# 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**: To meet its international commitment to reduce $CO_2$ output by 7% from the 1990 level by 2012, Canada will rely to some extent on terrestrial carbon uptake, particularly 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 $7 \times 10^6$ 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.

**Résumé** : Pour être en mesure de respecter ses engagements internationaux et réduire d'ici 2012 l'émission de $CO_2$ de 7%, en prenant comme base le niveau de 1990, le Canada devra jusqu'à un certain point compter sur le prélèvement terrestre de carbone, plus particulièrement via le reboisement des terres agricoles marginales. Les aspects économiques de ce reboisement sont examinés pour le nord-est de la Colombie-Britannique et l'ensemble de l'Alberta, considérant que le bois récolté pourrait être utilisé comme substitut du pétrole pour la production d'énergie ou comme puits sous forme de produits du bois. Environ $7 \times 10^6$ ha de terres agricoles marginales sont identifiées mais très peu pourraient raisonnablement être reboisées si le bois était utilisé comme substitut du charbon. Si le carbone est emmagasiné dans les produits du bois, près du tiers des terres peuvent raisonnablement être reboisées. Si des résultats similaires sont valides pour le reste du Canada, le reboisement peut être inclus dans l'arsenal de politiques. Avant que cela se réalise, plusieurs problèmes sérieux doivent cependant être résolus, incluant les problèmes associés au mécanisme à utiliser pour retirer à ces terres leur vocation agricole et en faire des plantations forestières.

[Traduit par la Rédaction]

## 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 Organization (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 stabilize 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 United States committed to reduce emissions to 7% below 1990 levels by the year 2012 (the actual commitment period for measurement purposes is 2008–2012). European Union countries agreed to reduce emissions to 8% of 1990 levels by 2012, as did countries hoping to gain membership to the European Union 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 Mt of $CO_2$-equivalent GHG emissions, or 162.5 Mt of carbon

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**Table 1.** Farmland area classified by land use (ha).

| Region | Improved land: Non-forage crops | Forage | Fallow | Pasture | Other | Unimproved land: Pasture | Other |
|---|---|---|---|---|---|---|---|
| B.C. Peace | 137 585 | 119 584 | 29 608 | 96 991 | 8 372 | 282 545 | 150 693 |
| Alberta ARA | | | | | | | |
| 1 (southeast)[a] | 758 862 | 111 072 | 409 004 | 218 121 | 36 764 | 2 090 655 | 36 764 |
| 2 (south central)[a] | 1 544 105 | 135 252 | 415 483 | 178 540 | 32 640 | 903 954 | 32 640 |
| 3 (southwest) | 857 419 | 216 449 | 83 443 | 194 053 | 77 602 | 1 039 605 | 129 337 |
| 4a (east central) | 821 625 | 115 872 | 127 406 | 180 642 | 18 571 | 498 009 | 92 857 |
| 4b (east 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 (northeast) | 591 720 | 446 670 | 76 622 | 351 051 | 24 372 | 685 566 | 268 096 |
| 7 (northwest) | 1 193 462 | 334 144 | 167 958 | 245 009 | 28 473 | 501 393 | 370 153 |

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

(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[2]). 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 2008–2012 is counted as a debit, and only the average annual growth on newly planted sites over the period 2008–2012 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 (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), and 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 B.C. 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 C should be discounted, with economists arguing in favour of discounting. Richards (1997) demonstrates that the time value of C will depend on the path of marginal damages, that is, on the relation between the concentration of atmospheric $CO_2$ and economic damages. 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).

[2]McIlveen, N. 1998. The Analysis and Modelling Group. The emissions outlook. Forest sector emissions trend. Paper presented at the Forest Sector Table meeting, 6 Nov. 1998, Montréal, Que. Mimeograph.

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## Value of agriculture and tree planting costs

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

The agricultural land types considered suitable for afforestation are primarily those associated with forage production and pasture. However, for each subregion, 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 B.C. 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 and 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 $1.20 \times 10^6$ 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, and 5, unimproved pasture is also considered suitable for afforestation. ARAs 1 and 2 are characterized by irrigated forage production and are considered too dry for planting trees.[3] 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 marginal agricultural land considered suitable for planting to trees is $7.25 \times 10^6$ ha. Little economic data is available for improved "other" land, so it is ignored in the analysis. This leaves $7.03 \times 10^6$ ha of marginal agricultural land that we consider suitable for afforestation for C uptake. Estimates of the costs per tonne of C 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* (B.C. Ministry of Agriculture, Fisheries and Food 1995, hereafter BCMAFF).

**Table 2.** Net annual returns to current agricultural activities ($/ha).

| Region | Forage[a] | Improved pasture | Unimproved pasture |
|---|---|---|---|
| B.C. Peace | 184.98 | 34.45 | na[b] |
| Alberta, ARA | | | |
| 1 (southeast) | 185.75[c] | 17.51 | 8.75 |
| 2 (south central) | 304.04[c] | 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]Not applicable.
[c]ARAs 1 and 2 have irrigated forage production, are too dry for planting trees, and are excluded from further analysis. The data are presented for comparison purposes only.

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 standardized 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 hectare (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.[4] The costs per hectare of lost forage and pasture production for all regions are provided in Table 2.

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 B.C.'s *Planning for Profit Enterprise Budgets* (BCMAFF 1996), it is assumed that planting costs for hybrid poplar are $1270/ha.[5]

## Afforestation and carbon uptake

Carbon is stored in trees (stem, branches, leaves, and roots), understory, forest litter, and forest soils. We calculate

[3] The ARA boundaries in Alberta are based of soil zones: brown, dark brown, black, or grey. The driest of these are ARA 1, which contains brown soils, and ARA 2, with dark brown soils in the southeast corner of the province. This is the area we consider too dry to plant trees. The remaining ARAs (and the B.C. Peace) contain either black or grey soils because they experience higher annual precipitation. We assume that these areas are suitable for growing trees.

[4] 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, is not reflective of the true social value of forage.

[5] An establishment cost of $514/acre is reported. However, subsequent work by Robinson Consulting and Associates places establishment costs of conventional species in British Columbia at $1500/ha and hybrid poplar at $4000/ha given a 12-year rotation (G. Robinson, personal communication). Estimates for establishment of hybrid poplar in northern Minnesota are in the range US$285–$338 (Can$425–$504)/acre (Agricultural Utilization Research Institute 1997) or close to those used in this study.

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**Table 3.** Carbon emission factors for selected energy sources.

| Fuel | Higher heating value (MJ/kg)[a] | Carbon content (kg C/kg fuel) | Carbon coefficient (kg C/GJ) | Carbon coefficient (incl. 99% combustion efficiency) (kg C/GJ) |
|---|---|---|---|---|
| Wood | 15.5–19.7[b] | 0.500 | 25.6[c] | 25.3[c] |
| Coal | 29.31 | 0.707 | 24.12 | 23.9 |
| Natural gas | 0.0317[d] | 0.482[d] | 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 |

**Note:** Power is the rate at which energy is transferred and is usually measured in watts, with 1 W = 1 J/s, with 1 kW·h = $3.6 \times 10^6$ J. One joule is the work done when a force of 1 N (1 N = 1 kg·m/s$^2$) is applied through a distance of 1 m. See Watson et al. (1996, p. 79).

[a]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 United States use high heating value while the rest of the world uses low heating value (G. Marland, personal communication; see also Watson et al. 1996, p. 80; Marland et al. 1995).

[b]Low value is converted from Slangen et al. (1997, p. 324); high value is calculated from data in the table.

[c]G. Marland, personal communication, and Marland and Pippin (1990).

[d]Values for natural gas are per cubic metre rather than per kilogram.

storage of C in total tree biomass (including roots) and, although inclusion of C stored in forest soils, floor, and understory 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 $v$ is stem wood volume, $A$ is maximum stem wood volume, $t$ is time in years, 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 United States 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 fertilization 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 (eq. 1), multiplied by an expansion factor (=1.57) to obtain total aboveground biomass. Root biomass ($R$) is related to aboveground biomass ($G$) as follows, with both measured in tonnes per hectare:

$$[2] \qquad R = 1.4319G^{0.639}$$

Finally, the carbon content of timber in the study region averages 0.187 t/m$^3$ for hardwoods (van Kooten et al. 1993, pp. 244–245).

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 United States indicate that sites with hybrid poplar have an average of 191 t C/ha in the top 1 m of soil, row crops an average of 179 t of soil C, and grass that is regularly cut 157 t/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/ha of soil C, 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 soil C/ha (p. 435). Guy and Benowicz (1998) note that forest soils in the study region store some 108 t C/ha compared with 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 C/ha per year is added to soil each year for 50 years when an equilibrium is reached (or 48 t/ha). 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.

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 C/m$^3$ of poplar biomass and using data in the

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last column of Table 3, we calculate that some 7.4 GJ/m$^3$ of energy are released. However, using the lower range for heating value from the first column, we find that 5.8 GJ/m$^3$ of energy are released. 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/t, while the Government of Alberta (1999) reports an HHV of 19.3–26.7 GJ/t 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 to generate an equivalent amount of energy. Finally, Girouard et al. (1996) report prices of $2.50–$4.00/GJ as costs for fossil fuels (natural gas, coal, and heavy fuel oil). For wood, CSL (1994) indicate a price of $40/t, which translates into an energy price of $2.58/GJ for the lower range of HHV for wood (Table 3). Using the latter price, we obtain a value of $7.50/m$^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 and 11.1 m$^3$. For convenience (to correspond with rotation age) and to ensure a consistent supply of wood in the future, only 1/15 of the area available for afforestation is planted in each year. 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.[6]

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 aboveground 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 regrowth 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 eq. 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/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:

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

[3*b*] $$C_S = 50c_s,\qquad \text{if physical C is not discounted}$$

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 3*a* 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.[7] 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 annualized by multiplying total C sink values by the discount rate. In the case of no discounting, however, C uptake is annualized by multiplying by 0.02, because it takes 50 years for the root, litter, and soil pools to reach their equilibrium levels, and no C from future growth of trees is included (as discussed above). The annualized values are also provided in Table 4.

The reason for annualizing C uptake is that, once we turn to C savings from fuel substitution, carbon uptake is infinite when physical C is not discounted (implying zero cost of C uptake). Yet, when no discounting of physical C occurs, it is impossible to annualize a C pool that achieves equilibrium in finite time. Any attempt to annualize the C pool (e.g., by choosing the average annual uptake rate for years it takes the pool to reach equilibrium) leads to the implicit assumption that the pool never attains equilibrium but continues to sequester C at the annual rate forever. Then costs of C uptake are understated. Unfortunately, there is no good way out

[6] 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 and a steady future flow of fibre to power plants. We also assume that it is possible to continue growing hybrid poplar without using fertilizer in future rotations. If fertilizer applications are required, costs of C uptake would be higher than estimated here.

[7] Obtained as $v(15)$ m$^3$ × 0.57 × 0.187 t C/m$^3$ × 0.5 × 0.02/year, where 0.57 converts merchantable volume, $v(15)$, to (non-bole) aboveground biomass with one half of this biomass in litter after 50 years.

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**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.

| | No discounting[a] | | 2% | | 4% | |
|---|---|---|---|---|---|---|
| Carbon account | Boreal | Prairie | Boreal | Prairie | Boreal | Prairie |
| **Total carbon (t C/ha)** | | | | | | |
| Merchantable or bole | 0 | 0 | 13.2 | 9.7 | 9.2 | 6.7 |
| Aboveground biomass | 0 | 0 | 7.5 | 5.5 | 5.2 | 3.8 |
| Roots | 56.6 | 47.6 | 47.8 | 40.1 | 40.8 | 34.1 |
| Litter | 12.9 | 9.9 | 16.1 | 12.3 | 10.2 | 7.8 |
| Soils | 48.0 | | 30.2 | | 20.6 | |
| Total C sink | 117.5 | 105.5 | 114.9 | 97.8 | 86.1 | 73.1 |
| **Annualized carbon (t C/ha per year)** | | | | | | |
| Total C sink | 2.350 | 2.110 | 2.297 | 1.956 | 3.443 | 2.923 |
| C prevented from entering the atmosphere due to wood burning[b] | 3.027 | 2.317 | 2.626 | 2.010 | 2.268 | 1.736 |
| Total C saving[c] | 5.378 | 4.427 | 4.923 (4.217) | 3.966 (3.397) | 5.711 (4.233) | 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 eq. 4*a* or 4*b*.
[c]Values in parentheses are annualized values when account is taken of staggered planting over 15 years, using eq. 5.

of the dilemma if one accepts that C benefits are not to be discounted.[8]

That some pools reach equilibrium also accounts for the fact that annualized C sink values in Table 4 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 multiplied by $r$ to annualize it over all time. In this case, however, there is no inconsistency or bias in calculating the costs of C uptake.

Assume that 3.78 $m^3$ of wood replace 1 t of coal, thereby offsetting the release of 0.707 t C to the atmosphere.[9] In the boreal region, then, 242.8 $m^3$/ha 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 of harvested wood will prevent release of 34.8 t C. This occurs every 15 years, so the annualized C prevented from going into the atmosphere will depend on the interest rate. The annualized values, $c_B$, are determined as follows:

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

$$[4b] \qquad c_B = \frac{C_B}{15}, \qquad \text{if } r = 0$$

where $C_B$ is the carbon that is prevented from going into the atmosphere by burning wood and the term in parentheses is the usual factor that discounts a stream of benefits accruing at intervals of 15 years into infinity. The annualized 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 annualized basis so that the requirement is reflected in each hectare that is eligible for afforestation. That is, it is assumed that only 1/15 of a hectare is planted each year for 15 years, followed by harvest and replanting on that 1/15 of a hectare. The conversion factor is

$$[5] \qquad \frac{C_A}{15r}\left(1-\frac{1}{(1+r)^{15}}\right)$$

where $C_A$ is the annualized carbon per hectare 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/$m^3$, while average hauling costs are \$10/$m^3$. Alberta Agriculture, Food and Rural Development (1997) employs a figure of \$22.05/$m^3$ for harvesting and hauling. Since costs of hauling vary by distance to power plants, we assume that harvest plus hauling costs are \$18/$m^3$ for agricultural areas located near existing power plants (ARAs 3 and 5), \$22/$m^3$ for areas considered to be an intermediate distance away (ARAs 4*a*, 4*b*, and 7), and \$26/$m^3$ for more distance areas (ARA 6 and B.C. Peace). From these costs, one must subtract \$7.50/$m^3$ in revenues (or costs saved by not burning coal).

We can now calculate the annualized costs of afforestation in the study region for each activity and subregion. This is done by adding to the values in Table 2 the annualized costs of repeated plantings at 15-year intervals, beginning with the current period, plus the annualized 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

[8] See Richards (1997) and Richards and Stokes (1995) for additional discussion.
[9] 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.

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**Fig. 1.** Costs of carbon uptake as a function of afforested area, western Canada, using hybrid poplar as a substitute for coal burning, infinite time horizon, with and without discounting.

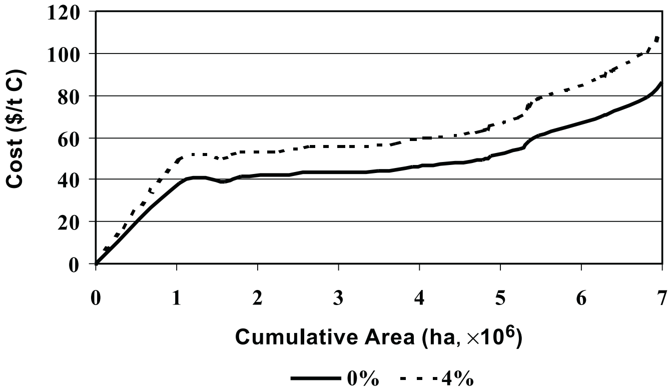


**Fig. 2.** Marginal costs of carbon uptake in western Canada using hybrid poplar as a substitute for coal burning, infinite time horizon, with and without discounting.

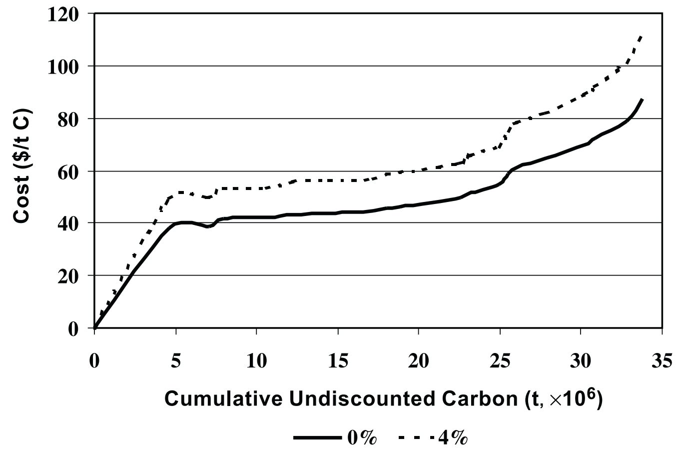


**Table 5.** Net annualized costs of removing C from the atmosphere by substituting wood burning for coal in electricity generation, by region and current agricultural activities ($/ha).

| Region | Forage | Improved pasture | Unimproved pasture |
|---|---|---|---|
| B.C. Peace | 388.05 | 276.47 | na[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 |

[a]Not applicable.

plants) and added costs of maintaining and (or) improving roads 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 C (Table 4), it is necessary to adjust the costs to take into account staggered plantings. The results are presented in Table 5.

As increasingly valuable marginal agricultural land is brought into production, (marginal) costs of C uptake rise (Table 4). Further, rates of C uptake will vary by region, boreal or prairie (see Table 5). Using this information, it is possible to determine the marginal costs of C uptake as a function of both the cumulative area of land converted to forest and the associated cumulative C removed from the atmosphere. The results are summarized in Figs. 1 and 2, where undiscounted C is on the abscissa in Fig. 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 exceed $20/t C, no more than $0.5 \times 10^6$ ha of land would be converted from its current agricultural activity to forestry. This result holds for costs up to $38/t C if physical C is not discounted and $49/t C if costs are discounted (even at a low rate). Suppose costs as high as $50/t C are tolerated. In that case, $4.8 \times 10^6$ ha could possibly be converted if physical C is not discounted, resulting in a reduction of C emissions of $22.7 \times 10^6$ t (undiscounted) over all remaining time. If C is discounted at 4% (or even 2%), one would convert only $1.6 \times 10^6$ ha yielding a total of $7 \times 10^6$ t of undiscounted C.

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/t 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/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

To investigate the storage in wood products option, 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 aboveground biomass) are as before. These are summarized 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

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**Table 6.** Annualized carbon "removal" components as a result of uptake in wood products when hybrid poplar is planted on agricultural land with 15-year rotation (t C/ha per year).

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

[a]See notes for Table 4.
[b]For the case where $\delta$ = 0.131.

**Table 7.** Net annualized costs of removing C from the atmosphere by storing wood in products, by region and current agricultural activities ($/ha).

| Region | Forage | Improved pasture | Unimproved pasture |
|---|---|---|---|
| B.C. Peace | 226.27 | 114.70 | na[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 |

[a]Not applicable.

20% of the amounts in Table 4. To obtain carbon fluxes for wood products, assume that proportion $\rho$ ($0 \le \rho \le 1$) of the C gets stored in products that decay (release C) at a rate $\delta$ ($0 \le \delta \le 1$) per year. Then, it is easy to show that the discounted C stored in wood products at time of harvest is

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

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 1–6 years, while lumber in housing has a half-life of 80–100 years. Winjum et al. (1998), on the other hand, point out that oxidation rates are 0.02/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, $\rho = 0.8$ (since 20% is waste) and $\delta = 0.131$. Results are provided in Table 6, including sensitivity analysis with respect to values of $\delta$.

The costs of harvesting and hauling trees is the same as for the case of wood burning, and varies with subregion as before. The returns are $7.50/m$^3$ for waste wood used in place of coal (as before) and, by assumption, $30/m$^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 Figs. 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/t C compared with $38/t C for the wood burning option, but upper end costs remain unacceptably high (Fig. 4). If a cut-off of $20/t C is chosen, then about $4.1 \times 10^6$ ha are converted if physical C is not discounted, yielding a net reduction in C output of $18.5 \times 10^6$ t. For low, but positive, discount rates, a $20 limit would reduce the amount of land to be converted to $2.3 \times 10^6$ ha and the C saving to 9.9 Mt. If higher costs of $50/t C are tolerated, $6.5 \times 10^6$ ha (28.9 Mt C) of agricultural land are converted in the case of no C discounting; this falls to $5.8 \times 10^6$ 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 $\delta$ 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 annualized C uptake. Likewise, reducing the value of $\delta$ lowers the costs of C uptake (not shown in the analysis). Our contention is that the values of $\delta$ 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.

## 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, C sink. Although many of the assumptions in the analysis are rather optimistic (e.g., planting costs of $1270/ha when costs of $4000/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 $20/m$^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

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**Fig. 3.** Costs of carbon uptake as a function of afforested area, western Canada, using hybrid poplar planted for use in wood products, infinite time horizon, and with and without discounting.

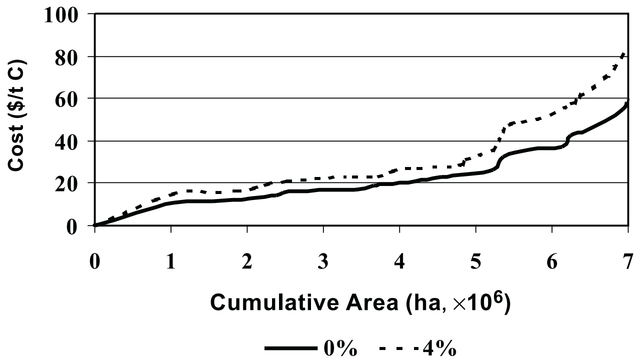
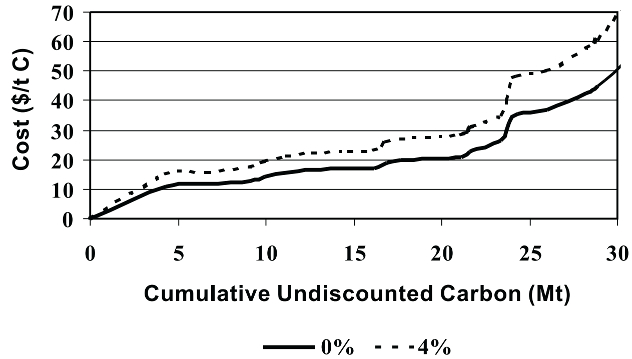



**Fig. 4.** Marginal costs of carbon uptake through afforestation in western Canada, using hybrid poplar planted for use in wood products, infinite time horizon, with and without discounting.




Canada's policy arsenal. For C uptake costs of $20/m$^3$ or less, it may be worthwhile to plant hybrid poplar on 2.3 × $10^6$ ha of a potential 7 × $10^6$ 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 × $10^6$ 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 × $10^6$ ha, and level of afforestation to 1.10 × $10^6$ 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, by not discounting physical C, it is implicitly assumed that the value of C damages in the future increase at the real rate of discount (Richards 1997). However, if C fluxes are annualized, the costs of C uptake are biased downwards for the scenario where physical C is not discounted.

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, etc.

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 5–10 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.[10] If planting costs are nearer $4000/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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[10]This assumes 100 000 ha are planted in each region at a cost of $1270/ha, plus the opportunity cost of lost agricultural returns for the first year, plus overhead and administration costs (assumed to add 50% to costs).

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