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Economics of Fossil Fuel Substitution and Wood Product Sinks when Trees are Planted to Sequester Carbon on Agricultural Lands in Western Canada

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Abstract

In order to meet its international commitment to reduce CO_2 output by 7% from the 1990 level by 2012, Canada intends to lean heavily on carbon uptake through afforestation of marginal agricultural land. The economics of afforestation is examined for Northeastern British Columbia and all of Alberta, with harvested wood used either as a replacement for coal in energy production or as a wood–product sink. Some 7 million ha of marginal agricultural land are identified, but very little could reasonably be afforested if wood is used as a substitute for coal. If C is stored in wood products, nearly one–third of the land might reasonably be planted to trees; if similar results hold for the rest of Canada, afforestation can be included in the policy arsenal. Before that can be done, however, some serious issues need to be resolved, including problems associated with the mechanism used to transfer land out of agriculture into plantation forest.

Introduction

Climate change is considered by some to be the world's most important environmental policy issue (Clinton and Gore 1993). Concern about anthropogenic emissions of greenhouse gases (GHGs), particularly CO_2, led the World Meteorological Organisation (WMO) and the United Nations Environment Program jointly to establish the Intergovernmental Panel on Climate Change (IPCC) in 1988. The first IPCC report was published in 1990; it led to the signing of the United Nations' Framework Convention on Climate Change (FCCC) in Rio de Janeiro in June 1992. The Convention committed signatories to stabilise atmospheric CO_2, with developed countries to reduce emissions to the 1990 level by 2000. The IPCC's second assessment report in 1996 (Houghton *et al*. 1996) was endorsed by the Second Conference of the Parties (COP) to the FCCC. Following this, at the Third COP in December 1997 at Kyoto, Japan, developed countries agreed to curtail their CO_2 emissions, but by varying levels. The US committed to reduce emissions to 7 percent below 1990 levels by the year 2012 (the actual commitment period for measurement purposes is 2008–2012). EU countries agreed to reduce emissions to 8% of 1990 levels by 2012, as did countries hoping to gain membership to the EU sometime in the future. Canada and Japan agreed to a 6% reduction, while Australia agreed to limit its increase in CO_2 emissions to no more than 8% by 2008 and Iceland to an increase of no more than 10%. Other developed countries agreed to limits that fell between the EU's 8% decrease and Australia's 8% increase. The Kyoto Protocol does not commit developing countries to CO_2 emission reduction targets, even though their emissions will soon account for more than one–half of total global emissions.

In 1990, Canadian emissions of CO_2 amounted to 596 million metric tonnes (Mt) of CO_2–equivalent GHG emissions, or 162.5 Mt of carbon (C); in 1996 (the latest year for which data are available), emissions amounted to 669 Mt of CO_2, or 182.4 Mt of C (Jacques 1998). Business as usual scenarios project annual emissions to remain stable to 2000, and then rise to 203.2 Mt of C in 2010 and 225–230 Mt in 2020 (see McIlveen 1998). To meet the Kyoto target, Canadian emissions must be 152.7 Mt C (560 Mt CO_2), some 25% (or 50.5 Mt C) below the level expected in the commitment period.

The Kyoto Protocol allows countries to claim as a credit any C sequestered as a result of afforestation (planting trees on agricultural land) and reforestation (planting trees on denuded forestland) since 1990, while C lost as a result of deforestation is a debit. The forest component of the Protocol has several interesting aspects, although each of these is under review as countries seek clarification on the Protocol's interpretation of terrestrial C sinks, especially forest sinks (see Canadian Forest Service 1998). Deforestation is defined as a change in land use, so when a site is harvested but subsequently regenerated there is no change in use and only the C credits associated with reforestation are counted, not the costs of C release. For example, if a mature forest stand is harvested sometime after 1990 and subsequently replanted before 2008, only growth of the newly established stand is counted as a credit; the debit from harvest is not counted. Only deforestation during the period 2008–12 is counted as a debit, and only the average annual growth on newly planted sites over the period 2008–12 is counted as a credit. Finally, only the commercial (and measurable) component of the trees is counted, so changes in soil carbon, for example, might be ignored, although this is also open to future negotiations (Canadian Forest Service 1998).

Canada expects a large part of its international commitment to reduce CO_2 emissions to come from forestry, with perhaps 25–40 percent of its Kyoto commitment coming via tree planting (see Canadian Forest Service 1998; Guy and Benowicz 1998: Nagle 1990). The federal government has created a “tables” process to examine various means of achieving its CO_2–reduction commitment (Environment Canada 1998). Afforestation of agricultural lands features prominently in this process (Canadian Forest Service 1998). The focus of investigations into afforestation (Nagle 1990; Guy and Benowicz 1998; and contracts that have been let) has been on identification of suitable (marginal) agricultural lands and the potential growth of trees to be planted. For the most part, economics has been ignored. In this study, we seek to rectify this shortcoming by examining the economics of afforestation in Alberta and the BC Peace region. In particular, we identify marginal agricultural lands and consider the costs of sequestering C on these lands when fast–growing, hybrid poplar is planted. Our perspective is longer than that of Kyoto, because we feel that the time required to establish plantations for C uptake on a large (massive) scale is too short to have much relevance for the Protocol’s commitment period. Rather, we consider the long term, which means finding a use for wood when it reaches maturity. Two uses are examined: substituting wood for coal as a fuel in energy production and storing C in paper and other wood products.

The cost–benefit analysis is in terms of discounted costs per physical unit (tonnes) of C uptake. While costs are to be discounted, a major source of contention in such cost–benefit analyses concerns the issue of whether physical carbon should be discounted, with the economist arguing in favour of discounting. Richards (1997) demonstrates that the time value of carbon will depend on the path of marginal damages—that is, on the concentration of atmospheric CO_2. If marginal damages are constant over time, then C storage can be discounted at the social rate; the more rapidly marginal damages increase over time, the less future C fluxes should be discounted. Given uncertainty over the relationship between atmospheric CO_2 concentrations and global climate change, and between climate change and economic damages, we have no *a priori* reason not to discount future C fluxes. In this study, we consider both cases where physical C is discounted and where it is not. When physical C is not discounted, it does not matter when (and thus if) C is sequestered. However, as we note below, when a no discounting scenario is included, a difficulty arises with respect to how one treats an infinite flow of C (see Richards and Stokes 1995).

Value of Agriculture and Tree Planting Costs

We investigate the potential for and costs of terrestrial C sequestration in Northeast BC and Alberta. Current agricultural land uses in the BC Peace River region and the seven Agricultural Reporting Areas (ARA) in Alberta are provided in Table 1 (Statistics Canada 1997a, 1997b). In the table, improved land includes non–forage crops, forage, fallow, pasture and other land, while unimproved land contains mainly pasture.

Table 1: Farmland Area Classified by Land Use (ha)

	Improved land					Unimproved land	
Region	Non–forage crops	Forage	Fallow	Pasture	Other	Pasture	Other
BC Peace	137,585	119,584	29,608	96,991	8,372	282,545	150,693
Alberta ARA							
1(S east)[a]	758,862	111,072	409,004	218,121	36,764	2,090,655	36,764
2 (S central)[a]	1,544,105	135,252	415,483	178,540	32,640	903,954	32,640
3 (S west)	857,419	216,449	83,443	194,053	77,602	1,039,605	129,337
4a (E central)	821,625	115,872	127,406	180,642	18,571	498,009	92,857
4b (E central)	1,055,335	128,412	110,745	186,410	19,614	338,949	117,684
5 (Central)	800,479	435,667	46,080	360,777	47,979	557,366	167,927
6 (N east)	591,720	446,670	76,622	351,051	24,372	685,566	268,096
7 (N west)	1,193,462	334,144	167,958	245,009	28,473	501,393	370,153

[a] ARAs 1 & 2 have irrigated forage production, are too dry for planting trees and are excluded from further analysis.

The agricultural land types considered suitable for afforestation are primarily those associated with forage production and pasture. However, for each sub–region, it is necessary to determine the specific agricultural land–use types appropriate for afforestation, and the value of those lands in agriculture. The land suitable for afforestation in the BC Peace River region is a mixture of land in crops, improved pasture and improved idle land. Since unimproved pasture (and crown range) consists mainly of pea vine and vetch that grow under mature aspen stands, it is forested already, and thus cannot be considered for afforestation. The same might be true for the two most northern Alberta regions (ARAs 6 & 7). Nonetheless, we assume that unimproved pasture can be grown to trees. If not, then the amount of marginal agricultural land available for planting is some 1.20 million ha less than employed in this study.

Land in crops that can be considered for growing trees is in forage (hay and alfalfa). For ARAs 3, 4 & 5, unimproved pasture is also considered suitable for afforestation. ARAs 1 & 2 are characterised by irrigated forage production and are considered too dry for planting trees. Therefore, they are excluded from further analysis, although it may turn out that growing trees using irrigation may be an economically viable C uptake option. Improved idle land ("other"), improved pasture and land in forage production are also considered to be "marginal" agricultural lands for the purpose of this study.

The total amount of marginal agricultural land that we consider suitable for planting to trees is 7.25 million ha. Little economic data is available for improved "other" land, so it is ignored in the analysis. This leaves 7.03 million ha of marginal agricultural land that we consider suitable for afforestation for C uptake. Estimates of the costs per tonne of carbon sequestered for each of these land types requires data on the net returns associated with the current agricultural activity (the opportunity cost of afforestation), the direct costs of afforestation, and the C uptake associated with the trees to be planted.

Data for hay production in British Columbia are from the *Planning for Profit Enterprise Budgets* (BC Ministry of Agriculture and Food 1995, hereafter BCMAFF). To estimate the differences in returns across regions of Alberta, representative yields and prices obtained from Alberta Agriculture (1998) are used for each of the ARAs.

Pasture is treated somewhat differently. A good market exists in both British Columbia and Alberta for private pasture rental. Rents are based on a standardised animal unit month (AUM), which is the forage consumed per month by a 450–kg cow. Using data for each ARA on stocking rates in AUMs per ha (Wroe *et al*. 1988) and the private market value of an AUM of pasture use (Bauer 1997), the opportunity cost of lost pasture use is estimated.[1] The costs per hectare of lost forage and pasture production for all regions are provided in Table 2.

Table 2: Net Annual Returns to Current Agricultural Activities ($ per ha)

REGION	Forage[a]	Improved Pasture	Unimproved Pasture
BC Peace	184.98	34.45	n.a.
Alberta, ARA			
1(Southeast)	185.75[b]	17.51	8.75
2 (South–central)	304.04[b]	23.64	11.82
3 (Southwest)	310.20	35.82	17.33
4a (East–central)	101.47	24.84	12.42
4b (East–central)	116.80	28.35	14.02
5 (Central)	260.56	46.93	20.26
6 (Northeast)	168.63	58.01	21.04
7 (Northwest)	178.75	34.45	15.15

[a] Forage is based on the net returns for hay and alfalfa, weighted by the production of each within the region.

[b] ARAs 1 & 2 have irrigated forage production, are too dry for planting trees and are excluded from further analysis. The data is presented for comparison purposes only.

The additional cost component that must be accounted for is the direct cost of afforestation, or planting cost. Direct afforestation cost depends on the species chosen for planting. For various regions of the Canadian Prairies, there are different species that could be considered for planting on agricultural land for the purpose of C uptake. For all regions, we consider fast growing hybrid poplar. We also consider planting a mix of species out of concern for biodiversity, although no attempt is made to value it. Using information from BC's *Planning for Profit Enterprise Budgets* (BCMAFF 1996), it is assumed that planting costs for hybrid poplar are $1270 ha^{-1}.[2]

Afforestation and Carbon Uptake

Carbon is stored in trees (stem, branches, leaves and root), understory, forest litter and forest soils. We calculate storage of C in total tree biomass (including roots) and, although inclusion of

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[1] The bulk of pasture/range use comes from public lands, which have long–term lease agreements. The price associated with these leases is considerably less than the value of forage consumed (Bauer 1997), and thus not reflective of the true social value of forage.

[2] An establishment cost of $514 per acre is reported. However, subsequent work by Robinson Consulting and Associates places establishment costs of conventional species in BC at $1,500 per ha and hybrid poplar at $4,000 per ha given a 12 year rotation (Gary Robinson, pers. comm., February, 1999). Estimates for establishment of hybrid poplar in northern Minnesota are in the range US$285–$338 (C$425–$504) per acre (Agricultural Utilization Research Institute 1997), or close to those used in this study.

C stored in forest soils, floor and under–story is still under discussion, we provide some estimates of changes in soil C. Calculation of the stream of C uptake over a specified time horizon requires estimates of tree growth (see Nagle 1990). We employ the Chapman–Richards function:

$$(1) \qquad v(t) = A(1-e^{-kt})^{m},$$

where A is maximum stem wood volume and k and m are parameters (Guy and Benowicz 1998). Hybrid poplar is generally chosen for C uptake because of its rapid rates of growth, and it is considered here. However, many clones exist and "… quoted growth rates of hybrid poplar vary tremendously across Canada and the northern USA making it difficult to estimate average values for each region" (Guy and Benowicz 1998, p.8). Available data on growth rates have been obtained under various management regimes, including fertilisation and irrigation. In this study, we use different parameter values for hybrid poplar in the boreal and prairie regions. For the boreal region, we set A=329 and k=0.156; for the prairie region, A=270 and k=0.143; m=3.0 for both zones (see Guy and Benowicz 1998).

Total C uptake is determined by the wood found in the bole (or commercial component of the tree), which is given by growth function (1), multiplied by an expansion factor (=1.57) to obtain total above–ground biomass. Root biomass (R) is related to above–ground biomass (G) as follows, with both measured in tonnes per ha:

$$(2) \qquad R = 1.4319\, G^{0.639}.$$

Finally, the carbon content of timber in the study region averages 0.187 t per m^3 for hardwoods (van Kooten *et al*. 1993, p.244–45).

To the carbon stored in biomass, we must add the change in soil C. Data on soil C is difficult to obtain. Field trials in the northern Great Plains of the US indicate that sites with hybrid poplar have an average of 191 tonnes of C per ha in the top 1 metre of soil, row crops an average of 179 t of soil C, and grass that is regularly cut 157 t per ha (Hansen 1993, p.435). However, grassland in the more humid eastern portion of the Great Plains rapidly loses some 20% of its soil C when cultivation occurs, implying that native grassland may contain as much as 224 t of soil C per ha, although the amounts would be lower in the more arid western region (p.431). Soil C rebuilds only slowly when cultivation stops. Older stands of hybrid poplar (average 15 years) in Hansen's sample averaged nearly 116 t of soil C per ha (p.435). Guy and Benowicz (1998) note that forest soils in the study region store some 108 tonnes of C per ha compared to cropland that stores some 60 t. Using this last relation and assuming that 2% of the difference is sequestered each year when land is converted from agriculture to forestry, 0.96 t of C yr^{-1} ha^{-1} is added to soil each year for 50 years when an equilibrium is reached (or 48 t ha^{-1}). Determining soil carbon associated with various uses of agricultural land is difficult. Given that Hansen (1993) finds row crops store more C than grassland that is regularly cut, we simply assume that there is no difference in the C sink potential of different agricultural land.

Substituting Wood for Fossil Fuels

Most trees grown on agricultural land will be used for pulpwood or burned for energy production, thereby replacing an energy–equivalent amount of fossil fuel in the generation of electricity. We consider the wood burning option first. When wood is burned in place of oil, natural gas or coal, it is necessary to determine the rates of C emissions for similar heating values. The relevant conversion factors are found in Table 3.

Table 3: Carbon Emission Factors for Selected Energy Sources[a]

Fuel	Higher Heating Value[b] (MJ per kg)	Carbon Content (kg C per kg fuel)	Carbon Coefficient (kg C per GJ)	Carbon Coefficient (incl. 99% combustion efficiency) (kg C per GJ)
Wood	15.5–19.7[c]	0.500	25.6[d]	25.3[d]
Coal	29.31	0.707	24.12	23.9
Natural gas	0.0317 (m^{-3})	0.482 (m^{-3})	13.78	13.6
Crude oil	42.82	0.850	19.94	19.7
Kerosene (jet fuel)	46.5	0.858	18.45	18.3
Gasoline	47.2	0.869	18.41	18.2
Diesel fuel	45.7	0.865	18.93	18.7
Liquid petroleum gas	50.0	0.818	16.36	16.2

[a] Power is the rate at which energy is transferred and is usually measured in watts (W), with 1 W=1 joule (J) per second (s), with 1 kilowatt hour (kwh)=3.6×10^6 J. One J is the work done when a force of 1 newton (1 N=1 kg m s^{-2}) is applied through a distance of 1 meter (m). 1 megajoule (MJ)=10^6 J; 1 gigajoule (GJ)=10^9 J; 1 petajoule (PJ)=10^{15} J. See Watson *et al*. (1996, p.79). [b] High heating value includes the energy of the condensation of water vapour contained in the combustion of products. In calculating C emissions, Canada and the US use high heating value while the rest of the world uses low heating value (Marland, pers. comm., 23-Dec-98; see also Watson *et al*. 1996, p.80; Marland *et al*. 1995).

[c] Low value is converted from Slangen *et al*. (1997, p.324); high value calculated from data in Table.

[d] Marland, pers. comm., 23-Dec-98, Marland and Pippin (1990)

In the study region, electricity is generated using natural gas, coal and hydro, with coal accounting for about 90% of the total. Therefore, we assume that burning wood biomass would replace an energy–equivalent amount of coal. Assuming 187 kg of C per m^3 of poplar biomass and using data in the last column of Table 3, we calculate that some 7.4 GJ of energy are released per m^3. However, using the lower range for heating value from the first column, we find that 5.8 GJ of energy are released per m^3. Using data in Table 3, we find coal releases some 29.4 GJ of energy per tonne. However, Natural Resources Canada (1997) uses an higher heating value (HHV) for sub–bituninous coal of 18.8 GJ per tonne, while the Government of Alberta (1999) reports an HHV of 19.3–26.7 GJ t^{-1} for coal. Using the latter values for coal, then, if poplar is burned in place of coal, some 2.6–4.6 m^3 of wood are needed for every tonne of coal replaced in order to generate an equivalent amount of energy. Finally, Girouard *et al.* (1996) report prices of $2.50–$4.00 per GJ as costs for fossil fuels (natural gas, coal and heavy fuel oil). For wood, CSL (1994) indicate a price of $40 per tonne, which translates into an energy price of $2.58 per GJ for the lower range of HHV for wood (Table 3). Using the latter price, we obtain a value of $7.50 per m^3 for poplar used in production of electricity.

It is assumed that hybrid poplar is planted and harvested after 15 years. At that time, the volume of timber available for harvest is 242.8 m^3 in the boreal region and 185.8 m^3 in the prairie region; respective MAIs at age 15 are 12.9 m^3 and 11.1 m^3. For convenience and to ensure a consistent supply of wood in the future, only one–fifteenth of the area available for afforestation is planted in each year. Even this may be an optimistic assumption as there will undoubtedly be delays (and transaction costs) associated with negotiations between government and farmers, and limits to the amount of area that can be planted in a given year.[3]

We keep track of carbon build–up in five different accounts, plus the fossil fuel substitution account (see also AACM International Pty Limited 1998). Besides the C saved from fuel substitution, the most important account is the bole or merchantable component of the tree. Equation (1) provides the growth of volume for this component, which is translated into C by multiplying by 0.187 t C m^{-3}. Carbon builds up in the bole until year 15, when it is assumed to enter into another account (e.g., wood products) or the atmosphere (by burning). A new stand of trees replaces the old, with the process assumed to continue indefinitely.

Next is above–ground biomass, not including the bole component, which consists mainly of branches and leaves. It is found using an expansion factor on merchantable volume and, in this case, constitutes 0.57 of bole volume. When trees are cut, all of the non–merchantable biomass is left on the site as slash. At that time, it enters the litter account, which is treated below. When a new stand of trees is planted, there is re–growth of the non–bole biomass. In this sense, the non–merchantable biomass is treated much like the merchantable component.

Third, carbon in the root pool is calculated from relation (2) for hardwoods. We assume a one–time growth in roots, after which decay causes C to enter the soil pool at a rate exactly offset by the rate at which new growth adds to the root pool.

Fourth, it is assumed that soils continue to increase in C content at a rate of 0.96 t per year for 50 years, after which soil C remains in balance (additions to soil C from roots and litter decay equals release to the atmosphere), unless land is converted to a use other than forestry. The overall gain to the soil C sink from afforestation can be determined from the following formula:

$$\text{(3a)} \qquad C_S = c_S\left(\frac{1-(1+r)^{-50}}{r}\right), \text{if physical C is discounted}$$

$$\text{(3b)} \qquad C_S = 50\, c_s, \qquad \text{if physical C is not discounted,}$$

where C_S is the (discounted) amount of carbon in the sink pool in equilibrium, c_s (=0.96 t) is annual addition of C to the soil sink and r is the social discount rate.

Finally, the litter pool consists of dead or dying biomass on the forest floor that releases C to the atmosphere through fire and decay and to the soil pool. It is a relatively small pool of C that changes rapidly. We assume that the litter account grows by a constant amount each year for 50 years, after which it is in equilibrium. At that point it is assumed that the litter pool is one–half the non–bole biomass. Equation (3a) can be used to determine the amount of (discounted) C in the litter account (C_L), with C_L and c_l (annual addition to litter pool) replacing C_S and c_s, respectively. For the boreal region, c_l=0.26 t C, while c_l=0.20 t C for the prairie zone.[4] In addition, there is a spike in the pool's biomass at harvest time. It is assumed that the slash component of the litter releases a constant amount of C into the atmosphere over the next 15 years so that it is depleted by the time of next harvest. This carbon spike and subsequent decay is important only if physical C is discounted; otherwise, it is zero.

A summary of the carbon sink pools when hybrid poplar is grown and harvested every 15 years is provided in Table 4. Carbon uptake is annualised by multiplying total C sink values by

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[3] Tree nurseries may not have sufficient seedlings and there are only certain times during the year when seedlings can be planted and expected to survive. We use a 15–year rotation rather than a shorter one to ensure sufficient plantings to ensure a steady future flow of fibre to power plants.

[4] Obtained as $v(15)\ m^3 \times 0.57 \times 0.187\ t\ C\ m^{-3} \times ½ \times 0.02\ yr^{-1}$, where 0.57 converts merchantable volume, $v(15)$, to (non–bole) above–ground biomass with ½ of this biomass in litter after 50 years.

the discount rate. In the case of no discounting, however, C uptake is annualised by multiplying by 0.02, because it takes 50 years for the roots, litter and soils pool to reach their equilibrium levels and no C from future growth of trees is included (as discussed above). The annualised values are also provided in Table 4.

Table 4: Carbon Stored in Ecosystem Components, Saved as a Result of Wood–for–Coal Substitution and Total Carbon Saving when Hybrid Poplar Planted is on Agricultural Land with 15–Year Rotation

Carbon Account	No Discounting[a]	2%	4%
	TOTAL CARBON (t C ha^{-1})		
Merchantable or bole			
– Boreal	0	13.2	9.2
– Prairie	0	9.7	6.7
Above–ground biomass			
– Boreal	0	7.5	5.2
– Prairie	0	5.5	3.8
Roots			
– Boreal	56.6	47.8	40.8
– Prairie	47.6	40.1	34.1
Litter			
– Boreal	12.9	16.1	10.2
– Prairie	9.9	12.3	7.8
Soils			
– Boreal and Prairie	48.0	30.2	20.6
Total C sink			
– Boreal	117.5	114.9	86.1
– Prairie	105.5	97.8	73.1
	ANNUALISED CARBON (t C ha^{-1} yr^{-1})		
Total C sink			
– Boreal	2.350	2.297	3.443
– Prairie	2.110	1.956	2.923
C prevented from entering the atmosphere due to wood burning[b]			
– Boreal	3.027	2.626	2.268
– Prairie	2.317	2.010	1.736
Total Carbon Saving[c]			
– Boreal	5.378	4.923 (4.217)	5.711 (4.233)
– Prairie	4.427	3.966 (3.397)	4.659 (3.453)

[a] When C is sequestered at one time but released later, a zero discount rate leads to no storage.

[b] Calculated using equation (4a) or (4b).

[c] Values in parentheses are annualised values when account is taken of staggered planting over 15 years, using factor (5).

The reason for annualising C uptake is that, once we turn to C savings from fuel substitution, carbon uptake is infinite when physical C is not discounted. But this has its own related problems. In Table 4, for example, the annualised C sink values are higher for a 4% as opposed to 2% discount rate. The reason is that a component of the C "removal" is a limited–time stream of benefits that is first discounted and then multiply by *r* to annualise it over all time. Unfortunately, there is no good way out of the problem if one accepts that C benefits are not to be discounted.[5]

Assume that 3.78 m^3 of wood replace one tonne of coal, thereby offsetting the release of 0.707 t C to the atmosphere.[6] In the boreal region, then, 242.8 m^3 ha^{-1} of wood that is available at harvest time and substituted for coal in generating electricity will prevent the release of 45.4 t C into the atmosphere. Likewise, in the prairie region, 185.8 m^3 ha^{-1} of harvested wood will prevent release of 34.8 t C. This occurs every 15 years, so the annualised C prevented from going into the atmosphere will depend on the interest rate. The annualised values, c_B, are determined as follows:

$$\text{(4a)}\qquad c_B = r\,C_B\left(\frac{1}{(1+r)^{15}-1}\right) \qquad \text{if } r > 0,$$

$$\text{(4b)}\qquad c_B = C_B \div 15 \qquad \text{if } r = 0,$$

where C_B is the carbon that is prevented from going into the atmosphere by burning wood and the term in braces is the usual factor that discounts a stream of benefits accruing at intervals of 15 years into infinity. The annualised values are also provided in Table 4.

Finally, it is necessary to adjust C uptake and C removal by wood burning for the assumption that it takes 15 years to establish a forest that ensures sustained harvests. The adjustment is done on an annualised basis so that the requirement is reflected in each hectare that is eligible for afforestation. That is, it is assumed that only one–fifteenth of a hectare is planted each year for 15 years, followed by harvest and replanting on that one–fifteenth of a hectare. The conversion factor is:

$$\text{(5)}\qquad \frac{C^A}{15r}\left(1-\frac{1}{(1+r)^{15}}\right),$$

where C^A is the annualised carbon per ha when no account is taken of the staggered plantings. The appropriate values are given in parentheses in the final rows of Table 4. When physical C is not discounted, the two values are the same.

The BCMAFF (1996) reports that contract harvesting costs for hybrid poplar are \$8 per m^3, while average hauling costs are \$10 per m^3. Alberta Agriculture, Food and Rural Development (1997) employs a figure of \$22.05 per m^3 for harvesting and hauling. Since costs of hauling vary by distance to power plants, we assume that harvest plus hauling costs are \$18 per m^3 for agricultural areas located near existing power plants (ARAs 3 & 5), \$22 per m^3 for areas considered to be an intermediate distance away (ARAs 4a, 4b & 7), and \$26 per m^3 for more distance areas (ARA 6 and BC Peace). From these costs, one must subtract \$7.50 per m^3 in revenues (or costs saved by not burning coal).

We can now calculate the annualised costs of afforestation in the study region for each activity and sub–region. This is done by adding to the values in Table 2 the annualised costs of repeated plantings at 15–year intervals, beginning with the current period, plus the annualised harvesting and hauling costs (minus revenues), which also occur at 15–year intervals, but begin after the first rotation. These costs vary with harvest levels and location, and are adjusted to take into account the cost savings from not having to pay for coal. Costs of converting power plants to wood (or building new power plants) and added costs of maintaining and/or improving roads

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[5] See Richards (1997) and Richards and Stokes (1995) for additional discussion on this issue.

[6] This assumption (energy from 3.78 m^3 wood = energy from 1 t coal) falls in the energy conversion range determined from Table 3, but has the added advantage that the same C is released to the atmosphere by wood as with the coal replaced.

are ignored, as are emissions of CO_2 from forestry activities and those saved from no longer having to mine and haul coal. Just as in the case of carbon (Table 4), it is necessary to adjust the costs to take into account staggered plantings. The results are presented in Table 5.

Table 5: Net Annualised Costs of Removing C from the Atmosphere by Substituting Wood Burning for Coal in Electricity Generation, by Region and Current Agricultural Activities ($ per ha)

REGION	Forage[a]	Improved Pasture	Unimproved Pasture
BC Peace	388.05	276.47	n.a.
Alberta, ARA			
3 (Southwest)	386.83	183.45	169.75
4a (Central)	259.63	202.83	193.62
4b (Central)	270.99	205.43	194.81
5 (Central)	350.03	191.69	171.92
6 (Northeast)	375.93	293.93	266.53
7 (Northwest)	347.48	240.52	226.21

From data in Tables 4 and 5, it is possible to determine the marginal costs of carbon uptake as increasingly valuable marginal agricultural land is brought into production. The results are summarised in Figures 1 and 2, where annualised C is on the abscissa in Figure 2. Only the cost curves for no discounting and 4% discounting of physical C are provided as the area and amount of C gained are not sensitive to discount rates of 2% versus 4% (when account is taken of staggered planting). The results indicate that, if investment projects are limited to those whose sequestration costs do not to exceed $20 per tonne of C, no more than 0.5 million ha of land would be converted from its current agricultural activity to forestry. This result holds for costs up to $38 per t of C if physical C is not discounted and $49 per t C if costs are discounted (even at a low rate). Suppose costs as high as $50 per t C are tolerated. In that case, 4.8 million ha could possibly be converted if physical carbon is not discounted, resulting in a reduction of C emissions of 22.7 million (undiscounted) tonnes over all remaining time. If C is discounted at 4% (or even 2%), one would convert only 1.6 million ha yielding a total of 7 million tonnes of undiscounted carbon.

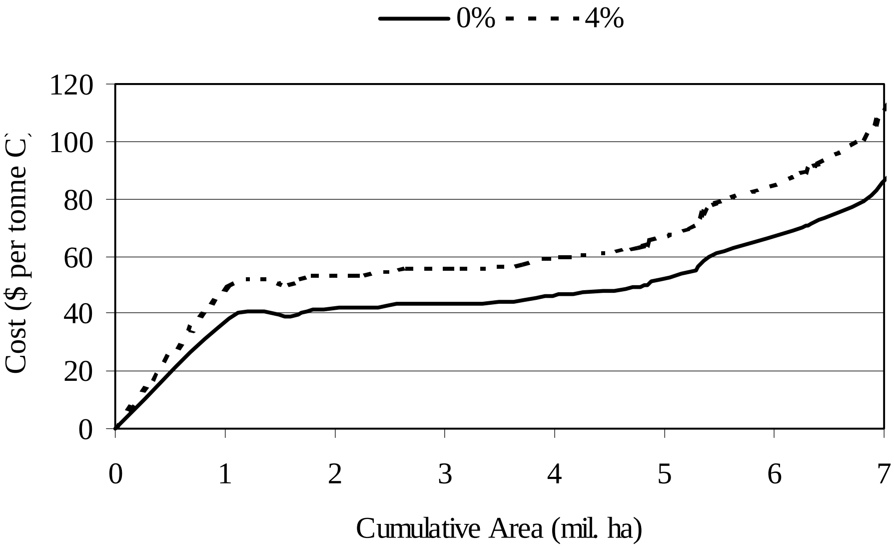

Figure 1: Costs of Carbon Uptake as a Function of Afforested Area, Western Canada, Hybrid Poplar as a Substitute for Coal Burning, Infinite Time Horizon, with and without Discounting

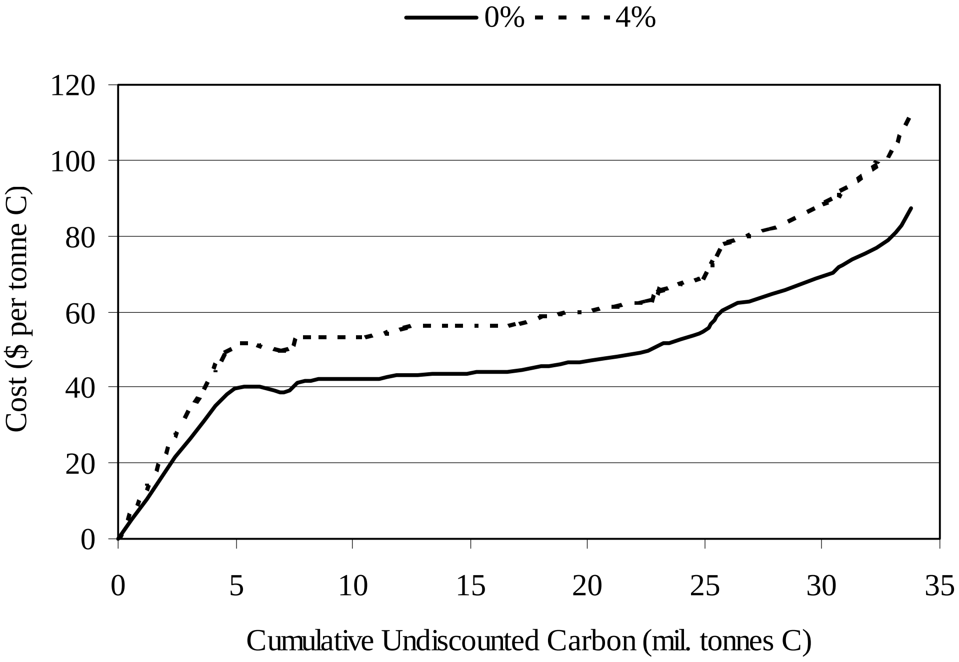

Figure 2: Marginal Costs of Carbon Uptake in Western Canada, Hybrid Poplar as a Substitute for Coal Burning, Infinite Time Horizon, with and without Discounting

The fossil fuel substitution option illustrates how sensitive decisions about how much agricultural land to afforest (C “removals” from the atmosphere) are to costs decision–makers are willing to tolerate (or the availability of other policy alternatives). If costs above $20 per tonne of C sequestered are intolerable, then the afforestation and biomass burning option is not one that can be relied upon to make a dent in Canada’s Kyoto commitments. On the other hand, if one draws the line at $50 per t C, the area that one can expect to afforest is still less than 25% of the total that might be identified for planting by foresters.

Storing Carbon in Wood Products

Storing carbon in wood products is another alternative that can be used to meet Canada’s Kyoto commitments. To investigate this strategy, we employ the same assumptions as in the case of wood burning, namely, that hybrid poplar is planted and harvested every 15 years. Again the reason for using hybrid poplar is that softwood species grow at too slow a rate and C uptake for rotations that include softwood species is well below that of hybrid poplar. The only different assumption pertains to the merchantable (bole) component of the tree at time of harvest. In the wood–product case, it is assumed that 20% of the bole is waste and burned (as in the previous analysis), with the remainder going into paper products (75%) and wood products such as lumber, posts and OSB (25%) (see Winjum *et al*. 1998). The question we want to answer is “Does this scenario lead to lower costs for C uptake than other afforestation scenarios?”

The C sink components of the ecosystem (litter, roots and non–bole, above–ground biomass) are as before. These are summarised in Table 6. Also found in Table 6 are the reductions in C resulting because bole waste (20%) is burned, replacing an energy equivalent amount of coal. This is determined as 20% of the amounts in Table 4. To obtain carbon fluxes for wood products, assume that proportion ρ ($0 \leq \rho \leq 1$) of the C gets stored in products that decay (release C) at a rate δ ($0 \leq \delta \leq 1$) per year. Then, it is easy to show that the discounted C stored in wood products at time of harvest is:

$$(6) \qquad [1 - \frac{\delta\rho}{1 + r - \delta} + (1 - \rho)]\, C_W,$$

where r is the social discount rate (which could be zero) and C_W is the carbon that goes into wood products when the site is harvested. Skog and Nicholson (1998) argue that paper products have a half–life of one to six years, while lumber in housing has a half–life of 80 to 100 years. Winjum *et al*. (1998), on the other hand, point out that oxidation rates are 0.02 per year for industrial roundwood products and 0.005 for paper products that end up in landfills. We assume that two–thirds of the paper products end up in landfills, releasing C at a very low rate, while the remainder releases C at a rate of 0.5; for other wood products, we assume a rate of decay of 0.02. The blended rate of decay, with 75% of wood going to paper and 25% to lumber and other building products, is 0.131. Thus, ρ=0.8 (since 20% is waste) and δ=0.131. Results are provided in Table 6, including sensitivity analysis with respect to values of δ.

Table 6: Annualised Carbon "Removal" as a Result of Uptake in Wood Products, Hybrid Poplar Planted on Agricultural Land with 15–Year Rotation (t C ha^{-1} yr^{-1})

Carbon Account	No Discounting[a]	2%	4%
Total ecosystem C sink			
– Boreal	2.350	2.297	3.443
– Prairie	2.110	1.956	2.923
Coal C saved by waste burning			
– Boreal	0.605	0.525	0.454
– Prairie	0.463	0.402	0.347
C in wood products			
– Boreal			
δ=0.131	2.056	1.511	1.114
δ=0.250	1.614	0.414	0.713
δ=0.500	0	0.024	0.077
– Prairie			
δ=0.131	1.574	1.151	0.844
δ=0.250	1.236	0.315	0.540
δ=0.500	0	0.018	0.059
Total Carbon Saving[b]			
– Boreal	5.012	4.334 (3.712)	5.011 (3.714)
– Prairie	4.147	3.509 (3.005)	4.114 (3.050)

[a] See notes on Table 4.

[b] For the case where δ=0.131.

The costs of harvesting and hauling trees is the same as for the case of wood burning, and varies with sub–region as before. The returns are $7.50 per m^3 for waste wood used in place of coal (as before) and, by assumption, $30 per m^3 for remaining wood that goes into products. This yields a blended net return to merchantable wood of $25.50. The net opportunity costs by region are given in Table 7.

Marginal cost curves for carbon removal by afforestation and a wood product sink are provided in Figures 3 and 4 for land area and annual undiscounted C, respectively. The lowest cost for removing C from the atmosphere in the wood product case is some $11 per t C compared with $38 per t C for the wood burning option, but upper end costs remain unacceptably high (Figure 4). If a cut–off of $20 per t C is chosen, then about 4.1 million ha are converted if physical C is not discounted, yielding a net reduction in C output of 18.5 million tonnes. For low, but positive, discount rates, a $20 limit would reduce the amount of land to be converted to 2.3 million ha and the C saving to 9.9 Mt. If higher costs of $50 per t C are tolerated, 6.5 million ha (28.9 Mt C) of agricultural land are converted in the case of no carbon discounting; this falls to 5.8 million ha (26.0 Mt C) for a discount rate of 4%. Clearly, the wood products' option is preferred to the wood burning option.

Increasing the value of δ to the levels indicated in Table 6 has a dramatic impact on costs of C uptake. This is seen from the significantly lower values of annualised C uptake. Likewise, reducing the value of δ lowers the costs of C uptake (not shown in the analysis). Our contention is that the values of δ that we employ are already optimistic and serve as a lower bound on the capacity of wood products, especially paper products, as a carbon sink.

Table 7: Net Annualised Costs of Removing C from the Atmosphere by Storing Wood in Products, by Region and Current Agricultural Activities ($ per ha)

REGION	Forage[a]	Improved Pasture	Unimproved Pasture
BC Peace	226.27	114.70	n.a.
Alberta, ARA			
3 (Southwest)	263.00	59.62	45.92
4a (Central)	135.80	79.00	69.79
4b (Central)	147.16	81.60	70.98
5 (Central)	226.20	67.86	48.09
6 (Northeast)	214.15	132.16	104.76
7 (Northwest)	185.70	78.75	64.44

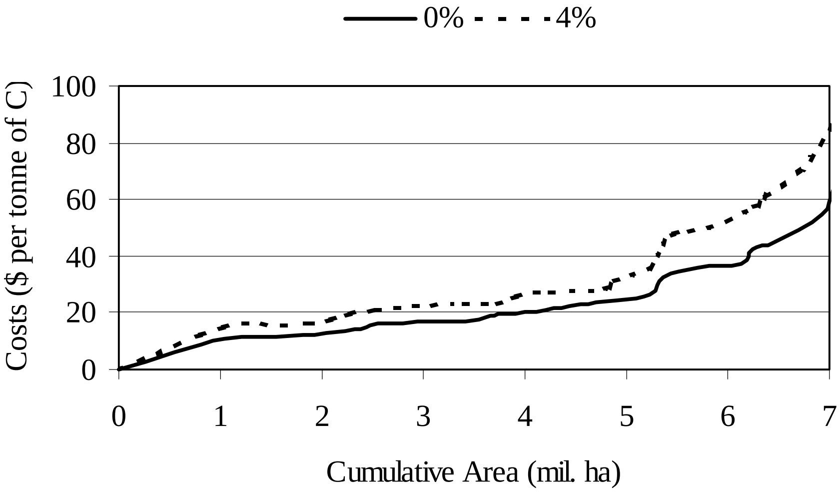

Figure 3: Costs of Carbon Uptake as a Function of Afforested Area, Western Canada, Hybrid Poplar Planted for Use in Wood Products, Infinite Time Horizon with and without Discounting

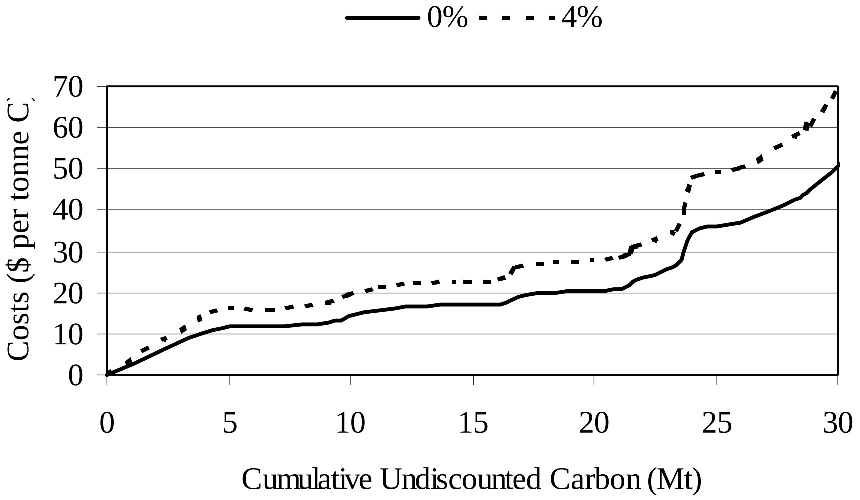

Figure 4: Marginal Costs of Carbon Uptake through Afforestation in Western Canada, Hybrid Poplar Planted for Use in Wood Products, Infinite Time Horizon with and without Discounting

Conclusions

In this study, the economics of afforestation were considered for the cases where harvested wood was used as a substitute for coal in energy production and as a wood–products, carbon sink. Although many of the assumptions in the analysis are rather optimistic (e.g., planting costs of $1270 per ha when costs of $4000 per ha have been reported, low rate of decay for paper products), the results do provide some indication of the possibility for afforestation programs. For a realistic cost of C uptake of less than $20 per m^3, the wood burning option is not likely to be viable, and one would expect very little (marginal) agricultural land to be planted to trees for this purpose. However, if wood is harvested and wood products subsequently hold C for a long time, then afforestation of marginal agricultural land could be a useful component of Canada's policy arsenal. For C uptake costs of $20 per m^3 or less, it may be worthwhile to plant hybrid poplar on 2.3 million ha of a potential 7 million ha of marginal agricultural land. Note that this is less than one–third of the agricultural land that a non–economist might identify as suitable for afforestation. On this land, some 9.9 Mt of C would be sequestered annually, or some 19.6% of Canada's Kyoto commitment. If these results hold for other regions of Canada, then as much as 60% of Canada's requirements could be met via afforestation.

Several concerns remain. First, we identified some 1.20 million ha of unimproved pasture as suitable for afforestation in northern Alberta. If this land already has significant crown canopy, costs would go up accordingly. Ignoring this land, will reduce the available marginal agricultural land to 5.73 million ha, and level of afforestation to 1.10 million ha, or 19.2% of available marginal agricultural land. In that case, afforestation in the region would account for no more than 3.8% of Canada's C uptake requirements. If a similar relation holds in the rest of Canada, then afforestation would account for no more than 12.5% of Canada's Kyoto commitment.

Second, because we investigated a scenario where physical carbon was not discounted and C flows were all annualised, the costs of C uptake may have been biased downwards.

Third, it is optimistic to assume that the required area can be planted within a 15–year period, particularly if this is extended to the entire country. The logistics of so doing are likely too great—there may not be sufficient planting stock, trees cannot be planted all year round, some planted areas will not take and will need to be re–established, *et cetera*.

Fourth, while such problems are one impediment to planting large areas to hybrid poplar, a greater obstacle is that of establishing proper incentives for landowners to grow hybrid poplar. Outright purchase of agricultural land will be financially infeasible, while financial incentives (planting plus annual subsidies) may be difficult to implement as this will require drawing up contracts between landowners and the government agency responsible for the program. Contracting is not costless, and strategic behaviour by landowners could result in much higher costs than anticipated, as well as delays. However, the problem of contracting in such cases is rarely discussed and much less investigated.

Finally, no hybrid poplar is likely to be planted before 2000 at the earliest, while large–scale planting may have to wait 5 to 10 years. Not only are there logistical impediments to a "quick start" to planting of hybrid poplar, but there are financing obstacles as well. A planting program would cost at least $750 million in the first year, and that would be an optimistic estimate.[7] If costs planting costs are nearer $4000 per ha, costs would amount to some $1.5 billion in the first year. All these and other biological and economic factors need to be investigated in greater detail. Unless this is done and the right incentives provided farmers, along with long–term guarantees, a large–scale planting program begun in the early 21st Century may be abandoned before trees even reach maturity.

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[7] This assumes 100,000 ha are planted in each region at a cost of $1270 per ha, plus the opportunity cost of lost agricultural returns for the first year, plus overhead and administration costs (assumed to add one–half to costs).

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