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The Economics of Forest Carbon Sequestration Revisited: A Challenge for Emissions Offset Trading

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The Economics of Forest Carbon Sequestration Revisited: A Challenge for Emissions Offset Trading

by

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Abstract

This paper provides an overview of the role that forestry activities play in mitigating climate change. The emphasis is on a comparison of carbon offset credits and a carbon tax/subsidy scheme for incentivizing reductions in the release of CO_2 emissions and increase in sequestration of atmospheric CO_2 through forestry. In addition to traditional issues related to additionality, leakages, and the transaction costs of determining and verifying how many carbon offsets are created, we investigate the importance of good governance and contracts. There are three options available to a public or private forestland owner for creating carbon offsets once tree reach maturity: (1) avoid or delay harvest; (2) harvest timber and use sawmill, logging and other residuals to generate electricity; and (3) sustainably manage the forest and carbon fluxes (i.e., post-harvest wood product carbon pools and avoided emissions from substituting wood for non-wood in construction or wood bioenergy for fossil fuels) to maximize net revenues. Delaying harvests or avoiding deforestation are considered important but outside the domain of a tax/subsidy or cap-and-trade scheme. With respect to bioenergy, the analysis suggests that, if there is a carbon dividend, it is likely to be small even if the life cycle of carbon is appropriately taken into account. Further, if there is some urgency to mitigate climate change, the use of wood bioenergy is more likely to result in a carbon debt, even with respect to coal, because of the need to weight CO2 according to when it is released to and removed from the atmosphere. Only holistic commercial forest management that is sustainable and incentivizes sequestration of carbon assures efficient mitigation of climate change. We demonstrate this by investigating carbon fluxes derived from an integrated forest management model and confirm this result more generally on the basis of a Faustmann rotation age model that explicitly includes benefits of storing carbon.

Keywords: climate change mitigation and forestry; carbon offsets and taxes; carbon life-cycle analysis; biomass energy; wood products versus cement and steel; discounting; governance and corruption

JEL categories: H23, Q23, Q42, Q54, G15

1. INTRODUCTION

To lend a sense of urgency to the Kyoto process of the United Nations Framework Convention on Climate Change (UNFCCC), G8 countries meeting in L'Aquila, Italy in 2009 agreed to limit the increase in global average temperature to 2°C above pre-industrial levels by reducing global greenhouse gas emissions by 50% and their own emissions by 80% or more by 2050. These are ambitious goals and governments have decided to rely on markets as opposed to regulations to achieve CO_2-emission reduction targets. The preference of most economists is for a tax on carbon, with a mirror-image negative tax (subsidy) to incentivize carbon removal from the atmosphere (van Kooten et al. 1995), but politicians have tended to shy away from taxes preferring emissions trading instead. This is reflected in Kyoto process, but to prevent the costs of compliance with Kyoto targets from rising inexorably, countries opted for a variety of instruments that they could use to meet their self-imposed targets. Terrestrial biological sinks and forestry activities were included as instruments that countries might use to achieve their targets. Thus, the focus in this paper is on the role of terrestrial sinks in mitigating climate change. In particular, the carbon dynamics of forest ecosystems and forestry activities, such as forest regeneration (tree planting), forest conservation and preservation, silviculture (e.g., fertilizing, thinning), harvesting, and post-harvest use of wood fiber, are the main topics of concern. Throughout the discussion, the emphasis is on forest economics and policy as it relates to carbon fluxes.

We begin in the next section by examining carbon offsets more closely and how terrestrial carbon offsets might fit into the overall scheme of carbon offsets. After all, the prices of carbon offsets in the market place are a reflection of the carbon tax that might be employed to achieve a similar degree of climate mitigation, although carbon offset markets and taxes could coexist (van Kooten 2013, pp.306-307). We then turn to the carbon in forest ecosystems, and what to do with forests that reach maturity, whether these had been planted or constitute original forest. We first consider conserving or preserving forests – preventing forest degradation and/or simply not harvesting them. Activities (or non-activities) that Reduce Emissions from Deforestation and forest Degradation (REDD) are not currently considered eligible under Kyoto rules, but they could be included at some future date, as discussed in section 3.

If forests are harvested, it becomes important to determine what happens to the timber and other woody material post-harvest. In section 4, we consider life-cycle aspects of carbon if wood biomass is burned in lieu of fossil fuels, primarily coal, to produce electricity, and an economic analysis of biomass burning. The case of post-harvest carbon sinks, and the emissions avoided to produce steel and/or concrete when wood replaces non-wood materials in construction, is examined in section 5. In these analyses we attempt to determine the validity and economic viability of carbon offsets that might be available from these forestry activities. Then, in section 6, we return to the carbon tax/subsidy to determine how it impacts rotation age. In a sense, the impact on rotation age reflects the earlier discussion, at least from an economics point of view, reinforcing the insights drawn from the preceding sections. We conclude in section 7 with some final observations.

2. CARBON OFFSETS

Greenhouse gas (GHG) emissions trading is the main policy vehicle currently considered by most governments and the international negotiation process for mitigating climate change, although regulations, subsidies for non-fossil fuel energy, and even carbon taxes are employed in various jurisdictions. Emission trading occurs when there is a cap on GHG emissions and emitters that exceed their individual targets can purchase emission reduction permits in the *compliance market* from those who are below their emission target. A carbon offset refers to an emissions reduction or equivalent removal of CO_2 from the atmosphere that is realized outside of the established emissions market, but can be used to counterbalance GHG emissions from the capped entity.

The benefits of using forest-sector carbon offsets are illustrated in Figure 1. Emissions must be abated by an amount 0E in the left panel of the figure, while the marginal costs of abating emissions is indicated by the upward sloping curve. In the right panel, the derived demand for forest carbon offsets is simply given by the difference between the targeted level of abatement, E, and the amount provided by the (mandatory) emissions abatement sector as the shadow price of reducing emissions falls from P^0 towards zero. Then, in the forest sector, the intersection of the derived demand for and marginal costs of carbon offsets determines the amount provided. In this example, C^* offsets are provided at a cost of P*, thereby reducing actual emissions abatement by $EE^* = 0C^*$.

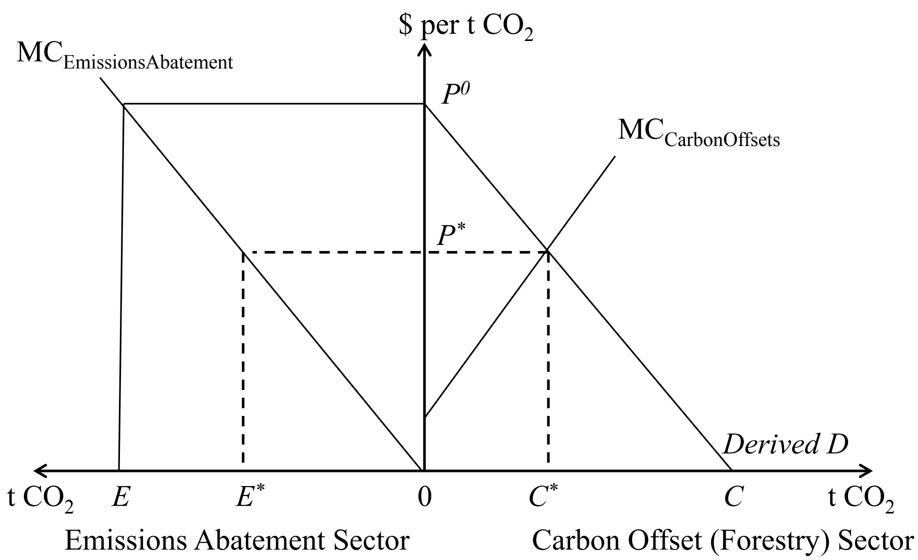

Figure 1: Compliance Markets and Effect of Forest Carbon Offsets

Forest-sector carbon offset credits reduce emitters' costs of complying with emission reduction targets, while buying time to enable them to develop and adopt emission-reducing technologies. On the negative side, however, offsets lower the cost of emitting CO_2, thus reducing incentives to invest in emission-reducing technologies. Further, carbon offsets are fraught with problems related to uncertainty and corruption (Helm 2010; van Kooten and de Vries 2013; van Kooten et al. 2015).

Tree planting and activities that enhance tree growth clearly remove carbon from the atmosphere and store it in living and dead biomass; thus, afforestation and reforestation should be eligible activities that create carbon offsets (IPCC 2000). Afforestation is defined as the establishment of growing trees on land that has not in the recent past been forested and where trees would not otherwise be planted. In similar fashion, reforestation refers to tree planting on a site previously forested, but where it is unlikely that the forest will be re-established. Likewise, silvicultural activities such as fertilization that enhance tree growth or otherwise increase the amount of carbon sequestered in a forest ecosystem would be eligible activities. Further, because deforestation releases significant amounts of CO_2 into the atmosphere (perhaps accounting for as much as one-fifth of emissions attributed to human activities), preservation and conservation of forests – that is, preventing degradation, conversion to other uses or simply delaying harvest – have been considered as eligible but somewhat more controversial means to obtain carbon offset credits.

Since most countries had not embarked on large-scale afforestation and/or reforestation projects prior to Kyoto's first commitment period (2008 to 2012), they would have had a debit on the afforestation-reforestation-deforestation (ARD) account. Consequently, the 2001 Marrakech Accord permitted countries to offset up to 9.0 megatons (Mt) of carbon (or 33 Mt CO_2) each year of Kyoto's first compliance period (2008-2012) through verified forest management activities that enhance carbon uptake. These could only be claimed against any ARD debits. In addition, some countries, most notably Canada (44 Mt CO_2 per year), the Russian Federation (121 Mt) and Japan (48 Mt), could claim carbon credits from business-as-usual forest management that need not be offset against ARD debits.

Permitting afforestation/reforestation activities in lieu of CO_2 emissions reduction led to a number of problems, some of which are related to measurement and monitoring, and thus transaction costs, but others are related to incommensurability and other problems in carbon offset trading. Issues include:

1. Additionality: The only activities that count are those that reduce atmospheric CO_2 above and beyond what would occur in the absence of incentives. If the tree planting activity would have been undertaken in the absence of policy to mitigate climate change, then the carbon benefits (i.e., carbon offset credits) related to the project should not be counted. In practice, there are many instances where trees are planted for a variety of reasons unrelated to climate change, but where those incurring the planting costs promote their project as one that creates carbon offsets. These offsets are then put up for sale, usually in the voluntary market, but, if properly certified by the sponsoring government, can be traded in the mandatory market. In the same way, proponents of forest conservation might lobby for carbon offset credits even though forest conservation might take place in any event for reasons unrelated to climate change mitigation.

2. Leakage: Payments that promote direct changes in land uses for the purpose of carbon sequestration often result in indirect changes in land use elsewhere that release CO_2, something known as a 'leakage'. At the micro-level, a landowner who is paid to plant trees might compensate for the loss in agricultural output by removing trees and planting crops elsewhere on her farm. At a macro-scale, tree planting causes agricultural output to decline, raising prices and leading landowners to expand cultivation onto

marginal lands currently in permanent pasture or forest, thereby releasing CO_2. Forest conservation might lead to greater harvests elsewhere, as was shown to be the case when the U.S. took steps to conserve forests in the Pacific Northwest to protect the endangered northern spotted owl. Leakages of 43% to 85% have been documented, and a failure to account for leakages can underestimate the costs of CO_2-uptake by one-third (van Kooten 2013, p.352).

3. Double dipping: The selling of multiple environmental services, such as carbon offsets and contracts to protect threatened wildlife habitat, in more than one market is known as 'double dipping' (Woodward 2011). It also occurs, for example, when a developed country invests in a tree planting project in China, say, and both countries claim the carbon reduction benefits.

4. Plethora of instruments: The Kyoto Protocol employs a variety of instruments that developed countries (listed in Annex B of the Kyoto agreement) can use to achieve their targets – (i) reduce domestic CO_2 emissions, (ii) purchase allowances from other rich countries (whose emissions are below target), (iii) sequester carbon in domestic biological sinks, (iv) purchase certified emission reductions (CERs) via the Protocol's Clean Development Mechanism (CDM), and (v) create earned reduction units (ERUs = CERs) by investing in emissions reduction projects in economies in transition through Kyoto's Joint Implementation mechanism. Forestry projects that sequester carbon, such as tree planting, are also eligible for CERs. The main problem with all these instruments is the lack of commensurability among projects, something that has been referred to as the **duration** problem (van Kooten 2009a).

5. Transaction costs and governance: Transaction costs refer to measuring, monitoring, verifying, enforcing and negotiating trades, while governance refers to the means by which trades are made. Both are affected by the institutional framework within a country and the nature of agreements among independent jurisdictions. This is discussed in more detail below, but it presumably would include such things as social capital, rule of law (independence of the judiciary) and freedom to engage in trade, which requires a degree of trust and the ability to make credible threats in the event of noncompliance.

These five issues are particularly pertinent for forestry where the greatest difficulty is that of tracking carbon fluxes. This results in particularly troublesome transaction costs and opaqueness regarding the economic value of carbon offsets, potentially leading to corruption.

Governance, Contracting and the Principal-Agent Problem

In contrast to a global carbon tax (assuming such a global tax could be agreed upon and effectively implemented), emission trading and carbon offset credits are fraught with difficulties related to governance. This is particularly true of forest projects, which are associated with high transaction costs, a great deal of uncertainty (viz., natural disturbances), questions regarding additionality, high potential for leakage, and lengthy time horizons that make it difficult to ascertain how much carbon a project actually sequesters (duration). This might explain why so few forestry projects have been certified under Kyoto's Clean Development Mechanism (CDM). As of January 2015, only 55 afforestation / reforestation projects had been certified, representing only 0.7% of total registered CDM projects (which number 7,597). These projects are spread across 23 countries and account for 140 Mt CO_2 offset credits.

The purchase of carbon offsets might be considered as similar to a payment for environmental services (PES), except that the aforementioned issues complicate drawing a direct analogy between the two. One problem that forestry projects have in common with PES systems is the need to create a baseline or counterfactual. For example, van Kooten et al. (2015) demonstrate that, for a private forest estate in southeastern British Columbia purchased by the Nature Conservancy of Canada, the baseline subsequently used to claim 750,000 tonnes of CO_2 offset credits was difficult to justify, even though an official certifier appeared to find nothing wrong. As its counterfactual, the Nature Conservancy assumed the forest estate would be clear cut within 15 years by an aggressive commercial operator. Compared to a commercial operator following accepted sustainable forest management guidelines, however, the authors find that protection of the forest could actually increase CO_2 emissions. Indeed, commercial harvesting following accepted sustainable management guidelines could result in a large carbon dividend relative to forest protection (as discussed further in section 5). This might also be the case in tropical regions if proper account is taken of the post-harvest use of wood and the carbon sequestered by the post deforestation-degradation land use – palm plantations, agricultural production, et cetera.

A further similarity relates to governance. Fukuyama (2014) identifies three sets of institutions as critical to governance: the state, rule of law and procedural accountability. A state that is powerful without accountability is a dictatorship, while a weak state that is kept in check by subordinate political forces is ineffective and at the extreme unstable (p.25). Rule of law is required to protect property rights, enforce contracts and ensure that the most powerful actors in the political system are bound by the same rules as other citizens (pp.23-24). Finally, procedural accountability is required to ensure the quality of outcomes. Despite democratic accountability, some countries lack a strong state and are characterized by pandering to various clientele and corruption; other countries have a strong state but little in the way of rule of law, thereby exhibiting the same characteristics of clientelism and corruption. In yet other countries, the state may be strong but decision makers are not held to account. Few countries score well on all aspects of governance (pp.59-65). Thus, it is little wonder that international institutions are completely inadequate and not up to the task of imposing a carbon tax or establishing regulations to address climate change (Fukuyama 2014, p.36; van Kooten 2004). This is especially true of carbon offsets.

Gong et al. (2010) examine the first CDM forestry project – the Guangxi project in China, which would sequester 0.77 Mt CO_2 over a 30-year crediting period by planting 4,000 ha of degraded land to multiple-use forestry. The project paid landowners \$4.50/tCO_2 upfront for the CERs, so the carbon offsets were credited before the carbon was even sequestered (p.1297). Although the project was considered to be financially attractive (partly due to low transaction costs), the authors found that only 55% of the project's land had subsequently been planted to trees. Some of the land turned out to be ill-suited to trees (too degraded and/or too expensive to reforest), but other areas were not planted because they turned out to have greater value in other uses (e.g., growing oranges) – the opportunity cost turned out to be too high. Equity considerations and other factors also played a role. Yet, it turns out that, in many such situations, parties often violate contracts to create carbon forest offsets well before the contract period is completed.

Contracts relating to the use of forestland are particularly difficult to enforce because of asymmetric information and the principal-agent (PA) problem. When it comes to carbon offsets, there are several layers to the PA problem and it is often difficult to identify the parties to a contract. First, there is the on-the-ground agent who is ultimately responsible for how the land is used. In many developing countries, the agent is the current user of the land, whether a farmer or 'gatherer' (hunter, logger, collector of tree fruits), but not the landowner. He or she may not rent the land, and may not even be aware that there is a contract to use the land to generate environmental services or create carbon offsets. Even if they are aware of or even a party to the contract, they may violate its terms as soon as a better opportunity to earn more revenue from the land presents itself. Of course, this will depend on the effectiveness of rule of law, which is weak in most developing countries (De Soto 2000).

On the other end of the process is the ultimate buyer of the carbon offset credits, who sets them against CO_2 emissions. The buyer might be a rich country government purchasing offsets to comply with its emission reduction target, or a firm buying credits directly from a certifier or in a mandatory compliance market such as the European Trading System (ETS).

Private firms might also purchase emission offsets in the voluntary market through, say, the Voluntary Carbon Standard (VCS). VCS is the main certifier of verified carbon units (VCUs) in voluntary markets, with 73 out of 1763 registered projects, or 4.1%, related to forestry and agriculture; these account for 2.572 Mt of voluntary CO2 credits.[1] Included among the registered projects are afforestation and reforestation projects (including reforestation of degraded forestlands), projects to receive offset credits for re-planting previously denuded land to rubber trees, and ones that reduce or delay harvests and prevent deforestation.

It would be a mistake, however, to think that the ultimate buyer is only concerned with climate change mitigation; it is more likely that the purchaser is content only to satisfy the *de jure* (and not necessarily the *de facto*) goal of complying with emission reduction targets. A private firm might also purchase VCUs as a marketing strategy to enhance the company's image. Finally, individuals might simply purchase VCUs because they are concerned about the impact that their CO_2 emissions have on the environment, perhaps out of concern for others (an altruist motive) or out of guilt, but they are often unaware or may not even care about whether these credits actually have an impact on global warming.

The seller of carbon offsets might be a government agency or a private company that is recognized as a provider of offsets, possibly even a certifier of offsets. There is then an agent who negotiates the contract for producing forest carbon offsets on behalf of the seller (contractor). The agent could be considered the intermediary between the contractor (here the principal) and the agents on the ground. The intermediary agent could be a certifier, a representative of the government, a cooperative acting on behalf of the on-the-ground agents, et cetera, but is also the ultimate guarantor that the contract is carried out. The intermediary agent acts to maximize her welfare by maximizing both the number of carbon offsets that can be 'certified' and their value; this agent also seeks to minimize transaction costs – measuring, reporting and verifying (monitoring) – while paying on-the-ground agents as little as

[1] See http://www.vcsregistry.com/registry-reports/ [accessed April 22, 2015].

possible. That is, the intermediary agent has no incentive to ensure compliance, with the effort expended on activities to do so dependent on the stream of payments, degree of oversight by the contractor, potential penalties (if any) of noncompliance, and the strength of the institutions in the country where the project takes place.

Where the state and rule of law are strong, and the political system is held accountable, as in the countries of northern Europe for example, the intermediary agent would act as a principal attempting to ensure that the on-the-ground agents are incentivized to produce the carbon offsets called for in the contract. Under such conditions and compared to developing countries, on-the-ground agents will have stronger property rights to the land and command higher payment for any certified credits. Even so, there remain opportunities for these agents to cheat and pursue better opportunities if these appear during the contract period, unless there exists social capital (viz., trust) that causes them to honor contracts that are difficult and costly to enforce. Neither does the intermediary certifying party have any incentive to police the agent, because the intermediary party as principal assumes the governance structure is sufficient to do so.

If there is any question regarding the validity of certified emission reductions, this would be addressed in a court of law. Given that the final purchaser of the forest carbon offsets is not concerned about their origin, no party has an incentive to litigate over the validity of any offsets produced by a project. Further, the difficulties in calculating the carbon fluxes associated with forests are so opaque that a court would have difficulty determining whether any contract actually produced the credits indicated (see van Kooten et al. 2009, 2015; Malmsheimer et al. 2011). To militate against these PA problems, governments and/or environmental NGOs certify certifiers to certify carbon offsets for sale in mandatory or voluntary markets. But there is no guarantee that the certifiers are gatekeepers that ensure forestry projects truly reduce concentrations of CO_2 in the atmosphere. Rather, certifiers are concerned about their own wellbeing, which often entails satisfying the client (the 'creator' and seller of carbon offsets) and otherwise behaving in a way that ensures future work as a certifier.

Good governance at the national level tends to be spotty and, as noted, probably not up to the task when it comes to the trading of forest carbon offsets. This is true even for countries in Europe as experience with the ETS has shown. Especially in countries of southern Europe where low-quality government and corruption are a problem (Fukuyama 2014; Beck and Wigle 2014), firms self-declared emission levels well above their actual emissions, thereby making it easy for them to generate emission reduction (carbon offset) credits that they could then sell on the ETS.[2] This resulted in the collapse of the ETS in early 2013 with prices well below €3 per tCO_2 after achieving a high of €32/tCO_2 shortly after its implementation in 2005. Under Phase III (2013-2020) trades have been less than €10/tCO_2 although that might change as the EU increases the emissions reduction target to 40% below base-year (1990)

[2] These offset credits are known as European unit allowances (EUAs), which are similar to global assigned amount units (AAUs) created when the emissions of a country listed in Annex B of the Kyoto Protocol are below its target.

emissions.[3] With corruption an underlying concern, policing and enforcement impose additional costs; as a result, ETS is considering auctioning permits instead of permitting trade.[4]

It is little wonder then that international institutions are completely inadequate and not up to the task of imposing a carbon tax or establishing regulations to address climate change (Fukuyama 2014, p.36). There were no mechanisms in place to oblige countries to meet Kyoto targets – the agreement was self-imposed with countries attempting to meet obligations only as a matter of status, even if this meant 'cooking the books' to meet targets (see also van Kooten 2004). The same appears to be true with respect to a potential follow-up agreement to Kyoto: According to decision 1/COP.20 of the UNFCCC, countries are to announce their Intended Nationally Determined Contributions (INDCs) prior to COP-21 in Paris in late 2015.[5] However, the setting of domestic targets is again entirely voluntary and there is unlikely to be any mechanism that compels adherence to targets.[6]

For the most part economists have addressed the PA problem by focusing on the payment mechanism. To encourage on-the-ground agents or landowners to participate in tree planting projects, for example, an upfront payment is clearly required, often to cover the initial planting cost. Then a second and final payment would be made at the end of the contract period, with this final payment providing the needed incentive to keep agents from violating the contract by converting land to an alternative use. The difficulty here is that the principal does not have sufficient a priori information about the relations between the intermediary and on-the-ground agents, the alternative land uses available, and how the opportunity costs of land might change during the contract period.

Engel et al. (2012), and Arguedas and van Soest (2011), attempt to address these shortcomings by studying contracts that vary payments so as to reduce the risks of land conversion. To protect forestland from being converted to an alternative use (see next section), Engel et al. (2012) propose a scheme that provides a fixed per-ha payment plus annual payments that vary according to an index of agricultural prices. They find that this approach is more efficient than one where variable payments are tied to the price of carbon. Arguedas and van Soest (2011) examine contracts that provide two payments: one payment covers fixed costs while the other covers variable costs. Their objective is to get farmers

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[3] Forward contracts for EUAs delivered December 2015 closed on February 20 at €7.49/tCO_2, while, in the UN-backed CDM market, a similar CER contract closed at €0.39/tCO_2 (http://climateobserver.org/carbon-markets-weekly-16-20-february/ [accessed February 25, 2015]).

[4] For excellent reviews of the economics of emission trading, and discussions of existing global efforts to implement trading schemes and other market incentives, see World Bank (2014) and Wikipedia (2015).

[5] See http://unfccc.int/focus/indc_portal/items/8766.php [accessed April 14, 2015].

[6] To date, Switzerland has agreed to reduce GHG emissions by 50% from 1990 levels by 2030, with the EU and Norway agreeing to reductions of at least 40% by 2030. The U.S. will "make best efforts" to reduce emissions by 26-28% from a 2005 baseline by 2025; Mexico set its INDC target at 22% below 2030 business-as-usual emissions. Russia would reduce emissions by 70-75% from 1990 by 2030, but only 20-30% via emission reductions with the remainder coming from rational forest use, protection, maintenance, and regeneration; however, current emissions are already 35% below 1990 levels. Lastly, Gabon would rely almost entirely on land use change (forestry) to reduce emissions by 50%. See http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx, [accessed April 1, 2015].

(agents) to reveal truthfully whether they face high or low marginal costs of converting land to other uses; that is, they want to get agents to reveal their ability to provide environmental services – to reveal the onsite supply function for environmental services. In that case, the principal can design contracts that are incentive compatible with the principal's objectives. In theory, this then eliminates the PA problem; practice turns out to be quite different.

Since forests are capable of removing CO_2 from the atmosphere and storing it as carbon in living and even dead biomass, forest activities can contribute to climate change mitigation. When a forest reaches maturity, the public or private landowner must decide what to do with the trees. Clearly, if the costs of harvesting trees exceed the commercial benefits, the forest will be left as wilderness. In that case, the forest is not part of the working or managed forest because it is 'located' beyond the extensive margin. This is true of much of the boreal forest in both Canada and Russia, since trees are simply too far from markets; but it is also true of forests in mountainous regions, where it is too costly to harvest trees due to the combination of difficult terrain and distance to markets. In some cases, it is better not to harvest mature forests because deforestation results in the release of more CO_2 than is socially desirable, or unsustainable forest operations degrade the forest to such an extent that more CO_2 is released than is socially optimal. Subsequent regeneration in these cases may be unable to recover the CO_2 released as a result of degradation (e.g., degraded soils result in a lower forest productivity) or deforestation. That is, the contribution to global warming caused by degradation or deforestation is less than the benefits from harvesting the trees plus the mitigation benefits of planting a new forest. Of course, if carbon can subsequently be stored in products or if wood biomass can substitute for the burning of fossil fuels, thereby lowering the overall release of CO_2, then it may yet be beneficial to harvest trees rather than preserve the forest. In an effort to better understand the economic challenges of using forest sector carbon offsets, we discuss these three components of forest management in greater detail in the next three sections. To do so, we examine forest ecosystem fluxes from both a biophysical (carbon life-cycle) and economic perspective, beginning with the issue of forest protection.

3. REDUCED EMISSIONS FROM FOREST PROTECTION: REDD AND REDD+

Forest protection mitigates climate change by preventing CO_2 from entering the atmosphere as a result of forest exploitation, especially tropical deforestation that accounts for perhaps as much as 20% of total emissions of anthropogenic greenhouse gases. Although forest conservation activities are currently not eligible for carbon offsets, concerns about tropical deforestation have resulted in efforts to make activities that Reduce Emissions from Deforestation and forest Degradation (REDD) eligible for certified offset credits. As a result of negotiations at Cancun in December 2010, the narrow role of REDD was expanded to include sustainable management of forests, forest conservation and the enhancement of forest carbon stocks, collectively known as REDD+ (see Kaimowitz 2008; Bosetti and Rose 2011; Buttoud 2012; Law et al. 2012). In this way, it has been possible to link the United Nations' Framework Convention on Climate Change (UNFCCC) and its Convention on Biological Diversity (CBD) – the other agreement signed at the 1992 Earth Summit in Rio de Janeiro. By accepting REDD+ activities as a means to create carbon offsets, the international community would signal its willingness to tradeoff biodiversity against climate change, at least to the extent that it becomes unclear as to whether and to what extent payments are for protecting biodiversity or mitigating climate change. Further, since deforestation and biodiversity are a much greater concern in developing than industrial countries, it also signals a willingness to use mechanisms for addressing climate change to redistribute income from developed countries to poor ones.

Even though REDD+ carbon credits entangle climate change and biodiversity (and perhaps other) objectives, some argue that the benefits for climate change can be significant. Sathaye et al. (2011) indicate that the non-carbon environmental benefits of forest preservation amount to 57.5-76.5 percent of the total protection benefits. Bosetti et al. (2011) report that greater reliance on reduced deforestation and other land-use activities could reduce the net costs of achieving a global target of 550 parts CO_2 per million by volume (ppmv) in the atmosphere by upwards of $2 trillion, an estimate cited by many climate researchers. It originates with Tavoni et al. (2007) who conclude that, by linking forestry management to the carbon market, there is a potential "free saving" of 50 ppmv in 2100, which corresponds to a lowering of the projected global average temperature in 2100 of ¼^{o}C. The saving comes as a result of a significant increase in the supply of carbon offset and thus a decrease in the price of carbon, although Tavoni et al. (2007) do not attribute this saving entirely to forest conservation (as they include other forest activities).

Kindermann et al. (2008) estimate that, by reducing global deforestation by 50%, CO_2 emissions could be reduced by 1.5-2.7 Gt per year at an annual cost of $17.2-28.0 billion. However, "these estimates are based on economic models that do not consider transactions costs and other institutional barriers, which raise costs in practice" (p.10306). Overall, these estimates are derived from a variety of models used by the IPCC in its projections (van Kooten 2013, pp.102-110, 125-134), and the assumption that a new climate agreement will be struck and administered under an ideal global governance structure – and thus not realizable.

The complexity that is introduced by REDD+ impacts the carbon price mechanism; by supplying the market with REDD+ carbon offsets, the price mechanism that ensures demand for credits equals supply is distorted because sales of REDD+ credits are used in place of emissions reductions. REDD+ offsets shift the $MC_{CarbonOffsets}$ in Figure 1 downwards and thus C^* further to the right, lowering the need for emission reductions to meet targets in compliance markets. Indeed, this is their purpose, although they are also a mechanism for developed countries to pay for environmental services provided by developing countries. While the concept is a reasonable one, implementation of such a PES system on an international scale is proving much more difficult than anticipated (Angelsen 2014). Additionality, leakage, double-dipping, transaction costs and governance are major concerns (as discussed above).

In the absence of an international cap-and-trade compliance scheme, REDD+ credits simply add to the plethora of ways in which a country can meet targets. Thus, a country such as Norway could reduce its emissions by paying a country with tropical forests to reduce deforestation below a BAU baseline. The baseline or reference rate of deforestation might be the average level of deforestation over the past decade (measured in terms of area or volume of timber). However, if the seller of the environmental services had been prepared to reduce rates of deforestation in the absence of REDD+ payments (perhaps because of greater domestic demand for reduced deforestation), then the forest protection project cannot be considered additional.[7] It is also possible that an environmental NGO or another country was simultaneously paying the country for protecting biodiversity that would preclude deforestation – a case of double dipping. Further, by reducing deforestation, the prices of certain species of timber are likely to increase, resulting in greater harvests of such timber or close substitutes in other countries, thereby offsetting the mitigation benefits, although perhaps not the biodiversity benefits. These issues highlight the most important aspect of REDD+, namely, the problems associated with contracting, measuring and monitoring compliance – transaction costs and governance.

Instead of dealing only with the sale and purchase of permits to emit CO_2, the emissions market has to deal with offset credits that really have nothing to do with CO_2 emissions from fossil fuel burning. REDD+ credits derive from a desire to pay countries to protect biodiversity – a payment for environmental services and a transfer of income from rich to poor – and have much less to do with mitigating climate change, although it does constitute an important consideration. By allowing these offsets into the carbon market, the corresponding carbon price does not reflect its true value, leading to inefficiency and reduced investments in R&D that conserve energy, enhance efficient use of fossil fuels or spur development of alternative energy sources. Thus, credits created by activities that protect biodiversity enter the global carbon market without actually contributing to a reduction in atmospheric CO_2.

A disturbing trend in this regard has seen the creation of carbon offset credits through reduced or delayed harvests in developed countries, with many such projects certified by the voluntary market (as discussed in the previous section). REDD+ was originally proposed as one means to reduce tropical deforestation, with related carbon payments seen as a means to incentivize forest protection. However, in developed countries, such as Canada and Russia, the creation of carbon offsets through reduced and delayed harvests can simply be viewed as rent seeking activities that do little more than facilitate avoidance of real measures to reduce CO_2 emissions, while providing potentially very large rents to forestland owners (or owners of the right to market any carbon offset credits that can be certified). For example, it appears that Russia may well use carbon benefits from forgone harvests to meet its self-declared INDC target in anticipation of climate negotiations at COP-21 (see above).

As another example, the Canadian province of British Columbia requires all government entities, such as government departments, universities and public schools, to be carbon neutral by purchasing carbon offset credits from the province's Pacific Carbon Trust (PCT) for any CO_2 they release to the atmosphere. The price of offsets is set equal to the province's carbon tax at \$30/tCO_2.[8] PCT purchases offsets from various sources, preferably from projects originating in BC, resulting in a scramble among potential sellers of offset credits to certify projects (Auditor General of British Columbia 2013). Of course, the

[7] Although forestland owners in North America are not included in the creation of REDD+ offsets for the compliance market, they can sell voluntary emission reductions (VERs) using a similar device. In British Columbia, for example, local communities, First Nations and NGOs have sought REDD+ payments for forestland that they had no intention of harvesting or degrading (see van Kooten et al. 2015; Auditor General of British Columbia 2013).

[8] For an overview of carbon taxes in the Canadian context see Beck and Wigle (2014).

easiest way to create offset credits in the province, particularly when timber markets are in recession, is to claim the avoided emissions of CO_2 from reduced or delayed harvests.

One study of reduced harvests in British Columbia found that upwards of 1.1 Mt CO_2 could be saved at costs ranging from less than \$1/tCO_2 to well over \$40/tCO_2 depending on location and assumptions regarding opportunity costs and the discount rate (Man et al. 2015). If opportunity costs are ignored, costs would not exceed about \$1/tCO_2 regardless of location; if the foregone revenue from reduced harvests was included, carbon credits could be created at costs ranging from about \$4/tCO_2 for forests located in BC's boreal zone, \$30/tCO_2 in the central interior and more than \$40/tCO_2 near the southern coast. However, including only the foregone revenue from reduced harvests ignores the opportunity cost associated with changes in carbon fluxes. In particular, by excluding as an opportunity cost the foregone carbon dividend associated with post-harvest wood product sinks and the subsequent uptake of CO_2 by faster-growing, newly planted trees, the costs of offsets are underestimated. Indeed, there may well be a decrease rather than increase in carbon offsets (Smyth et al. 2013). That is, reduced and delayed harvests would aggravate rather than mitigate climate change.

A special task force of the U.S. Society of Foresters investigated carbon offsets from forest conservation. It concluded that such projects are highly variable and depend on numerous assumptions, most of which are susceptible to bias and virtually insurmountable measurement errors (Malmsheimer et al. 2011). The task force pointed out that one of the main problems with forest carbon offset credits is the misguided belief that an unmanaged forest will accumulate and retain an amount of carbon greater than what the offset buyer is emitting over time – a false sense that, upon purchasing offsets, a buyer's activity is carbon neutral. Further, it concludes that the global benefits of forest offsets are overstated due to additionality and leakages that potentially nullify almost any carbon gains.

There is one other obstacle to REDD+. Economists conclude that there should be no difference for mitigation if we target price or quantity; indeed, if there is uncertainty about the costs of mitigating climate change while benefits are reasonably well known, a tax is preferred to cap-and-trade, with the opposite true if benefits are uncertain (Weitzman 1974). The problem is that REDD+ does not fit into either a tax/subsidy or emissions trading scheme because REDD+ projects neither release CO_2 nor remove it from the atmosphere. Rather, it constitutes only a threat of potential emissions. The REDD+ service is unlike any other tradable or taxable quantity – it is an alien intrusion into the marketplace. This is why it is so difficult to implement.

Nonetheless, given that tropical deforestation does contribute greatly to climate change, some effort is required to reduce it. The appropriate means for doing so is to treat REDD+ separately from carbon offsets. It is necessary to establish separate reference or baseline levels of deforestation, whether these are business-as-usual or a crediting baseline (Angelsen 2014), but the trading should concern levels of deforestation and not carbon. Unfortunately, this is politically unacceptable because, unless tied to climate change mitigation, the prices that countries would pay to prevent deforestation would be much smaller than they would be if REDD+ is somehow integrated into a scheme that enables countries or private firms to count them to emission reduction targets.

4. BIOMASS ENERGY AND CARBON FLUXES

To curb CO_2 emissions, governments are increasingly turning to wood biomass as one means of meeting renewable energy targets. In particular, it is becoming popular to co-fire biomass (wood pellets) with coal to reduce the CO_2-emissions intensity of existing coal plants (Hayter et al. 2004). This is appealing due to the low incremental investment required to retrofit established facilities and because energy produced from biomass is considered to be carbon neutral – CO_2 that is emitted during production of electricity is subsequently removed from the atmosphere by newly planted trees (Hayter et al. 2004, p.8; IPCC 2006; McKechnie et al. 2011, p.789; Skone et al. 2012, p.vii; Government of Canada 2012). In the European Union, for example, wood biomass is expected to become the most significant future source of renewable energy, and is projected to account for over half of total renewable energy production even though this could result in a wood deficit for Europe of 200 to 260 million m^3 by 2020 (European Commission 2013).[9] Already installed biomass generating capacity within the EU has increased from 1.44 GW in 2004 to 34.37 GW in 2012, which represents 43.3% of global biomass capacity; imports of wood pellets into the EU rose in step from an insignificant amount in 2002 to 8.3 million tonnes (Mt) in 2012 (FAO 2012), with about 1.4 Mt coming from Canada and nearly 1.8 Mt from the U.S.[10] More recently, the European Commission (2014) proposed a new policy framework with a more ambitious greenhouse gas reduction target of 40% of 1990 levels by 2030 (compared to the earlier target of 20% by 2020), with renewable energy expected to account for 27% of the EU's total energy production. Based on projections by Mantau et al. (2010), the annual biomass consumption for energy generation within Europe may grow to 752 million m^3 by 2030.

Other jurisdictions are following suite. For example, as a result of its 2009 *Green Energy and Green Economy Act*, the Canadian province of Ontario has recently completed the conversion of 517 MW of coal-fired capacity to burn only biomass (see van Kooten 2013, pp.375-381). In the U.S., as of 2010, only nine facilities with a total capacity of 469 MW were co-firing biomass with coal, although several other biomass-only generators built during the 1980s exist in California, Oregon and other regions where feedstock is available; these tend to be small power generators that use residual fiber and sawdust from sawmilling, black liquor from pulp mills and other biological waste materials (Skone et al. 2012). Overall, the U.S. had a total biomass generating capacity of 7.1 GW in 2011, which is expected to grow to 23.7 GW by 2040 whence it would account for about 15% of renewable generating capacity (U.S. EIA 2015). Compared to the EU and some other regions, the U.S. appears to be somewhat more reticent to invest heavily in biomass generating capacity.[11]

There exists a rich body of research on the greenhouse gas emissions impact of substituting forest

[9] For comparison, Canada's sustainable wood harvest supply amounts to about 230 million m^3, while the timber harvest in 2012 was 148 million m^3 (Natural Resources Canada 2014).

[10] See Natural Resources Canada's website on wood pellets at http://www.nrcan.gc.ca/node/13736 [accessed February 12, 2015].

[11] In the U.S., a major impetus for reducing coal-generated power is concerns about asthma rather than climate change (see Fact Sheet at http://www.epa.gov/mats/pdfs/proposalfactsheet.pdf p.3 [accessed February 23, 2015]). Biomass burning is less suited to reduce the incidence of asthma.

bioenergy for fossil fuels (see Miner et al. 2014; Sedjo 2013 for reviews). 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 entering the atmosphere as a result of 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. The distinctions are important as discussed below.

4.1 Tracking Carbon Fluxes: The Carbon Life-Cycle Analysis (LCA)

The initial approach used by analysts can be understood in the context of Figure 2. Suppose that electricity is generated in a given day or hour by a coal plant. In that case, an amount 0F of CO_2 enters the atmosphere and remains there indefinitely as indicated by the horizontal dashed line. Suppose instead that the power delivered on that day or hour was generated by burning wood biomass rather than coal. In that case, an amount 0K > 0F of CO_2 enters the atmosphere at time 0, thereby creating a carbon deficit equal to 0K – 0F. If trees are planted at t=0, the trees will begin to remove CO_2 from the atmosphere and store it in wood biomass, with the cumulative amount of CO_2 removed determined by the growth function as indicated by the S-shaped curve in Figure 2. At t=M, the amount of CO_2 left in the atmosphere as a result of burning wood biomass at t=0 equals the amount that would have been in the atmosphere if coal had been burned instead. Then, at t=N, the CO_2 that had been released by burning biomass will have been completely removed. Between t=M and t=N, the biomass option has resulted in a carbon dividend or benefit relative to the coal option. This is generally what is meant when biomass burning is declared to be carbon neutral.[12]

Presumably biomass will continue to replace coal for an indefinite number of periods. In that case, as shown by Walker et al. (2013), the picture in Figure 2 morphs from the single- (small scale) to the multi-period (large scale) of Figure 3. In each period trees are immediately planted in order to sequester the carbon just released by burning biomass for electricity. The (solid) straight line represents the cumulative amount of CO_2 emitted into the atmosphere by burning coal, with the slope of the line representing emissions in each period; the dashed line represents the cumulative emissions from burning biomass instead of coal. After N years, the cumulative fluxes from burning biomass equal those associated with burning the fossil fuel. The dashed line eventually becomes horizontal at the point N where the CO_2 emitted in the first period is fully sequestered by the growing forest planted in that period. "The cumulative analysis makes clear that the time required to begin realizing dividends from biomass energy is considerably longer than one might conclude if only a single year of emissions were evaluated" (Walker et al. 2013, p.150).

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[12] The idea of carbon neutrality can also be based on "the observation that C [carbon] removals from growth across a forest landscape will balance the CO_2 combustion emissions from burning biomass harvested in the forest if the forest is managed in a way that ensures that its C stock is not decreasing" (Lemprière et al. 2013, p.308). This also 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. We expand on the above quote in the discussion pertaining to Fig. 3.

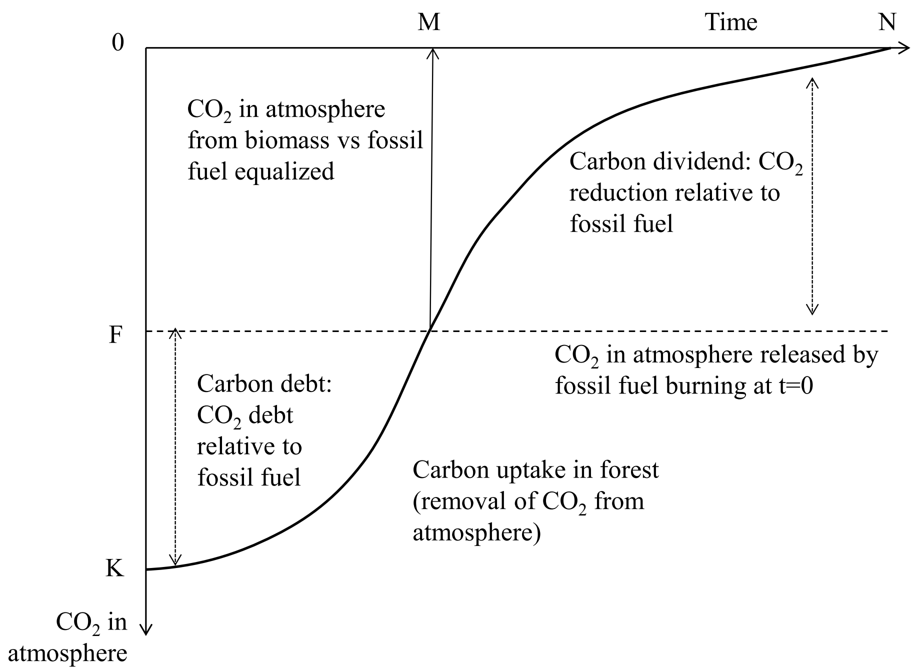


Figure 2: Carbon flux profile for biomass energy versus business-as-usual fossil fuel energy
Source: Walker et al. (2010)

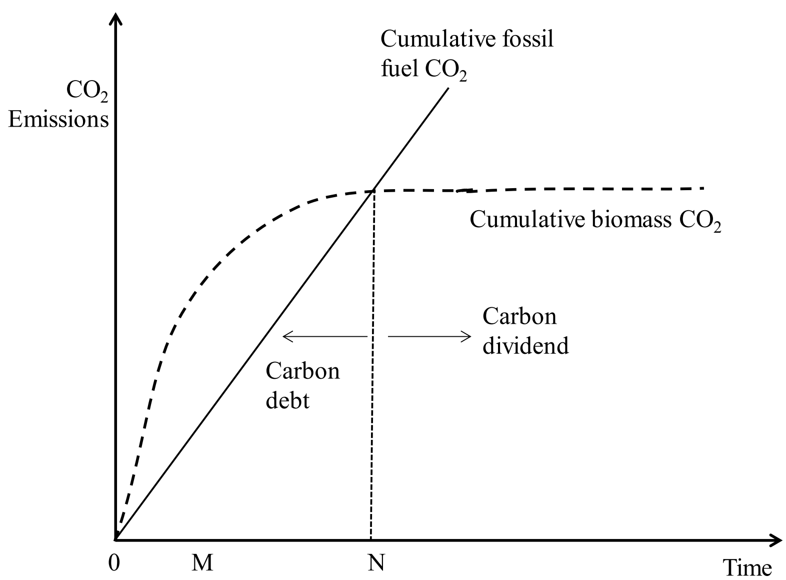


Figure 3: Carbon flux associated with fossil fuel and biomass energy production over time
Source: Walker et al. (2013)

For Massachusetts, 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.

The forgoing approach has intuitive appeal because of its simplicity: CO_2 emissions from fossil fuels "can be captured in biomaterials and vegetation, but only with the effect of reducing the opportunities for future capture, since the world's carbon sequestration potential is presumably limited. In contrast, at any future point in time carbon dioxide in the biosphere will be lower if wood biomass is allowed to substitute for fossil fuels" (Sedjo 2011). However, the simple analysis places undue restrictions on the analysis, which, when relaxed, paints a different picture (Sedjo 2013). For Sedjo (2013), it is the behavior of decision makers that makes the analysis more complicated (as discussed in the next section). For others, it is carbon's life cycle. 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 (i.e., 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. However, their conclusion is similar: the benefits of generating electricity from biomass depend on whether standing timber or forest floor residuals are used for bioenergy. For the Great Lakes-St. Lawrence forest region of Ontario, the authors find that, if pellets are produced from standing trees, the time taken to eliminate the carbon debt from biomass burning (see Figs. 2 and 3) takes some 38 years; if pellets are produced from forest residuals, the break-even point occurs after 16 years. Again, based on LCA considerations, forest residuals would decay over time, releasing carbon, whereas standing trees would continue to sequester carbon.

McKechnie et al. (2011) also found that, if 15% of biomass is not needed to dry the wood (as originally assumed), the time required to yield any net climate mitigation benefit is reduced from 38 to 29 years in the case of whole trees and from 16 to 11 years for residuals. The authors also looked at converting biomass to ethanol, but found this to be less attractive than conversion to wood pellets. Indeed, in some cases, they found that, with ethanol, it took more than 100 years to eliminate the initial carbon debt (see also Crutzen et al. 2008). Finally, while not expanding on this option, McKechnie et al. (2011) acknowledge that, if standing trees are harvested and converted to products that replace steel and cement as construction materials, there is no carbon debt but only a carbon dividend (p.794). This is discussed further in section 5 below.

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, for reasons noted in the earlier quote by Sedjo (2011). Thus, there is a distinction between CO_2 molecules released by burning fossil fuels and ones released when burning biomass; CO_2 emitted from biomass is denoted bioCO_2 to distinguish it from CO_2 emitted by fossil fuels.

Because CO_2 from fossil fuel burning cannot be removed from the atmosphere, the GWP_{bio} is a measure of the relative benefit of burning biomass. It is given by the ratio of the absolute global warming potential (AGWP) of $bioCO_2$ to that of CO_2 (Cherubini et al. 2011, p.418):

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

where C_0 refers to the initial pulse of CO_2 entering the atmosphere at t=0. T is the time horizon, and α_{CO2} and α_{bioCO2} are the radiative efficiencies of CO_2 and $bioCO_2$, respectively, with α_{CO2} clearly equal to α_{bioCO2}.[13] 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 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 Figure 3 (above) 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 $bioCO_2$ molecule only by regrowth of the forest from which the molecule originated – the vegetation sink;
2. potential removal of the $bioCO_2$ molecule either by vegetation growth or by the ocean; and
3. potential removal of the $bioCO_2$ 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

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

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

Since GWP_{bio} never declines completely to zero, one could consider biomass to be a better alternative to coal or even natural gas for generating electricity, but not a final solution to the climate problem. This is similar to the case of natural gas. While gas is preferred to coal because of its lower CO_2 emissions, its use is often looked upon as only a short-term measure. Likewise, biomass might be considered a better but still short-term measure towards an emissions-free society.

Scientists clearly 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 it provides a kind of *physically based discounting factor* by which the biomass emissions with deviating timing can be transformed into a permanent fossil carbon emission whose cumulative warming impact within a given time horizon is the same" (Helin et al. 2013, p.481, emphasis added). 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 C [carbon] pools in forest ecosystems: it is important to also consider C use and storage in HWPs [harvested wood products] and landfills, substitution of wood for more emissions-intensive products and fossil fuels, and land-use change involving forests. Such activities are highly interconnected, [and] … need to be based on an integrated assessment of the various mitigation possibilities" (Lemprière et al. 2013, p.298).

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.[14] In their life-cycle analysis of carbon in boreal ecosystems, for example, they note

[14] 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.

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). We return to these issues in section 5 below when we examine the economics of carbon in greater detail.

4.2 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 are important, with current emissions of CO_2 and removals from the atmosphere by sinks more important than later ones.[15] 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, p.481; Lemprière et al. 2013, p.308; Galik and Abt 2012). Indeed, economists since the time of Ciriacy-Wantrup (1952/1968) have used weights to compare the physical rates of resource extraction, such as rates of pumping from an oil well, to determine whether a policy is conserving or depleting.

The rate used to discount carbon fluxes can be used in the policy arena to put into practice the urgency of the need to address climate change. 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" (IPCC 2014, p.93) and that the once distant concern is now a pressing one as future climate change is largely determined by today's choices regarding fossil fuel use (Melillo et al. 2014), then we want to weight current reductions in emissions and removals of CO_2 from the atmosphere much higher than those in future years. This is the same as discounting future uptake of CO_2, with higher discount rates suggesting greater urgency in dealing with global warming. Figure 4 depicts such urgency, but for a level of urgency where discount rates are sufficiently high that burning of biomass for energy never leads to carbon neutrality. Indeed, if one were to accept that climate change is a more urgent matter (a relatively high discount rate), substituting biomass for fossil fuels may actually lead to a net increase in atmospheric CO_2 emissions. In Figure 4, forest carbon uptake is discounted to such an extent that carbon uptake in the more distant

[15] "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).

future is of little value today. As a result, the discounted future uptake of CO_2 from the atmosphere (regardless of the sink) is too small to offset the additional increase in CO_2 emissions when biomass substitutes for fossil fuels in power production.

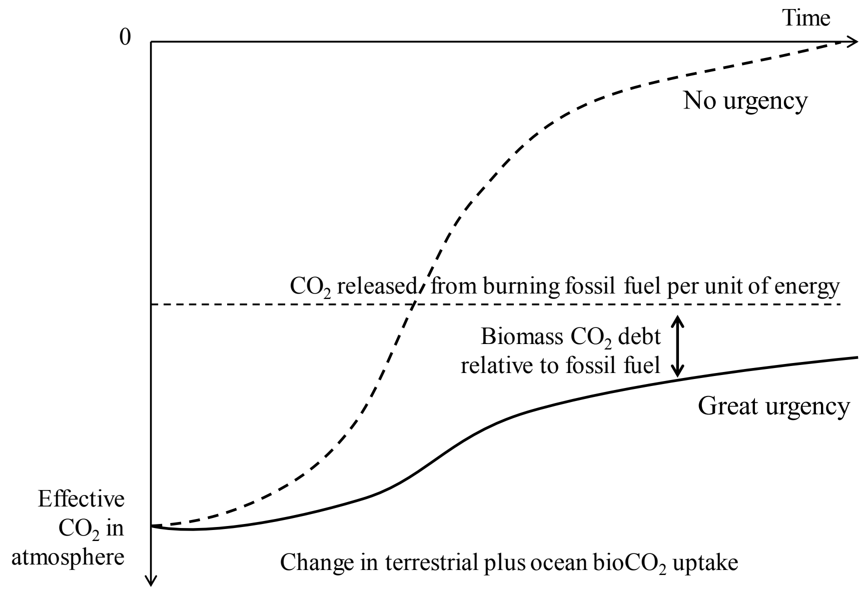


Figure 4: Carbon flux associated with fossil fuel and biomass energy production over time: Comparing lesser and greater urgency to address climate change

The change in the cumulative carbon flux (measured in terms of CO_2) from substituting biomass for coal, say, will depend on the relative emissions intensity of the inputs, as well as the geographic location, tree species or other types of crops (e.g., straw, hemp) that are available, and other variables. Carbon dioxide released from burning coal and wood varies greatly by the quality of coal and biomass, especially whether the biomass originates from hardwoods or softwoods. On average across all types of coal, 0.518 tonnes (t) of coal are required to produce 1.0 megawatt hour (MWh) of electricity, releasing 1.015 tCO_2 per MWh; for bituminous coal, which is used most commonly in power plants, only 0.397 t of coal are required per MWh, releasing 0.940 tCO_2 MWh^{-1} (Hong and Slatick 1994).[16] 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.[17] Since the majority of the world employs bituminous and subbituminous coal for power generation, with respective emissions intensities of 0.940 and 0.953 tCO_2 MWh^{-1}, biomass clearly releases significantly more CO_2 into the atmosphere per unit of energy than coal, and even more when compared to natural gas. In the following scenarios, an emissions-intensity for subbituminous coal of 0.94 tCO_2 MWh^{-1}) is assumed; for an equal mix of hardwoods and softwoods, 1.246 m^3 of wood are required to produce one

[16] See also http://www.ipcc.ch/meetings/session25/doc4a4b/vol2.pdf [accessed April 1, 2015] where carbon intensities for many fuels are provided.
[17] See http://www.canadianbiomassmagazine.ca/images/stories/table1-2.pdf [accessed April 1, 2015], which also provides carbon intensity data for coal.

MWh of energy, thereby releasing about 1.27 tCO_2.

To illustrate the issue further, a generalized Richards' growth function is employed to determine the sensitivity of bioenergy use to the perceived urgency of addressing climate change (see Appendix A for growth functions). The Richards' growth function is as follows:

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

where *v*(t) is volume (m^3/ha) as a function of age, β is a shape parameter, *k* is the growth rate, *m*>0 is the slope of growth (i.e., it affects the asymptote nearest to which maximum growth occurs), and *U* is the upper limit on growth (m^3/ha), with the lower bound of the function assumed to be zero. The financial rotation is determined from the following equation (see van Kooten and Folmer 2004, pp. 365-371):

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

where *r* is the discount rate. We apply equations (2) and (3) to two growth functions that could representative interior or 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 remaining parameters remain constant for the forest types: β=1.5 and *m*=0.25 for the interior forest, while β=1.5 and *m*=0.08 for the coastal forest. The volume curves and associated financial rotation ages are found in Figure 5.[18] We do not consider a very fast growing forest (e.g., a hybrid-poplar plantation with 5-year rotation) because it might more appropriately be considered an agricultural crop.

We assume that biomass is burned for energy and immediately replaced by a forest that recovers CO_2 at a speed 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, we subtract for each year the CO_2 removed from the atmosphere by subsequent growth of timber based on the growth curves of Figure 5 (again multiplying by 1.57 to account for logging residues and other coarse woody material), weighting the carbon according to the degree of urgency to address climate change. The rates used to discount the physical carbon increase from 0% (no urgency whatsoever) to 10% ('significant' urgency) at 2.5 percent intervals. The results for our four

[18] The R file used to construct Figures 5 and 6 is provided in Appendix B.

scenarios are provided in Figure 6.

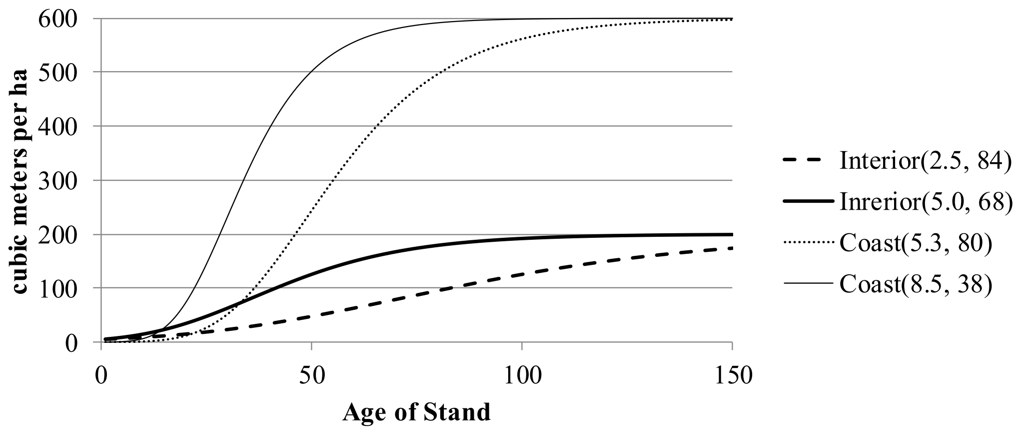
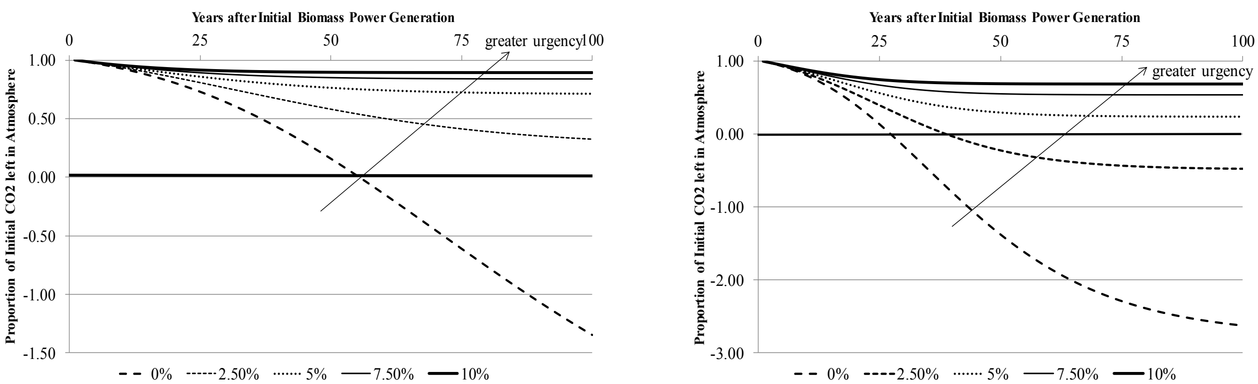
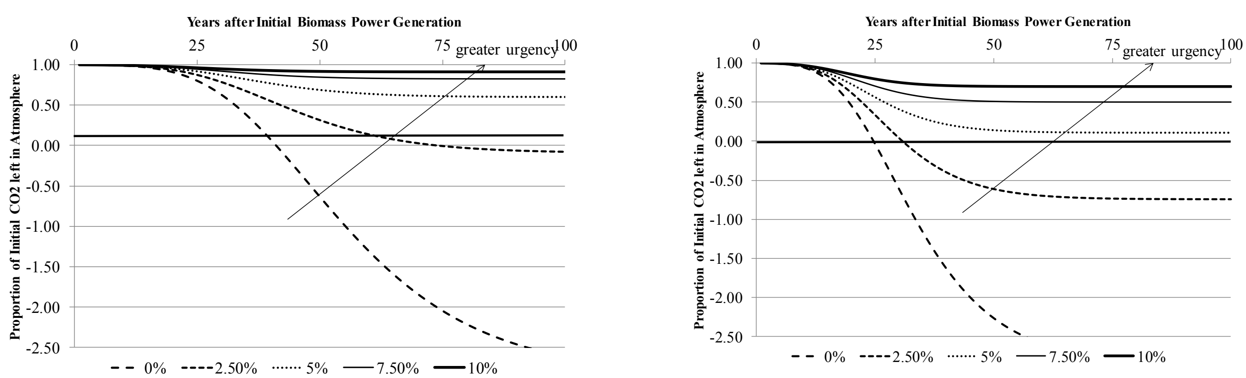


Figure 5: Growth Functions for Representative Coastal and Interior Forests, with Assumed Growth Rates and Approximate Financial Rotation Ages Provided in Parentheses



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



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

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

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

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

4.3 Economics of 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 (Moncton et al. 2015). Each of the five IPCC reports (1990, 1995, 2001, 2007, 2013) provides estimates of the climate sensitivity parameter. In the reports, the central estimates range from 2.5°C (1995, 2001) to 4.0°C (1990), with lower-bound values from 1.5°C (2013) to 2.0°C (2007) and upper-bound values from 4.2°C (2001) to 5.2°C (1990); other scientists report values between 0.8°C and 2.0°C (see Moncton et al. 2015, p.132). Lower estimates of the climate sensitivity parameter indicate that global warming is not a serious problem, and not worthy of a drastic policy response leading to the conversion of coal-fired power plants to burn biomass, although higher values of the climate sensitivity parameter ($\gg 2.5^{o}C$) might require a more drastic response. The fact that global temperatures have not increased in nearly two decades provides strong support for the view that drastic policy action should not be taken. This is discussed further below.

Second, as Sedjo and Tian (2012) and Sedjo (2013) argue, economists 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 follows directly from the types of forest management models economists build. In such models, 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. In practice, of course, the rational decision maker will adapt to new information, whether it pertains to changes in government policies, forestry investments elsewhere, changes to factors (especially crop prices) that affect farmland, et cetera, and revise decisions in such a way that the present value of expected net returns (or utility) is maximized. 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. We already see this in Japan and Germany, where decisions to eliminate or reduce reliance on 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.[19] 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

[19] "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).

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, 2009).

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 lumber mills, 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 international consequences, 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) examined trade in fuelwood, which constitutes roundwood used primarily for cooking and heating. They 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. 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.

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 from logging residues that would normally be left in the forest as there is little room to increase bioenergy from milling residues – availability of logging residues for bioenergy purposes is expected to increase from an insignificant amount in 2006 to 62.1 million m^3 by 2030, while mill residues would increase by less than 20 million m^3 (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 move between sectors and uses will have a large impact on the effectiveness of biopower policy" (Latta et al. 2013, p.380). 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 bioenergy is sourced solely from forests, logging residue requirements would increase anywhere from 3.4 to 21.9 million m^3, mill residues by 2.7 to 31.0 million m^3, and roundwood residues from 8.0 to 156.1 million m^3, depending on the scenario. However, if biomass can be sourced from either agriculture or forestry, or both, and land can move between these sectors, very little of the bioenergy needed to generate this electricity is projected to come from forestry.

Second, the supply of logging residues at a given time is limited by the amount of total timber removed for other products (Abt et al. 2014, p.5). In the vast majority of cases, it does not pay to harvest forests solely for bioenergy purposes. As noted in the previous point, sourcing biomass from agriculture is more cost effective.

Third, coarse and fine woody materials left in the forest upon harvest decay more rapidly than roundwood, 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 carbon flux is small. Nonetheless, there are important environmental benefits to leaving such material behind. Soils in many regions, and particularly the U.S. south and southeast, are highly eroded and depleted of organic matter; therefore, it is important to leave residues on the forest floor to ensure long-term sustainability of the forest ecosystem. Forest ecologists therefore recommend longer rotations because older forests produce more coarse and fine woody material; indeed, they recommend "stem-only harvest and longer rotations [that] permit a recovery of soil biodiversity and an accrual of detritus and soil organic matter" (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. As discussed in the next section, sustainability issues may become an impediment to the removal of coarse and fine woody material from the forest for pellet production.

In Canada, on the other hand, there are physical, economic and institutional constraints to the removal of forest residues. A report prepared for the UK's Department of Energy and Climate Change concludes that "in 2020 it may be possible to meet the UK's demand for solid biomass for electricity using biomass feedstocks from North America that result in electricity with GHG intensities lower than 200 kg CO_2e/MWh, when fully accounting for changes in land carbon stock changes" (Stephenson and Mackay 2014, p.18). The authors consider separate scenarios that require the continuous removal of upwards of all coarse and all fine woody materials from Canada's Pacific forests and from the boreal forest, and faster rates of harvest in British Columbia (see Stephenson and Mackay 2014, pp. 8-11, 130-132). Given the mountainous terrain and long haul distances, it is simply too costly to collect coarse and fine woody materials from BC forests and the boreal forest; indeed, Niquidet et al. (2012) find it is even too costly to haul roadside wastes (logging residues left where logging trucks are loaded) from forests in the BC interior to a dedicated biomass plant located near the sawmill to which the logs are brought. As haul distances increase, the marginal costs of wood fuel become exorbitant. To gather coarse and fine woody material, transport it to the roadside for loading, and then haul it to a pellet manufacturing facility or power plant will entail significantly higher costs. Further, logging companies with short-term contracts to harvest timber have little incentive to remove roadside wastes; rather, they cut logs at roadside to enhance their value and minimize hauling costs.

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

4.4 Forest Certification and Bioenergy

There are six natural gas fired power plants in the Netherlands with a combined capacity of 6,400 MW, a nuclear plant with a capacity of 485 MW, four coal plants with a combined capacity of 3,726 MW, and three power plants that co-fire biomass with coal that have a total capacity of 2,887 MW.[20] The largest coal-biomass power plant in Europe is Essent's Amir power plant located south-east of Rotterdam, which has a generating capacity of 1245 MW plus a heat generating capacity of 600 MW. It was converted in 2001 and is now able to co-fire nearly 800,000 tonnes of wood pellets annually, while also producing power from wood gas derived from 100,000 tonnes of construction and waste timber (with 33 MW capacity). On its website, Essent claims it employs wood pellets derived from sustainably managed forests in the U.S. state of Georgia that are controlled by its parent company RWE.

The Dutch government's September 2013 Energy Agreement for Sustainable Growth provided a road map to reduce energy consumption and increase the energy share of renewables to 14% by 2020. As indicted earlier, more recent EU targets for CO_2 emissions reductions are even more ambitious. Although the government intends to limit its subsidies to 3.5 Mt of wood pellets annually for the period 2015-2023, accounting for an anticipated two-thirds of industrial wood pellet use, it also wants to ensure that wood biomass for pellets comes from forests that are sustainably managed. The Dutch and others in the EU want to ensure that wood pellets are sourced from forests that are certified so that, in this way, they can avoid or at least deflect claims that the use of wood pellets might lead to an increase in CO_2 emissions for reasons related to unsustainable forest management practices and/or illegal logging. Beginning in 2015, the Netherlands will require that biomass from forest estates of 1000 ha or more be certified; by 2020, forests greater than 800 ha will need to be certified; and, by 2024, all forests providing bioenergy will need to be certified.[21] What does this imply?

There are essentially two types of certification: Certification of forest management, which occurs at the forest management unit level (individual forests), and certification of chain of custody, which occurs at the company level. Seven European bioenergy producers have formed the Sustainable Biomass Partnership (SBP) to establish certification for wood pellet producers and users. "The SBP has been developing a certification system to demonstrate compliance with the EU and country requirements with the main focus on Belgium, Denmark, the Netherlands and the UK. Under this system, it is not forest managers who are certified but the pellet mills and other biomass producers who are required to conduct a Supply Base Evaluation verifying the sustainable origin of woody biomass."[22]

The Forest Stewardship Council (FSC) and the Program for the Endorsement of Forest Certification (PEFC) are the only global organizations that certify sustainable forest management practices and chain of custody from the forest to the end user. The FSC has its own criteria and certification process, while

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[20] Information from http://en.wikipedia.org/wiki/List_of_power_stations_in_the_Netherlands [accessed March 30, 2015].

[21] See http://biomassmagazine.com/articles/11398/a-dutch-dilemma [accessed March 30, 2015].

[22] From http://www.nepcon.net/newsroom/biomass-boost-implications-fsc-and-pefc [accessed March 30, 2015].

PEFC is an umbrella organization that assesses and recognizes the criteria and processes of national certifiers, such as the Canadian Standard Association's (CSA) certification scheme and the Sustainable Forest Initiative (SFI), a U.S. scheme that certifies larger areas of forest in Canada than in the U.S. According to SBP, if bioenergy products are 100% certified by FSC and/or PEFC, they are exempt from SBP evaluation. However, if "the material is not FSC or PEFC certified or carries FSC or PEFC 'controlled' claims, it needs to be evaluated according to SBP's Sustainable Feedstock Standard. The Standard uses a risk-based approach similar to the FSC's Controlled Wood Standard, but with many additional requirements."[23] In essence, the SBP initiative is a nudge towards FSC or PEFC certification of forest management practices, with the EU likely to adopt certification of forest management and chain of custody for bioenergy, especially wood pellets.

As indicated in Table 1, the majority of forests in the U.S. are not certified, with the proportion of forestland certified for sustainable management much lower in the U.S. than in Canada and the EU-28. Further, criteria for certification of wood pellets by the EU could be quite stringent (see Sikkema et al. 2014), so much so that the U.S. Industrial Pellet Association is concerned that recent EU moves toward greater requirements to ensure wood pellets come from certified forests or come with a chain of custody certificate could lead to a reduction in their access to the European market.[24]

Table 1: Certification of Sustainable Forest Management and Chain of Custody, Program for the Endorsement of Forest Certification (PEFC) and Forest Stewardship Council (FSC)

		PEFC Certification			FSC Certification		
Country or Region	Forest Area ('000s ha)	Area ('000s ha)	% certified	CoC certifi-cates	Area ('000s ha)[a]	% certified	CoC certifi-cates[a]
Canada	310,134	121,143	39.1	175	53,605	17.3	876
United States	304,788	33,118	10.9	251	13,606	4.5	3,005
Europe	1,006,534	89,333	8.9	8,949	85,504	8.5	15,247
EU 28	178,399	68,590	38.5	8,825	34,266	19.2	13,635
Russia	809,210	2,758	0.4	14	38,418	4.7	321
Norway	10,218	9,143	89.5	50	475	4.6	43
Australia	147,452	10,398	7.1	229	967	0.7	303
Latin America	940,680	4,558	0.5	152	13,523	1.4	1,459
Asia	595,898	4,662	0.8	818	900	0.2	7,622
World	3,305,486	263,205	8.0	10,574	184,318	5.6	28,948

Source: FAO (2015), PEFC (2015), Sikkema et al. (2014)
[a] Source: Data provided via email communication with M. Patel, Director of Programs and Communication, Forest Stewardship Council Canada, Toronto. April 8, 2015 (www.ca.fsc.org) Data are from FSC and up-to-date as of April 7, 2015.

[23] Ibid. See also http://biomassa-unie.com/certificering-algemeen/ [accessed March 30, 2015].
[24] See http://www.theusipa.org/wood-pellet-periodical [accessed March 30, 2015].

Clearly, if Johnston and Crossley (2002) are any indication, it might be difficult to certify the use of logging residues and other coarse woody material from many, mainly private, forests in the U.S. South and South East. The same is true in British Columbia, for example, where logging residues are important to protect soils from eroding in mountainous areas while also providing important biodiversity benefits; harvesting best mimics natural disturbance when logging residues are left on the site after harvest. It may also be true of other regions, which might put a damper on efforts to increase co-firing of wood pellets to produce power.

5. MANAGING FOR CARBON: CARBON POOLS AND FOSSIL FUEL SUBSTITUTION

Rather than focusing on bioenergy and forest activities that reduce emissions from deforestation and forest degradation, we need to examine the carbon that enters into various pools within the forest ecosystem and post-harvest wood product pools. As Lemprière et al. (2013) note, "a cascading approach to the use of forest biomass has been found to have the most mitigation benefit: wood is first used for products, especially long-lived products that can substitute for emission-intensive materials; then recycled for other uses; and finally used for bioenergy" (p.297). Indeed, in their study of how Canada's forest resources can best be used to mitigate climate change, Smyth et al. (2014) find that commercial harvesting of trees to produce wood products is preferred to the option of storing carbon by leaving forests unmanaged, and that production of wood products leads to a greater carbon dividend than the use of wood biomass for energy (also see Kurz et al. 2013). In this section, we employ the more holistic approach of these authors, but then from an economic incentives perspective using an example from an interior BC forest. Then, in section 6, we examine the impact of carbon prices on forest rotation ages to generalize the results pertaining to the role of forests in climate mitigation.

Economic incentives are the best way to encourage public and private forestland owners to consider the climate impacts of forest management decisions. Forests can be left unmanaged but, as discussed above, this is unlikely to lead to desirable outcomes from a carbon sequestration point of view. Forests can, however, be managed to maximize the net present value of commercial and carbon benefits as long as carbon fluxes are appropriately incentivized. A tax can be imposed on any emissions released to the atmosphere and a subsidy provided for any carbon sequestered in ecosystem sinks, growing vegetation or product pools, plus any emissions avoided when biomass substitutes for fossil fuels in the production of energy or construction materials (e.g., steel, concrete). Technological advances in engineered wood products have enabled the construction of multi-story wood buildings and state-of-the-art multipurpose (even irregular shaped) buildings. Engineered products, such as cross-laminated timber (CLT), can be used in the construction of high rises as tall as 40 or more floors. Engineered products are now much less vulnerable to fire and pests, while wood buildings require less energy to heat or cool, thereby further reducing GHG emissions (Green and Karsh 2012). Taxes and subsidies encourage investment in wood buildings, for example, and would be applied at the time carbon is removed from or released to the atmosphere, with subsidies financed from carbon taxes.

To overcome issues related to measurement and monitoring, carbon offsets, and thus taxes and subsidies, can be based on an agreed upon forest management (growth and yield) model and observed changes in land use (van Kooten 2009b). The forest management model would specify the annual carbon uptake in the various components of the forest ecosystem from the time trees are planted until they are harvested, if at all. Each year, the landowner would receive carbon offset credits for the carbon removed from the atmosphere, which would depend on rates of tree growth, species, soil and other characteristics of the site that are determined in advance. At the time of harvest, the owner would pay a tax (or purchase offsets) based on the amount of CO_2 released from decaying residues left on the site, decaying residues resulting from processing and manufacturing, and decaying short- and long-lived products. It will, however, be necessary to determine how much roundwood and other biomass is harvested and how this wood is utilized. Decay rates for each carbon pool can be established a priori and the carbon fluxes resulting over infinite time can be discounted to the present to determine the emissions to be taxed at the time of harvest (see Galik and Abt 2012, and earlier discussion). In addition, it is possible to specify and provide a credit for the CO_2 emissions avoided when biomass is burned in lieu of fossil fuels, or the emissions avoided from producing non-wood materials when wood is substituted for steel or concrete in construction.

This is the approach van Kooten et al. (2015) used to determine the optimal management strategy for a 55,000 ha forest in southeastern British Columbia. The forest in question had been regularly harvested, but at a low level so there remain stands of mature timber as well as recently harvested, young stands. Mature stands sequester little if any carbon, but newly regenerated and young stands could sequester significant amounts of carbon for a long period if unmanaged and assuming no wildfires. As alternatives to retaining the forest in wilderness (an unmanaged state), the researchers considered conservation management, which would prevent degradation of the forest while harvesting small amounts of timber in support of this goal, and a management regime that seeks to maximize net commercial benefits plus revenues from the sale of carbon offset credits. Commercial management does not mean untrammeled exploitation as sustainable development criteria need to be satisfied.

Carbon flux outcomes depend on the management regime chosen, which, in turn, depends on the price of carbon. Further, the carbon offset credits that might be assigned will depend on the rate used to discount (or weight) carbon as to when it occurs. Finally, the carbon flux is impacted by the extent to which wood substitutes for non-wood in construction and the accreditation of CO_2-emission reductions, and the emissions savings when wood biomass is burned to produce energy in lieu of fossil fuels. Other parameters include decay rates for organic matter left on the forest site after harvest and the various post-harvest carbon pools, plus financial discount rates, costs of harvesting, gathering and hauling biomass to downstream facilities, and costs of processing and manufacturing, and rates of CO_2 emissions at each stage of the stump-to-products process. Some illustrative results are provided in Table 2 and Figure 7.

The results indicate that the unmanaged forest could generate more carbon offset credits than a forest managed for conservation (or prevent degradation). This follows because CO_2 emissions from harvesting and maintaining the forest in a non-degraded state reduce the ecosystem sequestration and post-harvest carbon storage benefits compared to the unmanaged forest. Essentially, the CO_2 released during activities to manage the forest for conservation exceed the gains in carbon storage as there are insufficient economies of size in commercial-type activities. At the same time, the presence of young stands in the unmanaged forest, along with discounting of carbon fluxes, leads to greater CO_2 sequestration than if the forest removes only a small amount of timber as part of conservation management. This is true even if a credit of 0.75 tCO_2/m^3 is provided to take into account the reduction in CO_2 emissions from not producing steel and concrete that is replaced by wood in construction

Table 2: Annualized Carbon Sequestered in Southeastern British Columbia Forest under Different Management Regimes, '000s tCO_2[a]

Forest Management Method	Emission offset credit,[b] (tCO_2/m^3)	Discount rate on carbon 0%		2%		4%	
		Price of carbon $/tCO_2$					
		$0	$10	$0	$10	$0	$10
Unmanaged		91.7	91.7	100.2	100.2	99.1	99.1
Conservation	0.25	-25.5	-23.0	-14.0	-12.5	-8.8	-8.3
	0.75	-7.2	-4.7	4.2	5.7	9.7	10.3
Commercial Management	0.25	8.1	22.4	57.1	60.3	77.3	80.2
	0.75	186.3	193.3	238.1	243.9	265.8	271.4

[a] Source: Calculated using data from van Kooten et al. (2015)

[b] Credit for emissions avoided producing concrete/steel when wood substitutes for non-wood in construction.

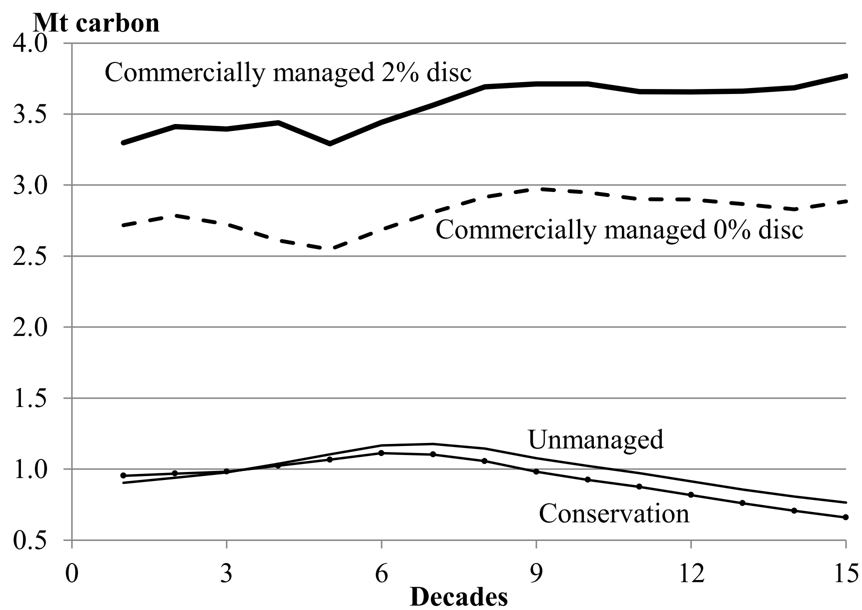

Figure 7: Annualized Discounted Carbon Uptake per Decade for Unmanaged, Conservation Managed and Commercially Managed Forest, 0% and 2% Carbon Discount Rates, 4% Monetary Discount Rate, Carbon Price = $10/$tCO_2$, and Credit of 0.75 tCO_2/m^3 for Reduced Emissions when Wood Substitutes for Non-wood in Construction

It turns out that a commercial operator who responds to incentives to create carbon offset credits (i.e., reduce carbon flux), especially early in the time horizon (due to discounting), lowers atmospheric CO_2 to a much greater extent than the conservationist. The commercial operator manages the forest to maximize income not only from the commercial sale of forest products but also the revenue from storing carbon in the ecosystem through sequestration and silvicultural management, and producing long-lived products with the lowest possible rates of decay. Nonetheless, as is the case when the forest is managed for conservation and thereby permits limited harvests, there are situations where the unmanaged forest with young stands of trees can sequester more carbon than a commercially managed forest because CO_2 emissions are unavoidable when harvests occur. However, if the substitution parameter is higher than 0.3 tCO_2/m^3, commercial management does better in terms of carbon benefits, as indicated in Table 2 and Figure 7. If the substitution parameter exceeds 1.0 tCO_2/m^3, which is not unusual as Hennigar et al. (2008) indicate substitution rates vary from 0.3-3.3 tCO_2/m^3, then commercial management will be preferred as a means of mitigating climate change in all circumstances.

van Kooten et al. (2015) considered an unmanaged forest that had young stands. If the forest was mature, it would not be sequestering any carbon as carbon uptake due to vegetation growth would be offset by decay. In drier regions, mature forests are susceptible to wildfire, pests and disease that could release large amounts of carbon, as illustrated by devastation caused by the mountain pine beetle in Colorado and the interior of British Columbia. Further, the determination of carbon offset credits is influenced by the state of the forest, assumptions regarding the various parameters used to measure carbon fluxes, which include product recovery factors from logs, proportion of woody material removed from harvested sites, the weights used to evaluate carbon occurring at different points in time (the urgency factor), and a host of other factors. As a result, transaction costs associated with the measurement and monitoring of carbon fluxes, and the associated governance and institutional issues, make it difficult to implement an incentive scheme, whether taxes or assignment of carbon offsets. The only options are to ignore forestry activities in the mitigation tool shed or base a tax/subsidy scheme, or accreditation of carbon offset credits, on a land-use contract that includes a model of forest growth and yield and can be monitored aerially or by satellite.

The forgoing results can be generalized by looking at the impact that a tax/subsidy scheme would have on rotation ages. However, such an approach would only be indicative of the potential of such a scheme but likely not workable in the real world of forest management where sustainability, tenure and other factors enter the analysis. With this caveat, we examine the impact appropriate incentives might have on harvest decisions and thus the potential of using models to direct forest activities toward mitigation of climate change.

6. ROTATION AGE WHEN CARBON FLUX IS TAKEN INTO ACCOUNT

A forest site is generally harvested on a periodic basis; it takes time for trees to grow and, when they reach maturity, the forestland owner will harvest the trees for sale. Suppose the landowner is only concerned to maximize the earnings from a one-time harvest of the trees growing on the site, without concern about the value of the land after harvest. At any time t, the rate of growth of the value of the stand is given by g(t) = V'(t)/V(t), where V(t) = (p–c) v(t) is the value of the stand at time t, p is the price of logs (\$/m^3), c is the cost of harvesting logs (\$/m^3), and v(t) is the volume of commercial logs (m^3) on the site at time t. Note that g(t) = v'(t)/v(t) if log prices and harvesting costs are constant. If the rate r used to discount monetary values exceeds g(t) at any time, the stand should be harvested immediately. If g(t) > r, harvest should be delayed until that time, t_F, when the growth in the value of the stand falls to equal the opportunity cost of money r; t_F is known as the Fisher rotation age.

A one-time optimal harvest age ignores future opportunities. If the landowner can replant the site after harvest and harvest trees again at a future date, it will pay to harvest somewhat earlier than time t_F simply because this will enable one to harvest the next crop of trees earlier. The opportunity cost of delaying harvest until t_F is the forgone rents from accessing the next crop of trees earlier. In essence, one needs to balance the rate of growth of mature trees against the higher rates of growth available by harvesting these trees and replacing them with younger, faster-growing ones. To demonstrate this, begin by considering bare land.

An initial investment in land for forestry purposes can be thought of as equating an initial investment in land and tree planting [V(t)+K] to the present value of timber harvest plus subsequent release of the bare land for further regeneration (tree planting) at t:

$$(4)\quad V(t) + K = [(p - c)\, v(t) + V(t)]\, e^{-rt}.$$

The financial or Faustmann rotation age is found by setting dV/dt = 0, which leads to

$$(5)\quad (p - c)\frac{dv(t)}{dt} = r\,[(p - c)\, v(t) + V(t)],$$

where the LHS in (3) is the value of incremental growth of the forest and the RHS is the foregone interest on the combined value of commercial volume had the stand been harvested plus the land value, V(t), had the land been sold as bare land at the time of harvest (t). We can find the optimal financial or Faustmann rotation age diagrammatically if we rewrite (3) as:

$$(6)\quad \frac{dv(t)}{dt} = r\left[v(t) + \frac{V(t)}{(p-c)}\right].$$

As illustrated in Figure 8, the optimal financial rotation age, denoted t^*, is found by taking the line given by the RHS of (6) and making it tangent to the curve given by the LHS of (6), as indicated in the upper left-hand quadrant. (The maximum sustainable yield rotation age, t_{MSY}, is also shown, and it is determined from v'(t)=v(t)/t.) The simple comparative dynamics that follow directly from Figure 8 are summarized in Table 3. Further, it is easy to determine that an ad valorem tax (% levy on standing timber) will cause the landowner to harvest sooner, while neither a yield tax (% levy on the value of timber at harvest time) nor a land tax (levy on site or land but not timber) will impact the optimal time of harvest (Montgomery and Adams 1995).

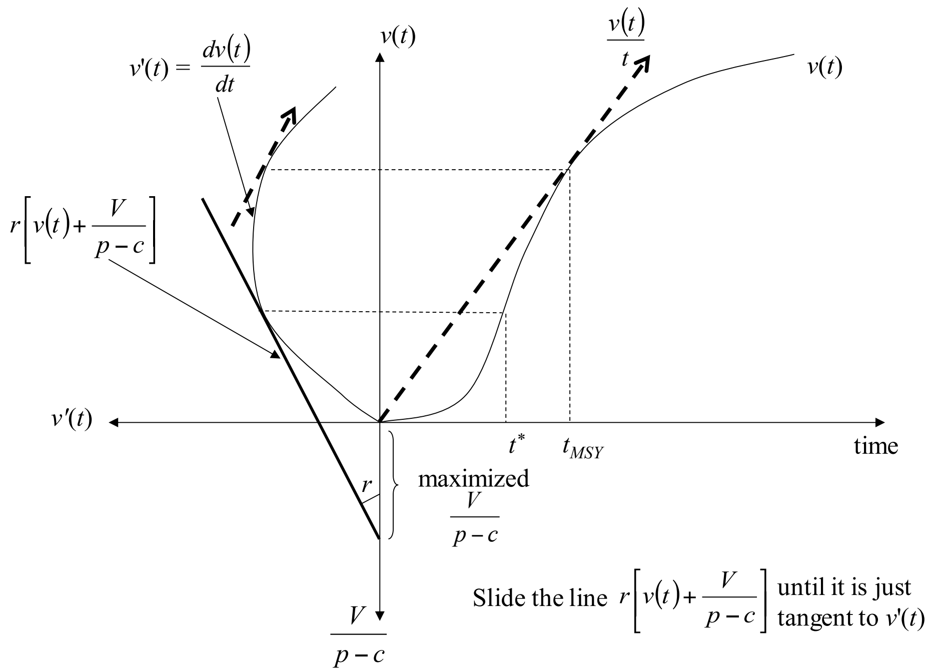

Figure 8: Determining the Optimal Financial/Faustmann Rotation Age

Table 3: Comparative Dynamics of the Simple Faustmann Model

Change in:	Optimal rotation age	Bare land value[a]
Higher *r*	–	–
Higher *p*	–	+
Higher *c*	+	–
Higher *K*	+	–

[a] The bare land value if often referred to in forestry as the soil expectation.

The optimal rotation age is affected by non-timber or amenity values that are realized continuously as opposed to only at the time of harvest. If the relationship between amenity values and stand age is well defined (so that the total of all amenity values depends on a forest's age in a regular way), it is possible to find an optimal rotation age that takes into account both commercial timber and amenity values, as Hartman (1976) initially demonstrated. However, forest ecosystems provide many types of non-timber amenities that range from water flow to forage for wild ungulates, and these vary in different and often non-continuous ways with forest age (see Bowes and Krutilla 1989; Calish et al. 1978). As Calish et al. (1978) illustrated, consideration of amenity values can result in harvests when this is not warranted by financial considerations or, as in the case of the spotted owl whose habitat requires old-growth forests, recommend against harvesting altogether despite lost commercial revenues. In the case of the spotted owl, there is a discontinuity in the relationship between forest age and the amenity value – no benefits accrue until the forest reaches a certain age or has developed certain characteristics. As a result, it is not always possible to determine an optimal time to harvest a forest, because attempts to optimize the returns to multiple amenity and commercial values leads to 'non-convexities' – the trade-offs among multiple conflicting values as a forest ages cannot be resolved (Swallow et al. 1990; Vincent and Binkley 1993).[25] The problem of determining the optimal time to harvest a site is aggravated when forest management decisions on one site affect the amenity values on adjacent or spatially-separated sites (Swallow and Wear 1993; Swallow et al. 1990, 1997). Optimal harvest decisions that take into account amenity values across sites can be made under certain restrictive assumptions that are rarely found in the real world.

A particular amenity value relevant in the context of forest rotation age relates to carbon sequestration. Since carbon can be priced, it is possible to consider the impact on harvest age of a forest ecosystem's ability to sequester carbon. Whereas amenity values in the context of Hartman (1976) were tied to the age of the forest, or to the volume of timber on the site, carbon values are a function of the rate of change in volume – the rate of change in the forest ecosystem's biomass. Faster growing trees sequester more carbon than slower growing ones, while harvesting releases carbon in the form of CO_2. The impact of releasing carbon is to delay harvest, while the prospect of replacing mature with faster growing trees leads to earlier harvests. Which of these two outcomes dominates is determined by biophysical factors (e.g., tree species, rates of carbon uptake), what happens to the stored carbon when trees are harvested, rates at which various carbon pools release carbon, and the urgency of the need to address climate change.

Following van Kooten et al. (1995), let carbon uptake at any time be given by $\varphi\, v'(t)$, where φ is a parameter that translates m^3 of biomass into tonnes of carbon (tC), but then measured in terms of tonnes of carbon dioxide (tCO_2),[26] and $v'(t) = dv/dt$, where v(t) is timber volume (m^3) at time t. The present value of the carbon flux over a rotation of length t is given by the sum of the discounted carbon uptake benefits over the rotation minus that released at harvest:

$$(7)\quad V^C(t) = \varphi p^C \int_0^t v'(s)\, e^{-rs}\, ds - \varphi(1-\beta)\, p^C\, v(t) e^{-rt},$$

where p^c is the (shadow) price of carbon ($\$/tCO_2$); β is the fraction of timber that goes into long-term storage in structures and landfills, and is referred to as the 'pickling' factor; *r* is the discount rate; and *s* is an integration factor. Upon integrating the first term in (7) by parts, we can then rewrite (7) as:

[25] For example, if the relationship between forest age and a particular amenity value is not convex throughout, it is possible that there are multiple solutions to the optimal harvest problem. Suppose the marginal benefits of delaying harvest of a site (MB) are continuously rising, but the marginal opportunity cost of delaying harvest (MC) first rises, then falls and finally rises again. If MC intersects MB at a point where MC is falling, this is a non-optimal solution. Assuming public policy causes the forestland owner to take into account amenity as well as commercial timber values, she should be incentivized to hold off harvest until MC rises again to the point where the slope of MC is greater than that of MB (see van Kooten and Folmer 2004, pp.379-382).

[26] The molecular weight of C is 12.0107 while that of oxygen (O) is 15.9994; therefore, the ratio of the weight of CO_2 to C is 3.6642, or approximately 44/12. The atomic numbers for C and O are 6 and 8, respectively.

$$(8)\quad V^C(t) = \varphi p^C \left(\beta v(t)\, e^{-rt} + r\int_0^t v(s)\, e^{-rs}\, ds \right).$$

So that forest companies correctly take into account the external benefits and costs of their decisions, they should receive a subsidy of φp_C for each m^3 of timber added to the growing stock – an annual subsidy equal to the total value of the carbon sequestered in that year. Likewise, they should face a tax levied on any harvests during the year that equals the external cost of the CO_2 released to the atmosphere. The tax would be given by $\varphi(1-\beta)p^C$ per m^3 of timber harvested.

The value of carbon p^C is the same at the margin, whether carbon is released (a cost to society) or sequestered (a benefit). Because CO_2 does not remain in the atmosphere indefinitely, p^C is the present value, for all time, of removing one unit of carbon from the atmosphere today. It is determined as the discounted value of the annual contribution to damage caused by one tonne of CO_2 summed over the expected number of years that the CO_2 is present in the atmosphere. It is simply assumed that p^C is constant over the rotation length.

Let $V^T(t) = V(t) + V^C(t)$. Equation (4) can now be rewritten to include the value of the carbon fluxes:

$$(9)\quad V^T(t) + K = e^{-rt}\left[\left(p - c + \beta\varphi p^C e^{-rt}\right)v(t) + r\varphi p^C \int_0^t v(s)\, e^{-rs}\, ds + V^T(t)\right].$$

The financial rotation age that takes into account the value of carbon sequestration is found by setting $dV^T/dt = 0$, which leads to

$$(10)\quad \left[(p-c) + \beta\varphi p^c e^{-rt}\right]\frac{dv(t)}{dt} = r\left[(p-c)v(t) - (1-2\beta)\varphi p^c e^{-rt} v(t) + r\varphi p^c \int_0^t v(s)e^{-rs} ds + V^T(t)\right],$$

where again the LHS in (10) is the value of incremental growth of the forest and the RHS is the foregone interest on the combined value of commercial volume had the stand been harvested plus the land value, $V^T(t)$, had the land been sold as bare land at the time of harvest. The only difference with respect to the interpretation of (5) is the presence of CO_2 payments, where the landowner is paid for tree growth that removes CO_2 from the atmosphere and penalized for CO_2 released at harvest. At harvest, however, the landowner does not get penalized for any carbon that subsequently enters a carbon pool where it might be stored for an indefinite period. The pickling parameter β takes into account the future carbon fluxes in product pools, including biomass used for energy.

Solving (10) for $dv(t)/dt$, gives a result similar to (6):

$$(11)\quad \frac{dv(t)}{dt} = r\left[\left\{\frac{(p-c) - (1-2\beta)\varphi p^c}{(p-c) + \beta\varphi p^c}\right\}v(t) + \frac{\varphi p^c}{(p-c) + \beta\varphi p^c}\int_0^t v(s)e^{-rs} ds + \frac{V^T(t)}{(p-c) + \beta\varphi p^c}\right].$$

Note that, if $p^c = 0$, we recover the Faustmann result and equation (11) becomes equivalent to (6).

Notice that, in terms of Figure 8, there is no longer a straightforward tangency between the LHS and RHS of (11). The situation is illustrated in Figure 9, where the tangency between the $v'(t)$ and the RHS of (11) occurs above that of the RHS of (6) resulting in an increase in the rotation age. How much the rotation age increases depends on the parameters in (11).

Given that we do not know the value of land, we can find the optimal rotation age using the analysis in van Kooten et al. (1995). The discounted value of timber benefits over a rotation of length t is given by $V_w = (p - c)\, v(t)\, e^{-rt}$. Further, the discounted value of carbon benefits over a rotation of length t is given by $V_c = \varphi p^c \left[v(t)e^{-rt} + r\int_0^t v(s)e^{-rs}ds \right] - \varphi p^c(1-\beta)v(t)e^{-rt}$, where the second term refers to the carbon released to the atmosphere upon harvest. The present value of the timber plus carbon benefits over all future rotations is:

$$(12)\ \mathrm{PV} = \frac{V_W + V_C}{1-e^{-rt}} = \frac{1}{1-e^{-rt}}\left[(p-c)v(t)e^{-rt} + \varphi p^C\left(v(t)e^{-rt} + r\int_0^t v(s)e^{-rs}ds - (1-\beta)v(t)e^{-rt} \right)\right].$$

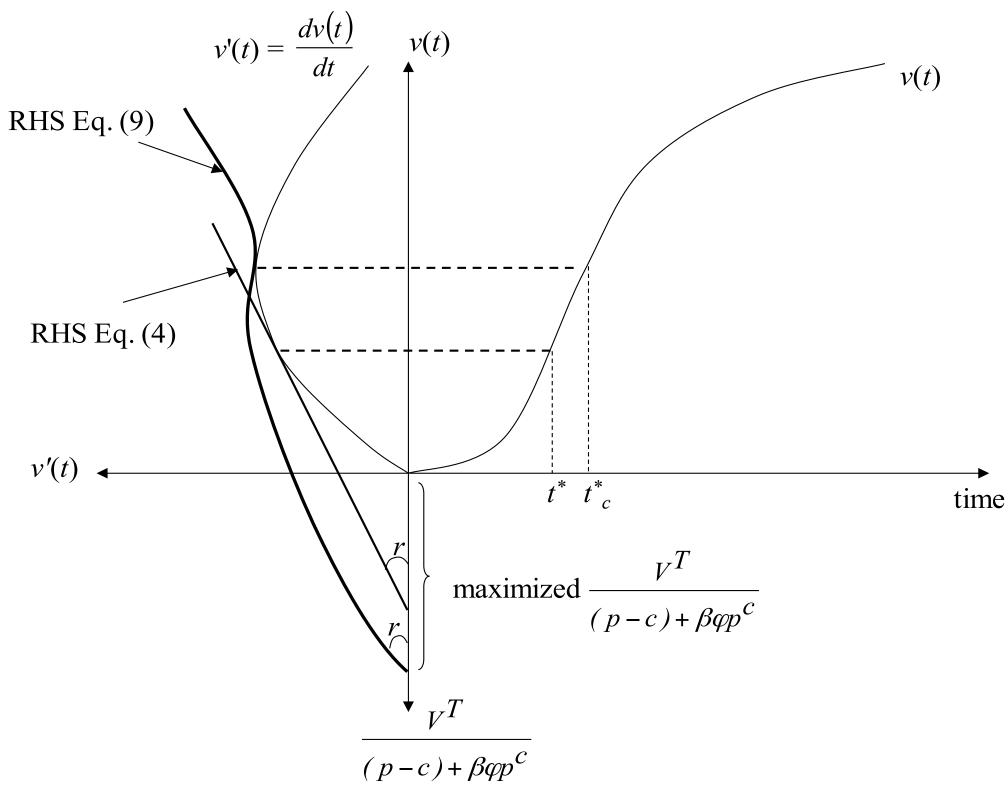

Figure 9: Determining the Optimal Financial Rotation Age when Carbon Fluxes are Priced

The optimal rotation age is found by setting the first derivative of PV to zero, which gives (van Kooten et al. 1995, p.369):

$$(13)\qquad (p-c+\varphi\beta p^c)\frac{v'(t)}{v(t)}+r\varphi p^c=\frac{r}{1-e^{-rt}}\left[p-c+\varphi\beta p^c+\frac{r\varphi p^c}{v(t)}\int_0^t v(s)e^{-rs}ds\right].$$

The optimal rotation age is found by solving for t in (13). Notice that, if $p^c = 0$, we get the standard result that the optimal Faustmann rotation age is determined from the following equation, which is identical to (3):

$$(14)\qquad \frac{v'(t)}{v(t)}=\frac{r}{1-e^{-rt}}.$$

We use these results to determine the optimal rotation age numerically for various values of timber prices and costs, tree species and their growth, prices of carbon, pickling factors, and discount rates. The background information and parameter values for three forest types are provided in Table 4, while the growth functions associated with the three forest types are provided in Figure 10 – a coastal rainforest, an interior/boreal forest and an interior forest planted with genetically-enhanced stock.

Table 4: Forest Growth Data for Western Canada

Item	Coastal Rainforest	Interior / Boreal forest	GE Interior / Boreal forest
Parameter values for $v(t) = k\, t^a e^{-bt}$			
K	0.0006	0.0008	0.0026
a	3.782	2.766	3.680
b	0.0310	0.0092	0.0580
Maximum sustained yield age (years)[a]	90	192	29
Maximum volume (m^3 ha^{-1})	1,020	340	282
Age of maximum volume (years)	122	300	63
Value of φ (kg m^{-3})	182	203	220
Average price of timber (\$ m^{-3})[b]	\$94.91	\$60.87	\$60.87
Average cost of harvesting/hauling (\$ m^{-3})[c]	\$67.07	\$34.87	\$34.87

[a] Maximum sustainable yield age is determined from $v'(t)/v(t) = 1/t$, or, in this case, $t_{MSY} = (a-1)/b$.
[b] Information on log prices from http://www.for.gov.bc.ca/hva/logreports.htm [accessed March 18, 2015]. Average prices but on the coast hemlock-balsam logs can sell for \$120-\$150/m3 and fir for \$140-\$200, while spruce-pine-fir sell \$62-\$80 per m3 in interior regions.
[c] Data from TIPSY growth model, http://www.for.gov.bc.ca/hts/growth/tipsy/tipsy_description.html [accessed March 18, 2015]. Costs can vary great in all regions due to many factors.

Rather than the generalized Richards function employed in section 4.2, we employ a single-peaked polynomial function in Table 4 (see also Appendix A); the commercial volume of timber declines after peaking, which is unlikely in the real world – more likely decay and growth would cancel one another. The growth functions in Figure 10 suggest that the forestland owner would pay taxes on carbon released after volume has peaked. Nonetheless, we use this function to emphasize the decline in commercial biomass once trees exceed some maximum volume, thereby releasing carbon to the atmosphere. However, the tax does not usually come into play or has limited impact as a result of discounting.

The results in terms of optimal rotation ages are found in Tables 5 and 6. Following Johnston and Crossley (2002), we only examine the stem dynamics rather than the ecosystem dynamics, although it would be simple to modify the model to consider carbon sequestered in all of the living and dead carbon pools (which was done in the more nuanced models of the previous section). Our primary interest is to examine the impact on post-harvest carbon pools and CO_2 emissions avoided when wood biomass substitutes for steel and concrete in construction.

Suppose that trees have no commercial value, but stands are managed for carbon uptake only. The results are provided in Table 5. As noted above, it may be optimal to harvest trees in our case because growth becomes negative and the landowner would have to pay a carbon tax as decaying trees would release CO_2 to the atmosphere – an artefact of our growth functions (Figure 10). However, we assume that, if the optimal rotation age exceeds the age at which volume is maximized, it would be wise never to harvest the trees. This is always the case if there were no post-harvest product pools that would store carbon at the time of harvest (β = 0). Otherwise, if carbon is stored in post-harvest pools, it may be worthwhile to harvest trees even if they have no commercial value. That is, even in the absence of commercial value, it is socially beneficial to harvest trees because CO_2 is removed from the atmosphere and permanently stored in structures and/or landfills, thereby mitigating the effects of climate change. This occurs only when β is at least ½ or more.

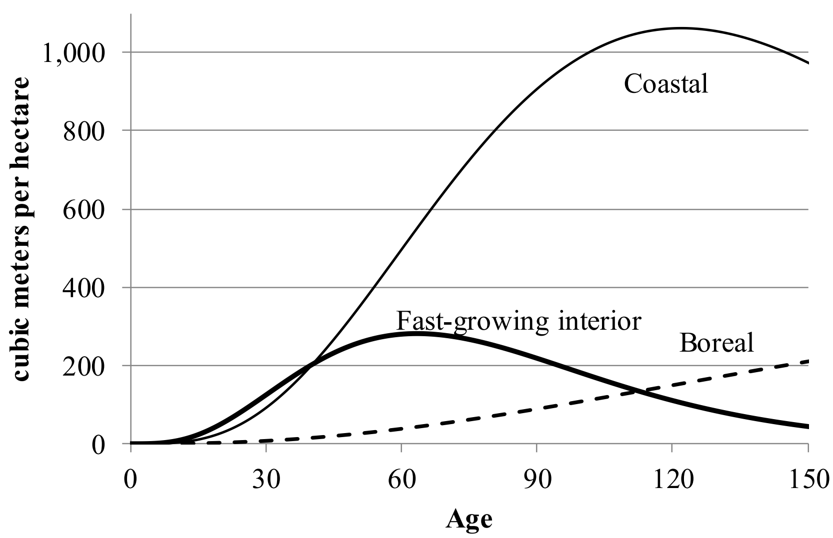

Figure 10: Growth Functions for Three Types of Forests, Coastal, Interior/Boreal and Genetically-modified Interior/Boreal

Table 5: Optimal Forest Rotation Ages when only Carbon Taxes and Subsidies are taken into Account (Commercial Value of Timber is Zero): Forest Types, Pickling Factors, and Discount Rates as Indicated (Years)[a]

Discount rate	Pickling Factor (β)			
	0	0.5	1.0	2.0
	Coastal Rainforest			
2.5%	**	68	64	62
5.0%	**	**	104	62
	Interior/Boreal Forest			
2.5%	150	82	77	74
5.0%	**	190	150	73
	Genetically-Enhanced Interior/Boreal Forest			
2.5%	**	43	40	39
5.0%	**	**	51	38

[a] ** indicates that the rotation age exceeds the age at which maximum volume is reached, so no harvest will take place.

When trees have commercial value and carbon fluxes are priced, comparative static results cannot be obtained analytically as is the case when only commercial values are taken into account (viz., Table 2). Hence, a numerical analysis is needed. The scenarios where the forest has both commercial value and value in mitigating climate change are provided in Table 6 for discount rates of 2.5% and 5.0%, and various values of the pickling factor (β) and carbon price (p^c). The log prices and harvesting costs used for these scenarios are provided in Table 4, while the GAMS code used to generate the scenarios is provided in the Appendix C. The results indicate that there may be times when the carbon benefits from leaving a forest unharvested may exceed the carbon plus commercial values from harvesting. This occurs when the pickling factor is small, $\beta \leq ½$, and the shadow price of carbon is high, $p^c \geq \$50/tCO_2$. In essence, one would not harvest trees if the costs of releasing carbon stored in the forest by harvesting exceed the benefits of harvesting and selling trees plus the subsidies earned from replanting the site with young, and thus fast-growing, stems.

Clearly, in the majority of cases, the opposite is the case – the benefits of harvesting and selling trees, plus the appropriately discounted subsequent carbon sequestration subsidies from regeneration with younger tree stock, exceed the carbon penalties of releasing CO_2 to the atmosphere. This occurs for lower carbon prices and higher values of β (the pickling factor) as indicated in Table 6. Indeed, as β increases, more of the post-harvest wood is stored in long-lasting wood product pools so that, when β = 1, there is no longer a carbon penalty attached to harvesting trees. Indeed, if β exceeds 1 (we employ β=2), the landowner or logging firm receives a carbon payment over and above the commercial value of the harvest. This occurs when avoided fossil fuel emissions in the production of steel and/or concrete are credited to the harvesting of trees as wood products substitute for non-wood in construction.

Overall, the rotation age increases as the price of carbon increases and falls with the pickling factor. Unlike with the financial rotation age where an increase in the discount rate reduced the rotation age (Table 3), the impact of changes in the discount rate is ambiguous. Finally, faster growth of the forest will reduce rotation age. These results are summarized in Table 7.

Table 6: Optimal Forest Rotation Ages when Carbon Taxes and Subsidies are taken into Account: Various Forest Types, Carbon Prices and Pickling Factors, Discount Rates of 2.5% and 5.0%[a]

Pickling factor	Financial Rotation Age	Price of Carbon $25/$tCO_2$	$50/$tCO_2$	$100/$tCO_2$	$150/$tCO_2$	$200/$tCO_2$
	COASTAL RAINFOREST			Years		
	Discount Rate 2.5%					
0		63	65	70	74	78
0.5	60	62	63	65	66	66
1		62	62	63	63	64
2		61	61	62	62	62
	Discount Rate 5.0%					
0		70	**	**	**	**
0.5	43	61	81	123	**	**
1		57	65	76	82	85
2		52	55	58	59	60
	INTERIOR/BOREAL FOREST					
	Discount Rate 2.5%					
0		75	79	86	91	96
0.5	70	74	76	78	79	79
1		73	74	75	75	76
2		72	73	73	73	73
	Discount Rate 5.0%					
0		105	175	**	**	**
0.5	42	76	138	150	**	**
1		65	83	111	130	145
2		56	61	64	67	69
	GENETICALLY-ENHANCED INTERIOR/BOREAL FOREST					
	Discount Rate 2.5%					
0		39	42	46	50	52
0.5	37	39	40	41	41	42
1		38	39	39	40	40
2		38	38	38	38	39
	Discount Rate 5.0%					
0		44	**	**	**	**
0.5	30	39	47	58	65	**
1		35	40	44	45	47
2		35	36	37	37	37

Source: Author's calculations

[a] Beginning with tree planting; ** indicates that the site remains unharvested.

Table 7: Comparative Dynamics of the Carbon-Faustmann Model

Change in:	Optimal rotation age	Change in:	Optimal rotation age
Higher r	?	Higher β	–
Higher p	–	Higher p^c	+
Higher c	+	Faster tree growth	–

As part of the debate surrounding the protection of spotted owl habitat, Harmon et al. (1990) concluded that it would be inappropriate to harvest old-growth forests in the Pacific Northwest because this would contribute to an overall increase in atmospheric CO_2. Subsequently, others have sought to protect mature forests for the same reason (as discussed above in the context of REDD+). Such an approach is clearly insufficient because it neglects the life cycle of carbon, particularly the ability to store carbon in post-harvest wood product pools. Nonetheless, there might be situations where the pickling factor is low and the shadow damage of atmospheric CO_2 sufficiently high enough to warrant leaving forests in their natural state. However, there remain the ever-present dangers of wildfire and pests, or black swan events (Taleb 2010),[27] which could strike mature forests and the ecosystem carbon they store causing massive release of carbon to the atmosphere as was the case with the mountain pine beetle infestation in the interior of British Columbia. These possibilities were not taken into account in Tables 5 and 6.

In the foregoing analysis, our focus was on the forest rotation age and not on the amounts of carbon stored; further, we did not consider the impact of biomass burning for energy. Therefore, in Table 8, we compare the carbon offset credits that might be created when post-harvest wood product pools are taken into account versus the use of wood as bioenergy. Results clearly indicate that, if climate change mitigation is a concern, post-harvest wood products sequester more carbon than can be attributed to emissions avoided from burning wood to generate electricity. This confirms our earlier results: only harvest and milling residues should be used for energy, with solid wood used to produce lumber, OSB, paper and other materials that will store carbon for an extended period. This is true even for fast-growing hybrid poplar, where wood fiber is better used for producing paper (low value of β) and wood panels (e.g., doors) and other products (higher values of β). Indeed, a strategy for mitigating climate change that relies on post-harvest wood product carbon storage will lead to 2.5 or more times the carbon offset benefits of one that relies on bioenergy from the same forest.

[27] Logging of old-growth forests in the U.S. Pacific Northwest was halted on national public lands in 1991 to protect the the Northern spotted owl under the Endangered Species Act (1972). Since then the spotted owl has been in decline due to unexpected and aggressive competition for habitat from the invading barred owl (Welch 2009). Biologists have proposed the culling of barred owl to protect the spotted owl.

Table 8: Cumulative and Annualized CO_2 Offsets Created with Spruce and Hybrid Poplar Forests, Carbon Storage in Forest Products and Biomass used to Produce Electricity in lieu of Coal, 2% Discount Factor

Pickling factor (β)	Spruce		Hybrid Poplar	
	Cumulative	Annual	Cumulative	Annual
		(tCO_2 per hectare)		
No account of harvest-related emissions				
0.0	31.3	0.6	66.1	1.3
0.5	78.4	1.6	268.7	5.4
0.8	107.3	2.1	392.8	7.9
Including harvest-related emissions				
0.0	30.8	0.6	62.3	1.2
0.5	77.9	1.6	264.8	5.3
0.8	106.7	2.1	389.0	7.8
Biomass energy, including harvest-related emissions (no pickling)				
No fuel offset	30.8	0.6	62.3	1.2
Fuel offset	30.9	0.6	62.4	1.2

Source: van Kooten (2013, p.345)

7. CONCLUDING DISCUSSION

The globe's forest ecosystems constitute important natural resources that provide commercial benefits, ecological services (e.g., water retention, waste assimilation, wildlife habitat), and recreational and non-use values. They also play an important role in the Earth's climate system, particularly as a source of CO_2 emissions and a carbon sink. Some 2,200 gigatons (Gt) of carbon are contained in terrestrial vegetation and soils, with 1,200 Gt of carbon stored in the globe's forests: 323 Gt of carbon is stored in boreal forests of Russia, 223 Gt in Canada's boreal forests, and 229 Gt, 115 Gt and 90 Gt are stored in the tropical forests of the Americas, Africa and Asia, respectively (FAO 2014). Annually 125 Gt of carbon, or nearly 460 Gt CO_2, is exchanged between vegetation and soils and the atmosphere, representing two-fifths of the total exchange between earth and the atmosphere, with forest ecosystems accounting for 80% (FAO 2014). Clearly, forests play an important role in determining the concentration of CO_2 in the atmosphere, with human activities related to deforestation, forest management, and reforestation / afforestation affecting the globe's CO_2 balance. Indeed, Tavoni et al. (2007) find that forestry activities could play a crucial role in achieving the goal of stabilizing the atmospheric concentration of CO_2 at 550 parts per million by volume – the objective of the 2009 L'Aquila meeting of the G8. They find that a global forestry program costing an estimated $1.1 trillion over nearly 100 years would provide benefits of $3.0 trillion relative to a program that meets the same objective but without forestry. The current review does not refute this finding, but does provide a perspective that calls into question cause for such optimism.

In this paper, activities that affect the uptake and release of carbon from forest ecosystems were examined primarily from an economics perspective. Our conclusion is that, while there are many ways in which forestry activities can mitigate climate change, some are more effective than others. Further, some activities preclude others, or are less cost-effective than others (van Kooten and Sohngen 2007; van Kooten et al. 2004, 2009), while some should not be undertaken at all because there are less costly alternatives (van Kooten et al. 1992). When we consider only forestry activities, this study finds that, while all types of forestry activities can mitigate CO_2 emissions, leaving forests indefinitely in an unmanaged state is generally not a good idea. Not only are forests susceptible to natural disturbance that could potentially release large amounts of carbon, but sustainable harvests and subsequent post-harvest use of wood can lead to large carbon dividends.

One post-harvest option is to burn biomass, especially logging residues and sometimes whole logs, to generate electricity as this currently appears the only economically viable use of wood for bioenergy. Nonetheless, there are constraints. In some cases, the collection of logging residues has a negative environmental impact – residues provide important nutrients to new growth. In others, costs of hauling logging residues and even roadside waste to a central processing facility are prohibitive. In yet other situations, the forests grow too slowly to recover within an acceptable time period the initial pulse of CO_2 entering the atmosphere from burning. Only for fast-growing species that might better be considered agricultural crops will there be a carbon dividend from bioenergy. As demonstrated here, co-firing wood pellets with coal to generate electricity will almost always lead to a carbon debt if there is any degree urgency to mitigate climate change. Nonetheless, in some cases, wood pellet production using sawmill residues, or even logging residues, makes sense from an economics and climate standpoint.

Overall, when all carbon sinks and forgone CO_2 emissions are taken into account, commercial forestry makes sense from a climate mitigation standpoint because of the post-harvest use of fiber. Post-harvest carbon is stored in lumber and other wood product sinks, while regeneration of harvested sites with younger, faster-growing trees (often the result of planting genetically improved growing stock) sequesters more carbon than the mature trees that were harvested. Where forest products substitute for steel and/or concrete in construction, the forgone emissions in the production of non-wood construction materials can also be counted towards the commercial activities. Finally, wood fiber not used to produce products or pulp can be burned to generate electricity, thereby reducing CO_2 emissions from fossil fuel burning. No fiber is left to decay except fiber that is needed to restore ecosystem health and fiber that is too costly to remove from the site, as its removal might well have led to greater CO_2 emissions than those that would have been saved by burning the waste fiber in place of fossil fuels.

There remain a couple of other issues that militate against the use of forestry activities to address climate change. The first is obvious: How compatible are short-lived forest carbon offsets with permanent CO_2-emission reductions? There have been all sorts of machinations to deal with the duration issue (van Kooten 2009a). Temporary certified emissions reductions (tCERs) enable buyers to offset emissions for one year, say year t, but the emissions in t must still be dealt with in years t+1, t+2 and so on; long-term CERs (lCERs) offset emissions for a compliance period of five years, and must then be covered by a permanent offset at the conclusion of the compliance period (van Kooten 2013, pp. 355-358). Keeping track of temporary and long-term CERs from forestry activities increases transaction costs and leads to governance issues.

Second, just as forests are susceptible to natural hazards, so the accounting of carbon fluxes is susceptible to the governance factors that were discussed in the paper. Whether in the voluntary or compliance market, carbon offsets from forestry activities can be employed as long as they are recognized by a reputable certifier. Because it is difficult to determine carbon fluxes over time from any one activity, let alone an activity measured against a counterfactual, and taking into account leakages and other pitfalls, the task of determining what might constitute a true flow of carbon offsets for any given scenario is almost impossible and certainly very costly. Even at the low prices at which carbon offsets trade in voluntary markets, verified carbon units can earn millions of dollars for their owners. Thus, rent seeking and the potential for corruption is unavoidable (van Kooten and de Vries 2013; Malmsheimer et al. 2011).

While forest ecosystems should be included in efforts to mitigate climate change, it is our opinion that the only viable instrument for doing so is a tax-subsidy scheme that integrates forest activities into a more general carbon tax scheme, and allows for post-harvest use of fiber, including, importantly, post-harvest wood product carbon sinks and emissions avoided when wood substitutes for non-wood construction materials. To implement such a scheme might require a contract that includes a simple forest inventory and yield model, the rate of decay of post-harvest fiber (based on age of harvest and anticipated use of logs by downstream processors), schedules pertaining to the crediting of avoided emissions (where wood is used in lieu of fossil fuels or less concrete and steel is produced), and satellite images of land use and land use changes. The authority or certifier need only confirm land use and how it changes to determine annual subsidy payouts or tax payments. More research into these types of contracts is required to determine the potential for carbon offsets in compliance and voluntary markets.

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APPENDIX A: ALTERNATIVE TREE/FOREST GROWTH FUNCTIONS

Some alternative growth functions are the following:[28]

Generalized Richards: $v(t) = L + \frac{U - L}{\left(1 - \beta e^{-kt}\right)^{\frac{1}{m}}}$, where *L* and *U* are the lower and upper asymptotes of the tree growth function, say volume (*v*) on a forest stand, t is the age of the trees, *m*>0 is the slope of growth (i.e., it affects the asymptote nearest to which maximum growth occurs), *k* is the growth rate, and β is a shape parameter determining the growth range.

Chapman-Richards: $v(t) = U(1 - \beta e^{-kt})^{\frac{1}{1-m}}$, where *U* is the upper asymptote, β is the growth range, *k* is the growth rate, and *m* is the slope of growth.

Generalized logistics: $v(t) = L + \frac{U - L}{1 - \beta e^{-kt}}$, where *U* and *L* are the upper and lower asymptotes, respectively, β is the growth range, and *k* is the growth rate. If *L*=0, then *U* can be interpreted as the carrying capacity as found in the traditional logistics growth function.

Logistics: $v(t) = \frac{U}{1 - \beta e^{-kt}}$, where parameters are defined as above.

Log-logistics: $v(t) = \frac{U}{1 - \beta e^{-k\ln(t)}}$, where parameters are defined as above.

Brody: $v(t) = U - (U - L)e^{-kt}$, where *U* is the upper limit to growth (asymptote), *L* is the volume at time zero, i.e., *v*(0)=*L*, and *k* is the growth rate.

Schnute: $v(t) = (R + \beta e^{-kt})^{m}$, where *R* is a reference value, β is the growth displacement, *k* is the growth rate, and *m* is the slope of growth.

Mitcherlich: $v(t) = U - \beta e^{kt}$, where parameter *U* refers to the upper asymptote, β is the growth range and *k* is the growth rate.

Gompertz: $v(t) = Ue^{-\beta e^{-kt}}$, where *U* refers to the upper asymptote, β is the growth range and *k* is the growth rate.

[28] Information on growth rates is from http://cran.r-project.org/web/packages/growthmodels/growthmodels.pdf [accessed April 1, 2015], which provides R code for calculating growth functions, and Fekedulegn et al. (1999).

von Bertalanffy: $v(t) = [U(1-m) - \beta e^{-kt}]^{\frac{1}{1-m}}$, where parameters are defined as above.

Weibull: $v(t) = U - \beta e^{-kt^{m}}$, where parameters are defined as above.

Single-peaked polynomial: $v(t) = R\, t^{a} e^{-kt}$, where R is a reference value, $a>0$ is a growth shape parameter, and k is the growth rate. Setting the first derivative of $v(t)$ equal to zero, i.e., $v'(t)=0$, and solving gives a peak volume at time $t = a/k$ of $v_{max} = R\,(a/k)^{a}\, e^{-a}$. This model is used in section 5 to emphasize the decline in commercial biomass once trees in a certain location exceed some maximum volume, thereby releasing carbon to the atmosphere.

APPENDIX B: R CODE FOR CALCULATING RESULTS IN SECTION 4.2

```
# Modeling forest growth and carbon uptake

library('growthmodels');
L <- 0; U <- 600;
beta <- 1.01; k <- 0.085; m <- 0.08;              # Coastal data Generalised Richards
#beta <- 1.5; k <- 0.025; m <- 0.25;              # Interior data Generalised Richards (k is growth rate)
Cwood <- 0.2777775; # tons of carbon per m3 (average of softwoods and hardwoods)
convert <- 44/12;                                 # conversion of carbon to CO2
emitcoal <- 0.94;                    # Emissions of CO2 per MWh for subbituminous coal (tCO2/MWh)
coaluse <- 0.531;                    # tonnes of subbituminous coal need to produce 1 MWh electricity
emitbio <- 1.27;                 # Emissions of CO2 per MWh for average hardwood & softwood biomass
mature <- 151;                   # years in horizon
wooduse <- 1.246;                # Cubic meters of wood needed to produce 1 MWh
coarse <- 1.57;               # factor to take into account non-commercial coarse woody material to burn

t <- 1:mature
#volume <- chapmanRichards(t, U, beta, k, m);
#volume <- gompertz(t,U,beta,k);
volume <- generalisedRichard(t, L, U, k, m, beta);
aa <- t(volume);
gvol <- t(aa[,-1]-aa[, -ncol(aa)])                # taking the difference between rows to get change in volume
carb <- Cwood*convert*gvol*coarse;       # tCO2 each year, not discounted (incl coarse material)

disc <- 0;                                        # starting discount rate on physical carbon
iter <- 5;                                        # iterations for discount rate change
dcarb <- array(0, c(mature-1, iter))       # discounted tCO2 each year
tt = t-1;

for (i in 1:iter) {
  discfac <- 1/(1/((1+disc)^-tt));
  discfac <- discfac[1:(length(discfac)-1)];
  dcarb[,i] <- discfac*carb;   # discounted tCO2 each year
  disc <- disc + 0.025;
}

cumcarbon <- apply(dcarb, 2, cumsum);   # cumulative discounted tCO2 each year over 2nd dimension
harvest <- U*coarse;                              # Amount of biomass harvested
initialemit<-(emitbio - emitcoal)*harvest/wooduse; #initial emissions from wood & saved coal emissions
atmoscarbon <- initialemit - cumcarbon;
xx <- atmoscarbon/atmoscarbon[1];       # divide to normalize values
write.csv(xx, file='carbon.csv')                # These two files are then used to create plots
write.csv(volume, file='vol.csv')
```

```
# ---------------------------------------------------------------------------------
# The following finds the optimal financial rotation age:   v'(t)/v(t) = r/(1-exp(-rt))
# where v(t) is the generalised Richards growth function -- volume a function of age
# ---------------------------------------------------------------------------------

library('nleqslv');  # solver for finding the solution to nonlinear function
rate <- 0.025;  #reset the discount rate for finding optimal rotation age

fun <- function (x) { beta*k*(1-exp(-rate*x))*exp(-k*x) - rate*m*(1+beta*exp(-k*x)) };

xstart <- 30;  # starting value for finding solution
rotationage <- nleqslv(xstart, fun, jac=NULL, method = c("Broyden", "Newton"), control=list(xtol=0.25));
"The optimal rotation age is" ; round(rotationage$x, digits=0)
```

APPENDIX C: GAMS CODE FOR CALCULATING THE OPTIMAL ROTATION AGE

```
$Title Calculate rotation ages based on maximizing equation (10)

$Oneolcom
$eolcom #
SETS
 t          periods  / 0*150 /
 tinit(t)     first time period
;
 tinit(t) = yes$(ord(t) eq 1);
 alias(t,s);

* Formula for calculating rotation ages: v(t)=k*t^a*exp(-b*t)
PARAMETERS
  k                /0.0026/
  a                /3.680/
  b                /0.058/
  ph   kg of carbon per m3 /220/
  beta pickling factor /0/
  Pc   price of carbon per tC /0/
  Pw   price of wood per m3 /60.87/
  dr   discount rate       /0.05/
  cst  harvest cost per m3  /34.87/
* From TIPSY, harvesting and hauling costs are $34.87 to $35.95 per m3
* in the interior, while logs sell for $60.87 ($62 to $80) per m3.
* On the coast, logs sell for $94.91 ($120 to $150 hembal, $140 to $200 fir)
* per m3 while fixed costs are about $30.91 (or $53.33) per m3 and variable
* costs of $36.16 per m3: Total cost are $67.07.
;

PARAMETERS
    phi         carbon kg converted to tonnes CO2
    age(t)       age of forest
    vol(t)      volume in each period
    dvol(t)      sum of discounted volume from beginning to period t
    Term1st(t)   first term in PV expression
    Term2nd(t)   second term in PV expression
    value(t)     present value in each time period
;

 phi = ph*44/12000;
 age(tinit)=0;   # Note the required change here follows definition of t
  loop (t, age(t+1) = age(t)+1);
 vol(tinit) = 0;
 vol(t)$(not tinit(t)) = k*(age(t)**a)*exp(-b*age(t));
 dvol(tinit) = 0;
   loop(t, dvol(t+1) = dvol(t) + vol(t+1)*exp(-dr*age(t+1)));
```

```
 Term1st(t) = Pc*phi*(vol(t)*exp(-dr*age(t)) + dr*dvol(t));
 Term2nd(t) = (Pw-cst-Pc*phi*(1-beta))*vol(t)*exp(-dr*age(t));
 value(tinit) = 0;
 value(t)$(not tinit(t)) = (Term1st(t) + Term2nd(t))*dr/(1-exp(-dr*age(t)));

Display Term1st, age, dvol, value;

VARIABLES
   bin(t)    binary variables
   z         objective value
;
Binary Variables bin;

EQUATIONS
  restrict    restriction that binary variables sum to one
  obj         objective function
;

*---------------------------------------------------------------------------
restrict..   sum(t, bin(t)) =E= 1;

obj..   z =E= sum(t, bin(t)*value(t));

MODEL Rotation /all/;

file rotate /RotationAge.csv/;
put rotate;
put 'Carbon Price',',','Pickling factor',',','Rotation Age'/;

FOR (dr=0.025 to 0.10 by 0.025,
 put 'Discount rate', ',', dr/;
 FOR (Pc=0 to 200 by 25,
  FOR (beta=0.0 to 2.0 by 0.5,
   Term1st(t) = Pc*phi*(vol(t)*exp(-dr*age(t)) + dr*dvol(t));
   Term2nd(t) = (Pw-cst-Pc*phi*(1-beta))*vol(t)*exp(-dr*age(t));
   value(t)$(not tinit(t)) = (Term1st(t) + Term2nd(t))*dr/(1-exp(-dr*age(t)));

   SOLVE Rotation maximizing z using MIP;
     loop (t, if(bin.l(t) eq 1, put Pc, ',', beta, ',', t.tl /););
  );
  put /;
 );
);
putclose rotate;
```