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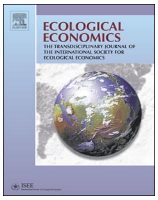

Analysis

# Back to the past: Burning wood to save the globe

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## 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.

## 1. 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-ETSAP and IRENA, 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, 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

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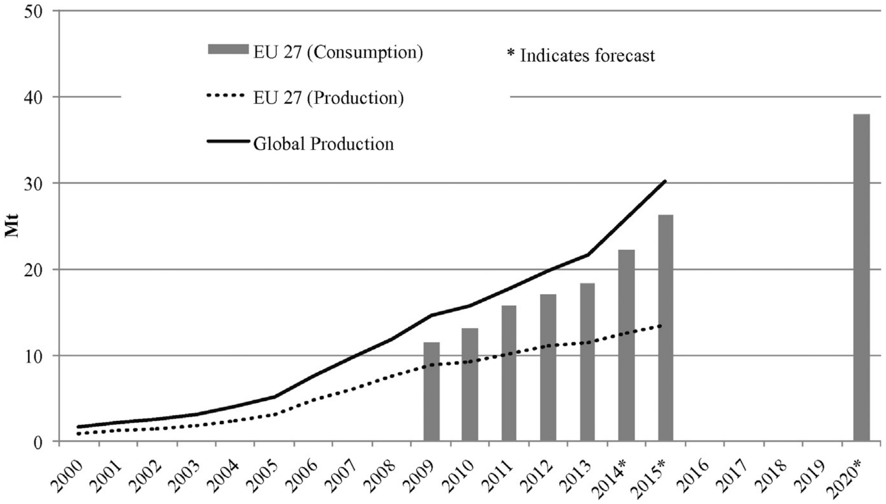

**Fig. 1.** Production and consumption of wood pellets in the EU-27 (Mt), 2000–2013 and forecasts for 2015 and 2020 Source: Pöyry (2011); Lamers et al. (2012); FAO (2015).

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 Fig. 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.

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 behooves 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.

## 2. 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 Fig. 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 below, when we investigate issues surrounding urgency and discounting.

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

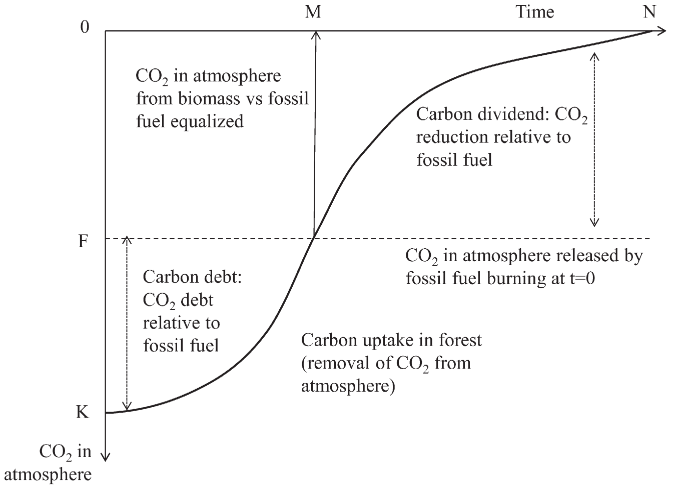

**Fig. 2.** Carbon flux profile for biomass energy versus business-as-usual fossil fuel energy Source: Walker et al. (2010).

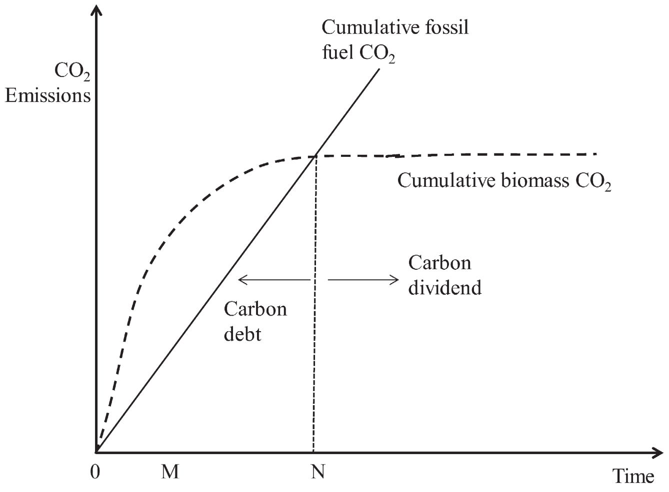

**Fig. 3.** Carbon flux associated with fossil fuel and biomass energy production over time Source: Walker et al. (2013).

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 Fig. 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]

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 Fig. 2 morphs from the single- (small scale) to the multi-period (large scale) of Fig. 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).

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$_{\text{bio}}$ 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):

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

where C$_0$ refers to the initial pulse of CO$_2$ entering the atmosphere at $t = 0$. T is the time horizon, and $\alpha_{CO2}$ and $\alpha_{bioCO2}$ are the radiative efficiencies of CO$_2$ and bioCO$_2$, respectively, with $\alpha_{CO2}$ clearly equal to $\alpha_{bioCO2}$.[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 CO$_2$ from fossil fuel burning remains constant through time as none is

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[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 CO2 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.

[3] It should be noted that $\alpha_{CO2}$ depends on the ratio of the concentration of CO$_2$ in the atmosphere after a small perturbation to the initial concentration.

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 Fig. 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 $\alpha_{bioCO2}$ $(=\alpha_{CO2})$ 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).

## 3. 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 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 (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, 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. Fig. 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 actually lead to a net increase in atmospheric $CO_2$ emissions. In Fig. 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

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[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.

[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).

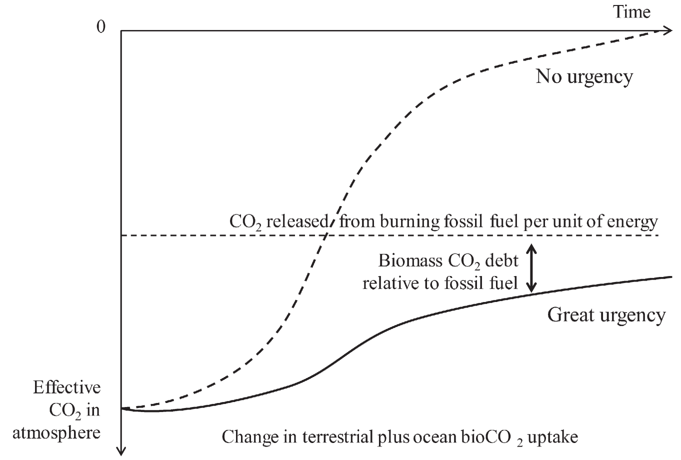

**Fig. 4.** Carbon flux associated with fossil fuel and biomass energy production over time: Comparing lesser and greater urgency to address climate change.

of the sink) is too small to offset the additional increase in $CO_2$ emissions when biomass substitutes for fossil fuels in power production.

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 MW 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 1 MWh of energy, thereby releasing about 1.27 $tCO_2$.

## 4. 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:

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

where $v(t)$ is volume ($m^3$/ha) as a function of age, $\beta$ 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 371):

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

where $r$ is the discount rate. We apply Eqs. (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: $\beta = 1.5$ and $m = 0.25$ for the interior forest, while $\beta = 1.5$ and $m = 0.08$ for the coastal forest. The volume curves and associated financial rotation ages are found in Fig. 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.

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 Fig. 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% intervals. The results for our four scenarios are provided in Fig. 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 $CO_2$

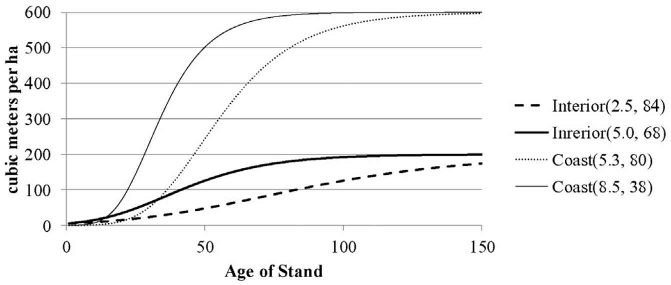

**Fig. 5.** Growth functions for representative coastal and interior forests, with assumed growth rates and approximate financial rotation ages provided in parentheses.

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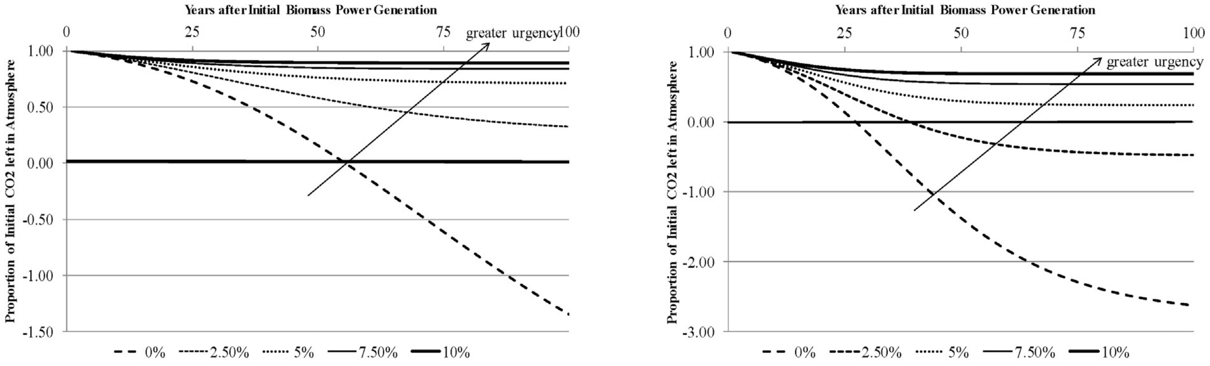
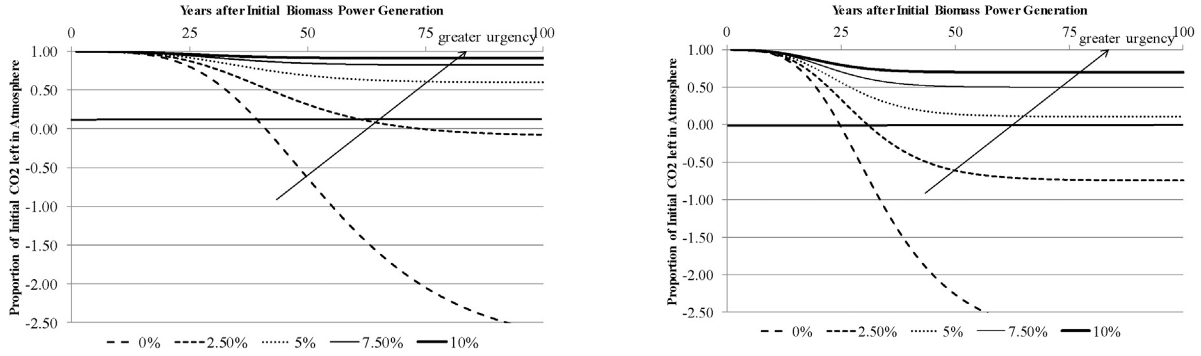
[6] See also http://www.ipcc.ch/meetings/session25/doc4a4b/vol2.pdf [accessed April 1, 2015] where carbon intensities for many fuels are provided.

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



*(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)*

**Fig. 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.

emissions associated with the fossil fuel alternative, the $CO_2$ left in the atmosphere is over and above that associated with coal.

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% 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).

## 5. 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 °C (1995, 2001) to 4.0 °C (1990), while other scientists report values between 0.8 °C and 2.0 °C (see Monckton 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 °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 (Hallmann 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 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.

## 6. 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.

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[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).

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, 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.

## 7. 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 fiber 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.

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