example, the Solid Standards project brings together various stakeholders (producers, traders and end users of solid biofuels and the actors involved in standardization and certification) in the form of information sessions, thereby increasing their ability to implement quality biomass projects that are sustainable and certified. Lastly, the Green Standard Certification Program (GSCP) is an initiative of the United Academy of Business (UAB)[2], which specifies the requirements for organizations in the development and implementation of green approaches for a safe, healthy and green environment that provides green services and products via a sustainable business. Certification is done through the issuance of Green Certificates, and requirements are evaluated according to international standards such as ISO 14064-3 for quantification, monitoring and social responsibility reports.

In Canada, the most concrete government initiative aimed at developing a certification process for forest biomass is the EcoLogo Program, an environmental labelling program launched by the federal government in 1988. The goal of the program is to compare products/services with others in the same category and to develop certification criteria that can be used to award the EcoLogo label to environmentally preferable products/services through an in-depth evaluation and audit process (EcoLogo 2011). EcoLogo has 122 sets of certification criteria for 250 types of products.

For example, the EcoLogo Renewable Low-Impact Electricity Products standard CCD-003 sets out electricity generation requirements. To comply with the standard, renewable low-impact electricity products (wind-powered electricity, water-powered electricity, biomass-fuelled electricity, etc.) must be generated in accordance with specific provisions; these are related, among other things, to the survival of threatened or endangered species, stakeholder consultation, land use (biodiversity, cultural values, etc.), control of potential environmental impacts and analysis of cumulative effects. The standard also sets out audit requirements intended to ensure product compliance with the criteria.

4. Conclusion

Many studies are currently being conducted on different aspects related to the implementation of forest biomass harvesting in boreal forests (harvesting techniques, equipment, processing, products, etc.). The environmental impacts of forest residue removal, as well as the more technical aspects, are now a primary concern for researchers and for the different jurisdictions involved in this new practice, which represents a new economic activity.

Thanks to the development of guidelines based on the best scientific information available, these jurisdictions can govern forest biomass harvesting. In this context, various issues such as biodiversity, water quality and riparian zones, soil productivity, stand productivity, and CO_2 emissions must be taken into account. First, public participation is essential in the process of identifying issues and impacts related to biomass harvesting. Public participation helps to highlight potentially conflicting values and avoid future conflict with the public. Similarly, it enables better conformity of the practice with local and regional values (André et al. 2010). Indeed, given their knowledge of the area, the actors present in the territory often are in the best position to identify the most important issues and the most plausible impacts.

2. http://www.green-certificate.com/ (accessed on August 21, 2013).

Second, field testing and validation are the best ways to take into account local issues and impacts. Although modelling can be used to predict the potential impacts of biomass harvesting on the environment, predictions can be considerably different from the actual effects measured in the field. Field validation provides a true picture of the real impacts of this practice by taking local conditions into account and improves our ability to predict future impacts. According to Stewart et al. (2010), field tests can also complement scientific literature by filling in gaps on topics for which information is unavailable. By the same token, although several site characteristics such as slope inclination and surficial deposit types can be assessed from map data, field validation of information obtained with mapping tools is necessary in order to develop a site prescription. For example, a field diagnostic can be used to assess the sensitivity and resilience aspects of a site in relation to soil productivity or biodiversity issues. Thus, it is possible to validate map data and to clarify and supplement them with information that can only be obtained by performing a field observation. In doing so, local issues and characteristics are better taken into account and allow for more informed decision-making.

Field validation of information obtained with mapping tools and monitoring of the actual effects of harvesting operations are very important for the development of biomass harvesting prescriptions that take local and regional realities into account and are therefore suited to the physical characteristics of the territory and values of the local communities. Studies and field visits therefore play a key role in supporting sustainable forest biomass harvesting.

Public participation and field validation are thus the foundation for harmonious and sustainable development of the use of forest residues at the local level. This foundation helps to generate reliable information in order to formulate more appropriate guidelines to govern the practice on a larger scale.

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Appendix 1: Biomass harvesting recommendations from different jurisdictions

Biodiversity and dead wood

American states	
South Carolina	Refer to Forest Biomass Harvesting Recommendations: A Supplement to South Carolina's Best Management Practices for Forestry (South Carolina Forestry Commission 2012). Avoid sensitive areas (e.g., water sources, seepage and unique habitats). Leave a sufficient amount of leaves, branches and debris in order to provide organic matter. On suitable sites, use biomass harvesting to control vegetation and strengthen the habitat of rare, threatened or endangered species. Retain three snags per acre when they are available and when it is consistent with OSHA requirements and when it is safe to do so. Retain woody debris of various sizes and decay classes on the ground. It is recommended to leave at least 1 tonne of coarse woody debris per acre. Plan biomass harvesting so as to maintain different types of habitats and age classes on the managed property.
Indiana	Refer to Harvesting Biomass. A Guide to Best Management Practices (Indiana Department of Natural Resources, N.D.). Limit or avoid harvesting biomass (logs) within high-quality natural communities or sensitive sites. Avoid biomass harvesting near federally listed threatened or endangered species or species in need of major conservation, unless removal favours the species' habitats. Retain downed dead wood that was on-site prior to the start of harvesting operations. Limit disturbance to existing coarse woody debris (logs, standing timber, snags). Snags should only be cut when they pose a safety risk. Whenever they are cut, they should be left on-site. Retain stumps, roots and forest litter. Distribute tree crowns and branches throughout the site to ensure the supply of nutrients. Retaining small slash piles can promote the habitat of certain species. Avoid biomass harvesting in riparian areas, outside of the crowns and branches of trees that would be removed during harvesting under riparian buffer zone management guidelines and BMPs.

	Protect sensitive and unique habitats (spring seepage, vernal pools and ponds, cliffs and ledges, cave entrances). In general, biomass harvesting near these sites should be avoided. Avoid biomass harvesting on reserves and in patches of standing trees within large regeneration openings.
Kentucky	Refer to Recommendations for the Harvesting of Woody Biomass (Kentucky Division of Forestry, 2011). Whenever possible, biomass harvesting operations should be carried out in conjunction with conventional harvesting or other management activities in order to minimize soil compaction and other detrimental effects on site productivity, water quality and quantity, wildlife habitats and other environmental impacts related to forest sustainability. Biomass harvesting should avoid or minimize the removal of residues on steep slopes with highly erodible soils, and other sensitive sites such as habitats for threatened or endangered species, particularly important areas, natural reserves, grasslands and wetlands. Be sure to leave enough woody debris to maintain site productivity and diversity of wildlife habitats. The Kentucky Division of Forestry and the Kentucky Department for Fish and Wildlife Resources recommend leaving between 15 and 30% of woody debris (tree crowns and butt logs) distributed throughout the cutting site. Biomass harvesting can have a positive effect on some wildlife populations while negatively affecting others. Retain key structural characteristics (snags, cavity trees and coarse woody debris). Harvesting activities that could destroy the habitats of federally listed threatened or endangered species are prohibited by the Endangered Species Act of 1973 and may be subject to civil or criminal penalties.
Maine	Refer to Woody Biomass Retention Guidelines. Considerations and Recommendations for Retaining Woody Biomass on Timber Harvest Sites in Maine (Benjamin 2010). Retain as much dead wood as possible (fine woody debris, coarse woody debris, logs, snags). Retain some green trees (trees with cavities and rot). Retain some seed trees (hardwood species). Retain biological legacies in buffer zones and clusters. Retain as many snags as possible. Retain as much pre-existing fine woody debris and coarse woody debris as possible. Retain forest litter, stumps, and roots as intact as possible.

Michigan	Refer to Within-Stand Retention Guidance (IC 4110) (Bielecki et al. 2012). Avoid or limit harvesting in areas of high conservation value and on sensitive sites. Avoid harvesting near habitats of threatened or endangered species, or species that must be protected. Retain coarse woody debris and snags of various sizes, decay classes and tree species. Retain approximately 17 to 33% of the harvesting residues (crowns and branches less than 4" in diameter). Retain more debris in stands with little woody debris prior to harvest. Retain as much pre-existing coarse woody debris as possible. Avoid removal of the forest floor, forest litter, stumps and roots.
Minnesota	Refer to Biomass Harvesting Guidelines for Forestlands, Brushlands and Open Lands (Minnesota Forest Resources Council 2007). Retain 20% of shrubs and small trees cut and left on-site. Retain as many snags as possible; avoid harvesting activities in hardwood tree clusters. Avoid biomass harvesting within sites where endangered or threatened plant or animal species are known to exist. Retain slash piles that show evidence of use by wildlife. Retain the forest floor, forest litter, root systems, and stumps. Retain as much coarse woody debris and fine woody debriss debris as possible. Retain all snags whenever possible. Retain approximately 30% of harvesting residues (20% of harvesting residues with an additional 10 to15% of fine woody debris from incidental breakage).
Missouri	Refer to Missouri Woody Biomass Harvesting Best Management Practices Manual (Missouri Department of Conservation 2010). Avoid harvesting in High Conservation Value Forests (HCVF). Retain seed trees of various species and sizes. Retain 7 to 25 cavity trees and 6 to 12 snags per acre. Avoid "hard edges" by creating a gradual transition into harvested areas.

	Create travel corridors in large harvests (> 40 acres). Retain a minimum of 33% of harvesting residues. Retain as much fine woody debris as possible. Retain woody debris of various tree species and sizes, with an emphasis on larger structures. Avoid removing all coarse woody debris. Retain 6 to 12 snags, depending on the vegetation type.
Northeastern United States	Refer to Forest Biomass Retention and Harvesting Guidelines for the Northeast (Forest Guild Biomass Working Group 2010). Avoid biomass harvesting in imperilled type forests (e.g., globally recognized or listed as S1 or S2 in a State National Heritage Program). The management of these type forests should be based on the local Natural Heritage Program or other local ecological expert advice. Restoration of sites where biomass harvesting may be appropriate (vegetation control, enhancement of critical habitats or reduction of fire risk) must be guided by ecological objectives and not designed solely for biomass supply. Protect old-growth stands from harvesting, except when it is necessary to maintain their ecological structure or function. Leave and protect the forest floor, forest litter, roots, stumps and a large proportion of coarse woody debris. Leave and protect live or decaying cavity trees and snags (e.g., standing dead trees > 10”). Leave snags that have been felled for safety reasons. Select and identify live trees to become part of future structures if these structures do not exist. Leaving all snags and decaying trees in disturbed forests (outbreaks, windfall, ice storms) may not be feasible. When an area is salvaged, leave patches covering between 5 and 10% of the total surface area. In some cases, the increase in insect populations on dead trees may limit the retention of unsalvaged patches. Leave a variety of tree species as snags, coarse woody debris and large felled trees. Leave and do not cut patches within or next to every 10 acres of regeneration in areas of even-aged structure. Unharvested patches (including riparian buffer strips) must represent a total of 5 to 15% of the harvested area. Retain patches surrounding shelter or cavity trees, large snags, and large downed trees to maximize the structure and diversity of habitats.

	Management designed to maintain multiple vegetation layers can be beneficial for the diversity of wildlife and plant species.
Vermont	Refer to Acceptable Management Practices for Maintaining Water Quality on Logging Jobs in Vermont (Department of Forests, Parks, and Recreation 2009). There is not a lot of information on biomass harvesting in the guide. One of the regulations calls for a license for total cuts of more than 40 acres (Title 10 V.S.A. Chapter 83, Section 2622). Another regulation requires whole tree harvesters to have a license to produce wood chips (Title 10 V.S.A. Chapter 83, Section 2648). A working group on biomass energy development was created in 2009 – the Forest Health subgroup – and is currently involved in the development of guidelines for biomass retention, forest health indicators and research on the carbon issue.
Pennsylvania	Refer to Guidance on Harvesting Woody Biomass for Energy in Pennsylvania (Pennsylvania Department of Conservation and Natural Resources, N.D.). Protect sensitive habitats (springs, riparian zones, caves, cliffs, pools and ponds). Protect cavity trees, snags, and fruit-producing shrubs and vines. Develop specific management plans for unique areas. Avoid disturbing endangered, threatened or rare species. Practices should protect or increase the number of habitats. Retain 15 to 30% of harvest residues. Retain slash during conventional timber harvests. Retain 2 to 5 non-merchantable logs per acre. Retain 1 to 5 snags per acre.
Southeastern United States	Refer to Forest Biomass Retention and Harvesting Guidelines for the Southeast (Forest Guild Southeast Biomass Working Group 2012). Avoid biomass harvesting in imperilled type forests (e.g., globally recognized or listed as S1 or S2 in a State National Heritage Program). The management of these type forests should be based on the local Natural Heritage Program or other local ecological expert advice. Restoration of sites where biomass harvesting may be appropriate (vegetation control, enhancement of critical habitats or reduction of fire risk) must be guided by ecological objectives and not be designed solely for biomass supply. In prescribed fire-adapted ecosystems, including many southeastern forests, less biomass will be available for harvest where fire is an active ecological process. However, when fire is excluded, biomass removal may be crucial to reintroducing prescribed fire safely. Protect old-growth stands from harvesting, except when it is necessary to maintain their ecological structure or function.

	Leave and protect roots, stumps and coarse woody debris on the ground. Leave and protect cavity and shelter trees and other decaying trees and snags, particularly the largest. Leave snags that have been felled for safety reasons on-site. Select and identify live trees to become part of future structures when these structures do not exist. Leave a variety of tree species as snags, coarse woody debris and large felled trees. Leaving all snags and decaying trees in disturbed forests (outbreaks, windfall, ice storms) may not be feasible. When an area is salvaged, follow the instructions in Table 1.
Wisconsin	Refer to Silviculture and Forest Aesthetics Handbook (Wisconsin Department of Natural Resources 2013). Retain a variety of seed trees and shrubs. Avoid harvesting on sites where endangered or threatened species have been identified by the state or federal government. Protect High Conservation Value Forests (HCVF), sensitive ecosystems, and species associated with greater conservation needs. Retain and limit disturbance to pre-existing coarse woody debris and fine woody debris. Retain 10% of harvest residues (crowns and branches < 4” diameter). An additional 10 to 15% of fine woody debris is expected from incidental breakage. Do not remove the forest litter, stumps or root systems. Retain snags based on the guidelines found in WI DNR Silviculture Handbook, chapter 24. The ultimate goal is to maintain 5 dry tons of fine woody debris per harvested acre.
California	Refer to A Review of Biomass Harvesting Best Management Practices Guidelines (North East State Foresters Association 2012). Although California does not have specific standards for intensive biomass harvesting, existing regulations address all forest biomass removal issues (Appendix 1). For example, the California Forest Practice Rules stresses the importance of leaving snags, shelter and nesting trees for the maintenance of habitats and forest health, apart from sites with specific conditions relating to safety, fire, insects and outbreaks.

Europe	
European Community	Refer to How Much Bioenergy Can Europe Produce Without Harming the Environment? (European Environment Agency 2006). Increase the share of protected areas, i.e., a reduction of 5% in the area available for wood production by each Member State in order to allow for an increase in protected areas. Increase the volume of dead wood, i.e., set aside 5 % of wood volume (individuals and small groups of retention trees) after harvesting in order to increase the amount of large diameter trees and dead wood. No intensification of use should occur in protected forest areas.
Denmark	Refer to Revised Assessment of Biomass Harvesting and Retention Guidelines (Evans et al. 2010). Harvesting is allowed in stands of special value for flora and fauna that are not primarily managed for wood production, but only after careful evaluation. Harvesting in Nature Conservation Areas is allowed unless it is in contradiction with nature conservation purposes.
Finland	Refer to Energy Wood Harvesting from Clearcuts, Guidelines for Finland (Äijälä et al. 2005). Leave dead wood in the forest and avoid damaging regenerating trees during harvesting. Leave hardwoods that do not threaten crop trees (aspen, common sallow, common alder and valuable hardwoods) to improve wildlife habitats. Avoid valuable habitats during harvesting and thinning. Stumps are not harvested in these zones. Avoid damaging anthills and the nests of mammals and birds. Safeguard the important diversity characteristics of special consideration habitats in forests. Refer to the Finnish Nature Conservation Act, the Finnish Forest Act, the Finnish Certification System Standard and Forest Management Recommendations. Large-diameter dead trees (standing or downed) and trees felled by the wind should not be harvested or damaged during harvesting. Leave decaying stumps: all stumps with a diameter > 15 cm; 25% of stumps with a diameter > 15 cm from the most recent harvest (biodiversity). All stumps should be left on-site in the following areas: steep slopes, rocky ground with fine soil (< 0.5 m thick), very rocky areas, riparian buffer zones, sites of natural or cultural interest, small wetland hollows, within 3 m of residual trees (this can also

	apply to the biodiversity and dead wood issue and to the protection of water and riparian areas issue).
United Kingdom	Refer to Forests and Water Guidelines (Forestry Commission 2003). Ensure the retention of sufficient dead wood for wildlife species. This should be covered by the normal site planning process, which should identify a definite area on-site where dead wood is either left standing or laying on the ground. If retained on the ground, it needs to be clearly separated from residual trees. Large-diameter dead wood (> 10 cm) must be left on-site during the removal of logging residues; wood from pine and hardwoods is the most biologically important. Only harvest logging residue biomass from the most common species in the stand.
Sweden	Refer to Recommendations for Extraction of Logging Residues and Ash Recycling (Hjerpe 2008). When extracting logging residues, it is important that trees, shrubs and dead wood that have been spared due to natural and cultural environmental considerations are left behind undisturbed. Forests with a high natural value – e.g., some wetland forests and key biotopes – must be excluded from extraction of logging residues if their natural value could be damaged. Extraction of logging residues should include only the most common tree species in the landscape. At least 1/5 of logging residues must be left in the clearcut area, preferably in locations that are exposed to the sun. It is especially important to leave crowns, large-diameter branches, and dead wood from hardwood trees, as well as the crowns of pines. Extraction of logging residues and ash recycling must be avoided in sensitive biotopes and during periods when animal life could be threatened. In areas where reindeer husbandry is practiced, extraction of logging residues must be avoided in high-value forests that contain tree-hanging lichens.
Canada	
New Brunswick	Refer to The New Brunswick Public Forest – Our Shared Future (New Brunswick Natural Resources 2005). New Brunswick's Crown forests are to be managed in a sustainable manner to ensure that the objectives set forth for diversity, wood production, wildlife habitats, watercourses and wetlands are achieved.

Water quality and riparian areas protection

American states	
North Carolina	Refer to North Carolina Forest Practices Guidelines Related to Water Quality (FPGs) (North Carolina Forest Service 2014); North Carolina Forestry Best Management Practices: Manual to Protect Water Quality – Amended in September 2006 (Brogan et al. 2006); and Sustainable Forestry Initiative® Standard (SFIS) – 2005-2009 Standard, Objectives 4, 5, 6 (Sustainable Forestry Initiative Inc. 2004). Implement best management practices for the protection of water quality and follow the forest practices guidelines for the protection of water quality. Select appropriate equipment for the site characteristics, particularly in wetlands and riparian areas. Minimize the frequency of biomass harvesting and returning to the site with harvesting equipment. Protect lakes, streams and riparian areas with buffer zones. Properly locate roads, landings and piling areas outside of riparian zones. Restrict harvest during wet periods.
South Carolina	Refer to Forest Biomass Harvesting Recommendations: A Supplement to South Carolina's Best Management Practices for Forestry (South Carolina Forestry Commission 2012). Do not remove understory vegetation or other forms of biomass from the primary streamside management zone on permanent or intermittent streams, aside from those permitted by best management practices. Avoid piling or stacking wood chips or fine material in special management areas and prevent contamination of streams by such material. Use alternate methods of stabilization such as seedlings, straw, hay bales, silt fences and erosion control fabric where residues are not sufficient to prevent erosion. Avoid the removal of stumps, root systems, leaf litter and forest floor for biomass. Limit biomass removal on slopes greater than 20% to reduce the risk of erosion. Avoid biomass removal that exposes mineral soil on steep slopes (>30%) or on sites that are at high risk of erosion.

Indiana	Refer to Harvesting Biomass. A Guide to Best Management Practices (Indiana Department of Natural Resources, N.D.). Adhere to the two following principles: - the steeper the slope, the more material that needs to be left; - the closer to water biomass harvesting is performed, the greater the necessity to leave material. Steep slopes and shallow soils are easily disturbed and eroded, so retain as much forest cover as possible to minimize soil exposure and compaction in these areas. Retain stumps, root systems, and forest litter layer as much as possible to maintain the soil structure, especially on streambanks and other areas that are at high risk of erosion. Avoid biomass harvesting in riparian management zones, except crowns and branches of trees normally removed during timber harvests under existing riparian management zone guidelines and best management practices. Protect sensitive and unique areas such as spring seeps, vernal pools and sinkholes. Biomass harvesting must be avoided near those sites.
Kentucky	Refer to Recommendations for the Harvesting of Woody Biomass (Kentucky Division of Forestry 2011). All commercial harvesting must comply with Kentucky's harvesting requirements and best management practices in accordance with the Kentucky Forest Conservation Act and the silvicultural best practices of the Kentucky Agriculture Water Quality Act. Forest biomass harvesting operations must be carried out in conjunction with conventional harvesting or other harvesting activities to minimize soil compaction and other detrimental effects on site productivity, water quality, wildlife habitats, and other environmental issues related to forest sustainability. Hardwood forests regenerate through stump sprouts and seedlings (natural or artificial regeneration); therefore, re-entry to harvest biomass following traditional harvesting should occur within 5 years of the traditional harvest. The removal of stumps, root systems and forest floor litter should be avoided in order to maintain site productivity for the regeneration and growth of a new forest. Timing harvest operations to avoid logging in wet soil conditions and concentrating equipment travel patterns can prevent unnecessary impacts such as compaction and rutting, which degrade site productivity.

	The removal of biomass has the potential to increase the surface and subsurface flow of water in response to soil disturbance, erosion and stream flow. Biomass harvesting should avoid or minimize residue removal on steep slopes with highly erodible soils and other sensitive sites such as habitats for threatened and endangered species, special consideration areas, nature preserves, grasslands and wetlands.
Maine	Refer to Woody Biomass Retention Guidelines. Considerations and Recommendations for Retaining Woody Biomass on Timber Harvest Sites in Maine (Benjamin 2010). Minimize soil disturbance. Woody biomass may be used to control water flow, prevent soil erosion, and stabilize exposed soil; these structures may be left on-site after harvest.
Michigan	Refer to Sustainable Soil and Water Quality Practices of Forest Land Manual (IC 4011) (Michigan Department of Natural Resources and Michigan Department of Environmental Quality 2009). Michigan's Woody Biomass Harvesting Guidance does not specifically address water quality protection measures related to forest biomass harvesting.
Minnesota	Refer to Sustaining Minnesota Forest Resources: Voluntary Site-Level Forest Management Guidelines for Landowners, Loggers and Resource Managers (Minnesota Forest Resources Council 2012). Avoid removing biomass in riparian management zones or within 25 feet of a flood plain (some roundwood harvesting is acceptable according to existing guidelines).
Missouri	Refer to Missouri Watershed Protection Practice. Management Guidelines for Maintaining Forest Watersheds to Protect Streams (Missouri Department of Conservation 2006). Streamside management zones measuring at least 50 feet in width should be implemented on the banks of all perennial and intermittent streams. Retain at least 33% of trees in the stream management zone (40 ft^2 of basal area). Avoid the use of heavy equipment. Retain most of the vegetation within the stream management zone.
Northeastern United States	Refer to Forest Biomass Retention and Harvesting Guidelines for the Northeast (Forest Guild Biomass Working Group 2010).

	Retention of dead wood is important for water quality as this material reduces overland flow and holds water. Leave and protect existing woody material in streams. Dead wood in riparian systems provides sites for vegetation colonization, forest island growth, floodplain development, and wildlife habitats. Leave and protect decaying trees (cavity/den trees), snags and large-sized coarse woody debris in bank or stream management zones. Keep vernal pools free of logging residues, crowns, branches and sediment from forestry operations. If logging residues fall into the pool during the breeding season, it is best to leave them in place to avoid disturbing egg masses or other breeding activity that may be occurring. Within 100 feet of the edge of a vernal pool, maintain a protected forest floor to provide deep litter and woody debris around the pool. Also avoid rutting, soil exposure or creating sources of sediment near vernal pools. Extra care should be taken when working in or around forest wetlands because of their importance for wildlife and ecosystem functions. Wetlands are low-fertility sites, and they may support rare natural communities so removing dead wood would be inappropriate.
Pennsylvania	Comply with all provisions of Chapter 102 of the Clean Streams Law (http://www.pacode.com/secure/data/025/chapter102/chap102toc.html; accessed on August 4, 2014) and Chapter 105 of the Dam Safety and Waterway Management Act (http://www.pacode.com/secure/data/025/chapter105/chap105toc.html; accessed on August 4, 2014). The Pennsylvania Department of Conservation and Natural Resources (PA DCNR) guidelines include a general discussion on stream crossings, roads, skid trails, and landing design. Riparian buffer zones should provide adequate protection, and prevent the contamination of water courses with soil, chemicals and/or petroleum. Operations should be carried out when soils are dry or frozen.
Southeastern United States	Refer to Forest Biomass Retention and Harvesting Guidelines for the Southeast (Forest Guild Southeast Biomass Working Group 2012). Retention of dead wood is important for water quality, as this material reduces overland flow and holds water. Leave and protect existing woody material in streams. Dead wood in riparian systems provides sites for vegetation colonization, forest island growth, floodplain development, and wildlife habitats.

	Leave and protect decaying trees (cavity/den trees), snags, and large-sized coarse woody debris in bank or stream management zones. Extra care should be taken when working in or around forest wetlands because of their importance for wildlife and ecosystem functions. Wetlands are low-fertility sites, and they may support rare natural communities so removing dead wood would be inappropriate.
Wisconsin	Refer to Best Management Practices for Water Quality (Wisconsin Department of Natural Resources 2010). Wisconsin's Forestland Woody Biomass Harvesting Guidelines do not specifically address water quality protection measures related to woody biomass harvesting.
California	Refer to California Forest Practice Rules (California Department of Forestry and Fire Protection 2013). In riparian areas, the Forest Practice Rules require that operations "protect, maintain, and restore trees (especially conifers), snags, or downed coarse woody debris" that provide habitats.
Europe	
Finland	Refer to Energy Wood Harvesting from Clearcuts, Guidelines for Finland (Äijälä *et al.* 2005). Collect as much logging residue as possible from the buffer strips next to waterways and small waterstreams. Do not store logging residue close to ditches. After harvest, leave ditches and furrows functional by removing logging residues, wood chips and stumps. Set boundaries around forest habitats of special consideration so that their characteristics will be protected. Leave unbroken buffer strips next to small waterstreams and forest ditches, and avoid disturbing the soil surface during operations by maintaining buffer strips. Even if the area is not a forest habitat of special consideration, leave an unbroken buffer strip next to small bodies of water, streams, and forest ditches. Avoid breaking up the soil surface when pulling stumps or making short hauls by maintaining buffer strips as follows: - 2-3 m from the edge of the ditch; - at least 3-5 m from the banks of brooks and springs; - 7-10 m from the banks of navigable waterways.

United Kingdom	Refer to Forests and Water Guidelines (Forestry Commission 2003).
Sweden	Refer to the Swedish Forestry Act. The technology, method, and time of extraction of logging residues and ash recycling must be chosen so that equipment does not cause transfer of sediments and organic material to waterstreams or damage to cultural and ancient remains. This will limit mechanical damage to trees.
Canada	
New Brunswick	The recommendations are the same as those in the "Biodiversity and Dead Wood" table in the previous section of this Appendix.

Maintaining soil and site productivity

(See **Appendix 2** for a detailed description of sensitive sites)

American States	
North Carolina	Refer to Sustainable Woody Biomass Harvesting: Minimizing Impacts (NC State University 2008). Harvest after leaf fall (late fall and winter months) whenever possible. Use processing equipment that removes nutrients from materials (on-site delimbing, chippers that exclude foliage, twigs and small branches) when harvest is unavoidable (dormant season).
South Carolina	Refer to Forest Biomass Harvesting Recommendations: A Supplement to South Carolina's Best Management Practices for Forestry (South Carolina Forestry Commission 2012). Biomass harvesting should be carried out in conjunction with commercial wood harvesting to minimize re-entry and disturbance. Use existing roads, skid trails, pathways and landings to minimize soil compaction. Limit harvesting on sites with shallow, very sandy or low-fertility soils. Avoid leaving piles of fine residues that impede regeneration or that concentrate nutrients. Retain as much foliage as possible. Consider using fertilizers, ash, or lime where nutrient depletion is a concern. Identify vulnerable soils and adjust harvesting accordingly.
Indiana	Refer to Harvesting Biomass. A Guide to Best Management Practices (Indiana Department of Natural Resources, N.D.).

	Leave at least one-third of the residues harvested, such as crowns and branches < 4 inches in diameter. In general, three main factors influence the proportion of crowns and branches that should be left on-site: - number of live trees left on-site; - time between harvests; - nutrient availability. Leave more ash, crowns and branches when harvesting intensity increases (and when the three preceding factors decrease). On sites with adequate productivity, retain one-quarter or one-fifth of crowns when one-third of the basal area is being removed every 15-20 years. In the case of a 30-acre clearcut, retain higher amounts of tree crowns (one-third of crowns). Other suggestions: - whenever possible, residues should be returned to the logging area and dispersed rather than accumulated at the landing; - make an inventory of the amount of woody debris present prior to logging to determine the amount of residues to be left on site. For example, in stands with little woody debris prior to logging, retain more residue (e.g., retain one crown out of every four or five harvested trees); if the stand contains a moderate amount of pre-existing woody debris, retain one crown out of every three trees harvested. Avoid removing the forest litter, forest floor or below-ground biomass, including stumps and roots. Leave additional residue (more than one-third of the crowns and branches harvested) on shallow, nutrient-poor soils. Whenever possible, retain existing woody debris: - move coarse woody debris off roads, skid trails and landings to allow for safer harvesting operations; - leave coarse and fine woody debris in place when they are used to stabilize soil on roads or skid trails after harvesting operations; - retain some snags or culls for wildlife when it does not constitute a risk for safety or insect pest to do so.
Kentucky	Refer to Recommendations for the Harvesting of Woody Biomass (Kentucky Division of Forestry 2011). Whenever possible, biomass harvesting operations should be carried out in conjunction with conventional harvesting or other management activities in order to minimize soil compaction and other detrimental effects on site productivity, water quality and quantity, wildlife habitats, and other environmental effects related to forest sustainability. Be sure to leave enough residual material to maintain site productivity and diversity of wildlife habitats. The Kentucky Division of Forestry and the Kentucky

	Department for Fish and Wildlife Resources recommend leaving between 15 and 30% of woody debris (crowns and butt logs) distributed throughout the logging site.
Maine	Refer to Woody Biomass Retention Guidelines. Considerations and Recommendations for Retaining Woody Biomass on Timber Harvest Sites in Maine (Benjamin 2010). Leave the litter layer, stumps and roots as intact as possible, except in certain cases during site preparation.
Minnesota	Refer to Sustaining Minnesota Forest Resources: Voluntary Site-Level Forest Management Guidelines for Landowners, Loggers and Resource Managers (Minnesota Forest Resources Council 2012). Do not remove the forest floor, litter layer or root system. Roads, skid trails, and landings should occupy no more than 1-3% of the site. Avoid additional biomass harvests on erosion-prone sites; install erosion control devices.
Missouri	Refer to Missouri Woody Biomass Harvesting Best Management Practices Manual (Missouri Department of Conservation 2010). Lengthen rotations or use uneven-aged management to promote soil fertility. Retain a minimum of 33% of logging residues.
Northeastern United States	Refer to Forest Biomass Retention and Harvesting Guidelines for the Northeast (Forest Guild Biomass Working Group 2010). In general, retain one-quarter to one- third of residual material, crowns and branches from harvesting (e.g., coarse woody debris) when one-third of the basal area is removed every 15-20 years. Three main factors influence the proportion of crowns and branches that should be left on site: - number of live trees left on-site; - time between harvests; - nutrient availability. When harvesting intensity increases (and the three preceding factors decrease), leave more residual material, crowns and branches; they are essential to protect site productivity. Retain woody debris of all sizes on the ground (fine and coarse woody debris, large downed logs).

	In general, leave woody debris distributed across the harvesting site. Piles of downed woody debris sometimes provide wildlife habitat, or the redistribution of downed woody debris causes excessive damage to soil or regeneration. Minimize the removal of needles or leaves by harvesting in winter, retaining fine woody debris on-site, or leaving felled trees on-site to allow needles to drop.
Pennsylvania	Refer to Guidance on Harvesting Woody Biomass for Energy in Pennsylvania (Pennsylvania Department of Conservation and Natural Resource, N.D.). Minimize soil compaction and rutting by matching operation techniques and season of operation to soil types and moisture levels. Minimize soil disturbance through careful design and location of landings, roads, and skid trails. Do not contaminate soils with equipment fuel or chemicals.
Southeastern United States	Refer to Forest Biomass Retention and Harvesting Guidelines for the Southeast (Forest Guild Southeast Biomass Working Group 2012). Leave one-third of residual material when there are woody debris on the ground. Retain woody debris of all sizes (fine and coarse woody debris, large downed logs) on the ground. In general, leave woody debris on the ground all across the logging site. This is easier when dead wood is left where trees are felled. If whole trees are skidded on a landing, it is better to bring the residues back to the logging site than to leave them in large piles at the landing. For example, Forest Stewardship Council guidelines say that "slash is concentrated only as much as necessary to achieve the goals of site preparation and the reduction of fuels to moderate or low levels of fire hazard." Use methods that leave woody debris and other natural forest litter scattered across the site when erosion is present. Harvest hardwood or mixed pine–hardwood forests in winter to reduce nutrient removal, if possible.
Wisconsin	Refer to Silviculture and Forest Aesthetics Handbook (Wisconsin Department of Natural Resources 2013). Retain the forest litter, forest floor, stumps and root systems.
California	Refer to California Forest Practice Rules (California Department of Forestry and Fire Protection 2013). The California Forest Practice Rules emphasize the ecological importance of woody debris on the ground for soil fertility, moisture conservation and microorganisms support, but the regulations require the removal of residual material rather than its retention.

Europe	
Denmark	Refer to Revised Assessment of Biomass Harvesting and Retention Guidelines (Evans et al. 2010). For conifers, leave needles on-site by pre-drying the material for at least 2 months during spring and summer. Avoid harvesting on exposed forest edges.
Finland	Refer to Energy Wood Harvesting from Clearcuts, Guidelines for Finland (Äijälä et al. 2005). Leave a certain amount of biomass with rich nutrient content in the harvested area: - the crown (1-2 m) is cut and left in the forest; - trees with a stump diameter < 4 cm are left in the forest; - hardwood trees are felled and left to dry on the ground, where their leaves fall off and decay. Fertilize with ash in turf areas. Leave 30% of logging residues on-site, ensuring that they are spread evenly throughout the harvesting area. Leave biomass with rich nutrient content in the harvested area: crowns (1-2 m) must be cut and left on-site; trees with a stump diameter < 4 cm must be left on-site; branches and twigs must be left on-site; hardwood trees must be left to dry on-site to facilitate leaf drop. Avoid disturbing the soil. Use biomass as a protective layer to reinforce the carrying capacity of the soil. Avoid soils with low carrying capacity. Harvest during the dry season when the ground is thawed or in winter when the ground is frozen. Do not harvest stumps on steep slopes susceptible to erosion or create clearing paths perpendicular to the slope. Soil types susceptible to erosion include sand and fine silts and their moraines.
United Kingdom	Refer to Revised Assessment of Biomass Harvesting and Retention Guidelines (Evans et al. 2010). Retain more than 20% of logging residues in harvested areas (preferably exposed to the sun), especially crowns, large branches, deciduous dead wood and pine crowns.
Sweden	Refer to Recommendations for Extraction of Logging Residues and Ash Recycling (Hjerpe 2008).

	Ash recycling should be done on-site when extensive amounts of logging residues are extracted at a particular point during the rotation period. Extraction of logging residues must be compensated with ash if: - total extraction of tree parts other than the stem during a rotation represents more than half a tonne of ash per hectare; - most of the conifer needles are not well dispersed. However, ash should always be recycled when logging residues are extracted in conjunction with the final cut, even if the extraction represents less than half a tonne of ash per hectare and conifer needles have been well dispersed, in cases where the soil is severely acidified or when the forest is growing on peatland. In regions that receive large quantities of nitrogen from atmospheric deposition, it is preferable that conifer needles be removed from the site, provided that the ash is recycled. In areas with low levels of nitrogen and high levels of biomass extraction, compensation should include both nitrogen and ash fertilization. The technology, method, and time of extraction of logging residues and ash recycling should be chosen so that equipment does not cause transfer of sediments and organic material to watercourses or damage to cultural and ancient remains. In this way, mechanical damage to trees is limited.
Canada	
New Brunswick	Refer to Forest Biomass Harvesting (Government of New Brunswick 2008). Do not remove the forest floor, including the litter layer, soil surface, stumps and root system. Forest biomass harvesting is limited to crowns, branches, foliage, non-merchantable stems of trees and shrubs, pre-existing dead wood and wood chips. Forest biomass harvesting is only to occur in eligible or low-risk areas. Foliage should remain on-site following harvest. Seasonal timing is to be considered in the planning of biomass harvesting. Harvest systems must be chosen to minimize soil disturbance, including compaction, rutting and erosion.
Ontario	Ontario is currently consolidating the guidelines for forest biomass harvesting (North East State Foresters Association 2012).
Quebec	Quebec is currently developing guidelines on forest biomass harvesting based on soil properties (North East State Foresters Association 2012).

Maintaining long-term productivity with appropriate silvicultural measures

American states	
North Carolina	Refer to Sustainable Woody Biomass Harvesting: Minimizing Impacts (NC State University 2008). Minimize biomass harvesting frequency and equipment entry. Use longer rotation periods whenever possible and whenever it is economically justifiable.
Kentucky	Refer to Recommendations for the Harvesting of Woody Biomass (Kentucky Division of Forestry 2011). Forest landowners should consider the best use of the trees to be harvested to maximize wood value and promote the sustainability of their forest while using forest biomass. All commercial harvesting must comply with Kentucky's harvesting requirements and best management practices (BMPs) in accordance with the Kentucky Forest Conservation Act and the silvicultural BMPs of the Kentucky Agriculture Water Quality Act. When considering short-rotation plantations (SRPs), select species that are native to Kentucky, that are appropriate for the site where the plantation will be established, and that have available markets. Some SRPs are invasive and highly aggressive and can negatively impact the environment and Kentucky's native forests. Harvesting creates conditions favourable to the establishment of non-native plants and aggressive native plants. Prescriptions for the treatment of invasive plants can be found on several internet sites, including http://www.invasivespeciesinfo.gov/plants/controlmech.shtml
Missouri	Refer to Missouri Woody Biomass Harvesting Best Management Practices Manual (Missouri Department of Conservation 2010). Avoid disturbing forest stands and trees marked in reserve. Avoid re-entering stands. Avoid high-grading; specific recommendations regarding tree numbers in the stand and their spacing are included in the manual. Avoid converting natural forests into plantations. Biomass harvesting can be used as part of a salvage operation. Biomass harvesting can be used to enhance aesthetics.
Minnesota	Refer to Biomass Harvesting Guidelines for Forestlands, Brushlands and Open Lands (Minnesota Forest Resources Council 2007).

	Avoid re-entering stands, especially if planting or regeneration treatments have occurred. Biomass harvesting can be used to meet fuel reduction goals, site preparation for regeneration and pine beetle management.
Michigan	Refer to Michigan Woody Biomass Harvesting Guidance (Michigan Department of Natural Resources and Environment 2010). Focus on the residual stand structure during intermediate harvests. Biomass harvesting can be used to control/reduce invasive or exotic plant species. Biomass harvesting can be used to reduce the number of trees at risk within recreational areas and fire risk areas. Biomass harvesting can be used to achieve salvage and sanitation goals.
Northeastern United States	Refer to Forest Biomass Retention and Harvesting Guidelines for the Northeast (Forest Guild Biomass Working Group 2010). Protect forest land from conversion to non-forest use and protect natural forests from conversion into plantations. Involve professional foresters in the development of a long-term management plan and the supervision of harvests. Hire a certified logger from the Master Logger Certification Program or other similar program. Follow all BMPs for the state or region. Plan and construct roads and skid trails based on professional advice and BMPs. Integrate biomass harvesting with other forest operations. Use logging techniques such as directional felling or use of residual material to protect soil from rutting and compaction from harvest machines. Use equipment that is appropriate to the site and operations.
Pennsylvania	Refer to Guidance on Harvesting Woody Biomass for Energy in Pennsylvania (Pennsylvania Department of Conservation and Natural Resources, N.D.). Avoid high-grading; focus on residual stand structure. Avoid re-entry into harvested stands. Biomass harvesting can be used to meet salvage and sanitation goals. Avoid converting natural forests into short-rotation woody crop plantations.

	Regeneration, residual stand conditions and restoration objectives can guide biomass harvesting practices.
Southeastern United States	Refer to Forest Biomass Retention and Harvesting Guidelines for the Southeast (Forest Guild Southeast Biomass Working Group 2012). Encourage decisions that allow the conservation of forests and avoid their conversion to non-forest use. Involve professional foresters in the development of a long-term management plan and in the supervision of harvests. Hire a certified logger from the Master Logger Certification Program or other similar program. Follow all BMPs for the state or region. Plan and construct roads and skid trails based on professional advice and BMPs. Integrate biomass harvesting with other forest operations. Use logging techniques such as directional felling or use of residual material to protect soil from rutting and compaction caused by harvest machines. Use equipment that is appropriate to the site and operations.
Wisconsin	Refer to Wisconsin's Forestland Woody Biomass Harvesting Guidelines (Wisconsin Department of Natural Resources 2008). Biomass harvesting can be used for site preparation, removal of invasive or exotic plant species, fuel reduction treatments and restoration treatments. Biomass harvesting can be used during sanitation and salvage operations. However, 5% of the area should remain unsalvaged.

Appendix 2: Sensitivity index of soils developed by different jurisdictions

Jurisdictions	Levels of risk		
	Types of harvest		
	High	**Moderate**	**Low**
	Harvesting to be avoided	**Conditional harvesting**	**Harvesting allowed based on some recommendations (Appendix 1)**
AMERICAN STATES			
Maine		- Low fertility sites - Shallow soil - Coarse sandy soil - Poorly drained soil - Steep slopes - Other erosion-prone sites **Condition:** Retain as many crowns and branches as possible	
Michigan		- Shallow, nutrient poor soils **Condition:** Leave additional residues (more than 33%)	
Minnesota	- Peatland - Aspen and hardwood stands on shallow soils (< 20 cm)	- Excessively drained sand - 20 to 50 cm soil **Conditions:** It is recommended to leave one-third of the fine woody debris on site	

		Equal distribution of coarse woody debris throughout the site	
Missouri		- Shallow soil - Steep slopes (> 35%) **Condition:** Avoid skidding	
Wisconsin		- Shallow soil (< 50 cm) - Shallow, nutrient-poor sandy soil - Ombrotrophic peatland **Condition:** Do not harvest fine woody debris	

EUROPE				
European Community	**Slope:** >25º (>47%) **Elevation:** <1500 m **Soil water regime:** Wet to a depth of 40 cm, > 11 months **Base saturation in soil:** ?	**Moderate-High** **Slope:** 10º – 25º (18 – 47%) **Elevation:** < 1500 m **Soil water regime:** Wet to a depth of 80 cm, > 6 months **Base saturation in soil:** ?	**Moderate-Low** **Slope:** 5º – 10º (9 – 18%) **Elevation:** < 1500 m **Peatland:** No **Soil water regime:** Wet to a depth of 80 cm, < 6 months **Base saturation in soil:** < 50%	**Slope:** < 5º (< 9 %) **Elevation:** < 1 500 m **Peatland:** No **Soil water regime:** Wet to a depth of 80 cm, < 6 months **Base saturation in soil:** > 50%

	Soil type (FAO Lv1): Ranker; Arenosol; Lithosol; Xerosol; Solonchak; Regosol; Acrisol; Solonetz; Marsh **Note:** Level of extraction: 0%	**Soil type (FAO Lv1):** Histosol; Ferralsol; Planosol **Note:** Level of extraction: 15%	**Soil type (FAO Lv1):** Podzol; Water **Note:** Level of extraction: 50%	**Soil type (FAO Lv1):** Cambisol; Chernozem; Podzoluvisol; Kastanozem; Rendzina; Gleysol; Phaeozem; Fluvisol; Luvisol; Greyzem; Andosol; Vertisol; Town **Note:** Level of extraction: 75%
Denmark	- Hardwood stands on sandy soils	- Inferior forest (especially mountain pine stands) **Conditions:** Restricted use of crown branches, and only after pre-drying. - Conifers (production classes < 9 m^3/ha/yr) **Conditions:** Harvest only after fertilization		
Finland	- Stony or rocky soil - Poor, dry soil - Low-fertility peatland - Site with nutritional issues - Slightly dry, medium fertility mineral soil dominated by pine - Dry soil dominated by pine, moss, heath - Very dry, coarse-textured soil dominated by pine, lichen			- Rich mineral soil, thick layer of black soil, hardwoods such as oak, beech, birch and alder, dense undergrowth - Fertile mineral soil dominated by hardwoods and spruce - Fertile mineral soil dominated by spruce with some hardwoods and pine, with some undergrowth **Condition:** Harvest 70% of residues or the equivalent in quantity of nutrients

France	- Soil with less than 10% clay content - Humus type: Mor/Dysmoder, Moder	- Soil with 10 to 25% clay content - Humus type: Mullmoder/Dysmull, Oligotrophic mull **Condition:** Only one harvest per rotation	- Soil with 25% clay content or more - Humus type: Mesotrophic mull, Eutrophic mull, Calcic mull, Carbonated mull
Scandinavia	- Mean annual temperature < 2°C - Soil depth < 30 cm - Ombrotrophic peatland - Mineral soil with pH < 4.8 - Mineral soil with sandy texture, pH between 4.8 and 6, mineralogy dominated by quartz		
United Kingdom	- Podzol (3, 3m, 3p) - Ironpan soils (4e, 4z) - Peaty gleysol (6p, 6z) - *Juncus* bogs (8a, b, c, d) - *Molinia* bogs (9a, b, c, d, e) - Ombrotrophic peatland (11a, b, c, d) - Rankers (13b, r, z, g, p) - Skeletal soils (13s) - Littoral soils (15s, d, e, i, g, w) **Notes:** Removal could be considered if nutrients or base cations are replaced via application of fertilizers, lime or ash (not necessary on *Juncus* bogs)	- Podzolic brown earths (1z) - Ironpan soils (4, 4b, 4p) - Ground water gleys (5, 5p) - Peaty gleys (6) - Surface water gleys (7, 7b, 7z) **Conditions:** Needles left on-site Residual material removal should be restricted to dry periods (secondary extraction can be done in wet periods) Sufficient quantities of residual material need to be retained onsite and on skid trails to protect soils from machinery traffic	- Brown earths (except podzolic) (1, 1d, u) - Calcareous soils (12a, b, t)

	A sufficient amount of residual material is retained to protect soils from machinery traffic		
CANADA			
New Brunswick	- Peatland - Shallow soil (depth less than 30 cm) - Stony or rocky soil - Dry and poor soil - Site in which nutrient inputs are lower than nutrient export because of whole-tree harvesting (based on a theoretical nutrient budget model)		
Ontario	- Very shallow soil (depth < 20 cm)	- Moderately sandy to sandy soil, at least 20 cm thick **Condition:** Ensure retention of organic matter on-site (e.g., winter harvesting, retention of dead or dying trees, low-intensity site preparation, etc.)	
Quebec	Site in which acidity inputs from atmospheric deposition and whole-tree harvesting are 200 eq ha^{-1} yr^{-1} greater than the short-term critical acid load that the soil can withstand		

Appendix 3: Recommendations to ensure soil productivity: an example for Quebec

As is the case for biodiversity, water quality and riparian zones, soil productivity is often already covered by existing guidelines developed for forest harvesting activities. However, certain sites are generally recognized as likely to suffer soil productivity losses with the removal of forest residues. These sensitive sites are the following:

- thin soils
- steep slopes
- very coarse-textured and coarse-textured soils
- sites with excessive drainage
- acidic, low-fertility sites.

Most jurisdictions have developed maps of their territory that can be used to classify sites based on certain characteristics (surficial deposits, vegetation, topography, etc.) and to prepare an overall portrait of site sensitivity to biomass harvesting. However, this mapping information must be validated in the field by means of simple tools, such as soil texture keys, indicator species, etc. A field assessment ensures that appropriate measures are implemented in the proper locations and makes it possible to avoid errors that could result from imprecise mapping information. **The definition and description of sensitive sites provided below are given as examples**. The codes in parentheses refer to Quebec's ecological classification system.

1. Shallow soils

The sensitivity of shallow soils to forest biomass harvesting can be explained by their susceptibility to erosion. Additionnal entries into such forest sites will increase the potential for physical soil damage. Furthermore, given the limited amount of soil, the available nutrient pool is very small. The soil depth criteria established for shallow soils vary from one jurisdiction to the next.

Quebec has a classification system for surficial deposit thickness, which is supported by maps of surficial deposits (Saucier et al. 1994). Soils considered to be shallow are the following:

- very thin or absent deposits (R); rocky outcrops are very common and cover more than 50% of the surface;
- thin to very thin deposits (Rx): modal thickness less than 50 cm. Rocky outcrops are common;
- very thin deposits (Mx): modal thickness less than 25 cm. Rocky outcrops are not common.

When mapping data are insufficient, field validation should be done, for example, by digging a hole with a shovel. On sites where soil depth is less than 25 cm, harvesting is not recommended. On sites where soil depth ranges from 30 to 50 cm, harvesting can be done, but only in connection with a winter cut or by ensuring that a portion of the residues is left on site.

2. Steep slopes

Removal of forest residues particularly affects sites with a steep slope because of their susceptibility to erosion. As in the case of sites with shallow soils, additionnal entries into these forest sites increase the risk of physical soil damage.

In Quebec, steep slopes can be identified from topographic land maps. The following types of slopes are sensitive to biomass harvesting (Létourneau et al. 2003):

- very steep slopes (F): 40% and over;
- steep slopes (E): 31% to 40%.

A field validation may also done.

Sites with a slope gradient greater than 30% should not be subjected to harvesting.

3. Very coarse-textured soil and coarse-textured soil

The sensitivity of sites with very coarse-textured soil or coarse-textured soil can be attributed to their low organic matter content. A soil's organic matter content partly determines its water and nutrient holding capacity; organic matter is also a source of nutrients for the soil. Soils that are already poor in organic matter may therefore be affected by the removal of logging residues (Thiffault et al. 2006).

In Quebec, **very coarse-textured soils** can be identified summarily based on the type of surficial deposits (Saucier et al. 1994). Very coarse-textured soils are the following:

- **Ice-contact deposits (2A)** are fluvioglacial deposits (2); they include eskers (2AE) (Figure 18), kames (2AK) and kame terraces (Figure 19). These deposits consist of sand, gravel, pebbles, stones and, occasionally, rounded to sub-rounded boulders. Their stratification often exhibits deformation and faulting. The range of particle size varies considerably with the strata. These deposits often encompass pockets of till (Figure 20).

Figure 18. Gravelly esker.
Source: René Thiffault

Figure 19. Kame terrace material.
Source: René Thiffault

Figure 20. Till.
Source: René Thiffault

- **Proglacial deposits (2B)** are fluvioglacial deposits (2); they include fluvioglacial deltas (2BD), esker deltas (2BP) and outwash deposits (2BE) (Figure 21). They are composed mainly of sand, gravel and rounded pebbles. These sediments are sorted and laid down in very distinct layers.

Figure 21. Fluvioglacial material.
Source: René Thiffault

- **Eolian deposits (9)** comprise active dunes (9A) and stabilized dunes (9B) (Figure 22). These bedded, well-sorted deposits generally consist of fine to medium sand.

Figure 22. Dune.
Source: René Thiffault

Coarse-textured soils are associated with the following types of deposits (Saucier et al. 1994):

- **Glacial deposits with a defined morphology (1B)** encompass drumlins and drumlinoids (1BD), mounds of till debris (1BT), dead-ice moraines (1BP), ribbed (Rogen) moraines (1BC), corrugated ground moraines (1BN), De Geer moraines (1BG), and end moraines (1BF) (Figure 23). These glacial landforms are generally composed of till (Figure 20).

Figure 23. Heart of a moraine.
Source: René Thiffault

- **Alluvial deposits (3A)** are fluvial deposits (3); they can be divided into current (3AC), recent (3AE) and old (3AN) deposits. These well-stratified deposits generally consist of gravel and sand, with a small proportion of silt and clay. They may also comprise organic matter.

- **Glaciolacustrine deposits (shallow-water facies) (4GS)** are lacustrine deposits (4). They are composed of sand and, occasionally, gravel.

- **Beach deposits (4P)** are lacustrine deposits (4). They are composed of sorted sand and gravel. They sometimes contain silt.

- **Marine deposits (shallow-water facies)** (5S) are marine deposits (5) consisting of sand and, occasionally, gravel; they are generally well sorted.

The surficial deposit classification system allows the general identification of very coarse-textured and coarse-textured soils. However, to obtain the most precise and accurate information possible, it is necessary to perform a field validation. This requires the use of a soil texture key

(Appendix 5). A soil identified as sand or loamy sand has a very coarse texture. Logging residues should not be harvested on these types of soil. However, if the soil more closely resembles sandy loam, it will have a coarse texture. On such sites, it is important to implement measures to conserve organic matter, which means harvesting in winter or leaving a certain proportion of coarse woody debris (large branches) on site.

4. Sites with excessive drainage

Sites with excessive drainage are characterized by low levels of organic matter. The removal of forest residues would deprive them of a potential source of organic matter that could increase the soil's water and nutrient holding capacity.

Quebec has developed a drainage classification system in which water flow criteria as well as deposit and soil characteristics are associated with the different drainage classes (Saucier et al. 1994). Only one class, the excessive drainage class (0), can be considered problematic in a biomass harvesting context.

Soil moisture:

- comes from precipitation and, occasionally, lateral drainage;
- excess water flows away rapidly;
- water table is absent.

Deposit characteristics:

- very stony, very shallow or bedrock deposit;
- mostly on gravelly sites, summits or steep slopes;
- texture is coarse to very coarse.

Soil characteristics:

- humus is generally thin;
- no mottles, only exceptionally present at contact point with bedrock.

In the field, indicator plant species for the boreal forest's dry soil moisture regime and poor nutrient regime can be used to identify sites with excessive drainage (Table 5) (Ringius and Sims 1997).

Table 5. Indicator species of dry and poor sites

Species
Trees and shrubs
Alnus crispa (Ait.) Pursh – Green alder / Mountain alder *Arctostaphylos uva-ursi* (L.) Spreng. – Common bearberry *Chimaphila umbellata* (L.) Bart – Prince's pine *Comptonia peregrina* (L.) Coult. * – Sweet-fern (Figure) *Epigaea repens* L. – Mayflower / Trailing arbutus *Juniperus communis* L. – Common juniper *Kalmia angustifolia* L. – Dwarf laurel / sheep-laurel *Ledum decumbens* (Ait.) Lodd. – Northern Labrador tea *Menziesia ferruginea* Sm. – False azalea *Rhododendron albiflorum* Hook. * – White-flowered rhododendron *Rhododendron canadense* (L.) Torr. – Canadian rhododendron *Shepherdia canadensis* (L.) Nutt. – Canadian buffalo-berry *Vaccinium vitis-idaea* L. var. minus Lodd. – Lingonberry / Mountain cranberry
Herbaceous plants
Cypripedium acaule Ait. – Stemless lady's-slipper / Common lady's-slipper
Ferns, club mosses and horsetails
–
Mosses and lichens
Cladina spp. – Caribou lichens / Reindeer lichens (Figure) *Kindbergia oregana* (Sull.) Ochyra* – Oregon beaked moss *Ptilium crista-castrensis* (Hedw.) De Not. – Plume moss

***** Indicator species at the edge of the boreal forest

Biomass harvesting should not be carried out on sites characterized by excessive draingage.

Figure 24. *Comptonia* **–** Sweet-fern.
Source: Nelson Thiffault

Figure 25. *Cladina* spp. – Caribou lichens / Reindeer lichens.
Source: Nelson Thiffault

5. Acidic, low fertility sites

Biomass harvesting affects naturally acidic, low fertility sites because of their low levels of nutrients, especially base cations (Thiffault et al. 2006). Indeed, on such sites, mineral weathering releases only small amounts of nutrients and the high acidity level limits the soil's capacity to retain base cations. Logging residues therefore represent an important source of nutrients for these sites.

The ecological type classification system may be used to identify acidic, low fertility sites (Ministère des Ressources naturelles et de la Faune 2006). Lichen ecological types on very thin or coarse-textured deposits are typical indicators of acidic, low fertility sites:

- Black spruce–lichen stand on very thin deposits, variable soil texture, xeric to hydric drainage (RE10)

- Black spruce–lichen stand on thin to thick deposits, variable soil texture, xeric to hydric drainage (RE11)

- Black spruce stand with mosses or ericaceous shrubs on very thin deposits, variable soil texture, xeric to hydric drainage (RE20)

- Black spruce stand with mosses or ericaceous shrubs, thin to thick deposits, coarse soil texture, xeric or mesic drainage (RE21)

In the field, sites dominated by lichens, ericaceous shrubs or thin humus may be indicative of site sensitivity; hence, biomass harvesting is not recommended.

Appendix 4: Soil texture key