Back to the Past: Burning Wood to Save the Globe

Craig M.T. Johnston[a,*]

G. Cornelis van Kooten[b]

Affiliations:

[a] Department of Forest & Wildlife Ecology, University of Wisconsin-Madison, USA

[b] Department of Economics, University of Victoria, Canada

[*]Corresponding author. Tel.: +1 608.890.3609
E-mail address: craig.johnston@wisc.edu (C.M.T. Johnston).

Abstract:

In an effort to reduce CO_2 emissions from fossil fuel burning, renewable energy policies incentivize use of forest biomass as an energy source. Many governments have assumed (legislated) the carbon flux from burning biomass to be neutral because biomass growth sequesters CO_2. Yet, trees take decades to recover the CO_2 released by burning, so assumed emissions neutrality (or near neutrality) implies that climate change is not considered an urgent matter. As biomass energy continues to be a significant strategy for transitioning away from fossil fuels, this paper asks the question: To what extent should we value future atmospheric carbon removals? To answer this, we examine the assumptions and pitfalls of biomass carbon sequestration in light of its increasing use as a fossil-fuel alternative. This study demonstrates that the assumed carbon neutrality of biomass for energy production hinges on the fact that we weakly discount future removals of carbon, and it is sensitive to tree species and the nature of the fuel for which biomass substitutes.

Keywords: Bioenergy, Climate Change, Forestry, Life Cycle Analysis, Discounting

JEL: Q23, Q42, Q50, C63

INTRODUCTION

In an effort to reduce carbon dioxide (CO_2) emissions from fossil fuel burning, renewable energy policies have promoted ‘carbon neutral’ biomass as an energy source. The Intergovernmental Panel on Climate Change (IPCC) is the governing authority on climate change and, in particular, the rules concerning carbon accounting (Sedjo 2013). Working under the auspices of the United Nations’ Framework Convention on Climate Change (UNFCCC), the IPCC (2006) says the emissions from biomass energy would be reported in the Agriculture, Forestry and Other Land-Use (AFOLU) sector at the time of harvest, and not the Energy sector when the wood is burned. Therefore, biomass energy may be viewed as ‘carbon neutral’ since emissions are subsequently removed by future growth. Many developed countries draft their domestic legislation in light of the IPCC carbon accounting principles, including those committed to the Kyoto Protocol of the UNFCC.

Yet trees may take decades to recover the CO_2 released by burning, so assumed emissions neutrality implies that climate change is not considered an immediate threat. That is, the carbon neutrality of biomass hinges on the fact that we count CO_2 removals from the atmosphere equally independent of when they occur (e.g., Schlamadinger and Marland 1999). When there is greater urgency to address climate change, however, more emphasis should be placed on immediate removals of CO_2 from the atmosphere and much less on removals that occur in the more distant future.

How pressing is the need to mitigate climate change? According to Article 2 of the UNFCCC, atmospheric greenhouse gas concentrations must be stabilized in a timely manner to prevent potentially dangerous climate change. The latest IPCC report indicates that the observed impacts of climate change are already “widespread and consequential” (IPCC 2014, p.93), while the U.S. National Climate Assessment (NCA) reiterated the warnings of the IPCC regarding climate change, suggesting that a once distant concern is now a pressing one as future climate change is largely determined by today's choices regarding fossil fuel use (NCA 2014).

To reduce emissions of CO_2 from fossil fuel burning, many countries intend to substitute biomass for coal in existing power plants, with some already having done so. This is appealing because extant coal plants can be retrofitted to burn biomass at relatively low cost. Thus, it is estimated that, as of 2011, some 230 coal plants co-fire with biomass on a commercial basis (IEA 2013). Biomass use in coal plants is bound to increase as more countries will need to rely on its assumed neutrality to meet their CO_2 emission reduction targets (Cremers et al. 2009).

In Europe, countries originally agreed to a binding target requiring 20% of total energy to come from renewable sources by 2020 (Directive 2009/28/EC). Then, in early 2014, the European Commission proposed a new framework with a more ambitious EU-wide renewable energy target of 27% by 2030. Europe expects one-half or more of its renewable energy target to come from biomass as member states look to the IPCC carbon accounting guidelines for support (European Commission 2013). To meet these targets, member states have individually adopted a variety of domestic policies to promote energy from biomass, including feed-in tariffs, a premium on market prices and tradable renewable energy certificates (RES-LEGAL 2014). As indicated in Figure 1, these measures are expected to increase European consumption of wood pellets to some 38 Mt per year, requiring significant imports of pellets from outside the EU.

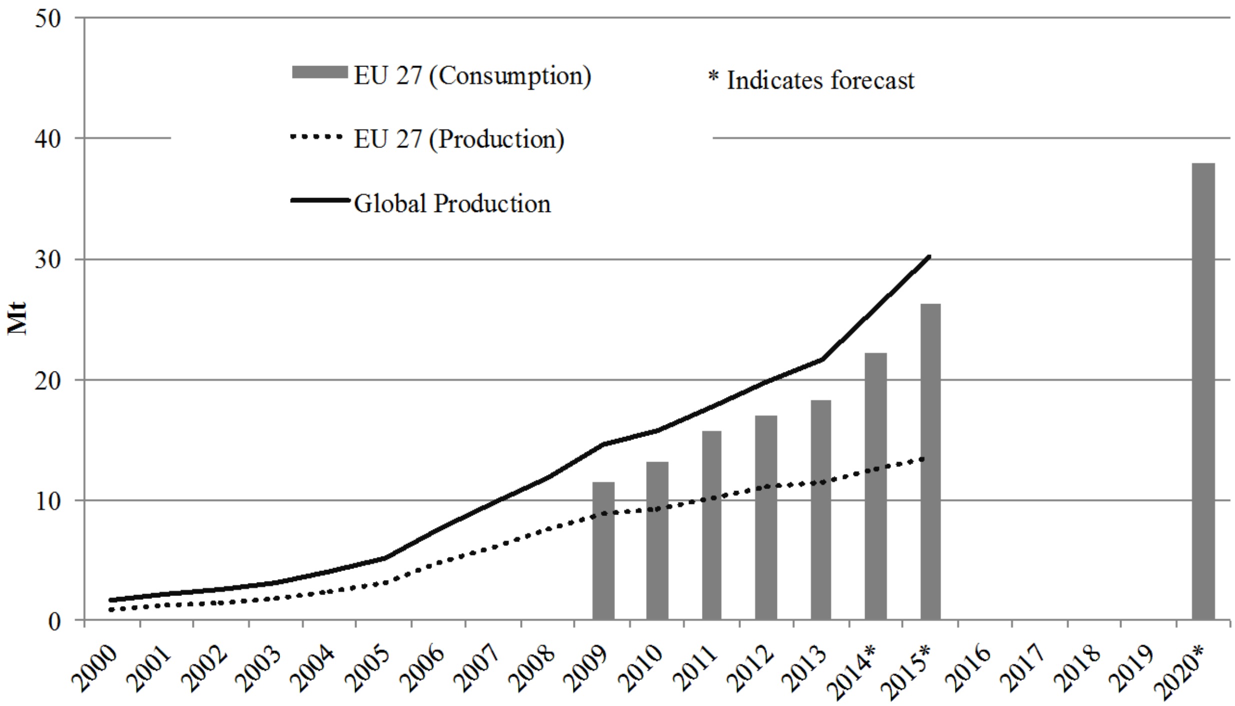


Figure 1: Production and consumption of wood pellets in the EU-27 (Mt), 2000-2013 and forecasts for 2015 and 2020
Source: Pöyry (2011); Lamers et al. (2012); FAO (2015)

In Canada, performance standards on coal-fired power plants now impose an upper limit on emissions of 420 kg CO_2 MWh^{-1} – equivalent, according to the government, to new highly-efficient combined-cycle gas turbines (Government of Canada 2012). The standard applies to combustion of coal and its derivatives, and all fuels burned in conjunction with coal, except for biomass which is deemed to be emissions neutral. This leaves open the option of blending 'zero-emissions' biomass to the point where the standard is met. As of 2014, two large-scale Canadian power plants have been retrofitted to run solely on wood biomass, including the Nanticoke Generating Station, which was the largest coal-fired power plant and one of the largest single sources of emissions in North America.

In the United States, a ruling by the Environmental Protection Agency in September 2013 (EPA 2013) requires new coal plants to have carbon capture and storage (CCS) capability, or otherwise achieve a particular performance standard. The construction cost of CCS-capable plants is prohibitive, but other costs make CCS not only economically unattractive but an unlikely option as CCS process increases the energy required to produce electricity by some 28% (EIA 2013). Again co-firing biomass with coal is viewed as an alternative compliance strategy to achieve emissions intensity in coal plants of 500 kg CO_2 MWh^{-1} (Edenhofer et al. 2011).

As biomass energy becomes increasingly important as a strategy for transitioning away from fossil fuels, and the CO_2 released from burning biomass takes some time to remove from the atmosphere by growing vegetation, it behoves us to ask how current versus future carbon fluxes should be valued. In particular, assumptions regarding the future carbon uptake potential in forest ecosystems affect the supposed carbon neutrality of biomass (Holtsmark 2012; McDermott et al. 2015). The purpose of the current study is, therefore, to examine how climate change mitigation policies, and the urgency expressed in dealing with potential future global warming, change our view of the life-cycle analysis (LCA) of CO_2 from fossil fuel versus biomass burning. In essence, we argue for an alternative, policy-based perspective on LCA. In doing so, we demonstrate that the assumed carbon neutrality of biomass energy hinges on the fact that future removals of carbon are treated almost the same as current ones.

We begin in the next section with an overview of the LCA of CO_2 in energy production; the aim is not to offer a definitive review, but only to provide context for our shift towards a policy focused analysis. We then argue why carbon fluxes need to be weighted according to when they occur, especially if there is some urgency in addressing climate change. It is the latter that accounts for the policy oriented approach to LCA. A model of carbon fluxes is used to demonstrate how the degree of urgency (different weighting schemes) affects the effectiveness of bioenergy in dealing with climate change. Sensitivity analysis with respect to weights, tree species and fuel types for which biomass substitutes gives some indication of the robustness of our proposal. Finally, we consider further challenges to the use of wood biomass energy that might reinforce or weaken our conclusion that policies to expand biomass burning to mitigate climate change need to be rethought.

TRACKING CARBON FLUXES: THE CARBON LIFE-CYCLE ANALYSIS (LCA)

There exists a rich body of research on the greenhouse gas emissions impact of substituting forest bioenergy for fossil fuels (Miner et al. 2014; Sedjo 2013). Much of the research has been by physical scientists, who have emphasized the carbon life-cycle characteristics of using biomass energy (Cherubini et al. 2011; McKechnie et al. 2011; Helin et al. 2013). In the various analyses, it is assumed that carbon dioxide from fossil fuel burning remains in the atmosphere indefinitely, so that any such emissions are considered to be irreversible. On the other hand, it is assumed that emissions of CO_2 from biomass burning can be removed from the atmosphere by the Earth's carbon sinks. These distinctions are important as discussed below.

The initial approach used by analysts can be understood in the context of Figure 2. Suppose that electricity is generated in a given day or hour by a coal plant. In that case, an amount 0F, of CO_2 enters the atmosphere and remains there indefinitely as indicated by the horizontal dashed line. Suppose instead that the power delivered on that day or hour was generated by burning wood biomass rather than coal. In that case, an amount 0K > 0F of CO_2 enters the atmosphere at time 0, thereby creating a carbon deficit equal to 0K – 0F. Because wood biomass has a higher carbon content (kg/GJ) than coal, the release of CO_2 from burning wood pellets exceeds that from coal (i.e., OK > OF)[1]. This issue is discussed in greater detail

---

[1] See http://www.ipcc.ch/meetings/session25/doc4a4b/vol2.pdf [accessed Sep 29, 2015] where carbon intensities for

below, when we investigate issues surrounding urgency and discounting.

If trees are planted at t=0, the trees will begin to remove CO_2 from the atmosphere and store it in wood biomass, with the cumulative amount of CO_2 removed determined by the growth function as indicated by the S-shaped curve in Figure 2. At t=M, the amount of CO_2 left in the atmosphere as a result of burning wood biomass at t=0 equals the amount that would have been in the atmosphere if coal had been burned instead. Then, at t=N, the CO_2 that had been released by burning biomass will have been completely removed. Between t=M and t=N, the biomass option has resulted in a carbon dividend or benefit relative to the coal option. This is generally what is meant when biomass burning is declared to be carbon neutral.[2]

---

many fuels are provided.

[2] The idea of carbon neutrality can also be based on “the observation that C [carbon] removals from growth across a forest landscape will balance the CO_2 combustion emissions from burning biomass harvested in the forest if the forest is managed in a way that ensures that its C stock is not decreasing” (Lemprière et al. 2013, p.308). This more closely represents the view of the IPCC (2006) since impacts of biomass energy are reported in the land use change and forestry sector, not in the energy sector.

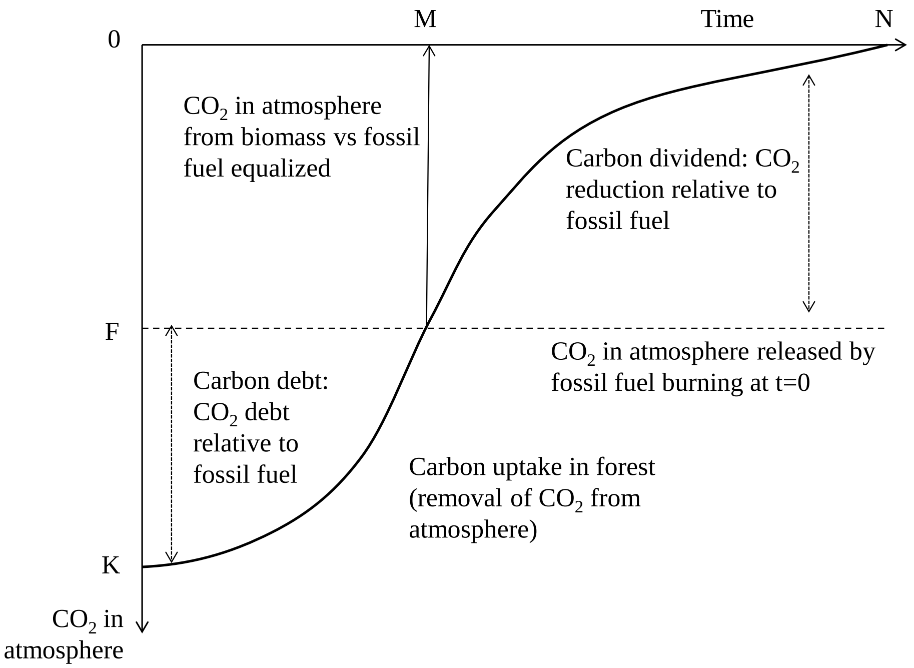


Figure 2: Carbon flux profile for biomass energy versus business-as-usual fossil fuel energy Source: Walker et al. (2010)

Presumably biomass will continue to replace coal for an indefinite number of periods. In that case, as shown by Walker et al. (2013), the picture in Figure 2 morphs from the single- (small scale) to the multi-period (large scale) of Figure 3. In each period trees are immediately planted in order to sequester the carbon just released by burning biomass for electricity. The (solid) straight line represents the cumulative amount of CO$_2$ emitted into the atmosphere by burning coal, with the slope of the line representing emissions in each period; the dashed line represents the cumulative emissions from burning biomass instead of coal. After N years, the cumulative fluxes from burning biomass equal those associated with burning the fossil fuel. The dashed line eventually becomes horizontal at the point N where the CO$_2$ emitted in the first period is fully sequestered by the growing forest planted in that period. “The cumulative analysis makes clear that the time required to begin realizing dividends from biomass energy is considerably longer than one might conclude if only a single year of emissions were evaluated”

(Walker et al. 2013, p.150).

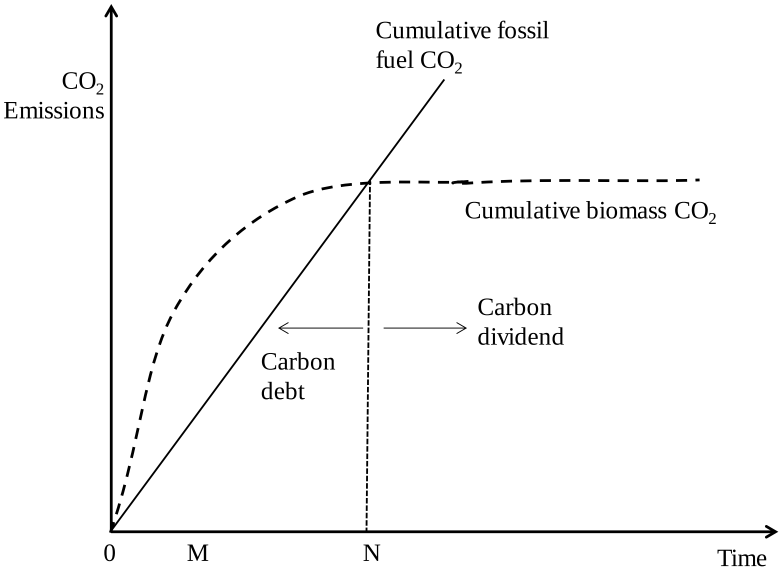


Figure 3: Carbon flux associated with fossil fuel and biomass energy production over time Source: Walker et al. (2013)

Using this framework, Walker et al. determine that, if the source of biomass is dedicated harvests of mixed wood, it takes 45 to more than 90 years for the carbon debt to be recovered in the case of coal plants and gas electric plants, respectively. However, if the only source of biomass energy is logging residues, it takes only 10 to 30 years to recover the carbon debt. The reason for this difference is the life-cycle analysis (LCA): the carbon associated with harvesting of whole trees for burning would otherwise have remained on site sequestering carbon. In the case of logging residues, the trees would have been cut in any event and the carbon associated with the residues would otherwise have been released to the atmosphere through decay if not used as bioenergy.

Several studies have subsequently proposed alternative life-cycle analyses for carbon fluxes associated with biomass burning. McKechnie et al. (2011) build upon the Walker et al. (2010) analysis by focusing to a greater extent on the forest ecosystem's carbon dynamics. In their LCA, they consider the changes in forest carbon resulting from biomass harvest for bioenergy plus the changes in greenhouse gas emissions when biomass is converted to wood pellets and co-fired with coal to produce electricity. The authors find that, if pellets are produced from standing trees, the time taken to eliminate the carbon debt from biomass burning takes some 38 years; if pellets are produced from forest residuals, the break-even point occurs after 16 years.

Cherubini et al. (2011) use the notion of global warming potential (GWP) to determine the prospective carbon dividend from biomass burning. The GWP of CO_2 from fossil fuel burning is taken to equal 1 regardless of the time horizon. Thus, there is a distinction between CO_2 molecules released by burning fossil fuels and ones released when burning biomass; CO_2 emitted from biomass is denoted bioCO_2 to distinguish it from CO_2 emitted by fossil fuels. Because CO_2 from fossil fuel burning cannot be removed from the atmosphere, the GWP_{bio} is a measure of the relative benefit of burning biomass. It is given by the ratio of the absolute global warming potential (AGWP) of bioCO_2 to that of CO_2 (Cherubini et al. 2011, p.418):

$$(1)\ \mathrm{GWP_{bio}} = \frac{\mathrm{AGWP_{bioCO2}}}{\mathrm{AGWP_{CO2}}} = \frac{C_0 \int_0^T \alpha_{bioCO2} f(t)dt}{C_0 \int_0^T \alpha_{CO2}\, y(t)dt} \ ,$$

where C_0 refers to the initial pulse of CO_2 entering the atmosphere at t=0. T is the time horizon, and α_{CO2} and α_{bioCO2} are the radiative efficiencies of CO_2 and bioCO_2, respectively, with α_{CO2} clearly equal to α_{bioCO2}.[3] The functions *y*(t) and *f*(t) are the respective decay functions of atmospheric CO_2 and bioCO_2, and represent the fraction of the initial emission that is still found in the atmosphere at time t (Cherubini et al. 2011, p.415). As already noted, CO_2 originating from fossil fuel burning is assumed not to decay; that is, the fraction of the initial emission of

---

[3] It should be noted that α_{CO2} depends on the ratio of the concentration of CO_2 in the atmosphere after a small perturbation to the initial concentration.

CO_2 from fossil fuel burning remains constant through time as none is removed through ocean/biosphere uptake. Thus, $GWP_{CO2} = 1 = y(t)\ \forall t$ and regardless of T, while GWP_{bio} depends on $f(t)$, which is the fraction of $bioCO_2$ that remains in the atmosphere at time t from burning biomass at t=0. In essence, $f(t)$ measures the fraction of $bioCO_2$ removed from the atmosphere by the ocean and biosphere sinks over time.

Using a figure similar to our Figure 3 to motivate the analysis, Cherubini et al. (2011) argue that a $bioCO_2$ molecule released to the atmosphere by burning biomass can be removed by growing new trees (vegetation), by the ocean carbon sink, or by a terrestrial sink. Thus, they identify three cases for their life-cycle analysis of bioenergy:

1. potential removal of the bioCO2 molecule only by regrowth of the forest from which the molecule originated – the vegetation sink;
2. potential removal of the bioCO2 molecule either by vegetation growth or by the ocean; and
3. potential removal of the bioCO2 molecule by either of the above or by the larger terrestrial biosphere.

The speed at which a $bioCO_2$ molecule would be removed from the atmosphere – the function $f(t)$ – depends on the atmospheric concentration of CO_2 at time t, and the rates that each of the three sinks sequester carbon. This requires the use of a climate model. The authors use the Bern 2.5CC model to determine that, if the forest rotation age is 40 years and the time horizon is 100 years, the narrow approaches of Walker et al. (2010) and McKechnie et al. (2011) would result in a GWP_{bio} of 0.43 compared to 0.16 if all sinks were considered; for a forest with rotation age of 80 years, the comparable GWP_{bio} values are 0.86 and 0.34, respectively. For clarification, had the GWP_{bio} values been greater than 1.0, this would have meant that, for equivalent emissions of CO_2 per unit of electricity produced, fossil fuels would be the preferred method of generating electricity. It turns out that GWP_{bio} values exceed 1.0 only when the time horizon is particularly short relative to the rotation age. Bioenergy is preferred to fossil fuels when GWP_{bio} is less than 1.0, which is almost always the case in Cherubini et al.'s (2011) life-cycle analysis.

The forgoing analyses neglect the impact that, since biomass burning releases more CO_2 than coal or gas in generating electricity, there is a temperature uptick that needs to be considered. Because α_{bioCO2} (=α_{CO2}) depends on the ratio of the atmospheric concentration of CO_2 after a small perturbation to the initial concentration of CO_2, global temperature is impacted. Therefore, the initial carbon debt (see Figs. 2 & 3) results in an increase in temperature, which implies that biomass burning is carbon neutral before it is climate neutral (Helin et al. 2013). That is, the GWP_{bio} is greater than indicated by Cherubini et al. (2011). Indeed, Miner et al. (2014, p.598) calculate that, for loblolly pine harvested every 20 years and a 100-year time horizon, the GWP_{bio} would be 0.12 if carbon neutrality is to be achieved but 0.26 if the objective is climate neutrality. Further, the value of GWP_{bio} will likely vary depending on the speed of forest growth and time between harvests (Holtsmark 2015).

Scientists favor the use of radiative forcing as the appropriate method for measuring the climate impacts of bioenergy. The advantage of the GWP_{bio} approach is that biomass emissions with deviating timing can be transformed into a permanent fossil carbon emission equivalent within a given time horizon (Helin et al. 2013). However, the concept of radiative forcing is not used in policy discussions (Lemprière et al. 2013, p.301). While physical scientists might generally prefer the use of radiative forcing, or the GWP_{bio} measure, for analyzing the benefits of bioenergy, economists and other policy analysts are more circumspect. They would argue that assessments of mitigation must go beyond just considering the carbon stored in forest ecosystems; rather, it is important to also consider the carbon stored in harvested wood products

(HWPs) and landfills, substitution of wood for more emissions-intensive products and fossil fuels, and land-use changes involving forests (Lemprière et al. 2013).

Kurz et al. (2013), Lemprière et al. (2013) and Smyth et al. (2014) take a systems approach to forest carbon that considers carbon fluxes associated with the forest ecosystem dynamics that result from human activities (planting, fertilizing, thinning, harvesting) and natural forces (weather, wildfire, pests, disease). A systems approach also considers carbon stored in product pools, and CO_2 emissions avoided when wood replaces steel and cement in construction and/or wood biomass replaces fossil fuels in energy production.[4] In their life-cycle analysis of carbon in boreal ecosystems, for example, they note that "the age-class structure currently found in North America's boreal forests is a transient, non-sustainable phenomenon arising from a period with higher disturbance rates followed by a period with lower disturbance rates," with carbon stocks currently greater than their long-term sustainable maximum (Kurz et al. 2013, p.263). If left undisturbed, these forests will inevitably become net emitters of CO_2 to the atmosphere. However, the boreal forest becomes a mitigation source once forest management, solid wood product sinks and opportunities for bioenergy are taken into account within the LCA framework (Lemprière et al. 2013: Smyth et al. 2014).

URGENCY AND DISCOUNTING

When it comes to biomass energy, the time that incremental carbon is in the atmosphere may be on the order of decades, in which case it contributes to climate forcing. Thus, if there is some urgency to remove CO_2 from the atmosphere to avoid such climate forcing, the timing of emissions and removals of carbon is important, with current emissions of CO_2 and removals

---

[4] Concrete requires five times and steel 24 times more energy to produce than an equivalent amount of sawn softwood. Wood is also five times more insulating than concrete and 350 times more than steel.

from the atmosphere by sinks more important than later ones.[5] This implies that carbon fluxes need to be weighted as to when they occur, with future fluxes discounted relative to current ones, which, as noted above, is the purpose of the GWP measure (Helin et al. 2013; Lemprière et al. 2013; Galik and Abt 2012). Indeed, economists since the time of Ciriacy-Wantrup (1952/1968) have used weights to compare the physical rates of resource extraction, such as rates of pumping from an oil well, to determine whether a policy is conserving or depleting, with Schlamadinger and Marland (1999) doing so in the context of carbon accounting.

The rate used to discount carbon fluxes can be used to address urgency in the policy arena. Clearly, if global warming is not considered a problem, the economist might use a zero discount rate, in which case it really does not matter if biomass growth removes CO_2 from the atmosphere today, 50 years, or even thousands or millions of years from now – it only matters that the CO_2 is eventually removed. In that case, coal and biomass are on a similar footing and, since coal is more energy efficient, it would be preferred to biomass.

If, on the other hand, global warming is already "widespread and consequential" and that the once distant concern is now a pressing one as future climate change is largely determined by today's choices regarding fossil fuel use (Melillo et al. 2014), then we want to weight current reductions in emissions and removals of CO_2 from the atmosphere much higher than those in future years. This is the same as discounting future uptake of CO_2, with higher discount rates suggesting greater urgency in dealing with global warming. Figure 4 depicts such urgency, but for a level of urgency where discount rates are sufficiently high that burning of biomass for energy never leads to carbon neutrality. Indeed, if one were to accept that climate change is a more urgent matter (a relatively high discount rate), substituting biomass for fossil fuels may

---

[5] "The lower the desired limit of global temperature increase, the lower the stabilization level of greenhouse gas concentrations in the atmosphere, and the more rapidly the greenhouse gas emissions need to be reduced" (Helin et al. 2013, p.476).

actually lead to a net increase in atmospheric CO_2 emissions. In Figure 4, forest carbon uptake is discounted to such an extent that carbon uptake in the more distant future is of little value today. As a result, the discounted future uptake of CO_2 from the atmosphere (regardless of the sink) is too small to offset the additional increase in CO_2 emissions when biomass substitutes for fossil fuels in power production.

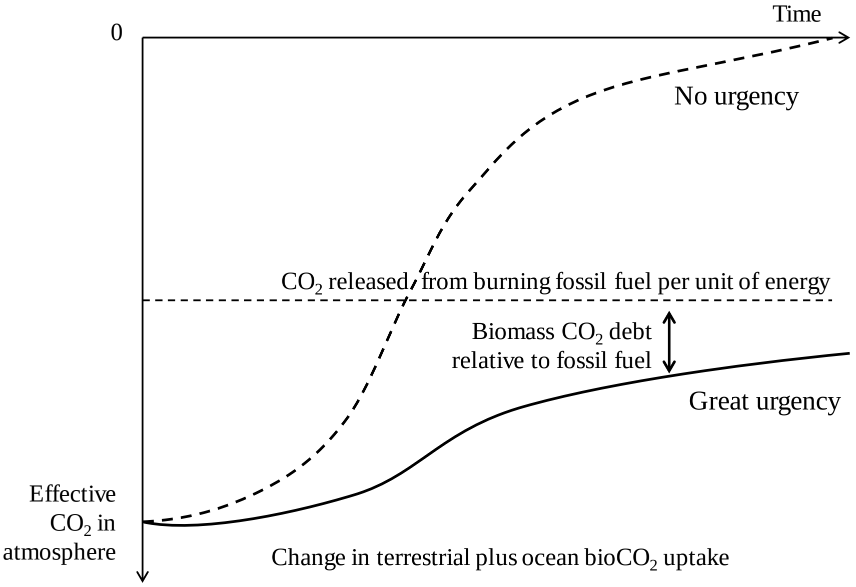


Figure 4: Carbon flux associated with fossil fuel and biomass energy production over time: Comparing lesser and greater urgency to address climate change

The change in the cumulative carbon flux (measured in terms of CO_2) from substituting biomass for coal, say, will depend on the relative emissions intensity of the inputs, as well as the geographic location, tree species or other types of crops (e.g., straw, hemp) that are available, and other variables. Carbon dioxide released from burning coal and wood varies greatly by the quality of coal and biomass, especially whether the biomass originates from hardwoods or softwoods. On average across all types of coal, 0.518 tonnes (t) of coal are required to produce 1.0 megawatt hour (MWh) of electricity, releasing 1.015 tCO_2 per MWh; for bituminous coal, which is used most commonly in power plants, only 0.397 t of coal are required per MWh, releasing 0.940 tCO_2 MWh^{-1} (Hong and Slatick 1994).[6] Approximately 0.658 t of biomass are required to produce 1.0 MWh of electricity – nearly twice the weight required for bituminous coal (requiring greater fossil fuel emissions just to transport the extra material). The average emissions intensity is 1.170 tCO_2 MWh^{-1} for hardwoods and 1.242 tCO_2 MWh^{-1} for softwoods, although the moisture content of the wood is a significant driver.[7] Since the majority of the world employs bituminous and subbituminous coal for power generation, with respective emissions intensities of 0.940 and 0.953 tCO_2 MWh^{-1}, biomass clearly releases significantly more CO_2 into the atmosphere per unit of energy than coal, and even more when compared to natural gas. In the following scenarios, an emissions-intensity for subbituminous coal of 0.94 tCO_2 MWh^{-1} is assumed; for an equal mix of hardwoods and softwoods, 1.246 m^3 of wood are required to produce one MWh of energy, thereby releasing about 1.27 tCO_2.

A SIMPLE MODEL OF CARBON SEQUESTRATION

To illustrate the issue further, the following generalized Richards' growth function is employed to determine the sensitivity of bioenergy use to the perceived urgency of addressing climate change:

$$(2)\quad v(t) = \frac{U}{\left(1-\beta e^{-kt}\right)^{\frac{1}{m}}},$$

where $v(t)$ is volume (m^3/ha) as a function of age, β is a shape parameter, k is the growth rate, $m>0$ is the slope of growth (i.e., it affects the asymptote nearest to which maximum growth occurs), and U is the upper limit on growth (m^3/ha), with the lower bound of the function assumed to be zero. The financial rotation is determined from the following equation (see van

---

[6] See also http://www.ipcc.ch/meetings/session25/doc4a4b/vol2.pdf [accessed April 1, 2015] where carbon intensities for many fuels are provided.

[7] See http://www.canadianbiomassmagazine.ca/images/stories/table1-2.pdf [accessed April 1, 2015], which also provides carbon intensity data for coal.

Kooten and Folmer 2004, pp. 365-371):

$$(3)\ \frac{v'(t)}{v(t)} = \frac{\beta k e^{-kt}}{m\left(1+\beta e^{-kt}\right)} = \frac{r}{1-e^{-rt}},$$

where r is the discount rate. We apply equations (2) and (3) to two growth functions that are representative of interior and coastal forests found in Canada and the northern U.S. Growth rates of 2.5% and 5.0% are assumed for the interior forest, and rates of 5.3% and 8.5% are assumed for the coastal forest, with respective site capacities (upper asymptotes) of 200 m^3 and 600 m^3. The values of the other parameters remain constant for the forest types: β=1.5 and m=0.25 for the interior forest, while β=1.5 and m=0.08 for the coastal forest. The volume curves and associated financial rotation ages are found in Figure 5. We do not consider a very fast growing forest (e.g., a hybrid-poplar plantation with 5-year rotation), because such a forest might more appropriately be considered an agricultural crop. That is, we distinguish between forestry and agriculture, and very short rotations may well fall in the purview of agriculture and not forestry.

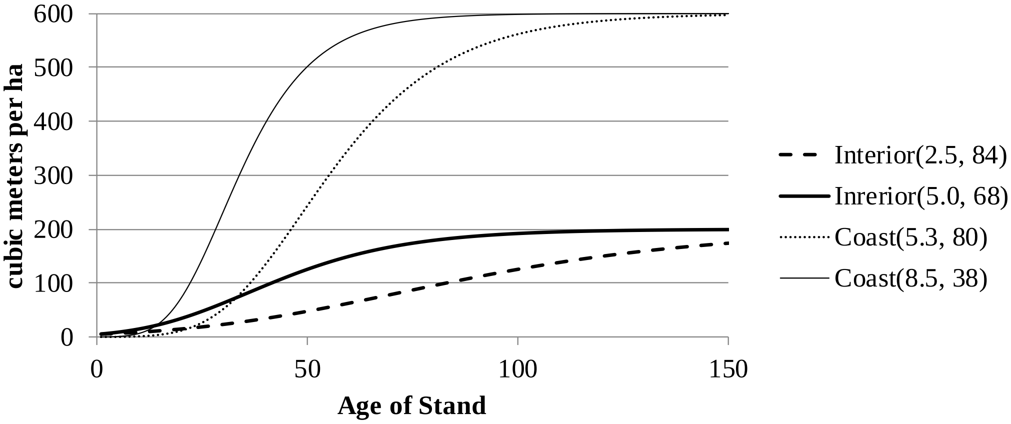
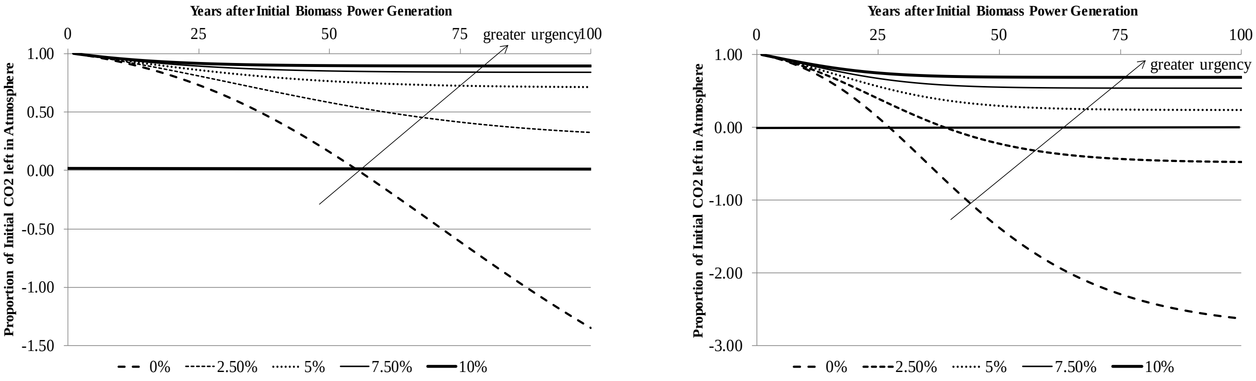


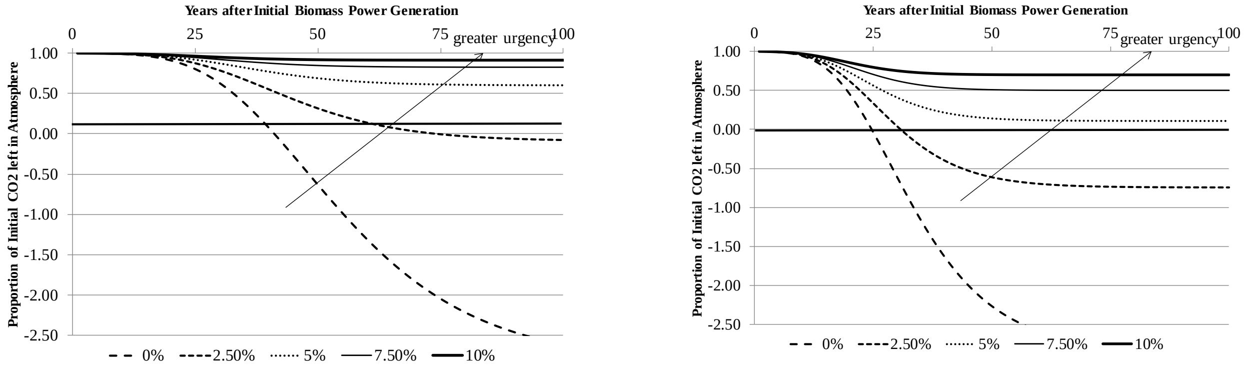
Figure 5: Growth Functions for Representative Coastal and Interior Forests, with Assumed Growth Rates and Approximate Financial Rotation Ages Provided in Parentheses

We assume that biomass is burned for energy and immediately replaced by trees that recover CO_2 at a rate that differs from one forest to another. However, we set the amount of biomass burned equal to the capacity (or upper asymptote) of the relevant site multiplied by 1.57 to account for possible coarse woody material that might be harvested (van Kooten et al. 1999). Using these values, we calculate the MWh of electricity that would be generated by burning the wood, assuming carbon and heat content based on an average of hardwoods and softwoods. We subtract from the initial release of CO_2 the emissions that would have been released if an equivalent amount of power had been generated using subbituminous coal. The initial emissions are normalized to 1.0 to make the scenarios comparable to one another. Finally, for each year we subtract the CO_2 removed from the atmosphere by subsequent growth of timber based on the growth curves of Figure 5 (again multiplying by 1.57 to account for logging residues and other coarse woody material), weighting the carbon according to the degree of urgency to address climate change. The rates used to discount the physical carbon increase from 0% (no urgency whatsoever) to 10% ('significant' urgency) at 2.5 percent intervals. The results for our four scenarios are provided in Figure 6.

If CO_2 is not discounted then it really does not matter how long it takes before the CO_2 is recovered from the atmosphere. In that case, all of the CO_2 emitted by burning forest biomass to produce power will eventually be returned to the vegetation sink, although it could take anywhere from 24 years (coastal forest, high growth rate) to 55 years (interior forest, low growth rate) to recover the carbon. Even for a very low rate of discount of 2.5%, perhaps equal to the social rate of discount that one might apply to monetary values, a carbon dividend could be realized as soon as 30 years except in the case of the slow growing interior forest when a carbon dividend is never realized as 27% of the initial carbon remains permanently in the atmosphere. It is important to note that, since we have already subtracted the CO_2 emissions associated with the fossil fuel alternative, the CO_2 left in the atmosphere is over and above that associated with coal.



(a) Interior Forest with Growth Rates of 2.5% (left panel) and 5.0% (right panel)



(b) Coastal Forest with Growth Rates of 5.3% (left panel) and 8.5% (right panel)

Figure 6: Proportion of CO_2 Remaining in the Atmosphere in Years after Biomass is Burned for Electricity, Replacing Coal, and Site is Regenerated with Forests Growing at Different Rates, Negative Values Indicate a Carbon Dividend, Positive Values Indicate a Carbon Debt

More worrisome from a policy perspective is the case where a low discount rate of 5% is used to weight future removals of CO_2 from the atmosphere by tree growth. This rate is sometimes applied to social investments and would be considered an appropriate rate for discounting investments in financial carbon offsets, say. Some 10 to 70 percent of the CO_2 emitted into the atmosphere remains there permanently, while it takes 26 or more years to remove even half of the carbon initially emitted. When the rate used to discount physical carbon increases above this relatively low value, which is necessary if climate change is somewhat of an urgent problem, more than half of the CO_2 is left in the atmosphere when bioenergy from forests is used to generate electricity. Indeed, when there is somewhat more significant urgency to address climate change so that the rate reaches 10% or more, the benefits of replacing fossil fuels in power plants disappears. Certainly, one would not want to rely on slow-growing forests that characterize much of the north hemisphere (Canada, Russia and northern Europe).

ECONOMICS CHALLENGES TO WOOD BIOMASS ENERGY

The economics of mitigating climate change through forest activities requires a systems-oriented approach that assesses various carbon fluxes over time, as well as the opportunity costs of options not chosen (or perhaps not even considered). The preceding discussion of wood biomass as an energy source provided insights into the struggles that biophysical scientists have in dealing with complex interactions that clearly fall in the purview of economics. In this section, we examine the same issue from the perspective of the economist, who has to balance costs of climate mitigation against potential benefits, even if these are not known with certainty. What are the problems from a policy perspective?

First, climate models are not the best vehicle for determining the dividend attributable to the use of wood pellets co-fired in thermal power plants. The veracity of climate models remains contentious, with some models considered better than others at predicting but none having been validated against observational data (Bakker 2014). Indeed, the value of the climate sensitivity parameter (how much the global temperature would increase with a doubling of atmospheric CO_2 from the pre-industrial level of 280 ppm to 560 ppm) remains an issue. Each of the five IPCC reports (1990, 1995, 2001, 2007, 2013) provides estimates of the climate sensitivity parameter ranging from 2.5^{o}C (1995, 2001) to 4.0^{o}C (1990), while other scientists report values between 0.8^{o}C and 2.0^{o}C (see Moncton et al. 2015, p.132). Lower estimates of the climate sensitivity parameter indicate that global warming is not a serious problem, although higher values ($\gg$2.5^{o}C) might require a more drastic response.

Second, as Sedjo and Tian (2012) and Sedjo (2013) point out, economists often attribute rational expectations to decision makers (Muth 1961). Therefore, forestland owners will have planted trees in anticipation of their use as a bioenergy source. Thus, any carbon released by burning biomass to generate electricity today had already been sequestered beforehand, so there is no carbon debt to consider. The rational expectations argument assumes forest-sector decision makers in each period plant and harvest stands of timber, expand or contract forestland holdings, fertilize and/or thin extant stands, and decide on the use to which any forest biomass is put on the basis of future prognostications. That is, to the extent that decision makers anticipate the future, it is possible that landowners have already invested in the production of wood biomass for energy purposes.

Third, prices and opportunity cost are considerations of importance to economists. If coal is replaced by biomass in the production of electricity, the price of coal will inevitably fall thereby causing a decision maker elsewhere to increase the capacity of coal-fired power plants. For example, if coal is no longer used to generate electricity in the U.S. or UK, its price will fall and India might expand its production of electricity using coal. There is evidence of this in Japan and Germany, where decisions to eliminate or reduce nuclear power have led to greater use of coal generation because coal provides reliable generating capacity at a lower cost than natural gas (as natural gas prices are higher in these countries than in North America). This represents a leakage associated with bioenergy that needs to be taken into account.

Fourth, the largest impacts of using wood for bioenergy relate to land-use changes and effects on wood products.[8] Because land is the most important input into the production of bioenergy, incentives to produce energy from biomass distort land use by converting cropland from food production into bioenergy crops, including wood biomass in some regions (Ince et al. 2011, 2012; Moiseyev et al. 2011), and thereby raising food prices. It is likely that, despite the forgoing analysis, CO_2 emissions are increased rather than reduced as a result of distorting land use, especially once increased chemical use is included, while technologies to produce electricity from wood pellets (or liquid fuels from ethanol) get locked in (Klein and LeRoy 2007; Crutzen et al. 2008; Searchinger et al. 2008). Ultimately, the rate at which land is devoted to produce energy from biomass is sensitive to the level of risk aversion of the land holder; if future biomass markets are uncertain, then less land will be converted for bioenergy purposes (Hallman and Amacher 2012).

Fifth, with the exception of the U.S. South and a few other places where plantation forests and private industrial ownership dominate, and where land shifts more easily between forestry and other uses, the opportunity costs of producing wood pellets can be high. In many forest regions, wood pellets are produced from shavings, sawdust and chips from sawmilling or plywood production, or from increased effort to remove residuals from harvested sites. In British Columbia, for example, the availability of wood fiber for the production of pulp, oriented strand board (OSB), medium density fiberboard (MDF), and other products, including wood pellets, is the direct result of lumber production. Without sawmills, there is no fiber available for other uses. Given that some mill residues are already used for on-site heating and electricity, remaining

---

[8] "The current default accounting guidelines of the UNFCCC assume that C removed from the forest replaces C in harvested wood products (HWPs) derived from harvest in prior years such that the total pool of HWPs remains constant. The additions to the HWP pool are assumed equal to the releases from the pool, and the simplifying accounting assumption is that all C added to the HWP pool is immediately emitted to the atmosphere. In reality, however, the global HWP C pool has not yet reached steady state and is still increasing in size" (Kurz et al. 2013, p.272).

residues are sold in competitive markets. If wood pellet prices relative to those of pulp, OSB, MDF and other products are high enough, fiber will be directed to wood pellet production (Stennes et al. 2010; Niquidet and Friesen 2014). However, in most circumstances, bioenergy is the marginal demander of fiber so that any factors that cause the price of pulp, OSB, et cetera, to increase will cause wood pellet manufacturers to drop out of the market. Only direct subsidies or high feed-in tariffs can offset uncertainty regarding prices of products that compete for residual fiber, enabling pellet producers to remain competitive.

Finally, policies that incentivize production of wood pellets for generating electricity, for example, have consequences in international wood product markets, and it is necessary to examine the economic impacts of renewable energy policies in an international context. Studies by Raunikar et al. (2010) and Buongiorno et al. (2011) concluded that increased fuelwood demand would lead to the convergence of fuelwood and industrial roundwood prices, while the prices of other forest products, including sawnwood and panels, would rise significantly. Härtl and Knoke (2014) show that increasing timber prices may lead to a greater amount of fuelwood production at the expense of sawlog and pulpwood supply. While fuelwood is used principally in developing countries for subsistence, the recent rise in bioenergy demand is a rich-country phenomenon that is currently met by residuals from the manufacture of wood products, much of which is converted to wood pellets for co-firing with coal to generate electricity. Hence, international wood product trade models should take into account the relationships among logs, wood products and biomass for energy.

Using an integrated international forest products trade model, Johnston and van Kooten (2015a) find that a doubling of the demand for wood pellets in the EU (8.3 Mt was burned in 2012) would increase the cost of pellets to electricity generators by nearly 90%. Prices of lumber would decline in Europe by some 7%, but prices of fiberboard, particle board and pulp would increase by some 10%. The reasons for this are discussed in the next paragraph. Given that the EU is likely to require three times as much wood biomass as modeled, the price of wood biomass fuel would increase significantly and thus negatively impact the EU's ability to rely on wood bioenergy to the extent currently envisioned.

Subsidies that increase the demand for wood residues for bioenergy will have two offsetting impacts – (1) increase the production of lumber and plywood, and (2) reduce the production of pulp, OSB, MDF, et cetera. An increase in the value of sawmilling residues effectively increases the value of a log to the sawmill operator, or, analogously, reduces the cost of producing lumber (Latta et al 2013, p.379). This causes the sawmilling sector to increase demand for logs and, thereby, increase lumber output (Johnston and van Kooten 2015b; Abt et al. 2012). However, increased production lowers the price of lumber and thus offsets this incentive. Along with sustainability requirements that limit the increase in timber harvests, in most jurisdictions the added availability of residues from greater lumber production will be minor compared to the second effect: wood pellet production bids biomass away from other uses (Stennes et al. 2010). In that case, there will be a decline in the output of pulp, OSB, MDF and similar products that rely on residues, which means that less carbon is stored in these engineered wood products, some of which are relatively long lived and increasingly used in construction instead of steel or concrete. Although the increase in lumber output will increase carbon stored in products, the overall effect will be a reduction in the carbon stored in post-harvest products and an increase in the use of non-wood construction material.

WOOD BIOMASS ENERGY: LOGGING RESIDUES

The increased price of residuals will result in the removal of more residue fiber from the forest after harvest. Any expansion in wood bioenergy in the U.S. to 2030 is projected to come primarily from increased logging residues, and to a lesser extent mill residues (Ince et al. 2011). In the eastern and southern U.S., increased incentives such as higher prices could result in as much as 65% of the logging residues to be available for wood pellet production (see Abt et al. 2014). However, forecasts of very large increases in bioenergy from logging residues are unlikely to be realized for several reasons.

First, the level of ease with which land can be changed between sectors and uses may well determine the effectiveness of bioenergy (Latta et al. 2013). Such flexibility would lead to greater reliance on energy crops, agricultural residues, and, to a lesser extent, short-rotation woody crops (hybrid poplar and willow). Latta et al. (2013) examine scenarios to provide between 25 terawatt hours (TWh) and 200 TWh of biomass electricity annually in the U.S. in the short run (to 2025) and long run (2040). If biomass can be sourced from either agriculture or forestry, or both, and land can move between these sectors, very little of the bioenergy needed to generate this electricity is projected to come from forestry.

Second, the supply of logging residues at a given time is limited by the amount of total timber removed for other products (Abt et al. 2014, p.5). In the vast majority of cases, it does not pay to harvest forests solely for bioenergy purposes. As noted in the previous point, sourcing biomass from agriculture is more cost effective. Niquidet et al. (2012) find it may be too costly to haul roadside wastes (logging residues left where logging trucks are loaded) from forests in the BC interior of Canada to a dedicated biomass plant located near the sawmill to which the logs are brought.

Third, coarse and fine woody materials left in the forest upon harvest decay more rapidly than round-wood, thereby releasing CO_2 to the atmosphere. This fiber source favors bioenergy because the CO_2 released by burning would otherwise have been emitted rather quickly in any event – the opportunity cost of carbon flux is small. Indeed, forest ecologists recommend longer rotations because older forests produce more coarse and fine woody material (Johnston and Crossley 2002). The environmental benefits of leaving slash and other woody materials in the forest after harvest are neglected in studies examining the use of logging residues for bioenergy, but could become an impediment to the removal of coarse and fine woody material from the forest for pellet production. Further, logging companies with short-term contracts to harvest timber have little incentive to remove roadside wastes; rather, they cut logs at roadside to enhance their value and minimize hauling costs.

Unlike forests in parts of the U.S. south, the majority of Canada’s forests are publicly owned, as are those of the U.S. Pacific Northwest and other jurisdictions (Wilson et al. 1998). Public tenures prevent forests from being transferred to other uses, including agriculture, and restrict harvest levels over extended periods of time; they also prescribe certain management practices and impose fees that might discourage greater use of woody materials for bioenergy (Wang and van Kooten 2001; Bogle and van Kooten 2015). As a result, institutional limits and tenure arrangements, which can lead to principal-agent problems (Bogle 2012), can be an important impediment to the expansion of biomass supply for energy purposes. As Bogle and van Kooten (2013, 2015) point out in the case of natural disturbance, regulations imposed by the principal (public forestland owner) on agents (logging companies) to get them to harvest less desirable mountain pine beetle damaged or susceptible trees is undermined by the economic incentives the agents face.

SUMMARY AND DISCUSSION

The potential benefits of substituting biomass for coal to produce energy might be greatly exaggerated. Indeed, depending on the source of biomass and the perceived urgency with which society should mitigate climate change, using biomass to generate electricity might result in greater warming rather than less. Some have discounted the value of future carbon removals with a fixed discount rate (e.g. Schlamadinger and Marland 1999); the problem then becomes what is the appropriate rate to use?

Neglected in our discussion has been the CO_2 emissions related to harvesting, hauling and processing of timber into pellets, and shipping the pellets to the power plant. The same could be said about coal, although coal is mined at what essentially amounts to a single point on the landscape, and then loaded directly onto rail cars or hauled directly by truck to a power plant, usually with little or no further processing except crushing at the power plant. This contrasts with forest biomass that is harvested over a large landscape, with logs and sometimes roadside wastes trucked to processing facilities (Niquidet et al., 2012); logs are processed into lumber and other valuable products, with residues from these processes made available for energy purposes. However, the process of converting fibre into wood pellets, torrefied pellets or charcoal for use in coal plants releases a significant amount of CO_2.

If we consider biomass from agricultural operations, the residues need to be gathered (harvested), transported and processed, and account needs to be taken of greenhouse gas emissions related to agrochemicals, primarily fertilizers that are also employed to enhance tree growth in plantations. The greenhouse gases emitted in the production, harvest and processing of energy crops often exceeds the reduction in emissions from replacing fossil fuels (Crutzen et al., 2008).

The production of timber or other energy crops increases land values (Ince et al., 2011, 2012; Moiseyev et al., 2011). This reduces land available for food production, which increases food prices thus harming the poorest in developing countries the most because they spend a greater proportion of their income on food. It also incentivizes the conversion of wetlands to cropland and natural forests to plantations, thereby reducing biodiversity and important ecological services.

Finally, greater reliance on biomass for energy will increase the demand for wood residues, increasing their price in competition with wood manufacturers (who produce various industrial materials from wood residues) and pulp and paper producers (Stennes et al., 2010). This might make biomass too expensive to burn in power plants. Policies to promote biomass energy would then reduce economic activity in other wood using sectors (Raunikar et al., 2010; Johnston and van Kooten, 2014), and increase electricity prices to the detriment of the least well off (Popp et al., 2011).

While electricity from biomass has merit in some cases, a nostalgic return to the past might also bring with it energy poverty, which many experienced in the past and still is the experience of many living in developing countries. Misguided policies to increase reliance on wood biomass for energy yield little if anything in the way of reduced CO_2 emissions.

ACKNOWLEDGEMENTS

This research was supported by Canada's Social Sciences and Humanities Research Council and NSERC's Value Chain Optimization Network.

REFERENCES

Abt, K.L., R.C. Abt, C.S. Galik and K.E. Skog, 2014. Effect of Policies on Pellet Production and Forests in the U.S. South: A Technical Document Supporting the Forest Service Update of the 2010 RPA Assessment. Gen. Tech. Rep. SRS-202. 33pp. Asheville, NC: USDA Forest Service, Southern Res. Sta. http://www.theusipa.org/Documents/US_Forest_Service_Report_2015.pdf [accessed April 16, 2015].

Bakker, A.M.R., 2014. *The Robustness of the Climate Modelling Paradigm*. PhD Dissertation, VU University, Amsterdam, The Netherlands. Available from http://dare.ubvu.vu.nl/handle/1871/52184 [accessed February 13, 2015]

Bogle, T.N., 2012. *Timber Supply on Public Land in Response to Catastrophic Natural Disturbance: A Principal-Agent Problem*. Unpublished PhD dissertation. 116pp. Department of Geography, University of Victoria, Victoria, Canada.

Bogle, T.N. and G.C. van Kooten, 2013. Options for Maintaining Forest Productivity after Natural Disturbance: A Principal-Agent Approach, *Forest Policy & Economics* 26(1): 138-144.

Bogle, T.N. and G.C. van Kooten, 2015. Protecting Timber Supply on Public Land in Response to Catastrophic Natural Disturbance: A Principal-Agent Problem, *Forest Science* 61(1): 83-92.

Buongiorno, J., R. Raunikar and S. Zhu, 2011. Consequences of Increasing Bioenergy Demand on Wood and Forests: An Application of the Global Forest Products Model, *Journal of Forest Economics* 17: 214-229.

Cherubini, F., G.P. Peters, T. Berntsen, A.H. Strømman and E. Hertwich, 2011. CO_2 Emissions from Biomass Combustion for Bioenergy: Atmospheric Decay and Contribution to Global Warming, *Global Change Biology Bioenergy* 3: 413-426.

Ciricacy-Wantrup, S.V., 1968. *Resource Conservation. Economics and Policies*. 3rd Edition. Berkeley, CA: University of California, Agricultural Experiment Station. (1st Edition 1952).

Cremers, M.F.G., 2009. Ed. Tech. Status of Biomass Co-Firing IEA Bioenergy Task 32.

Crutzen, P.J., A.R. Mosier, K.A. Smith and W. Winiwarter, 2008. N_2O Release from Agro-biofuel Production Negates Global Warming Reduction by Replacing Fossil Fuels, *Atmospheric Chemistry and Physics 8*(2): 389-395.

Edenhofer O., R. Pichs-Madruga, Y. Sokona, K. Seyboth and P. Matschoss (editors), 2011. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, UK: Cambridge University Press.

EIA, 2013. US Energy Information Administration. Annual Energy Outlook, 2013; with Projections to 2040. (2013)

EPA, 2013. United States Environmental Protection Agency. http://www2.epa.gov/sites/production/files/201309/documents/20130920technicalfactsheet.pdf

European Commission, 2013. A New EU Forest Strategy: Forests and the Forest-Based Sector. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, 20.9.2013.Com(2013) 659 Final.

FAO, 2015. Forest Database. Food and Agricultural Organization of the United Nations. http://www.fao.org/forestry/46203/en/ [accessed August 11, 2015].

Galik, C.S. and R.C. Abt, 2012. The Effect of Assessment Scale and Metric Selection on the Greenhouse Gas Benefits of Woody Biomass, *Biomass and Bioenergy* 44: 1-7.

Government of Canada, 2012. Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations. Canada Gazette. http://www.gazette.gc.ca/rp-pr/p2/2012/2012-09-12/html/sor-dors167-eng.html (viewed June 3, 2014).

Hallmann, F.W., and G.S. Amacher. Forest Bioenergy Adoption for a Risk-Averse Landowner Under Uncertain Emerging Biomass Market. *Natural Resource Modeling.* 25.3 (2012): 482-510.

Härtl, F., and T. Knoke, 2014. The Influence of the Oil Price on Timber Supply. *Forest Policy and Economics*: 39: 32-42.

Helin, T., L. Sokka, S. Soimakallio, K. Pingoud and T. Pajula, 2013. Approaches for Inclusion of Forest Carbon Cycle in Life Cycle Assessment – A Review, *Global Change Biology Bioenergy* 5: 475-486.

Holtsmark, Bjart. "Quantifying the global warming potential of CO2 emissions from wood fuels." GCB Bioenergy 7.2 (2015): 195-206.

Holtsmark, Bjart. "Harvesting in boreal forests and the biofuel carbon debt."Climatic change 112.2 (2012): 415-428.

Hong, B.D. and E. R. Slatick, 1994. Carbon Dioxide Emission Factors for Coal. In Energy Information Administration, Quarterly Coal Report, January-April 1994, DOE/EIA-0121(94/Q1), August, pp.1-8. Washington, DC. http://www.eia.gov/coal/production/quarterly/co2_article/co2.html [accessed April 1, 2015].

Ince, P.J., A.D. Kramp and K.E. Skog, 2012. Evaluating Economic Impacts of Expanded Global Wood Energy Consumption with the USFPM/GFPM Model, *Canadian Journal of Agricultural Economics* 60(2): 211-237.

Ince, P.J., A.D. Kramp, K.E. Skog, D. Yoo and V.A. Sample, 2011. Modelling Future U.S. Forest Sector Market and Trade Impacts of Expansion in Wood Energy Consumption, *Journal of Forest Economics* 17(2): 142-156.

IPCC, 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. 1132pp. Cambridge, UK: Cambridge University Press.

IPCC, 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use*. Intergovernmental Panel on Climate Change. At http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html [accessed September 10, 2015]

Johnston, J.M. and D.A. Crossley, Jr., 2002. Forest Ecosystem Recovery in the Southeast US: Soil Ecology as an Essential Component of Ecosystem Management, *Forest Ecology and Management* 155: 187-203.

Johnston, C.M.T. and G.C. van Kooten, 2015a. Increasing Europe's Bioenergy Demand: Who Benefits? Submitted to *Journal of Forest Economics*.

Johnston, C.M.T. and G.C. van Kooten, 2015b. Economics of Co-firing Coal and Biomass: An Application to Western Canada, *Energy Economics* 48: 7-17.

Johnston, C.M.T., and G.C. van Kooten, 2014. Economic Consequences of Increased Bioenergy Demand, *Forestry Chronicle* 90(5): 636-642.

Klein, K. and D.G. LeRoy, 2007. The Biofuels Frenzy: What's in it for Canadian Agriculture? Green Paper prepared for the Alberta Institute of Agrologists. March 28, 56pp. University of Lethbridge, Lethbridge, AB. http://www.aic.ca/whatsnew_docs/Klein%20Final%20%234.pdf [accessed Febuary 17, 2015]

Kurz, W.A.,_C.H. Shaw, C. Boisvenue, G. Stinson, J. Metsaranta, D. Leckie, A. Dyk, C. Smyth, and E.T. Neilson, 2013. Carbon in Canada's Boreal Forest — A Synthesis, *Environmental Reviews* 21: 260-292.

Lamers P., M. Junginger, C. Hamelinck and A. Faaij, 2012. Developments in International Solid Biofuel Trade – An Analysis Of Volumes, Policies, and Market Factors, *Renewable and Sustainable Energy Review* 16: 3176-3199.

Latta, G.S., J.S. Baker, R.H. Beach, S.K. Rose and B.A. McCarl, 2013. A Multi-sector Intertemporal Optimization Approach to Assess the GHG Implications of U.S. Forest and Agricultural Biomass Electricity Expansion, *Journal of Forest Economics* 19: 361-383.

Lemprière, T.C., W.A. Kurz, E.H. Hogg, C. Schmoll, G.J. Rampley, D. Yemshanov, D.W. McKenney, R. Gilsenan, A. Beatch, D. Blain, J.S. Bhatti and E. Krcmar, 2013. Canadian Boreal Forests and Climate Change Mitigation, *Environmental Reviews* 21: 293-321.

McDermott, Shana M., Richard B. Howarth, and David A. Lutz. "Biomass Energy and Climate Neutrality: The Case of the Northern Forest." Land Economics 91.2 (2015): 197-210.

McKechnie, J., S. Colombo, J. Chen, W. Mabee and H.l. MacLean, 2011. Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels, *Environmental Science & Technology* 45: 789-795.

Melillo, J.M., T.C. Richmond and G.W. Yohe, Eds., 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. National Climate Assessment. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2

Miner, R.A., R.C. Abt, J.L. Bowyer, M.A. Buford, R.W. Malmsheimer, J. O'Laughlin, E.E. Oneil, R.A. Sedjo and K.E. Skog, 2014. Forest Carbon Accounting Considerations in US Bioenergy Policy, *Journal of Forestry* 112(6): 591-606.

Moiseyev, A., B. Solberg, A.M.L. Kallio and M. Lindner, 2011. An Economic Analysis of the Potential Contribution of Forest Biomass to the EU RES Target and its Implication for the EU Forest Industries, *Journal of Forest Economics* 17: 197-213.

Muth, J.F., 1961. Rational Expectations and the Theory of Price Movements, *Econometrica* 29(3): 315-335.

NCA, 2014. National Climate Assessment of the United States government. Global Climate Changes Impacts in the United States. http://nca2014.globalchange.gov/report

Niquidet, K. and D. Friesen, 2014. Bioenergy Potential from Wood Residuals in Alberta: A Positive Mathematical Programming Approach, Canadian Journal of Forest Research 44(12): 1586-1594.

Niquidet, K., B. Stennes and G.C. van Kooten, 2012. Bio-energy from Mountain Pine Beetle Timber and Forest Residuals: The Economics Story, *Canadian Journal of Agricultural Economics* 60(2): 195-210.

Popp A., J. P. Dietrich, H. Lotze-Campen, D. Klein, N. Bauer, 2011. The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. Environ. Res. Lett. 6 034017.

Pöyry, 2011. "Pellets – Becoming a Global Commodity? Global market, players and trade to 2020," (April 2011). http://www.poyry.com/linked/services/pdf/144.pdf (Accessed April 2013).

Raunikar, R., J. Buongiorno, J.A. Turner and S. Zhu, 2010. Global Outlook for Wood and Forests with the Bioenergy Demand Implied by Scenarios of the Intergovernmental Panel on Climate Change, *Forest Policy and Economics* 12: 48-56.

Sedjo, R.A., 2011. Carbon Neutrality and Bioenergy. A Zero-Sum Game? Paper #RFF DP 11-15. April. 31pp. Washington, DC: Resources for the Future.

Sedjo, R.A., 2013. Comparative Life Cycle Assessments: Carbon Neutrality and Wood Biomass Energy. Paper #RFF DP 13-11. April. 18pp. Washington, DC: Resources for the Future.

Sedjo, R. and X. Tian, 2012. Does Wood Bioenergy Increase Carbon Stocks in Forests? Journal of Forestry 110(6): 304-311.

RES-LEGAL, 2014. European Commission Legal Sources on Renewable Energy. http://www.res-legal.eu/ (accessed February 21, 2014)

Searchinger, T.D., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes and T. Yu, 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change, *Science 319*(February 29): 1238-1240.

Schlamadinger, B. and G Marland, 1999. Net effect of forest harvest on CO2 emissions to the atmosphere: a sensitivity analysis on the influence of time. *Tellus (1999), 51B*: 314–325.

Smyth, C.E., G. Stinson, E. Neilson, T.C. Lemprière, M. Hafer, G. J. Rampley and W. A. Kurz, 2014. Quantifying the Biophysical Climate Change Mitigation Potential of Canada's Forest Sector, *Biogeosciences* 11: 3515-3529.

Stennes, B., K. Niquidet and G.C. van Kooten, 2010. Implications of Expanding Bioenergy Production from Wood in British Columbia: An Application of a Regional Wood Fibre Allocation Model, *Forest Science* 56(4): 366-378.

Stephenson, A.L. and D.J.C. MacKay, 2014. Life Cycle Impacts of Biomass Electricity in 2020. Scenarios for Assessing the Greenhouse Gas Impacts and Energy Input Requirements of Using North American Woody Biomass for Electricity Generation in the UK. Report #URN 14D/243. July. 154pp. London, UK: Department of Energy and Climate Change, Crown Copyright. https://www.gov.uk/government/publications/life-cycle-impacts-of-biomass-electricity-in-2020 [accessed February 26, 2015] van Kooten, G.C. and H. Folmer, 2004. *Land and Forest Economics*. Cheltenham, UK: Edward Elgar.

van Kooten, G.C., E. Krcmar-Nozic, B. Stennes and R. van Gorkom, 1999. Economics of Fossil Fuel Substitution and Wood Product Sinks when Trees are Planted to Sequester Carbon on Agricultural Lands in Western Canada, *Canadian Journal of Forest Research* 29(11): 1669-1678.

Walker, T., P. Cardellichio, J.S. Gunn, D.S. Saah and J.M. Hagan, 2013. Carbon Accounting for Woody Biomass from Massachusetts (USA) Managed Forests: A Framework for Determining the Temporal Impacts of Wood Biomass Energy on Atmospheric Greenhouse Gas Levels, *Journal of Sustainable Forestry* 32(1-2): 130-158.

Walker, T., P. Cardellichio, A. Colnes, J.S. Gunn, B. Kittler, B. Perschel, C. Recchia and D.S. Saah, 2010. Massachusetts Biomass Sustainability and Carbon Policy Study: Report to the Commonwealth of Massachusetts Department of Energy Resources. Natural Capital Initiative Report NCI-2010- 03. Brunswick, ME: Manomet Center for Conservation Sciences. http://www.mass.gov/eea/docs/ doer/renewables/biomass/manomet-biomass-report-full-hirez.pdf [accessed February 11, 2015]

Wilson, W.R., 1998. Commercial Forestry: The Road to Sustainability in British Columbia. Proceedings: *Forest Management into the Next Century*. Madison WI.

Wang, S. and G.C. van Kooten, 2001. *Forestry and the New Institutional Economics*. Aldershot, UK: Ashgate Publishing.