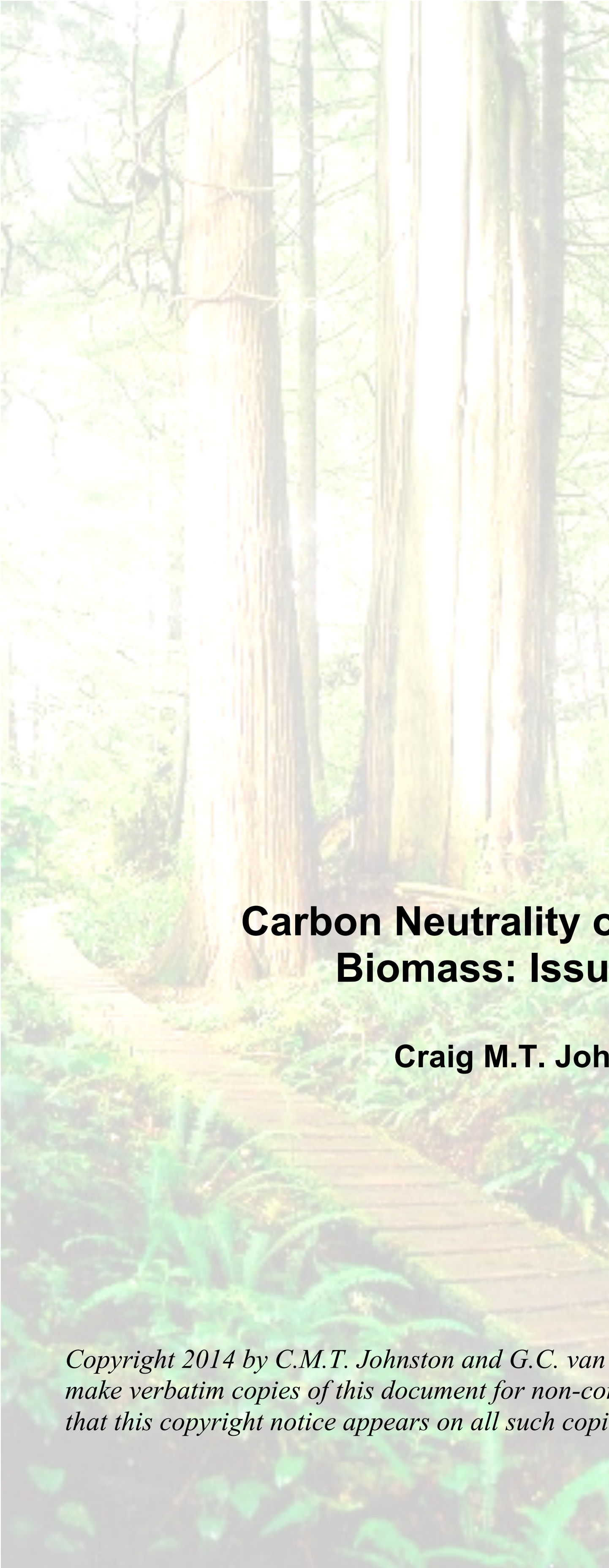


WORKING PAPER
2014-06

REPA

Resource Economics & Policy Analysis Research Group

Department of Economics
University of Victoria

Carbon Neutrality of Hardwood and Softwood Biomass: Issues of Temporal Preference

Craig M.T. Johnston and G. Cornelis van Kooten

November 2014

REPA Working Papers:

2003-01 – Compensation for Wildlife Damage: Habitat Conversion, Species Preservation and Local Welfare (Rondeau and Bulte)
2003-02 – Demand for Wildlife Hunting in British Columbia (Sun, van Kooten and Voss)
2003-03 – Does Inclusion of Landowners' Non-Market Values Lower Costs of Creating Carbon Forest Sinks? (Shaikh, Suchánek, Sun and van Kooten)
2003-04 – Smoke and Mirrors: The Kyoto Protocol and Beyond (van Kooten)
2003-05 – Creating Carbon Offsets in Agriculture through No-Till Cultivation: A Meta-Analysis of Costs and Carbon Benefits (Manley, van Kooten, Moeltne, and Johnson)
2003-06 – Climate Change and Forest Ecosystem Sinks: Economic Analysis (van Kooten and Eagle)
2003-07 – Resolving Range Conflict in Nevada? The Potential for Compensation via Monetary Payouts and Grazing Alternatives (Hobby and van Kooten)
2003-08 – Social Dilemmas and Public Range Management: Results from the Nevada Ranch Survey (van Kooten, Thomsen, Hobby and Eagle)
2004-01 – How Costly are Carbon Offsets? A Meta-Analysis of Forest Carbon Sinks (van Kooten, Eagle, Manley and Smolak)
2004-02 – Managing Forests for Multiple Tradeoffs: Compromising on Timber, Carbon and Biodiversity Objectives (Krcmar, van Kooten and Vertinsky)
2004-03 – Tests of the EKC Hypothesis using CO2 Panel Data (Shi)
2004-04 – Are Log Markets Competitive? Empirical Evidence and Implications for Canada-U.S. Trade in Softwood Lumber (Niquidet and van Kooten)
2004-05 – Conservation Payments under Risk: A Stochastic Dominance Approach (Benítez, Kuosmanen, Olschewski and van Kooten)
2004-06 – Modeling Alternative Zoning Strategies in Forest Management (Krcmar, Vertinsky and van Kooten)
2004-07 – Another Look at the Income Elasticity of Non-Point Source Air Pollutants: A Semiparametric Approach (Roy and van Kooten)
2004-08 – Anthropogenic and Natural Determinants of the Population of a Sensitive Species: Sage Grouse in Nevada (van Kooten, Eagle and Eiswerth)
2004-09 – Demand for Wildlife Hunting in British Columbia (Sun, van Kooten and Voss)
2004-10 – Viability of Carbon Offset Generating Projects in Boreal Ontario (Biggs and Laaksonen-Craig)
2004-11 – Economics of Forest and Agricultural Carbon Sinks (van Kooten)
2004-12 – Economic Dynamics of Tree Planting for Carbon Uptake on Marginal Agricultural Lands (van Kooten) (Copy of paper published in the Canadian Journal of Agricultural Economics 48(March): 51-65.)
2004-13 – Decoupling Farm Payments: Experience in the US, Canada, and Europe (Ogg and van Kooten)
2004–14– Afforestation Generated Kyoto Compliant Carbon Offsets: A Case Study in Northeastern Ontario (Biggs)
2005–01– Utility-scale Wind Power: Impacts of Increased Penetration (Pitt, van Kooten, Love and Djilali)
2005–02 –Integrating Wind Power in Electricity Grids: An Economic Analysis (Liu, van Kooten and Pitt)
2005–03 –Resolving Canada-U.S. Trade Disputes in Agriculture and Forestry: Lessons from Lumber (Biggs, Laaksonen-Craig, Niquidet and van Kooten)

2005–04–Can Forest Management Strategies Sustain the Development Needs of the Little Red River Cree First Nation? (Krcmar, Nelson, van Kooten, Vertinsky and Webb)
2005–05–Economics of Forest and Agricultural Carbon Sinks (van Kooten)
2005–06– Divergence Between WTA & WTP Revisited: Livestock Grazing on Public Range (Sun, van Kooten and Voss)
2005–07 –Dynamic Programming and Learning Models for Management of a Nonnative Species (Eiswerth, van Kooten, Lines and Eagle)
2005–08 –Canada-US Softwood Lumber Trade Revisited: Examining the Role of Substitution Bias in the Context of a Spatial Price Equilibrium Framework (Mogus, Stennes and van Kooten)
2005–09 –Are Agricultural Values a Reliable Guide in Determining Landowners' Decisions to Create Carbon Forest Sinks?* (Shaikh, Sun and van Kooten) *Updated version of Working Paper 2003-03
2005–10 –Carbon Sinks and Reservoirs: The Value of Permanence and Role of Discounting (Benitez and van Kooten)
2005–11 –Fuzzy Logic and Preference Uncertainty in Non-Market Valuation (Sun and van Kooten)
2005–12 –Forest Management Zone Design with a Tabu Search Algorithm (Krcmar, Mitrovic-Minic, van Kooten and Vertinsky)
2005–13 –Resolving Range Conflict in Nevada? Buyouts and Other Compensation Alternatives (van Kooten, Thomsen and Hobby) *Updated version of Working Paper 2003-07
2005–14 –Conservation Payments Under Risk: A Stochastic Dominance Approach (Benítez, Kuosmanen, Olschewski and van Kooten) *Updated version of Working Paper 2004-05
2005–15 –The Effect of Uncertainty on Contingent Valuation Estimates: A Comparison (Shaikh, Sun and van Kooten**)**
2005–16 –Land Degradation in Ethiopia: What do Stoves Have to do with it? (Gebreegziabher, van Kooten and.van Soest)
2005–17 –The Optimal Length of an Agricultural Carbon Contract (Gulati and Vercammen)
2006–01 –Economic Impacts of Yellow Starthistle on California (Eagle, Eiswerth, Johnson, Schoenig and van Kooten)
2006–02 -The Economics of Wind Power with Energy Storage (Benitez, Dragulescu and van Kooten)
2006–03 –A Dynamic Bioeconomic Model of Ivory Trade: Details and Extended Results (van Kooten)
2006–04 –The Potential for Wind Energy Meeting Electricity Needs on Vancouver Island (Prescott, van Kooten and Zhu)
2006–05 –Network Constrained Wind Integration: An Optimal Cost Approach (Maddaloni, Rowe and van Kooten)
2006–06 –Deforestation (Folmer and van Kooten)
2007–01 –Linking Forests and Economic Well-being: A Four-Quadrant Approach (Wang, DesRoches, Sun, Stennes, Wilson and van Kooten)
2007–02 –Economics of Forest Ecosystem Forest Sinks: A Review (van Kooten and Sohngen)
2007–03 –Costs of Creating Carbon Offset Credits via Forestry Activities: A Meta-Regression Analysis (van Kooten, Laaksonen-Craig and Wang)
2007–04 –The Economics of Wind Power: Destabilizing an Electricity Grid with Renewable Power (Prescott and van Kooten)
2007–05 –Wind Integration into Various Generation Mixtures (Maddaloni, Rowe and van Kooten)
2007–06 –Farmland Conservation in The Netherlands and British Columbia, Canada: A Comparative Analysis Using GIS-based Hedonic Pricing Models (Cotteleer, Stobbe and van Kooten)

2007–07 –Bayesian Model Averaging in the Context of Spatial Hedonic Pricing: An Application to Farmland Values (Cotteleer, Stobbe and van Kooten)
2007–08 –Challenges for Less Developed Countries: Agricultural Policies in the EU and the US (Schure, van Kooten and Wang)
2008–01 –Hobby Farms and Protection of Farmland in British Columbia (Stobbe, Eagle and van Kooten)
2008-01A-Hobby Farm's and British Columbia's Agricultural Land Reserve (Stobbe, Eagle, Cotteleer and van Kooten)
2008–02 –An Economic Analysis of Mountain Pine Beetle Impacts in a Global Context (Abbott, Stennes and van Kooten)
2008–03 –Regional Log Market Integration in New Zealand (Niquidet and Manley)
2008–04 –Biological Carbon Sequestration and Carbon Trading Re-Visited (van Kooten)
2008–05 –On Optimal British Columbia Log Export Policy: An Application of Trade theory (Abbott)
2008–06 –Expert Opinion versus Transaction Evidence: Using the Reilly Index to Measure Open Space premiums in the Urban-Rural Fringe (Cotteleer, Stobbe and van Kooten)
2008–07 –Forest-mill Integration: a Transaction Costs Perspective (Niquidet and O'Kelly)
2008–08 –The Economics of Endangered Species Poaching (Abbott)
2008–09 –The Ghost of Extinction: Preservation Values and Minimum Viable Population in Wildlife Models (van Kooten and Eiswerth)
2008–10 –Corruption, Development and the Curse of Natural Resources (Pendergast, Clarke and van Kooten)
2008–11 –Bio-energy from Mountain Pine Beetle Timber and Forest Residuals: The Economics Story (Niquidet, Stennes and van Kooten)
2008-12 –Biological Carbon Sinks: Transaction Costs and Governance (van Kooten)
2008-13 –Wind Power Development: Opportunities and Challenges (van Kooten and Timilsina)
2009-01 –Can Domestication of Wildlife Lead to Conservation? The Economics of Tiger Farming in China (Abbott and van Kooten)
2009-02 – Implications of Expanding Bioenergy Production from Wood in British Columbia: An Application of a Regional Wood Fibre Allocation Model (Stennes, Niquidet and van Kooten)
2009-03 – Linking Matlab and GAMS: A Supplement (Wong)
2009-04 – Wind Power: The Economic Impact of Intermittency (van Kooten)
2009-05 – Economic Aspects of Wind Power Generation in Developing Countries (van Kooten and Wong)
2009-06 – Niche and Direct Marketing in the Rural-Urban Fringe: A Study of the Agricultural Economy in the Shadow of a Large City (Stobbe, Eagle and van Kooten)
2009-07 – The Economics and Policy of Global Warming (van Kooten, Beisner and Geddes)
2010-01 – The Resource Curse: A State and Provincial Analysis (Olayele)
2010-02 – Elephants and the Ivory Trade Ban: Summary of Research Results (van Kooten)
2010-03 – Managing Water Shortages in the Western Electricity Grids **(**Scorah, Sopinka and van Kooten)
2010-04 - Bioeconomic modeling of wetlands and waterfowl in Western Canada: Accounting for amenity values (van Kooten, Withey and Wong)
2010-05 – Waterfowl Harvest Benefits in Northern Aboriginal Communities and Potential Climate Change Impacts (Krcmar**,** van Kooten and Chan-McLeod)
2011-01 – The Impact of Agriculture on Waterfowl Abundance: Evidence from Panel Data (Wong**,** van Kooten and Clarke)

2011-02 – Economic Analysis of Feed-in Tariffs for Generating Electricity from Renewable Energy Sources (van Kooten)
2011-03 – Climate Change Impacts on Waterfowl Habitat in Western Canada (van Kooten, Withey and Wong)
2011-04 – The Effect of Climate Change on Land Use and Wetlands Conservation in Western Canada: An Application of Positive Mathematical Programming (Withey and van Kooten)
2011-05 – Biotechnology in Agriculture and Forestry: Economic Perspectives (van Kooten)
2011-06 – The Effect of Climate Change on Wetlands and Waterfowl in Western Canada: Incorporating Cropping Decisions into a Bioeconomic Model (Withey and van Kooten)
2011-07 – What Makes Mountain Pine Beetle a Tricky Pest? Difficult Decisions when Facing Beetle Attack in a Mixed Species Forest (Bogle and van Kooten)
2012-01 – Natural Gas, Wind and Nuclear Options for Generating Electricity in a Carbon Constrained World (van Kooten)
2012-02 – Climate Impacts on Chinese Corn Yields: A Fractional Polynomial Regression Model (Sun and van Kooten)
2012-03 – Estimation of Forest Fire-fighting Budgets Using Climate Indexes (Xu and van Kooten)
2012-04 – Economics of Forest Carbon Sequestration (van Kooten, Johnston and Xu)
2012-05 – Forestry and the New Institutional Economics (Wang, Bogle and van Kooten)
2012-06 – Rent Seeking and the Smoke and Mirrors Game in the Creation of Forest Sector Carbon Credits: An Example from British Columbia (van Kooten, Bogle and de Vries)
2012-07 – Can British Columbia Achieve Electricity Self-Sufficiency and Meet its Renewable Portfolio Standard? (Sopinka, van Kooten and Wong)
2013-01 – Climate Change, Climate Science and Economics. Prospects for an Alternative Energy Future: Preface and Abstracts (van Kooten)
2013-02 – Weather Derivatives and Crop Insurance in China (Sun, Guo and van Kooten)
2013-03 – Prospects for Exporting Liquefied Natural Gas from British Columbia: An Application of Monte Carlo Cost-Benefit Analysis (Zahynacz)
2013-04 – Modeling Forest Trade in Logs and Lumber: Qualitative and Quantitative Analysis (van Kooten)
2013-05 – Living with Wildfire: The Impact of Historic Fires on Property Values in Kelowna, BC (Xu and van Kooten)
2013-06 – Count Models and Wildfire in British Columbia (Xu and van Kooten)
2014-01 – Is Free Trade the End All Be All? The Case of Log Exports (van Kooten)
2014-02 – Bioeconomics of a Marine Disease (Conrad and Rondeau)
2014-03 – Financial Weather Options for Crop Productions (Sun and van Kooten)
2014-04 – Modelling Bi-lateral Forest Product Trade Flows: Experiencing Vertical and Horizontal Chain Optimization (Johnston and van Kooten)
2014-05 – Applied Welfare Analysis in Resource Economics and Policy (van Kooten)
2014-06 – Carbon Neutrality of Hardwood and Softwood Biomass: Issues of Temporal Preference (Johnston and van Kooten)

For copies of this or other REPA working papers contact:

REPA Research Group
Department of Economics
University of Victoria PO Box 1700 STN CSC Victoria, BC V8W 2Y2 CANADA
Ph: 250.472.4415
Fax: 250.721.6214
http://web.uvic.ca/~repa/

Carbon Neutrality of Hardwood and Softwood Biomass: Issues of Temporal Preference

Craig M.T. Johnston[a,b]

G. Cornelis van Kooten[a]

Affiliations:

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

[b] Corresponding author. Tel.: +1 250 472 4421.
E-mail address: craig@uvic.ca (C.M.T. Johnston).

Abstract:

The carbon flux from burning biomass for energy is often legislated, or simply assumed, to be carbon neutral as subsequent forest growth sequesters carbon lost during energy production. In this sense, there may be no net contributions to atmospheric carbon flux associated with biomass energy. However, trees may take decades to recover the CO_2 released by burning, so assumed neutrality hinges on the fact that we count CO_2 removals equally independent of when they occur. If dealing with climate change is an urgent matter, we may give higher weight to current CO_2 emissions over those that occur in the decades to come. If there is no urgency in dealing with climate change, then all types of biomass will eventually return to carbon neutrality. Yet, if climate change is deemed an urgent matter, biomass never returns to carbon neutrality as we give future CO_2 removals less weight. If urgency is high enough, biomass may be more emissions intensive than coal, as the discounted future removals are not enough to offset the relatively higher emissions intensity experience by burning biomass for energy. The race to adopt aggressive renewable energy targets implies climate change mitigation is an urgent matter. Yet, the increasing reliance on biomass for energy production suggests there is no time preference. In the end, the potential benefits of substituting biomass for coal to produce energy might be greatly exaggerated.

Keywords: Bioenergy, Climate Change, Forestry

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. Carbon flux from burning biomass is often legislated or simply assumed to be carbon neutral as subsequent growth sequesters carbon from the atmosphere (IPCC, 2006). 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, and that such removals offset emissions. 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 United Nations Framework Convention on Climate Change (UNFCC), atmospheric greenhouse gas concentrations must be stabilized in a timely manner to prevent dangerous anthropogenic interference with the climate system. Further, the latest IPCC report indicates that the observed impacts of climate change are already "widespread and consequential" (IPCC, 2014). 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 (IEA, 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. While wind turbines and solar panels are the face of such efforts, Europe expects one-half or more of its renewable energy target to come from biomass (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/or tradable renewable energy certificates (RES-LEGAL, 2014). As indicated in Figure 1, these measures are expected to increase European consumption of wood pellets to an estimated 38 Mt per year, requiring significant imports of pellets from outside the EU.

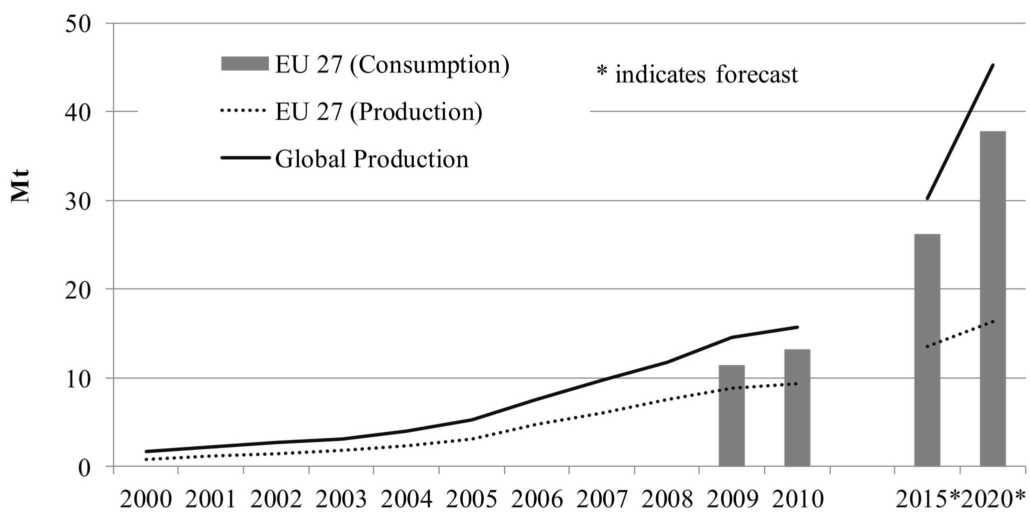


Figure 1: Production and consumption of wood pellets in the EU-27 (Mt), 2000-2010 and forecasts for 2015 and 2020
Source: Lamers et al., 2012; Pöyry, 2011

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 on 'carbon neutral' 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 recent 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 a definite dead end. The CCS process increases the energy required to produce electricity by some 28% (EIA, 2013). Here again co-firing biomass with coal is viewed as an alternative compliance strategy to achieve emission intensity in coal plants of 500 kg CO_2 MWh^{-1} (Edenhofer et al., 2011).

As biomass energy continues to be a significant strategy for transitioning away from fossil fuels, the question becomes: To what extent should we value future atmospheric carbon removals? In particular, as climate change mitigation has become a timely matter, what contribution does future carbon uptake in forests ecosystems make to the mitigation of climate change? The purpose of this study is to 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.

METHODS AND DATA

In Figure 2, we illustrate how biomass is assumed to be carbon neutral, and in particular, how it may be used to reduce CO_2 emissions from fossil fuel burning. CO_2 flux is depicted on the vertical axis and time on the horizontal. The CO_2 emitted by burning fossil fuels to generate, say, one MWh of electricity results in a one-time increase in atmospheric CO_2 denoted by a negative value and, assuming no decay of atmospheric CO_2, illustrated by the horizontal dotted line. Assume that biomass is instead burned to generate that one MWh of electricity at time $t = 0$; this results in more CO_2 emissions than would occur with the burning of fossil fuels – a significant point discussed in more detail below. Unlike fossil fuels, however, newly planted trees then begin to remove CO_2 from the atmosphere. At time $t = M$, the cumulative carbon flux from the biomass source will equal that from the fossil fuel source, and eventually should exceed it for $t>M$; by substituting biomass for fossil fuels, less CO_2 is emitted into the atmosphere because growing trees removes CO_2 from the atmosphere and stores it as carbon in biomass. At some future time, say $t = N$, tree growth removes as much CO_2 from the atmosphere as was added by burning the biomass at time $t = 0$. Carbon neutrality is thus based on the assumption that CO_2 released by burning wood is subsequently removed from the atmosphere by growing biomass.

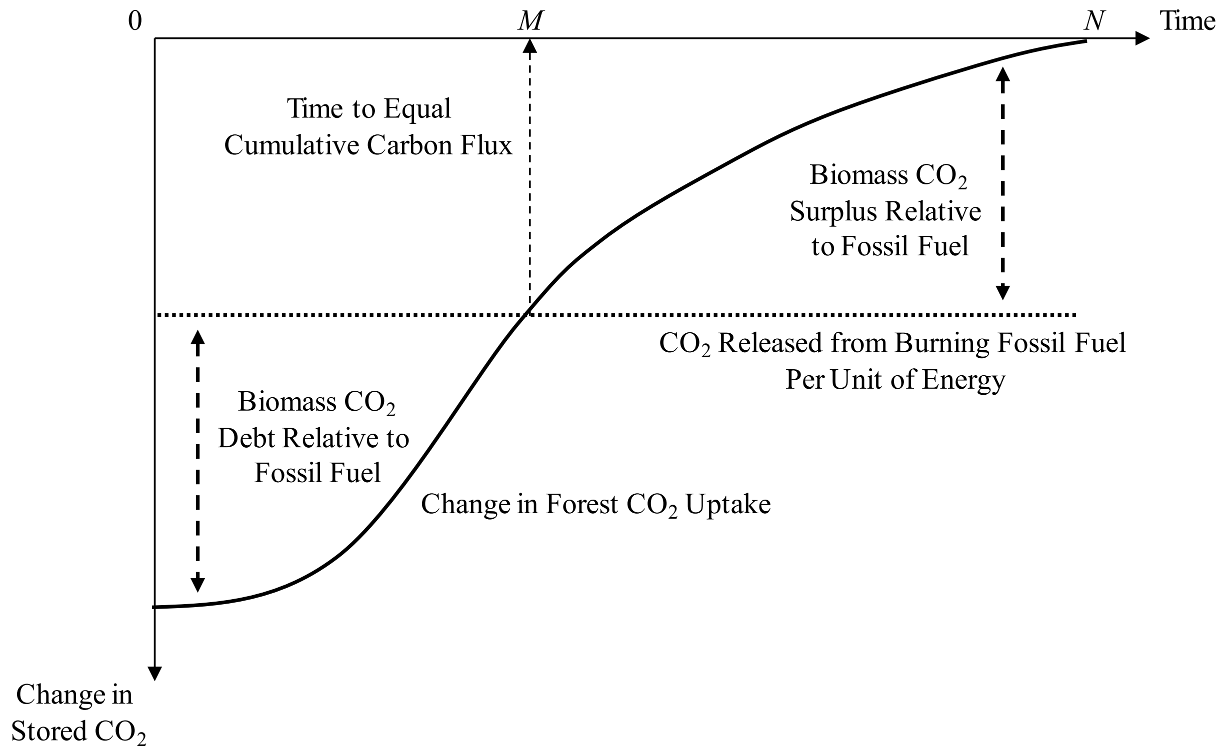


Figure 1: Carbon flux associated with fossil fuel and biomass energy production over time

The carbon neutrality of biomass holds just as well for coal – only the time taken to remove the original release of CO_2 differs. Therefore, it is important to weight (discount) CO_2 uptake and release according to when it occurs. If global warming is not considered a problem, we 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 considered the serious threat envisioned by the IPCC and the NCA, 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 3 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 Figure 3, forest CO_2 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 carbon from the atmosphere is too small to offset the additional increase in CO_2 emissions when biomass substitutes for fossil fuels in power production.

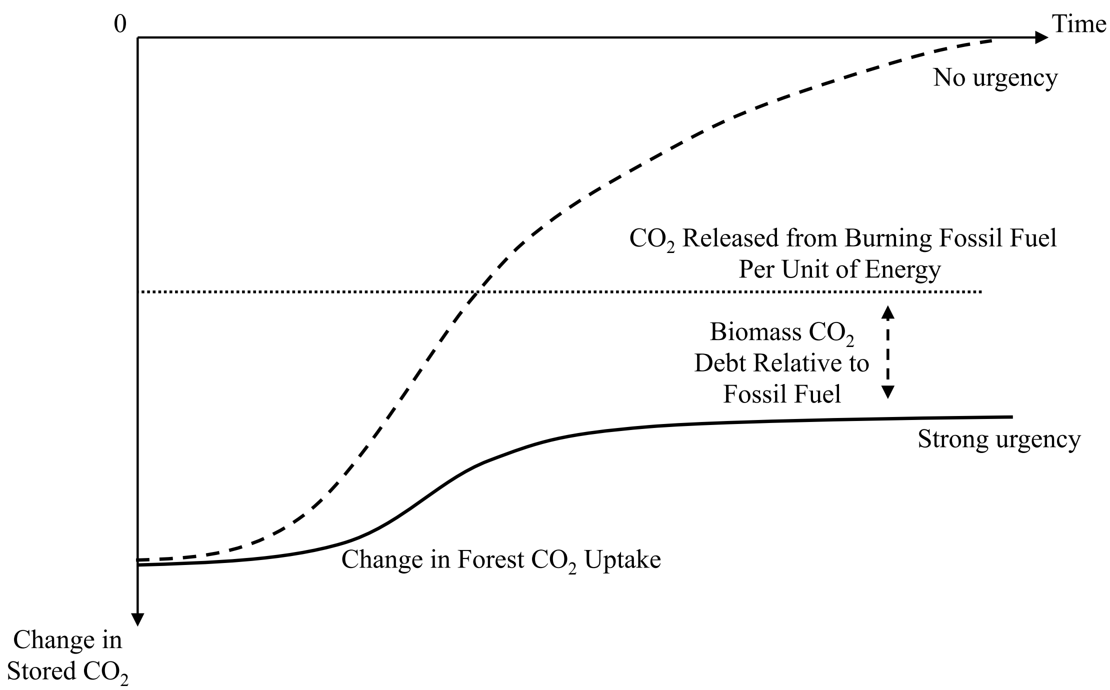


Figure 2: Carbon flux associated with fossil fuel and biomass energy production over time: greater urgency to address climate change

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 tree species or other type of crop (e.g., straw, hemp). Carbon dioxide released from burning coal and wood varies greatly by the quality of coal and type of biomass. In terms of energy efficiency, burning coal to generate electricity dominates burning of biomass, whether the biomass originates from hardwoods or softwoods. From Table 1, an average 0.518 tonnes (t) of coal are required to produce 1.0 MWh of electricity (assuming a heat rate of 10,498 and specified heat contents for various coal types as indicated). For the most commonly used bituminous coal, only 0.397 t of coal are required per MWh. Although wood species vary by density, all have a heat content of around 16.00 MMBtu t^{-1}. As a result, approximately 0.658 t of biomass are required to produce 1.0 MWh of electricity – nearly two times the amount required for bituminous coal. This can be translated into emissions intensities as indicated in Table 1. Thus, the average emissions intensity over all coal types is 1.015 tCO_2 MWh^{-1}, compared to 1.170 tCO_2 MWh^{-1} for hardwoods and 1.242 tCO_2 MWh^{-1} for softwoods. However, 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.

Accounting for carbon flux associated with bioenergy is further exacerbated by the fact that CO_2 emissions and uptake vary greatly by tree and plant species. To illustrate this point, consider the CO_2 intensities of lodgepole pine (*pinus contorta*) and white spruce (*picea engelmannii*) reported in Table 1. Both species emit approximately 1.24 tCO_2 MWh^{-1}, but they vary greatly in terms of their growth and stand dynamics, which affects the time profile of carbon sequestration. Thus, if CO_2 fluxes are weighted as to when they occur, this will impact the decision as to whether to employ biomass as a substitute for fossil fuels. To highlight the significance of the carbon neutrality assumption, we illustrate how stand characteristics and growth functions affect estimates of CO_2 flux over time, and then how these are impacted by the perceived urgency to mitigate climate change. We find that one species may be preferred over another on the basis of its growth.

Table 1: Energy Content and Emission Parameters for Select Coal and Biomass Fuel Types

Input *Type*	Heat Content[a] (MMBtu/tonne)	C Content (%)	Density[b] (kg/m^3)	Fuel used[c] (t/MWh)	CO_2 Intensity[d] (t/MWh)	Fibre Required[e] (m^3/MWh)
Coal						
Anthracite	30.14	92.0%		0.349	1.177	
Bituminous	26.48	64.5%		0.397	0.940	
Lignite	13.25	34.0%		0.794	0.990	
Subbituminous	19.83	49.0%		0.531	0.953	
Average	22.43	59.9%		0.518	1.015	
Biomass						
Hardwood						
Hickory	15.99	48.5%	817	0.658	1.170	0.805
East. Hophombeam	15.99	48.5%	806	0.658	1.170	0.817
Apple	16.15	48.5%	782	0.652	1.159	0.834
White Oak	16.00	48.5%	758	0.658	1.169	0.868
Sugar Maple	15.96	48.5%	710	0.659	1.173	0.929
Red Oak	15.96	48.5%	710	0.659	1.173	0.929
Beech	15.96	48.5%	710	0.659	1.173	0.929
Yellow Birch	15.98	48.5%	697	0.658	1.171	0.945
White Ash	15.98	48.5%	697	0.658	1.171	0.945
Hackberry	16.00	48.5%	613	0.658	1.169	1.072
Tamarack	16.00	48.5%	613	0.658	1.169	1.072
Paper Birch	15.95	48.5%	600	0.660	1.173	1.099
Cherry	16.01	48.5%	589	0.657	1.169	1.116
Elm	15.96	48.5%	576	0.659	1.172	1.144
Black Ash	15.95	48.5%	565	0.660	1.173	1.168
Red Maple	15.98	48.5%	552	0.659	1.171	1.193
Boselder	15.99	48.5%	528	0.658	1.170	1.246
Average Hardwood	16.01	48.5%	666	0.658	1.170	1.006
Softwood						
Jack Pine	16.01	51.5%	504	0.657	1.241	1.304
Norway Pine	16.01	51.5%	504	0.657	1.241	1.304
Hemlock	16.01	51.5%	469	0.657	1.241	1.402
White Spruce	16.01	51.5%	466	0.657	1.241	1.412
Lodgepole Pine	15.96	51.5%	438	0.659	1.245	1.505
Aspen	16.04	51.5%	433	0.656	1.239	1.514
White Pine	15.98	51.5%	422	0.659	1.244	1.560
Balsam Fir	15.98	51.5%	422	0.659	1.244	1.560
Cottonwood	16.00	51.5%	398	0.658	1.242	1.652
Basswood	16.00	51.5%	398	0.658	1.242	1.652
Average Softwood	16.00	51.5%	445	0.658	1.242	1.486

Sources: EIA (2013), IEA (2013), IPCC(2006)

Notes: Carbon dioxide emissions are calculated from the carbon content of each fuel input using a factor of (44/12). That is the atomic weights of carbon dioxide over carbon.

[a] Based on 20% moisture content (M.C.) of biomass

[b] Air dry (20% M.C.)

[c] Calculated as (Heat Rate/Heat Content*1,000,000)*2,204.62. A heat rate of 10,498 btu/kWh is assumed (EIA, 2013)

[d] Calculated as (Fuel Used*C Content)*(44/12)

[e] Calculated as (Fuel Used/Density)*1,000

The data used in this study are for a one-hectare (ha) plot, with stand characteristics consistent with those found in the Prince George forest region of British Columbia, Canada. A summary of stand characteristics for two tree species (lodgepole pine and white spruce) considered in this application is provided in Table 2. The BC Ministry of Forests, Lands and Natural Resource Operations' (BC Ministry of Forests and Range, 2010) Tipsy version 4.1 software is employed to project the tree basal area (TBA) of the two timber species. TBA is the cross-sectional area at breast height (BH = 1.3m above ground) used to estimate tree volumes and stand composition. Model input data for each yield table consist of the species composition, regeneration delay, site index, operational adjustment factors (to account for gaps, endemic losses, waste, etc.) and initial density.

Table 2: Summary statistics of landscape and species

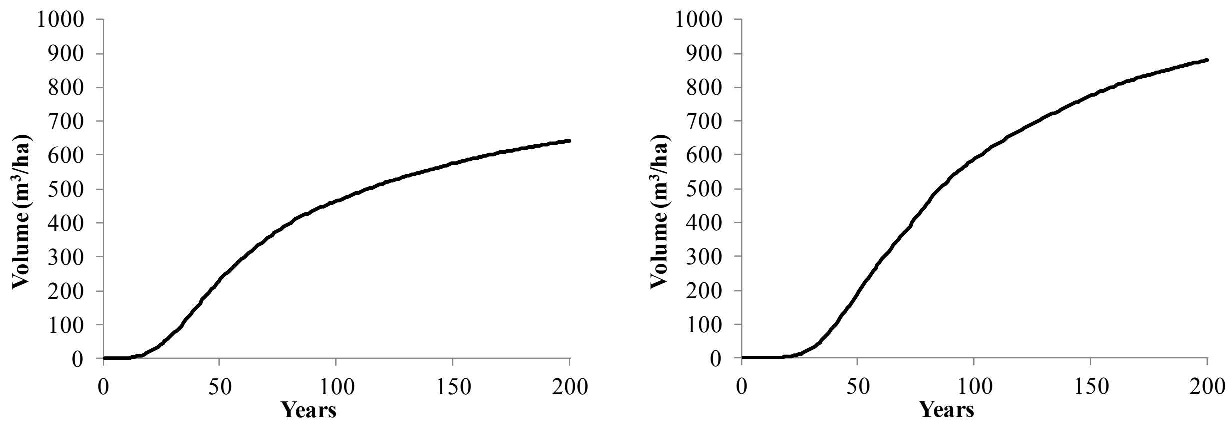
	Lodgepole pine	White spruce
Scientific Name	*pinus contorta*	*picea engelmannii*
Forest Region	Prince George	Prince George
Forest District	Dawson Creek	Dawson Creek
Biogeoclimatic Zone	BWBS	BWBS
Average Slope	10%	10%
Site Index	20	19.6
Stock Height (cm)	13	21
Initial Density	1,600	1,600
Curve	*Thrower (1994)*	*Goudie (1984)*
a	7.6298	9.7494
b	1.3563	1.4660
c	0.8940	1.2870

With the information from Table 2, Tipsy uses the following height-age (site index) curves for lodgepole pine and white spruce, respectively, to estimate growth:

$$H = 1.3 + (SI - 1.3)\frac{\left(1 + e^{\left(a - b\ln(50 - 0.5) - c\ln(SI - 1.3)\right)}\right)}{\left(1 + e^{\left(a - b\ln(A - 0.5) - c\ln(SI - 1.3)\right)}\right)}, \tag{1}$$

$$H = 1.3 + (SI - 1.3)\frac{1 + e^{\left(a - b\ln 50 - c\ln(SI - 1.3)\right)}}{1 + e^{\left(a - b\ln A - c\ln(SI - 1.3)\right)}}, \tag{2}$$

where *H* is the average dominant height (m), *SI* is the site index (average BH at age 50 years), and A is the breast-height age (years). The projected volume (m^3 ha^{-1}) of lodgepole pine and white spruce in the Dawson Creek forest district of Prince George with an initial density of 1,600 trees ha^{-1} is provided in Figure 4.



(a) lodgepole pine (*pinus contorta*) (b) white spruce (*picea engelmannii*)

Figure 3: Projected volume (m^3 ha^{-1}) in Dawson Creek forest of Prince George district with average slope of 10% & initial density of 1,600 trees ha^{-1}

To estimate the amount of CO_2 removed from the atmosphere, the projected volume was adjusted using the following calculation:

$$CO2_t = \frac{V_t \times D \times \rho \times \frac{44}{12}}{1000}, \tag{3}$$

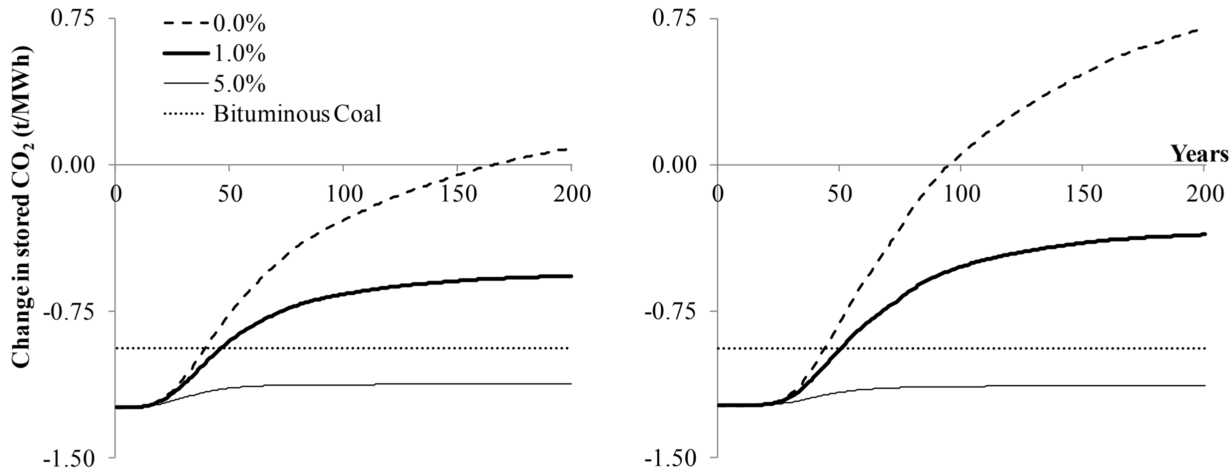
where $CO2_t$ is the amount of CO_2 sequestered at time t (tCO_2 ha^{-1}), V_t is the volume at time t (m^3/ha) of the tree variety, D is the density of the tree variety (kg m^{-3}), ρ is the proportion of carbon by tree species, adjusted by the relative atomic weight of carbon dioxide over carbon, and divided by 1000 to convert kg to tonnes. The total discounted CO_2 (*TDC*) removed from the atmosphere for these two tree species is calculated as a function of each annual increment of CO_2 sequestered, discounted as to when it occurs. Thus,

$$TDC = \sum_{t=1}^{T} \left(\frac{(CO2_t - CO2_{t-1})}{(1+r)^t} \right), \tag{4}$$

where r is a weight (discount rate) on CO_2 uptake and release according to when it occurs. A higher value of r implies there is greater urgency to address climate change, although this implies that future removals of CO_2 from the atmosphere are weighted less.

RESULTS

To calculate the change in stored CO_2 over time, the discounted amount of CO_2 removed from the atmosphere is added to the initial release of CO_2 from burning biomass, which is a negative flux, and then converted to a per MWh basis (see Table 1). The calculations are provided in Figure 5 for lodgepole pine and white spruce across a selected range of discount rates. The release of CO_2 during energy production is assumed to occur at time $t = 0$, releasing 1.24 tCO_2 MWh^{-1} for lodgepole pine and white spruce, but only 0.94 tCO_2 MWh^{-1} for bituminous coal. The change in CO_2 storage associated with burning biomass for energy production is nonlinear, as the initial emissions are offset by subsequent sequestration as trees grow, but discounted as to when this occurs. Again, the CO_2 cumulative flux associated with burning bituminous coal is indicated with a flat line as any subsequent carbon uptake or natural decay of CO_2 in the atmosphere is assumed to be negligible.



(a) lodgepole pine (*pinus contorta*)   (b) white spruce (*picea engelmannii*)

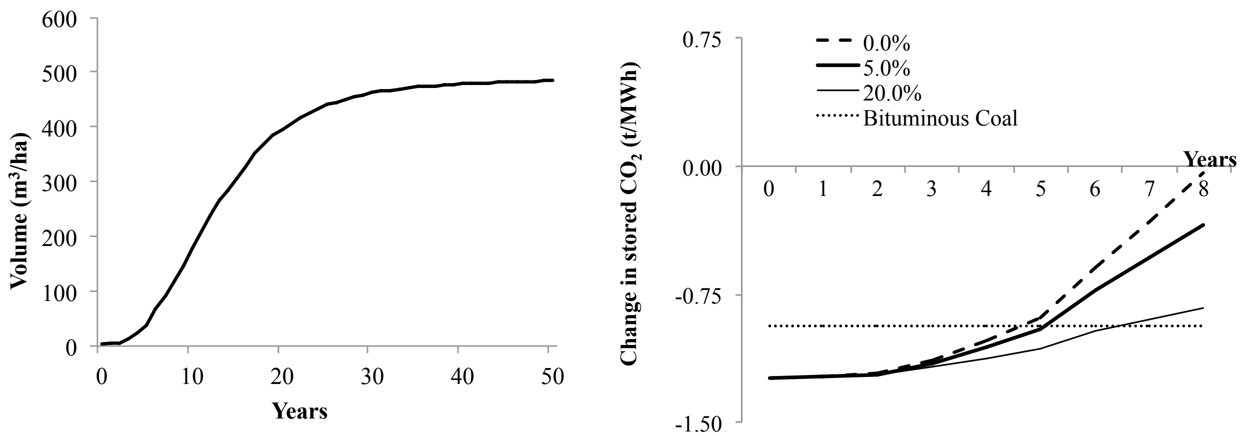
Figure 1: Projected cumulative carbon flux (tCO_2) associated with fossil fuel and biomass energy production for select climate change urgencies for two tree species

As evident from Figure 5, carbon neutrality occurs at different times in the future for the two species, but only for a 0% discount rate – that is, only if there is no urgency to address global warming. For lodgepole pine, it takes 166 years for the CO_2 released at the time of burning to be removed from the atmosphere by subsequent tree growth; in contrast, it takes only 95 years for emissions released when generating electricity from white spruce to become carbon neutral. The reason for this discrepancy is that white spruce grows faster and has a higher density than lodgepole pine. When there is greater urgency to prevent global warming so that current removals of CO_2 from the atmosphere are weighted more than future removals (which is equivalent to using higher rates to discount physical carbon), the date at which current CO_2 emissions are neutralized occurs much further in the future, if at all. Indeed, if climate change is deemed to be a quite urgent matter, biomass burning is never carbon neutral, regardless of the tree species used to offset emissions. In this application, a discount factor of 5 percent is assumed to represent urgency with respect to mitigating global warming, in which case subsequent sequestration of carbon by pine or spruce is insufficient to ever offset the initial carbon deficit associated with substituting biomass for coal. That is, changes the energy source for generating electricity from coal to biomass leads to an increase in atmospheric CO_2 as opposed to a reduction as desired by renewable energy policies.

While many native species, such as lodgepole pine and white spruce, take decades to recover the CO_2 that is released by burning, there is a trend to use fast-growing species with short-rotations for bioenergy. In North America, many regions rely on hybrid poplar (*Populus spp.*) plantations to meet the growing demand for renewable energy sources, particularly in the Southeastern United States. Here, hybrid poplar is primarily derived from four species: black cottonwood (*Populus trichocarpa Torr. & Gray*), eastern cottonwood (*Populus deltoides Bartr. Ex Marsh*.), Japanese poplar (*Populus maximowiczii A. Henry*) and European black poplar (*Populus nigra L.*) (Stanton et al., 2002). How does the urgency to mitigate climate change affect the CO_2 flux associated with the use of biomass energy from hybrid poplar plantations? Yields of hybrid poplar vary substantially (Laureysons et al., 2004), particularly in the US South East (Devine et al., 2010). Maximum biomass productivity varies with harvest cycles anywhere between three to eleven years (Sartori and Lal, 2006). As well, hybrid poplar yield is sensitive to variations in climate and soil characteristics (Traux et al., 2012).

Certain assumptions must be made to simulate the carbon flux associated with biomass energy production from hybrid poplar. First, an eight-year rotation is assumed for hybrid poplar grown specifically for bioenergy (Traux et al., 2012). Second, since hybrid poplar is derived from various species, with cottonwood among the most common, it is assumed that 1.65 m^3 of hybrid poplar is required to produce 1 MWh of energy (see Table 1 for consistent). With an assumed heat content of 16.0 MMBtu $tonne^{-1}$, density of 398 kg/m^3, and carbon content of

51.5%, the resulting emissions intensity of hybrid poplar is assumed to be 1.24 $tCO_2\ MWh^{-1}$. Finally, although the estimated growth function will inevitably vary by the composition of hybrid poplar, it is assumed that growth follows a height-age (site index) curve consistent with equation (2), with site index of 50.1 m (average BH at age 50 years), $a = 8.926$, $b = 1.876$, and $c = 1.635$. The resulting estimated volume ($m^3\ ha^{-1}$) of a hybrid plantation with similar site characteristics as outlined in Table 2 is provided in Figure 6(a).



(a) volume (m^3/ha) (b) change in stored CO_2 ($t\ MWh^{-1}$)

Figure 2: Projected cumulative carbon flux associated with fossil fuel and biomass energy production for select climate change urgencies for two tree species

The discounted carbon flux from hybrid poplar is calculated consistent with equations (3) and (4), and is depicted in Figure 6(b). The release of CO_2 during energy production is assumed to again occur at time $t = 0$, releasing 1.24 $tCO_2\ MWh^{-1}$ for hybrid poplar and only 0.94 $tCO_2\ MWh^{-1}$ for bituminous coal. Thus, using hybrid poplar for energy purposes similarly relies on the fact that we count the future uptake of carbon as the plantation re-grows. Using a 0.0% discount rate (no climate change urgency), the burning and subsequent regrowth of the hybrid poplar plantation is carbon neutral over the eight-year cycle, resulting in an effective emissions intensity of 0.0 $tCO_2\ MWh^{-1}$. However, if there is some urgency to deal with global warming the plantation fails to re-capture all the released CO_2 associated with energy production. For a rate of 5.0%, the effective emissions intensity is 0.35 tCO_2 MWh^{-1}, rather than 0.0 tCO_2 MWh^{-1} for a carbon neutral input. If there is a great deal of urgency in addressing climate change, as might be represented by a 20.0% weight, the effective emissions intensity is 0.83 tCO_2 MWh^{-1}, only slightly lower than 0.94 tCO_2 MWh^{-1} for bituminous coal. Thus, if global warming is deemed an urgent matter, coal may be preferred as an energy source over biomass from hybrid popular plantations, especially if one were to take into account other factors, such as greenhouse gas emissions from the fertilizers used in plantations of fast-growing tree species.

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.

Neglected in this research 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 an increasing number today. Misguided policies to increase reliance on wood biomass for energy yield little if anything in the way of reduced CO_2 emissions. Surely there must be more sensible alternatives for addressing climate change.

ACKNOWLEDGEMENTS

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

REFERENCES

BC Ministry of Forests and Range, 2010. Growth and Yield Modelling: Tipsy. Research Branch, Victoria, BC.

Crutzen P. J., A. R. Mosier, K. A. Smith, W. Winiwarter, 2008. N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics 8, 389-395.

Devine W.D., C.A. Harrington, D.S. DeBell, 2010. Intra-annual growth and mortality of four Populus clones in pure and mixed plantings. New For 39:287–299

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

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

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).

IEA Bioenergy Task 32, 2009. International Energy Agency: Technical Status of Biomass Co-Firing. Arnhem, 11 August 2009. Edited by M.F.G. Cremers.

IEA-ETSAP and IRENA, 2013. Biomass Co-firing: Technology Brief.22. Crutzen P. J., A. R. Mosier, K. A. Smith, W. Winiwarter, 2008. N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics 8, 389-395.

Ince P. J., A. D. Kramp, K. E. Skog, D. Yoo, V. A. Sample, 2011. Modelling future U.SW. forest sector market and trade impacts of expansion in wood energy consumption. J. For. Econ. 17, 142-156.

Ince P. J., A. D. Kramp, K. E. Skog, 2012. Evaluating economic impacts of expanded global wood energy consumption with the USFPM/GFPM model. Can. J. of Agric. Econ. 60, 211-237.

IPCC, 2006. Intergovernmental Panel on Climate Change, Guidelines for National Greenhouse Gas Inventories. Vol. 4. Agriculture, Forestry and Other Land Use. (2006) http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

IPCC, 2014. Intergovernmental Panel on Climate Change, Climate Change 2014: Impacts, Adaptation, and Vulnerability. http://ipcc.ch/report/ar5/wg2/

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

Lamers P., M. Junginger, C. Hamelinck, A. Faaij, 2012. Developments in international solid biofuel trade – an analysis of volumes, policies, and market factors. Renew. & Sus. Energy Rev. 16, 3176-3199.

Laureysons, I., J. Bogaert, R. Blust, and R. Ceulemans, 2004. Biomass production of 17 poplar clones in a short- rotation coppice culture on a waste disposal site and its relation to soil characteristics. Forest Ecology and Management 198(2-3):295-309.

Moiseyev A., B. Solberg, A.M.L. Kallio, 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. J. For. Econ. 17, 197-213.

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., 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, S. Zhu, 2010. Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change. For. Pol. & Econ.12, 48-56.

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

Sartorti, F., and R. Lal. 2006. Potential soil carbon sequestration and CO_2 offset by dedicated energy crops in the USA. Critical Reviews in Plant Science 25:441-472.

Stanton, B., J. Eaton, J. Johnson, D. Rice, B. Schuette, and B. Moser. 2002. Hybrid poplar in the Pacific Northwest: The effects of market-driven management. Journal of Forestry 100:28-33.

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. For. Sci. 56, 366-378.

Traux, B., D. Gagnon, J. Fortier, and F. Lambert, 2012. Yield in 8 year-old hybrid poplar plantations on abandoned farmland along climatic and soil fertility gradients. Forest Ecology and Management. 267, 228-239.