Chapter 8

Estimating net greenhouse gas (GHG) emissions from wood energy use

Issues and the current state of knowledge

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HIGHLIGHTS

- This chapter reviews findings from recent research related to GHG accounting for wood-based energy.
- The review affirms the possibility of understanding how and to what degree the use of wood for energy can result in GHG benefit.
- The review finds no agreement yet on various assumptions that would exactly specify the degree of GHG benefi9ts offered by the use of wood for energy.
- Major factors affecting estimates of net GHG emissions of wood energy include temporal and spatial scale of the analysis, baseline conditions considered, GHG metrics used, market-induced changes in land use and management, types and sources of wood feedstick, types of fossil fuel systems displaced, and uncertainties in estimates.
- There is an opportunity to work for a broader consensus on the assumptions that should be included when accounting for GHG emissions from wood energy.
- A consequential life cycle analysis (CLCA) that compares C emissions from a wood-burning facility and follow-on C change on land over time between the business-as-usual and alternative bioenergy use cases is a useful framework to solve the problem of C accounting related to wood energy.

8.1 Introduction

Use of woody biomass from sustainably managed sources to produce energy is considered an important strategy to mitigate climate change because the resource is renewable (biomass regrowth on land recaptures emitted carbon dioxide (CO_2) due to biomass burning) and can substitute for fossil-fuel-based energy such as coal and natural gas. However, consensus on the degree of contribution of woody biomass to climate change mitigation is lacking. The reason for this lack of consensus is that different analysts include different carbon (C) stock changes (e.g. C stock change where feedstock is taken, C stock change due to indirect land use and management changes), different time frames (e.g. 10–20years versus 100 years), different greenhouse gas (GHG) metrics (e.g. GHG flux versus net cumulative radiative forcing), different types and sources of wood feedstock (e.g. feedstock sourced from existing forest versus feedstock sourced from new plantations versus use of logging residue), different baselines (e.g. reference point baseline versus anticipated future baseline), and types of life cycle analysis (LCA) framework (e.g. attributional LCA versus consequential LCA) that influence the estimated GHG impacts of wood energy.

Current policy and scientific discussion have identified different views (Pena et al., 2011; US EPA, 2011) on the role ofwoody biomass use for energy in reducing atmospheric GHG emissions. Both the European Union (EU) and the US Environmental Protection Agency (US EPA) are in consultation processes to determine in what way or to what degree emissions from the generation of wood energy should be counted as net GHG emissions to the atmosphere. Three options discussed by US EPA (2011) include: (1) categorical exclusion, which considers wood emissions as having no net effect on GHGs in the atmosphere; (2) categorical inclusion, which counts wood emissions equal to the initial emission from burning; and (3) an option that estimates the fraction of wood emissions that should be counted as equal to fossil fuel emissions. The first view suggests that biomass is inherently C neutral, meaning that net GHG emissions from biomass remova1 and their combustion for bioenergy is zero. This is based on the rational that growth of sustainably managed biomass resources will offset all emissions related to biomass burning. An emission factor of "zero" would be applied when accounting for GHG emissions ofbioenergy. The accounting approach used by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006) for preparing national GHG inventories uses an accounting framework in which GHG emissions from wood burning are not counted in the energy sector, but instead are counted by loss of carbon from forest harvest. To avoid double counting, an emission factor of zero for biomass combustion is reported in the energy sector (IPCC, 2006). Therefore, this approach---applying a zero emission factor in the energy sector--does nor account for changes in forest C due to changes in levels of wood energy use. Use of a zero emission factor is realistic in the case of annual agricultural crops because C released from harvest is recaptured by the crop grown in the following year. However, for perennial crops and forests with long rotations, emissions from wood biomass for energy may take several years to be offset by feedstock regrowth (Helin et al., 2012; Zanchi et al., 2012). The second view considers that combusting biomass for energy releases C in the atmosphere just as fossil fuel combustion does, and therefore proposes that emissions from biomass burning should be treated in the same way that emissions from fossil fuel burning are treated. An emission factor of "one" would be applied when accounting for GHG emissions related to bioenergy. The third view would assign an emission factor between "zero" and "one" (or potentially more) and would depend on the type and source of biomass. This view considers that increased biomass removal and use for energy emits C to the atmosphere, and for at least some time period, while C changes on the land, more C is in the atmosphere than without biomass burning; therefore, bioenergy is not inherently C neutral.

The degree to which woody biomass can offset emitted C and whether bioenergy is C neutral has been a topic of numerous investigations (e.g. Schlamadinger et al., 1995; Schlamadinger and Marland, 1996a; Fargione et al., 2008; Searchinger et al., 2009; MCCS, 2010; Cherubini et al., 2011a, 2011b; Repo et al., 2011; Colnes et al., 2012; Haberl et al., 2012; Helin et al., 2012; Holtsmark, 2012a; Pingoud et al., 2012; Zanchi et al., 2012). In general, these studies indicate that emissions resulting from burning woody biomass for energy are not offset at the same time as they occur, and therefore woody biomass is not inherently C neutral (i.e. net emission from biomass burning is not zero) and how we estimate the degree to which woody biomass can contribute to climate mitigation depends on several factors, including prior and anticipated future land use that influences terrestrial C stock level before and after bioenergy expansion, efficiency of bioenergy production technology, types of fossil fuels being replaced, time horizon considered, types and sources of biomass feedstock used, and baseline and system boundary considered. Accordingly, these studies call for a more comprehensive accounting framework that considers both biophysical and economic dynamics associated with woody-biomass-related emissions and sinks.

The answer to the question of whether climate policies should encourage expanded woody biomass removal for bioenergy will depend on our ability to identify GHG impacts, including both the degree and timing of net reductions in GHG emissions. The degree and timing of reductions in GHG emissions may, in principle, be evaluated by tracking C emissions and sequestration across its entire life cycle using LCA methods (Ingerson, 2009; Bird et al., 2011; Lippke et al., 2011). LCA is an analysis framework used to evaluate the potential environmental burden (impacts) of a product or service throughout its life cycle (Cherubini et al., 2009; Finnveden et al., 2009; Levasseur et al., 2010; Lippke et al., 2011). Two types of LCAs are distinguished: attributional LCA (ALCA) or consequential LCA (CLCA), which are designed to answer different questions related to environmental impact of a product or a service (Brander et al., 2009; Finnveden et al., 2009; Lippke et al., 2011). ALCA provides information on impacts of processes during production, consumption, and disposal of a product without considering indirect consequences arising from changes in the output of a product (Brander et al., 2009). For example, an ALCA identifies the magnitude of emissions from burning biomass fuel and/or fossil fuel within a product's life cycle, but it does not identify the amount of avoided emissions that may occur due to substitution of wood energy for fossil fuel energy outside a product's life cycle. In contrast, CLCA estimates the effects of changes in the level of production, consumption, and disposal of a product on emissions, including effects outside an ALCA system boundary (Brander et al., 2009). For example, a CLCA may include market-induced effects such as the effect that increased demand for wood energy and increasedd revenue will have in influencing private forest landowners, to retain more land in forest, to plant more forest, or intensify management (Daigneault et al., 2012; Nepal et al., 2012; Sedjo and Tian, 2012; Sedjo, 2013). Many ALCA estimates consider sustainably grown woody biomass that is used for energy to be C neutral because C will be regrown in forests over an extended time. But they do not consider the timing of emissions and removals (the same weight is given to emissions and C storage that occur in the present, or any time in the future) and do not include indirect land use and other indirect effects (Bird et al. 2011; Cherubini et al., 2011a, 2011b; Helin et al., 2012; Pingoud et al., 2012). A CLCA can avoid these limitations, although extra uncertainties arise with use of CLCA.

The LCA framework that is chosen will substantially influence the estimated climate mitigation role of wood-based bioenergy and would thereby affect policies and programs (Malmsheimer et al., 2011). The choice of LCA would depend on the particular event being examined and the specific questions being addressed. For example, if we are interested in understanding the level of emissions associated with a particular activity, then an ALCA may be applied. Conversely, if we are interested in changes in emissions over time, a CLCA may be applied. This chapter reviews recent literature on GHG accounting of wood-based bioenergy. The review accepts the view that GHG effects of a wood energy system should be evaluated using CLCA principles that comprehensively examine baseline and alternative wood bioenergy systems and should consider the interaction of markets and investment with forest management and forest ownership when estimating the follow-on changes in C stock on the land. Specifically, this review chapter highlights the importance of considering factors that influence net C emission effects of wood bioenergy use, including: (1) appropriate system boundary and a baseline or reference system; (2) appropriate time horizons for emissions and sinks and for GHG metrics; (3) market-induced effects on land use and management changes; (4) effects of different types and sources of wood biomass feedstock; (5) effects of substituting wood energy systems for fossil fuel systems; and (6) effects of uncertainties and measures to assess those uncertainties.

8.2 Aim and scope

The main aim of this chapter is to identify key issues related to C accounting of wood-based bioenergy and to discuss their effects on estimates of net C emissions over time based on findings of recent research. Because of wide commercial adoption, it focuses on woody biomass utilization for electric power and heat generation. A choice about each issue is discussed based on the synthesis. The issues identified include: (1) the system boundary that delineates biological, industrial, and market processes included along with the temporal and spatial scale of the analysis; (2) baseline or reference situations to use when evaluating use of a wood energy system; (3) time frame for analysis; (4) metrics used to measure GHG impacts; (5) market-induced changes on land use and management affecting land C change; (6) net C emission effects by type and source of woody biomass feedstock; (7) effects of substituting wood for fossil fuels; and (8) effect of uncertainties in C accounting. Because ALCA accounting methods are limited in addressing these issues, the discussion and synthesis uses CLCA methods to evaluate these issues.

The review relied on more than 100 publications to develop a synthesis on these issues. Comprehensive reviews are already available on topics related to LCA of bioenergy, including both woody biomass and agricultural biomass for generation of biofuel, heat, and electricity (e.g. Cherubini et al., 2009; Cherubini and Strømman, 2011; Helin et al., 2012). The synthesis presented in this chapter differs from past reviews, in that it focuses exclusively on C accounting issues related to wood energy generation for heat and electricity (power) and provides a more detailed discussion on market-induced land use and management change effects of expanded bioenergy use. Because there are special cases of accounting for logging residue and mill residue where the alternative fate for the wood is decay rather than continued forest growth, most discussion in this chapter focuses on C accounting for use of main stems of trees used for energy. However, some aspects of C accounting for logging residue use are also discussed.

8.3 Issues and current state of knowledge in estimating net GHG emission effects of wood energy

8.3.1 System boundary

Specification of a system boundary is a key step for any LCA of a wood energy system because the magnitude and degree to which wood energy can contribute to GHG mitigation over time is dependent on the choice of system boundary. A system boundary describes the processes, their inputs, and their outputs that are included and the extent of these processes over time and space, thus delineating temporal and spatial boundary for the analysis (Cherubini et al., 2009; Pena et al., 2011; Helin et al., 2012). A clear definition of system boundaries is critical in understanding GHG mitigation effects of wood energy systems (Bird et al., 2011; Malmsheimer et al., 2011; Helin et al., 2012).

Figure 8.1 illustrates the processes within a specified boundary and the C flows to and from the atmosphere associated with those processes and the use of woody biomass for energy. Forests take up CO_2 from the atmosphere and store it in biomass. When a forest is harvested, a portion of C stored in aboveground tree biomass could be transferred to harvested wood products and/or a portion could be used for energy. Transportation of wood consumes fossil fuels, releasing CO_2 to the atmosphere. The C stored in the wood used to produce energy is released to the atmosphere. If the wood is used to produce long-lived wood products, C is stored in those products in use. The by-products of wood processing at mills, the mill residue, can be used as feedstock for bioenergy, which also releases CO_2. Solid arrows in Figure 8.1 indicate CO_2 uptake, and dotted arrows indicate the CO_2 emissions. Use of woody biomass for energy can involve two sets of forestlands (Figure 8.1). One forestland area (Figure 8.1, Forest area A) provides wood directly to a wood burning facility (through direct removals/harvest). With increased prices and revenue, private landowners are more likely to retain or expand land in forest and/or intensify management to provide more wood. The result can be an increase in C stored in forests that partly or entirely offset C emissions from biomass combustion

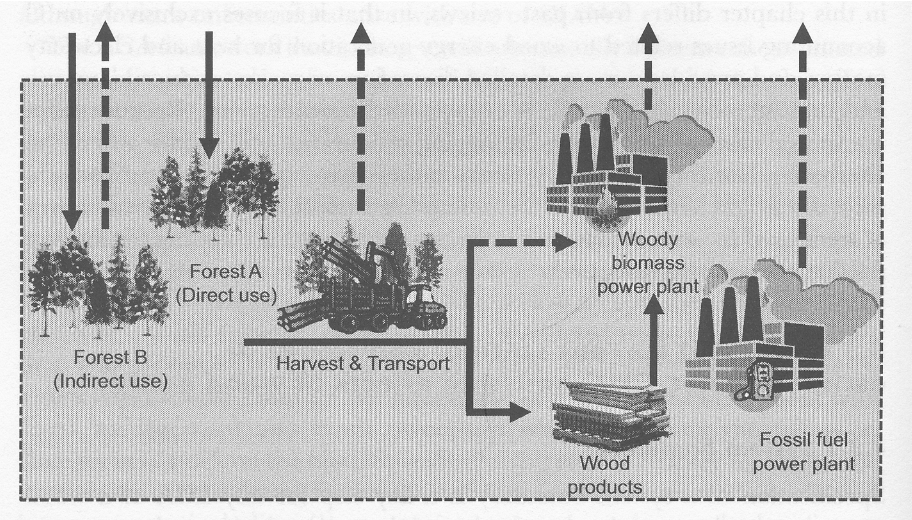

Figure 8.1 A simplified illustration of the processes inside the system boundary showing carbon flows to and from the atmosphere due to wood biomass use for energy - solid arrows indicate CO_2 uptake from the atmosphere; dashed arrows indicate CO_2 release to the atmosphere due to harvest, transport, and burning of wood biomass for energy; the rectangle represents the system boundry

over a given time period. Such changes in land use or management due to market-induced force represent indirect land use or management change (Figure 8.1, Forest area B). Thus, the selected system boundary should encompass sources or sinks of GHG associated with direct and indirect effects arising from use of woody biomass energy (World Resource Institute, 2006; Chum et al., 2011; US EPA, 2011).

The system boundary will also specify the temporal and spatial scale of the analysis. Such scales of analyses could be a forest stand (e.g. MCCS, 2010; Zanchi et al., 2012), a landscape (e.g. McKechnie et al., 2011; Colnes et al., 2012), or larger. Several studies argue that applying stand-level C dynamic results to establish emission effects of a wood burning facility is inaccurate because C dynamics are different over a broader landscape compared with C dynamics representing a single stand (Lucier, 2010; Miner, 2010; O'Laughlin, 2010; Malmsheimer et al., 2011). Consequently, these studies suggest a need for a landscape-level analysis (or broader) over time to accurately evaluate net emission effects of increased bioenergy production.

The time frame chosen will also influence the level of estimated effect. For instance, offsetting increased cumulative emissions through biomass regrowth is slow initially, and offsets are low to negative (compared with a reference case) during years immediately after harvest (MCCS, 2010; Zanchi et al., 2012). Thus, analysis covering a short time frame (e.g. 20-30 years) may show different net GHG effects from those for a long time frame (e.g. 100 years). Examples of alternative system boundries for C accounting of biomass energy may include the following:

- Consider the impact of increased wood use for operation of a single wood burning facility and the changes in GHG emissions and forest C fluxes only on the land where wood biomass is obtained for burning. Time frame for wood burning increase is one year of facility operation; time frame for forest C change is 100 years; and time frame for analysis is 100 years.
- Same as above except time frame for wood burning increase is 30 years of facility operation.
- Consider the impact of increased wood use for the operation for all new wood burning facilities in a country and the forest C fluxes on all land (forest and non-forest). Time frame for wood burning facilities is 50 years; time frame for land C change is 100 years; and time frame for analysis is 100 years.

8.3.2 Baseline or reference situation

Net emission effects over time of a bioenergy system need to be evaluated against an appropriate baseline system or the reference case. US EPA (2011) defines baseline or reference as:

> any datum against which change is measured. Such a datum serves as the "reference" against which other conditions or changes can be compared. It might be a "current baseline," in which case it represents observable, present-day conditions. It might also be a "future baseline," which is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.

The reference case for wood energy should be a description of forestland use or land management that would occur in the absence of the proposed bioenergy system. Without such reference to land use, we would be ignoring biomass feedstock growth and changes in C stock on land that would occur in the absence of bioenergy production (Searchinger et al., 2008; Cherubini and Strømman, 2011; Hudilburg et al., 2011; Helin et al., 2012; Schulze et al., 2012). In addition, a fossil energy system may be specified as part of the reference system. Three types of baselines suggested for C accounting of bioenergy systems (Pena et al., 2011; US EPA, 2011) include: (1) reference point baseline; (2) business-as-usual or anticipated future baseline; and (3) comparative baseline.

8.3.2.1 Reference point baseline

This baseline is the amount of C stored at the beginning of a time period over which wood energy use will be evaluated. The objective is to answer the question of whether more or less C is stored in the wood energy system at the end of an assessment period than there was at the beginning (US EPA, 2011). Fargione et al. (2008) used a reference point baseline approach in evaluating whether more or less C was stored in a crop-based biofuel system at the end of an evaluation period than that which was stored at the beginning. Malmsheimer et al. (2011) proposed use of a "reference point" baseline approach to evaluate net emission impacts of a wood-based bioenergy system. With this framework, if forest C in a region increases over a time period, even with increased wood removals for energy, then net emissions associated with increased wood energy use are judged to be zero. If forest C decreases, then emissions are judged to be equivalent to fossil fuel emissions. An ALCA typically uses a reference point baseline to evaluate the net C emissions associated with a particular set of activities over time.

8.3.2.2 Business-as-usual or anticipated future baseline

The business-as-usual (BAU) baseline is a projected series of annual biomass emissions and land C levels that are expected if wood energy use is not increased. The level of fossil fuel emissions is not included in the baseline case or increased bioenergy case. The bioenergy case includes the series of annual biomass emissions and land C levels. The objective is to answer the question as to how much more or less C is stored during and/or at the end of an assessment period for the wood bioenergy system compared with the BAU case (US EPA, 2011). This approach is used by White et al. (2013), Daigneault et al. (2012), Sedjo and Tian (2012), and Nepal et al. (2012). In evaluating potential net change in emissions due to increased demands for bioelectricity, White et al. (2013) considered total C stock change on both agriculture and forestland, comparing two cases of increased wood-based electric power production with a BAU baseline scenario over the period 2010–2030. Similarly, Sedjo and Tian (20 12) evaluated emission consequences of a projected increase in wood use by comparing increased wood energy use scenarios with a baseline over a 50-year period. Likewise, Nepal et al. (2012) compared alternative scenarios of high wood energy consumption with a BAU wood energy use scenario over 50 years. They compared changes between the BAU and high wood energy cases in wood burning emissions, C sequestration on US timberland, and C stored in harvested products. One limitation of using a BAU baseline is that there can be considerable uncertainty in net emissions estimates generated by uncertainty in projecting the emission and C storage associated with both a BAU baseline and alternative cases. A CLCA could use a BAU baseline to evaluate changes in emissions over time between BAU and alternative wood energy scenarios.

8.3.2.3 Comparative baseline

This baseline is similar to the BAU baseline but compares projected net GHG emissions for a wood energy system with net emissions for a fossil fuel system that produces the same amount of electricity and/or heat. The objective for using a comparative baseline is to answer the question of how much net CO_2 emission would differ over an assessment period between the baseline fossil energy system and the wood energy system (US EPA, 2011). Zanchi et al. (2012) Colnes et al. (2012) McKechnie et al. (2011) and MCCS (2010) used a comparative baseline approach to investigate net GHG emissions effects of woody biomass use for energy. Zanchi et al. (2012) estimated net increase in GHG emissions due to increased use of logging residue, wood from plantations on marginally productive land, and additional wood harvest in natural forests to replace coal, oil, or natural gas systems. Colnes et al. (2012) developed a projected "BAU" baseline that used fossil fuels and then projected the change in atmospheric C if wood biomass were used to produce electric power. Similarly, McKechnie et al. (2011) assessed net GHG emission effects of: (1) using forest biomass to produce wood pellets and electric power versus using coal for electric power; or (2) using forest biomass to produce ethanol versus production of gasoline and use in a light-duty vehicle, with all cases being in Ontario, Canada. Similarly, MCCS (20 10) compared cumulative C emissions of biomass energy relative to continued burning of fossil fuels, including coal, oil, and natural gas, for electricity and heat production. As for the use of an anticipated future baseline, the comparative baseline approach has inherent uncertainties in projections of GHG emissions and C stock change levels (US EPA, 2011). A CLCA could use a comparative baseline to evaluate changes in emissions over time between BAU energy system and alternative wood energy system scenarios.

8.3.2.4 Selection of the baseline

Selection of a baseline approach depends on the policy context and the purpose of the analysis (US EPA, 2011). For example, if the objective is to understand to what degree (i.e. what fraction of) biomass emissions should be counted as a net addition to the atmosphere, then an estimate of how much reference energy (e.g. fossil fuel) may be displaced is not required. However, if the intention is to determine full life cycle impacts of increased bioenergy use, net emissions for a wood energy system need to be compared with net emissions for a fossil energy system being displaced (Bird et al., 2011; Cherubini and Strømman, 2011). Estimated GHG effects of using wood energy can differ substantially depending on the energy system replaced (MCCS, 2010; Pena et al., 2011; Zanchi et al., 2012), indicating the importance of correctly identifying the fossil energy system to be replaced (Pena et al., 2011).

8.3.2.5 Including the effect of demand expectations when using a BAU baseline: two approaches

Because current forest management practices and investment decisions are influenced by anticipated future markets for wood (Daigneault et al., 2012; Sedjo and Tian, 2012; Sedjo, 2013), baseline and alternative cases should incorporate such anticipatory effects. For example, private forest landowners may retain more land in forests, expand forests by planting more trees, or intensify forest management (e.g. more frequent thinnings) in anticipation of future revenue due to increased wood energy demand and prices. There are two substantially different ways to envision and use a BAU baseline and alternative cases that include the effect of anticipated demand on land use and management. The first way is to envision that the BAU case (without anticipated substantial increase in wood energy use) and an alternative case with anticipated increase in demand and resulting difference in land use and management begin at some indefinite point in the past, and what has been actually observed is an "alternative" case that included anticipation to increased wood energy demand that caused an extra accumulation of biomass (compared with the non-observed BAU case) on the land prior to its harvest and wood energy emissions. With this reasoning, past anticipation and biomass accumulation can be viewed as offseting present emissions to some degree (Sedjo, 2013). The second way to use BAU and alternative cases that include anticipated investment is to begin the cases at the present time and track how an increase in current and continuing emissions compared with a BAU case induces extra investment in forestland and intensified management that contributes to offsetting increased continuing emissions over time. This second way of viewing BAU and alternative cases is most commonly used. Several studies have used such forward-looking or rational expectation approach, endogenously accounting for the amount of forest investments due to wood energy usage and examining the resulting impacts on the amount of C captured by the forest system (e.g. Daigneault et al., 2012; Sedjo and Tian, 2012; Sedjo and Sohngen, 2013). It is difficult, however, to make estimates for the first way of viewing BAU and alternative cases that would incorporate the magnitude of forest investments or management changes that occurred in the past due to expected increases in bioenergy demand. Although costly and time-consuming, a forest landowner's survey could help provide information on such past impact of anticipated wood energy demand.

8.3.3 Time horizon considered when evaluating wood energy GHG emissions

A key difference between wood and other biomass energy (e.g. agricultural crop residues) is the time difference between C release to the atmosphere and C sequestration from the atmosphere through biomass regrowth on land (Bird et al., 2011; Cherubini et al., 2011a, 2011b; Pena et al., 2011; Helin et al., 2012; Pingoud et al., 2012; Zanchi et al.. 2012). In the case of annual agricultural crops, C released from biomass is recaptured by the crop planted the next year—there is no substantial time lag between CO_2 emission and C recapture through regrowth (Pena et al., 2011; Helin et al., 2012; Zanchi et al., 2012). Thus, the assumption of C neutrality commonly used in LCAs of bioenergy is realistic in the case of annual crops. However, for perennial crops and forests with long rotations, emissions may take years to be offset by feedstock regrowth (Schlamadinger and Marland, 1996a; Helin et al., 2012). Therefore, consideration of appropriate time horizon and timing of C emissions and sequestration is an important aspect of C accounting for wood energy. In general, the chosen time frame for accounting net emissions of wood energy would allow consideration of C sequestration in trees and emissions or C change associated with establishing, growing, or regenerating the forest, including land use change and other management activities (Malmsheimer et al., 2011).

Studies have shown that estimated net GHG effects of using roundwood or logging slash for energy is time-dependent, thus emphasizing the need to consider appropriate time horizon and timing of emissions and sinks in GHG accounting of wood energy systems (Schlamadinger et al., 1995, 1997; Schlamadinger and Marland, 1996a; Johnson, 2009; Marland, 2010; MCCS, 2010; McKechnie et al., 2011; Malmsheimer et al., 2011; Repo et al., 2011;

Zanchi et al., 2012). In addition, other studies have shown that even if a wood energy system is C neutral over a given time period (i.e. biomass regrowth over time offsets the eqwuivalent amount of C released due to biomass used for energy), the system is not climate neutral because emissions and sequestration of C by biomass growth occur at different times (Cherubini et al., 2011a, 2011b; Pingoud et al., 2012). Before being captured by biomass regrowth, extra CO_2 molecules spend time in the atmosphere (Cherubini et al., 2011a, 2011b). Over a finite time horizon, which is determined by the policy context (e.g. reducing climate change impacts during the next 30 or 100 years), sequestration can lag behind emissions, resulting in net increase in global warming. Thus, the net GHG effect of bioenergy systems depends on amount and timing of GHG emissions and recapture over time (Sathre and Gustavson, 2011).

Due to a time lag between emissions and significant sequestration, there is a period when a C debt extends over a C payback period when the net emissions for the bioenergy case are higher than for the baseline or fossil energy case (Fargione et al., 2008; Searchinger et al., 2009; MCCS, 2010). The time needed to attain parity between bioenergy emmissions and baseline case emissions can range from a few years to more than a century, depending on prior land use and management, source and type of feedstocks, and bioenergy production technology and fossil fuel technology being replaced (Schlamadinger and Marland, 1996a, 1996b; Fargione et al., 2008; Zanchi et al., 2012).

In general, studies identify the time horizon used when estimating GHG offset benefits of wood energy. For example, Zanchi et al. (2012) analyzed C recovery for different wood biomass sources over time from a typical Norway spruce (**Picea abies**) stand in Austria compared with the use of fossil fuel. They found that C debt is paid off after 175, 300, and 295 years of coal, natural gas, and oil were displaqced, respectively, when wood for energy is provided by roundwood from timber harvests that are 60-80 percent above a baseline harvest case. In contrast, the C payback time was dramatically shorter when logging residues were used (0, 7, and 16 years when coal, oil, and natural gas were displaced, respectively). McKechnie et al. (2011) integrated LCA and forest C analysis to assess change in GHG emission of increased forest bioenergy over 100 years, using case studies of wood pellet and ethanol production and use in Ontario, Canada. They showed that GHG emissions due to harvests for bioenergy initally exceeded avoided fossil-fuel-related emissions. However, they reported that electricity generation from wood pellets began reducing overall emissions related to electricity generation from coal after 16 years when harvest residues were used, and after 38 years when standing trees were used. Likewise, a study by MCCS (2010) considering wood use from representative forest stand in Massachusetts, USA, showed that switching to woody biomass began reducing GHG emissions after the first five years when oil-fired combined heat and power (CHP) capacity was replaced, but would take more than 90 years when woody biomass replaced natural gas electric capacity. Similarly, Colnes et al. (2012) found that using wood from southeastern US forests for an expansion of electric power generation could begin providing a GHG emission reduction after 35–50 years, depending on the replaced fossil fuel technology. Studies also indicate that net GHG offset accumulates to various levels over extended time horizons after the C payback period (Cherubini et al., 2011a, 2011b; Repo et al., 2011; Holtsmark, 2012a; Mitchell et al., 2012; Pingoud et al., 2012).

There is no formal agreement on the appropriate time frame to consider when evaluating net GHG emission impacts of wood energy. In general, the time frame chosen is guided by policy or economic decision (Schlamadinger et al., 1997; US EPA, 2011; Helin et al., 2012; Zanchi et al., 2012). Short time frames (20–30 years) (e.g. Righelato and Spracklen, 2007; Hudiburg et al., 2011) may be selected if the focus is on meeting near-term emissions reduction targets. However, several other studies (e.g. Marland et al., 2007; O'Laughlin, 20 10) argue that consideration of short time horizons provides a limited perspective on GHG effects of bioenergy use. A longer time frame is most relevant for studying long-term climate impacts of bioenergy systems because environmental studies are typically driven by a concern for long-term climate impacts (Schlamadinger et al., 1997; Ekvall and Weidema, 2004; O'Laughlin, 2010; Sedjo, 2010). The Intergovernmental Panel on Climate Change (IPCC) uses a time horizon of 100 years to estimate global warming potential (IPCC, 2007) of GHGs, and several studies use a time period of 100 years in their analysis of GHG effects of bioenergy (e.g. Marland and Schlamadinger, 1997; McKechnie et al., 2011; Repo et al., 2011). To choose a time period of less than 100 years would suggest that wood energy emissions cause a greater net radiative forcing effect (described in the next section) than other GHGs that are evaluated over 100 years. For example, a methane emission causes 21-25 times more radiative forcing than a CO_2 emission (US EPA, 2013).

8.3.4 GHG impact metrics

The preceding discussion highlights the importance of the time dimension in analysis of GHG effects of bioenergy use. Evaluating net GHG impact of wood emission on the atmosphere that includes initial emission and follow-on land C change requires a GHG metric. An ALCA sums C emissions and sequestration over an indefinite time period and assigns a characterization factor of zero for the global warming impact of biogenic CO_2 emissions, assuming that C emissions are balanced by forest regrowth over some indefinite time period (Cherubini et al., 2011a, 2011b; Bright et al., 2012). Because emissions and land C change occur at different times, a climate impact metric is needed that takes into account the timing of both emissions and sinks (Schlamadinger and Marland, 1996a; Helin et al., 2012). Several time-dependent metrics have been proposed.

Schlamadinger et al. (1995) introduced time-dependent C neutrality (CN) factor, defined as cumulative net emission reduction provided by a bioenergy system to a given point in time relative to the reference system, divided by emissions for the reference case to that given time. The CN factor has been used, for example, by White et al. (2013), Holtsmark (2012b), and Zanchi et al. (2012). A CN factor of zero means emissions from a bioenergy system through a given time equal those from the reference system (Zanchi et al., 2012). A CN value less than zero at a given time indicates that cumulative emissions from the bioenergy system are higher than those from reference system—there is a C debt. A CN value between zero and one indicates that net emissions for bioenergy system are less than for the reference fossil fuel system. A CN value of one indicates that the bioenergy system has offset all emissions of the reference system, or in other words, savings in net emissions due to use of the bioenergy system are equal to emissions from the reference system. A CN factor greater than one means that the bioenergy system has offset all emissions of the reference system and has sequestered additional C on land. This situation can occur, for example, when marginal agriculture land is reforested and CN factor is greater than one at the point the first biomass from a previously grown biomass plantation is burned and replaces emissions from a reference system.

A similar indicator, "C payback time" (time to recover the "C debt"), has been used in other studies (Fargione et al., 2008; Searchinger et al., 2009; MCCS, 2010; Colnes et al., 2012). C payback time refers to the time required for net wood energy emissions, including additional forest C sequestration, to equal the reference (fossil system) emissions (time needed to make zero C debt) (Berndes et al., 2011; Helin et al., 2012; Zanchi et al., 2012). Studies suggest that C payback time in case of woody biomass can range from a few years to several decades, depending on prior land use, types and sources of feedstock affecting biomass feedstock growth, replaced fossil fuel technology (e.g. coal, natural gas, oil), and efficiency of wood energy production technology (Schlamadinger and Marland, 1996b; Fargione et al., 2008; McKechnie et al., 2011; Zanchi et al., 2012).

Although they are useful indicators, one limitation of both of these indicators is that they do not directly characterize the impact on climate in terms of radiative forcing during the period of C debt and thereafter. Several other studies used metrics based on cumulative radiative forcing (CFR) to estimate global warming potential (GWP) of a bioenergy system within a given time frame (Cherubini et al., 2011a, 2011b; Sathre and Gustavsson, 2011; Holtsmark, 2012a; Pingoud et al., 2012). The GWP is the time-integrated global mean radiative forcing of a pulse emission of a given gas, over some given time period, stated in tonnes of CO_2, that would have produced the same CRF (IPCC, 1990; Shine et al., 2005). For example, for a 100-year time period, methane (CH_4) and nitrous oxide (NO_2) gases have 25 and 298 times higher GWP than CO_2, respectively (Bird et al., 2011; Cherubini et al., 2011a).

The GWP metric is used within the Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC). Although GWP has been criticized for not being able to represent the impact of GHG gas emissions on temperature and being based on a purely physical metric (not being based on an analysis of damages caused by the emissions), this metric is widely used owing to its simplicity, ease of calculations, and transparency (Shine et al., 2005).

A number of studies suggest that the metric to measure GHG effects of bioenergy systems should be CRF over 100 years (Cherubini et al., 2011a, 2011b; Helin et al., 2012; Holtsmark, 2012a; Pingoud et al., 2012). To choose a time period of less than 100 years would suggest that the net radiative forcing effect for wood biomass is greater than for other GHGs whose impacts are evaluated over 100 years. Another reason is that measuring GHG effects with CRF is simpler and presents less uncertainty compared with estimating the effects by temperature change (Kendall et al., 2009). Using this GHG metric, we can evaluate the impact of an initial wood emission (for wood from various sources) and follow-on C change on the land. For example, using the biogenic CO_2 metric described above, the CO_2 equivalent of biogenic CO_2 emissions from roundwood produced from forests evaluated by MCCS (2010), and used in accordance with state of Massachusetts biomass regulations (MADOER, 2011), is 0.68 tonnes CO_2 equivalent per tonne of wood CO_2 emissions.

In recent years, several alternative applications of CRF-based GWP indices have been proposed for improved GHG accounting related to bioenergy (Cherubini et al., 2011a, 2011b; Pingoud et al., 2012). Cherubini et al. (201 la, 2011b) proposed a unit-based index, GWP_{bio}, to estimate radiative forcing for biomass from forests or agricultural crops with various rotation periods. GWP_{bio} was used in an attributional life cycle evaluation where the reference case is the forest C level at a fixed starting time. Emissions and land C changes are tracked from the fixed point in time. This is essentially a dynamic attributional LCA. Similarly, Pingoud et al. (2012) proposed a GW_{biouse} factor to describe the net climate impacts of storage of C in long-lived wood products.

8.3.5 Land use change

Using wood for energy involves use of land and provides revenue to landowners and thereby can influence their investments in forests. Changes in land use or management regime will change C stocks in forests and other land, and the magnitude of such changes could be minimal to substantial (Fargione et al., 2008; Searchinger et al., 2009; Fritsche et al., 2010; Berndes et al., 2011; Cherubini and Strømman, 2011; Chum et al., 2011; Pena et al., 2011). A change in management regime does not involve conversion of land from one use to another. For example, shortening harvest age or increasing the timing and frequency of thinning or removal of logging residue does not involve changes in land use. A change in land use involves conversion of land from one use to another use. For example, cropland can be converted to forest plantations to supply biomass feedstock. Conversely, forest land can be converted to cropland. In the former case, the land use change (LUC) will increase C stock on land relative to its prior use, increasing the mitigation benefit. In the latter case, C stocks on new land will be lower compared with its prior use. Existing literature distinguishes two categories of LUCs: direct and indirect (Fritsche et al., 2010; Berndes et al., 2011; Bird et al., 2011; Cherubini and Strømman, 2011; Chum et al., 2011; US EPA, 2011).

Direct LUC is caused by a direct conversion from an existing land use to a new land use to supply biomass feedstock; an indirect LUC is caused by promise of future revenue for biomass. If an indirect LUC results in net increase in emissions, it is termed leadage. If it results in a net decrease in emissions (more C storage), it is termed spillage. For example, increased demand for biomass feedstock (e.g. pulpwood) induces landowners to retain land in forest, rather than converting to another use, or converting non-forest to forest. Most literature defines direct LUC as change that occurs within a limited system boundary that includes land providing biomass and defines indirect LUC as change that occurs elsewhere outside that limited system boundary (Fritsche et al., 2010; Berndes et al., 2011; Bird et al., 201; Cherubini and Strømman, 2011; Chum et al., 2011; US EPA, 2011). However, a system boundary definition may not be a useful way to distinguish between the two because, for example, if an analysis includes an entire country, any LUC would then be within the system boundary (Fritsche et al., 2010). A more accurate distinction is to consider any changes on land use due to market forces as indirect LUC.

Studies indicate that both direct and indirect LUCs could lead to substantial net increase in emissions or net increase in C storage (Leemans et al., 1997; Righelato and Spracklen, 2007; Fairgione et al., 2008; Searchinger et al., 2008; Melillo et al., 2009; Wise et al., 2009). Existing LCA methods for liquid biofuels require inclusion of direct LUC effects, but there is no widely accepted method for including the impact of indirect LUC (Cherubini and Strømman, 2011). The quantification of GHG emissions from both direct and indirect LUC inherently involves uncertainty (Berndes et al., 2011; Chum et al., 2011), and the uncertainty should be evaluated.

There is general consensus that expanded woody bioenergy use can result in both direct and indirect LUC. The potential increase or decrease in emissions due to direct LUC can be estimated, for example, using reference land use and C stock data (Chum et al., 2011). However, estimating indirect LUC involves studying market demand and land supply interactions in the economy and requires a market equilibrium model to analyze the effects across different sectors, including agriculture and forestry. Although increased land use emissions from biofuel production have been reported to be notable, such leakage effects in case of woody bioenergy have been found to be relatively smaller (Chum et al., 2011), primarily because of offsetting spillage effects of market incentives provided by expanded bioenergy leading to retaining or expanding forest area and/or investment in forest plantations and intensified forest management (Abt et al., 2010; Daigneault et al., 2012; Sedjo and Tian, 2012; Nepal et al., 2014). For example, in a recent study, Nepal et al. (2014) found that 78–80 percent of the increased cumulative C emissions due to increased wood energy use in the US could be offset over 50 years by biomass regrowth on land, differences in C storage in harvested wood products (HWP), differences in C in logging slash left to decay in forests, and differences in C on land due to altered transfers between forest and non-forest land. Similarly, taking into account the harvest and planting decisions affected by demand for wood energy, Abt et al. (2010) reported a reduction in emissions of up to 39 Tg of carbon dioxide equivalent (CO_2e) per year when about 50 percent of logging slash available from 10 southeastern US states were utilized to replace coal in power generation. In another study, Daigneault et al. (2012) incorporated market factors and concluded that increased demand for wood energy would increase global timber prices and harvests, leading to new investments in forest stocks that would reduce net global C emissions.

8.3.6 Other issues

8.3.6.1 Evaluation of C emissions by feedstock types and displacement of specific fossil fuel systems

Sources and types of wood-based feedstocks that can be used for bioenergy include roundwood (main stem of trees), logging residues, mill residues, pile and burn wood wastes, and construction wastes. The types of feedstocks being used and whether they are sourced from existing forests or plantations grown to produce biomass for energy greatly influence the time to pay off the C debt (Schlamadinger et al., 1995; McKechnie et al., 2011; Repo et al., 2011; Colnes et al., 2012; Zanchi et al., 2012). In general, in the absence ofmarket-induced investment in forestry, net GHG emissions associated with use of logging residues over a given time period will likely be smaller, due to avoided decay in forests, than use of roundwood from many types of existing forests over the same time period. The GHG benefit associated with using logging residues depends on the decomposition rate of the residues if they were left to decay in forests (Repo et al., 2011; Zanchi et al., 2012)—thehigher the avoided decomposition rate, the greater the GHG benefit over a given time period. In contrast, emissions due to increased use of roundwood for energy can take a longer and more variable time—dependingon forest and treatment conditions—to recover from the atmosphere through biomass regrowth (McKechnie et al., 2011; Colnes et al., 2012). Roundwood use from private land also provides revenue to landowners, which can influence them to retain land in forest or invest in planting or more frequent thinning, which can each result in more C stored in forests.

The payback time for logging residue in the Zanchi et al. (20 12) study ranged from 0 to 16 years, compared with 175–300 years for increased roundwood harvests from sustainably managed Norway spruce stands in Austria. When marginal agricultural lands with low C stocks are converted to short-rotation wood crops, the payback time was less than zero, regardless of reference fossil fuel replaced, because the plantations were established with the purpose of providing biomass for energy, absorbing C before being released to produce energy. Other studies (McKechnie et al., 2011; Colnes et al., 2012) presented similar results, concluding that the C payback period for logging residues were shorter than the C payback period for standing trees. McKechnie et al. (201 1) showed that forest C debt due to wood energy use was offset in 16 years when harvest residues were used and 38 years when standing trees were used to generate electricity (using pellets) within the Great Lakes/St. Lawrence forest region of Ontario, Canada.

Studies also indicate the importance of selecting an appropriate reference fossil fuel energy system in GHC accounting of bioenergy because the projected GHG benefit of bioenergy system may be misleading if the comparison is made with a fossil fuel system that is unlikely to be displaced by bioenergy (Bird et al., 2011). For example, the GHG mitigation benefit is higher when more GHG-intensive fuel such as coal is replaced versus replacement of oil or natural gas (MCCS, 2010; McKechnie et al., 2011; Zanchi et al., 2012).

8.3.6.2 Uncertainty in estimates

Estimation of net C emissionsof wood energy over a given period of time is associated with inherent uncertainties that can occur at several stages in the accounting process due to uncertainty in modeling assumptions and input parameters. If the effects of a potential increase in wood energy use are being evaluated with respect to a BAU or comparative baseline, there are uncertainties about the emissions and land C storage projections for both the reference case and the bioenergy case. The projections involve uncertainties in markets for forestland, which are influenced by demand for wood products, wood energy, and ecosystem services and demand for non-forest land uses, particularly agricultural uses (Malmsheimer et al., 2011). These uncertain demands cause uncertain land use changes and forest management changes. If logging residue is used, there is uncertainty in the logging residues decay rate for the reference case. When using a comparative baseline, there is additional uncertainty in the efficiency of the wood energy system relative to the reference case fossil energy system. Finally, additional uncertainties are due to exogenous catastrophic events such as wildfire, disease outbreak, and hurricanes.

Although gauging the effects of uncertainties is challenging, clearly indicating sources and magnitudes of uncertainty helps put boundaries on estimated GHG impacts of using a wood-based bioenergy system. Monte Carlo simulation can be used to estimate confidence intervals for estimated GHG effects (Heath and Smith, 2000; Soimakallio et al., 2009; Spatari and MacLean, 2010; Nepal et al., 2012). The approach is to define probability distributions for each uncertain variable in the model, generate a large number of samples for which each sample has a value from each distribution, and use the model successively with the sampled input variables to produce a distribution of the output values of estimated GHG impact (Heath and Smith, 2000; Soimakallio et al., 2009). An alternative approach is to provide sensitivity analyses, evaluating a small number of cases where one or more input variables are adjusted to determine the effect on estimated GHG impact (e.g. McKechnie et al., 2011; Holtsmark, 2012b).

Table 8.1 summarizes these key issues, and Table 8.2 summarizes likely CO_2 mitigation impacts of wood energy use and associated level of uncertainty in attaining the indicated level of emission offset by feedstock type and source as reported in recent literature. In general, use of logging residues is found to provide a higher C mitigation benefit, coupled with lower level of uncertainty, compared with roundwood for all time frames considered (short, medium, and long term). Clearly, C mitigation benefit of logging residues removal depends on assumed logging residues decay rates and the effects of residues removal on long-term site productivity, nutrient balances, and other site characteristics in the reference and alternative cases that influence both vegetation and soil C pools. Concerns have been raised that repeated removal of both coarse and fine woody residues can result in reduced site productivity and poor biomass growth, whereas some studies conclude that they do not universally reduce site productivity, especially if small-diameter residues are removed (Page-Dumroese, 2010). However, the effects of logging residues removal on long-term site productivity, nutrient balances, and other site characteristics, and their associated effects on forest and soil C pools, vary by specific forest sites, soil types, and management practices, The C mitigation benefit of roundwood use generally increases and the level of uncertainty decreases with longer time spans. For roundwood from private land, where land use and management can change with market-induced investment, potential additional mitigation benefits can vary depending on regional land investment options, but uncertainty in the level of market-induced investment benefit can be high. The largest C mitigation benefit, coupled with very low level of uncertainty, is obtained when wood is obtained from plantations dedicated to produce biomass for energy on marginal land (if no leakage occurs) and from use of wood waste, such as pile and burn residues on forest sites, mill residues, and municipal wood waste, where decay or non-energy burning is avoided. Use of indirect wood-industrial residue and wood waste-can provide high benefits, particularly if methane emissions from waste disposal are avoided. Because the type of avoided emissions can be uncertain, there is medium uncertainty for a high level of benefit. Similarly, planting of fast-growing species after harvest of existing forests provides notable C mitigation benefits in the

Table 8.1 Summary of key issues influencing estimates of net C emission effects of wood energy use and suggested choices in C accounting of wood energy system

Key issue	*Description*	*Application/suggested use*
Type of LCA		
Attributional life cycle analysis (ALCA)	• Considers a sustainably grown biomass. • Does not identify the amount of avoided emissions that may occur due to substitution of biomass energy for fossil fuel energy outside a product's life cycle. • Does not consider the timing of emissions and removals.	• The choice of LCA will depend on the particular event being examined and the specific questions being addressed. For example, if we are interested in understanding the level of emissions associated with a particular activity, then an ALCA may be applied. Conversely, if we are interested in changes in emissions over time, a CLCA may be applied.
Consequential life cycle analysis (CLCA)	• Allows for comprehensive examination of wood energy systems in the context of the biophysical and economic interactions, including emissions at the time of conversion and follow-on changes in C stock on the land due to direct, as well as market-induced (indirect), land use and management change. • Extra uncertainties may arise.	
System boundary		
Stand level	• Incomplete perspective	• Less likely
Landscape level	• Broader perspective	• More likely
National level	• Broader perspective	• More likely

Baseline		
Reference point	• Net GHG in the atmosphere during and at the end of an assessment period is compared with GHG in the atmosphere at the beginning.	• The choice of baseline will depend on the constraints and objectives of the policy context for the C accounting.
Business-as-usual (BAU)	• Emissions from proposed bioenergy system are compared with emissions from expected future scenario of wood energy consumption; does not consider fossil fuel displaced.	
Comparative	• Net emissions from bioenergy system being evaluated are compared with emissions from an alternative fossil fuel system.	
Timing of emissions and sinks		
Period of operation of bioenergy system	• e.g. 1 year, 30 years	• Depending on the metric used to estimate GHG impact, this period could extend from each year's wood burning emissions or it could extend to 100 years after the start of the bioenergy system.
Period over which to track C change on the land	• e.g. 100 years	
Time-dependent GHG metrics		
C neutrality factor	• Identifies whether the cumulative emissions from the bioenergy system are higher than, lower than, or equal to those from reference system.	• Less likely to be used as it does not directly characterize the impact on climate in terms of radiative forcing during the period of C debt and thereafter.
C payback time	• Refers to the time required to fully offset initial bioenergy emissions by biomass regrowth or other land C change (time needed to make zero C debt).	• Same as above.

Table 8.1 continued

Key issue	*Description*	*Application/suggested use*
Global warming	• The time-integrated global mean radiative forcing of a pulse emission of a given gas, over some given time period stated in tonnes of CO_2 that would produce the same cumulative radiative forcing.	• More likely to be used because GWP based on CRF over 100 years has the benefit that is the same metric used to gauge the impact of each type of GHG by IPCC.
Land use change (LUC)		
Direct LUC	• Caused by direct conversion of existing land use to a new land use to supply biomass feedstock.	• Need to consider the net emission effect of LUC due to wood energy.
Indirect LUC	• Caused by promise of future revenue for biomass. Leakage occurs when iLUC results in greater emissions. Spillage occurs when iLUC results in more C storage.	
Uncertainty	• Uncertainties can occur at several stages in the accounting process due to uncertainty in modeling assumptions and input parameters.	• Need to evaluate the effect of uncertainties on estimated net C emission of wood energy use through Monte Carloe simulation or sensitivity analysis.

Table 8.2 CO_2 emission offset impacts of wood energy use and associated level of uncertainty in attaining the level of positive offset indicated by feedstock type and source

Source and type of feedstock	Spatial boundary	*CO2 mitigation impact and associated level of uncertainty*					
		Short term (10 years)		*Medium term (50 years)*		*Long term (centuries)*	
		Coal	*Natural gas*	*Coal*	*Natural gas*	*Coal*	*Natural gas*
Logging residues*	Stand	+/– (L)	+/– (L)	+ (L)	+ (L)	++ (L)	++ (L)
Temperate stemwood without market-induced forest investment	Stand	– – – (L)	– – – (L)	+/– (H)	– (M)	++ (L)	+ (L)
Temperate stemwood with market-induced forest investment	Landscape (regional/ national)	– – (M)	– – (M)	++ (M)	+ (M)	++ (L)	+ (L)
Boreal stemwood without market-induced forest investment	Stand	– – – (L)	– – – (L)	– (M)	– – (M)	+ (L)	+ (L)
New plantations on marginal agricultural land (if no leakage)	Stand	+++ (VL)	+++ (VL)	+++ (VL)	+++ (VL)	+++ (VL)	+++ (VL)
Forest substitution with fast growth plantation (if no old growth forest replaced)	Stand	– (L)**	– (L)**	++ (H)**	+ (H)**	+++ (L)	+++ (L)
Indirect wood (mill residues, waste wood, etc.)	Location specific	+++ (M)	+++ (M)	+++ (M)	+++ (M)	+++ (M)	+++ (M)

Notes: The emission offset impacts reported in this table are based on the carbon neutrality (CN) metric.
– / – – / – – – The wood energy system emits more CO_2 than the reference system.
+/– The wood energy system emits either more or less CO_2 than the reference system depending on specific pathways.
+ / ++ / +++ The wood energy system emits less CO_2 than the reference system (+++ suggest a CN value of >1; + suggest a CN value of <1; and ++ suggest a CN value of ≤1.
VL/L/M/H Very low/low/medium/high level of uncertainties.
* The impact depends on logging residue decay rate in the reference case and the long-term effect of residue removal on soil productivity.
** The impacts could be lower if demand for bioenergy continuously harvests and replaces existing forests.
Source: Adapted from Agostini et al. (2013)

long term with low level of uncertainty (if no old growth forest is replaced). Clearly, to realize such a benefit of substitution, plantations must reach a C accumulation level that is higher than the C stock level of the replaced forest.

8.4 Summary and conclusions

This review identifies the current state of knowledge in biogenic C accounting for wood energy systems based on a review of the recent literature. Specifically, the synthesis identifies key factors influencing estimates of net GHG emissions associated with expanded use of wood energy and how these factors could be considered in a GHG accounting system. One of the strengths found from C accounting studies is the possibility of understanding how and to what degree the use of wood for energy can result in GHG benefits. The key weakness, however, is the limited agreement on various assumptions that would exactly specify the degree of GHG benefits offered by wood energy. There exists an opportunity to work forward for a broader consensus on the assumptions that should be used when accounting for GHG emissions from wood energy. The major challenge to achieving such a broader consensus is imposed by the difficulty in deciding on assumptions in choosing alternative features (trade-offs) of analysis (e.g. simplicity, uncertainty, time sequence sensitivity).

In summary, three general views of GHG accounting for wood energy have been recently discussed. One view (categorical exclusion) argues that wood used for bioenergy has no effect on net C emissions in the atmosphere, and therefore net C emissions from burning biomass should be excluded from GHG accounting related to bioenergy (emission factor = 0). Another view (categorical inclusion) considers that net C emission from burning wood is equivalent to burning fossil fuel and accordingly proposes to count all emissions from burning biomass in GHG accounting (emission factor = 1). A third view proposes to estimate the fraction of wood emissions that should be counted as equal to fossil fuel emissions through a dynamic comparative approach that counts C emissions and sequestration along the life cycle of biomass production and use, including emissions from sources and follow-on C changes on hand (emission factor - 0-1). The fact that wood energy, depending on source, can result in at least a near-term increase in atmospheric GHGs, relative to a case where wood energy is not used, reduces the likelihood of the categorical exclusion option being chosen for C accounting of wood energy. Also, the fact that initial emissions from increased use of wood for energy will be offset by market-induced investments in management and forestland area on private land reduces the likelihood that policy will consider the categorical inclusion. A consequential life cycle analysis framework that compares C emissions from a wood burning facility and foll-on C change on land over time for the BAU and alternative bioenergy cases will most likely be used to indicate how to account for C emissions and C storage over time.

Defining an appropriate system boundary is a critical initial step in C accounting because it delineates biological, industrial, and market processes involved, as well as the temporal and spatial scale of the study and identifies inputs and outputs to include in the analysis. Regional- to national-level analyses are needed rather than forest-stand-level analyses because stand-level analyses can provide an incomplete perspective. Definition of baseline or reference system is another critical step because GHG impact estimates depend on the baseline system with which they are compared. Depending on the objective and the policy context, three types of baselines are proposed: (1) a reference point baseline, where net GHG in the atmosphere (or conversely C stored on land) during and at the end of an assessment period is compared with GHG in the atmosphere (or C on land) at the beginning; (2) a BAU or anticipated future baseline, where emissions from a proposed bioenergy system are compared with emissions from an expected future scenario ofwood energy consumption without considering the fossil system displaced; and (3) a comparative baseline, where net emissions from a bioenergy system being evaluated are compared with emissions from an alternative fossil fuel system. Identification of the appropriate reference energy system to be displaced is a key aspect of such a baseline. The choice of baseline will depend on constraints and objectives of the policy context for the C accounting.

Characterizing the timing of emissions and sinks is another key component of C accounting because the net emission effects depend on time needed by new biomass growth to replenish the amount of C released due to biomass removal and burning. The first time frame to define is the period of operation of the bioenergy system (e.g. one year, 30 years). A second time frame is the period over which to track C change on the land (e.g. 100 years). Depending on the metric used to estimate GHG impact, this period (e.g. 100 years) could extend from each year's wood burning emissions or it could extend to 100 years after the start-up of the bioenergy system. Various time-dependent metrics are available to estimate GHG effects, including "C neutrality factor," "C payback time," and global warming potential (GWP). based on cumulative net radiative forcing (CRF). GWP based on CRF over 100 years has the benefit that it is the same metric used to gauge the climate impact of each type of GHG.

Review results indicate that for use of wood from private lands, the C change due to market-induced investment to retain forest, plant additional forest, or intensify forest management (indirect land use and management change) can significantly influence the mitigation benefit of wood energy. Recent studies for the US suggest that a large proportion (up to 80 percent) of increased cumulative emissions due to expanded wood energy could be offset within 50 years by market-induced indirect change in land use and management. The review also identified the need to take into account the differences in time to pay back C debt, which can differ widely by feedstock type and source. The mitigation effect of logging residue use is likely to be greater and have less uncertainty than use of roundwood from forests. C payback time for roundwood use can range widely due to bariation in initial forest density, age, and growth, as well as due to uncertainty in indirect land use change. Feedstock growth for energy use in new plantations on marginal agricultural lands with initial low C stock will provide a more immediate mitigation benefit from bioenergy use than the longer-term benefits of the use of biomass from existing forests. Another important issue is that the C mitication benefit of wood energy is generally higher when a more GHG-intensive fuel (such as coal) is replaced compared with less GHG-intensive fuels (such as oil or natural gas). Finally, the review identified that uncertainties are inherent in various stages of wood biomass production and use, influencing results, and that uncertainties and sensitivity analyses should be an integral part of C accounting related to wood energy.

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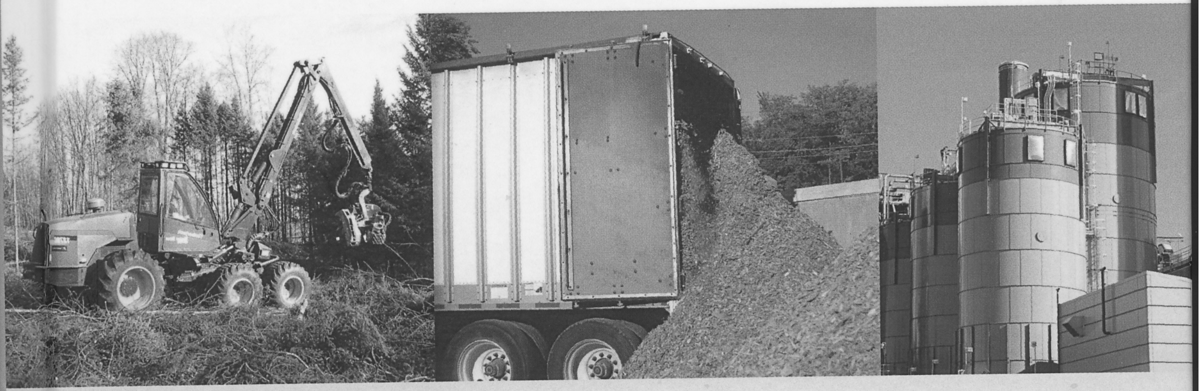
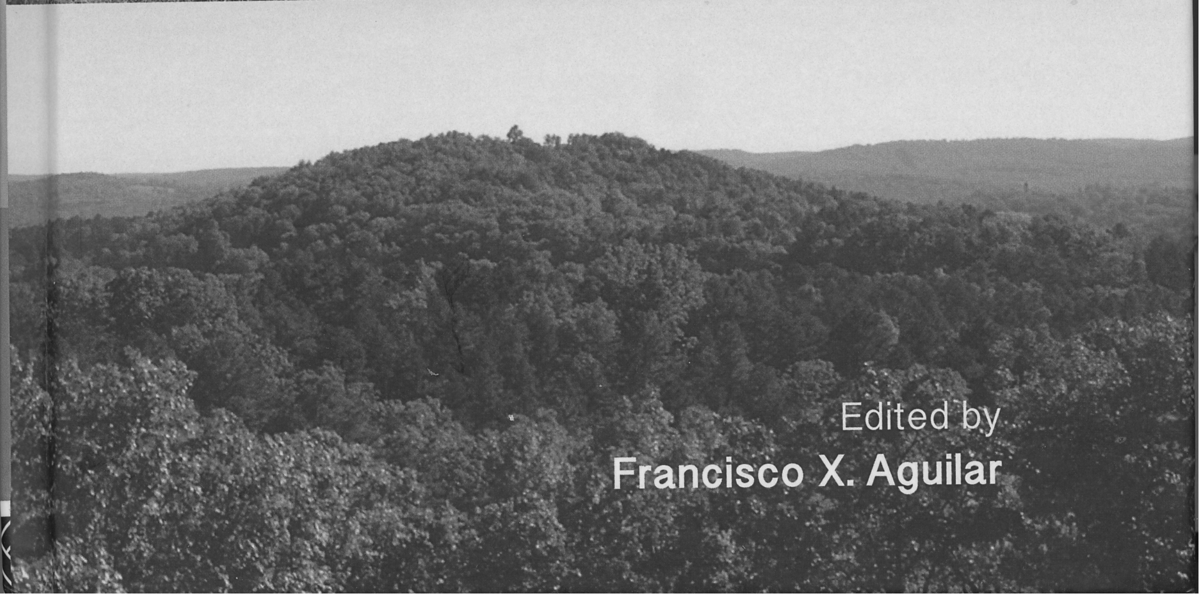
Resource management, economics and policy





Edited by
Francisco X. Aguilar

First published 2014
by Routledge
2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

and by Routledge
711 Third Avenue, New York, NY 10017

Routledge is an imprint of the Taylor & Francis Group, an informa business

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
Wood energy in developed economies: resource management, economics and policy / edited by Francisco X. Aguilar.
pages cm
Includes bibliographical references and index.
1. Fuelwood industry – Europe. 2. Fuelwood industry – North America. 3. Fuelwood industry – Government policy – Europe. 4. Fuelwood industry – Government policy – North America. 5. Renewable energy sources – Europe. 6. Renewable energy sources – North America. I. Aguilar, Francisco X.
HD9769.F843E859 2014
333.95′397 – dc23
2014008196

ISBN: 978-0-415-71169-2 (hbk)
ISBN: 978-1-315-88441-7 (ebk)

Typeset in Baskerville
by Florence Production Ltd, Stoodleigh, Devon, UK

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Edwards Brothers Malloy on sustainably sourced paper