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Economics of Afforestation for Carbon Sequestration in Western Canada

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Abstract

The Kyoto Accord on climate change requires developed countries to achieve CO_2-emissions reduction targets, but permits them to charge uptake of carbon (C) in terrestrial (primarily forest) ecosystems against emissions. Countries such as Canada hope to employ massive afforestation programs to achieve Kyoto targets. One reason is that foresters have identified large areas that can be afforested. In this paper, we examine this forestry option, focusing on the economics of afforestation in western Canada. In particular, we develop marginal C uptake curves and show that much less land is available for afforestation than would be the case if economics is ignored. We conclude that, while afforestation is a feasible weapon in the greenhouse policy arsenal, it might not be as potent as many forest-sector analysts make out.

Key words: Climate change and the economics of afforestation; Kyoto Accord

Economics of Afforestation for Carbon Sequestration in Western Canada

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Background

Climate change and related global warming are caused by so–called greenhouse gases (GHGs) that permit the sun's rays to pass through the earth's atmosphere, but prevent heat from radiating back into space by trapping it. While GHGs include methane (CH_4), nitrous oxides (N_2O) and a group of artificial gases known as halocarbons (or CFCs), the most dominant GHG (outside of water vapour) is carbon dioxide (CO_2), in terms of anthropogenic emissions and potential to affect climate. It is feared that human activities, primarily fossil fuel burning and tropical deforestation, are responsible for increasing atmospheric concentrations of CO_2. This is shown in Table 1, which suggests an average 1.3×10^9 tonnes (gigatons or Gt) of carbon (C) are added to the atmosphere each year as a result of human activities. Compared to the size of global sinks such as oceans and the soil, which are also indicated in Table 1, the contribution of humans is rather small.

Table 1: Annual Anthropogenic Flux and Size of the Globe's Carbon Sinks (Gt C)

Item	Average annual flux	Approximate sink size
CO_2 sources		
Emissions from fossil fuels and cement production	5.5 ± 0.5	
Net emissions from changes in tropical land uses	1.6 ± 1.0	
TOTAL ANTHROPENIC EMISSIONS	7.1 ± 1.1	
Partitioning amongst reserves		
Atmosphere	3.3 ± 0.2	800
Oceans	2.0 ± 0.8	40,000
Northern Hemisphere forest regrowth	0.5 ± 0.5	—
Soils	n.a.	1,500
Above ground biomass	n.a.	600–700
Inferred Sink (Difference)	**1.3 ± 1.5**	**≈43,000**

Source: Houghton *et al.* (1996); n.a. means not available

Over the past two centuries, atmospheric concentrations of CO_2 have increased by about 25 percent, from approximately 285 parts per million by volume (ppmv) to 356 ppmv, with most of this increase occurring in the past 100 years. If other GHGs are included, equivalent CO_2 levels were approximately 290 ppmv at the beginning of the industrial revolution, 310 ppmv in 1900 and some 440 ppmv by 1995. Mean global surface temperatures have increased some 0.3^o to 0.6^oC since the mid 1800s, and by some 0.2^o–3^oC in the last 40 years. Between 1861 and 1910, mean global temperatures remained relatively flat, but were some 0.1^oC below the 1861 level in 1910. Between 1910 and about 1940, temperatures rose by some 0.5^oC, remained flat between 1940 and 1975, and then rose a further 0.2^oC in the two decades since 1975 (Houghton *et al.*, 1996, p.26).[1] Controversies about the causes of climate change remain, including whether global warming currently is or will in the future even occur (e.g., Emsley 1996).

Climate change is considered by some to be the world's most important environmental policy issue (Clinton and Gore 1993). Average global temperatures are projected to increase by 1.0–4.5^{o}C under a double CO_2 atmosphere (Kattenberg *et al.* 1996). Concern about anthropogenic emissions of GHGs led the World Meteorological Organisation (WMO) and the United Nations Environment Program jointly to establish the Intergovernmental Panel on Climate Change (IPCC) in 1988.[2] 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 was published in 1996 (Houghton *et al.* 1996) and 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 relative to what they were in 1990.[3] Developed countries agreed to varying levels of emissions reduction. 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. Within the EU, some countries will be required to reduce emissions by less than other countries. Thus, the Netherlands will need to reduce emissions by only 6%, while Germany will reduce them by some 20% or more (because inefficient industries in the East will be closed or rebuilt). 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.

The Kyoto Protocol does not call for sanctions against countries failing to meet their targets—the Protocol is voluntary. Moral suasion will be brought to bear on those countries failing to live up to their agreement, but this will occur only if there is general compliance. With the exceptions of Germany and the UK, most countries signing the FCCC have been unable to meet the Rio target (e.g., Canada's emissions in 1996 exceeded 1990 emissions of CO_2 by more than 12%), and most are unlikely to meet the Kyoto target. Nonetheless, countries are committed to reducing anthropogenic GHG emissions in the long run. As an interim measure, policies to remove CO_2 from the atmosphere and store it as carbon in terrestrial ecosystems have taken on some importance. Already in 1989, the Noordwijk Declaration that was signed by 68 countries proposed increasing global forest cover as a means of slowing climate change.

The Kyoto Protocol allows countries to claim as a credit any C sequestered as a result

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[1] One might have expected a greater increase in mean global surface temperatures after World War II rather than before it, because of the greater increase in fossil fuel use.

[2] WMO and UNEP had already convened the First World Climate Conference and established the World Climate Program in 1979.

[3] The First COP in 1995 issued the "Berlin Mandate" that eventually led to the Kyoto Protocol.

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 (see Canadian Forest Service 1998). 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. 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.[4] 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. The amount of C to be credited as a reduction is determined by measuring the inventory on the site at the end of the commitment period minus the inventory at the beginning of the period, divided by the number of years to give the annual value. However, inventory measurement will be difficult and costly, and mean annual increment (MAI) may be used as a fall back for determining C uptake. 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 open to future negotiations (Canadian Forest Service 1998).

Most countries are unlikely to adopt large–scale afforestation programs before the late 1990s, and even reforestation of sites harvested since 1990 will not occur before at least the mid 1990s and be ongoing thereafter. For most forests, such as those found in Scandinavia, Russia, Canada and the US, the major producing countries, the increase in biomass over the first two decades after planting is generally imperceptible. In many instances, growth tables do not even begin until the third or fourth decade. Thus, any measure of C uptake by forests taken in the Protocol's accounting period 2008–2012 will be small, or biased upwards if MAI over the entire rotation is used as a proxy for actual growth. It would appear, therefore, that forest policies are important in the intermediate term, and not the short term of the Kyoto Protocol. An exception occurs if high–yielding varieties of hardwood species are used in place of more natural, commercially valuable species, but planting such species could result in adverse environmental consequences.

Planting trees involves more than simply carbon uptake in forest biomass, because what happens to the C balance of the soil and to products produced from harvested timber are also important. Wood can substitute for fossil fuels and wood products continue to serve as a C sink for many years after the trees are harvested. Policies can be oriented towards greater substitution of wood for non–wood products (e.g., wood studs rather than aluminium ones) and simply greater use of wood products. Wood products' research is one means of encouraging greater substitution and use of wood, but so are subsidies or other policies that reduce the price of wood products. Planting trees and increasing the supply of wood is one way to reduce prices. In general, it appears that plantation forests are a cost–effective means of sequestering C (Sedjo *et al*. 1995).

Forests store carbon by photosynthesis. For every tonne (t) of carbon sequestered in forest biomass, 3.667 t of CO_2 is removed from the atmosphere. However, C is stored not only in above–ground biomass, but also in decaying material on the forest floor and, importantly, in the soil (Binkley *et al*. 1997). Soil carbon should perhaps be taken into account, but current Kyoto requirements do not include soil carbon.

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[4] At least this is the way some countries interpret the Protocol.

The main purpose of cost–of–mitigation studies is to provide benchmarks for comparing alternative strategies, so that the least cost strategies can be implemented. The cost–benefit analysis is in terms of discounted costs per physical unit (tonnes) of C uptake, with disagreement over where physical quantities should be discounted. For example, the Global Environment Facility (GEF) of the World Bank and United Nations can allocate funds to desirable C–uptake projects. In determining project feasibility, GEF recommends against discounting of C sequestered and stored in terrestrial ecosystems in the future, although future costs are to be discounted. 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 (see also Richards and Stokes 1995). In this study, we consider both cases where physical C is discounted and where it is not.

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 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. Canada expects a large part of its international commitment to reduce CO_2 emissions to come from forestry, with perhaps 25 percent of its Kyoto commitment coming via tree planting (see Canadian Forest Service 1998; Guy and Benowicz 1998: Nagle 1990).

The purpose of this study is to examine the potential for planting trees on marginal agricultural land as one method for Canada to achieve its CO_2–emissions reduction commitments. More particularly, we investigate the claims of foresters that afforestation of marginal lands in (mainly western) Canada can make a significant contribution to Canada's international commitments. We examine the simple case where trees are planted for a period of 50 years, without considering what happens to them or the land after that time. This mimics the research that has been done to date (e.g., Nagle 1990; Guy and Benowicz 1998), except that we add an economics component. The study area encompasses the Peace River region of British Columbia and all of Alberta.

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 2. In the table, improved land includes non–forage crops, forage, fallow, pasture and other land, while unimproved land contains mainly pasture.

Table 2: Farmland Area Classified by Land Use (ha)

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

[a] See Table 3.

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. In the BC Peace and the two most northern Alberta regions (ARAs 6 & 7), it can also be assumed that unimproved pasture is already forested.

Land in crops that can be considered for growing trees is in 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, improved pasture and land in forage production are considered to be “marginal” agricultural lands. 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.[5] The costs per hectare of lost forage and pasture production for

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[5] 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

all regions are provided in Table 3.

Table 3: 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 (Southeast)	304.04[b]	23.64	11.82
3 (Southwest)	310.20	35.82	17.33
4a (Central)	101.47	24.84	12.42
4b (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 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}.[6]

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

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thus not reflective of the true social value of forage.

[6] 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.

where A is maximum stem wood volume and k and m are parameters (Guy and Benowicz 1998). Parameter values for the study region are provided in Table 4.

Hybrid poplar is generally chosen for C uptake because of its rapid rates of growth. 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. Based on the data in Table 4, species recommended for planting in western Canada reach culmination of mean annual increment (of nearly 23 m^3 per ha for the boreal region and 18 m^3 per ha for the drier prairie region to the south) at some 8 years after planting. The MAI over the first 25 years of growth is 12.4 m^3 ha^{-1} for the boreal region and 9.9 m^3 ha^{-1} for the drier prairie region; comparable values at 50 years are 6.6 m^3 ha^{-1} and 5.4 m^3 ha^{-1}, respectively.

Table 4: Parameters for the Chapman–Richards Growth Function, Boreal and Prairie Regions of Western Canada[a]

	Function Parameter		
Species and region	*A*	*k*	*m*
Softwood boreal	147	0.037	3.0
Softwood prairie	215	0.027	3.0
Hybrid poplar boreal	329	0.156	3.0
Hybrid poplar prairie	270	0.143	3.0
Other hardwood boreal	278	0.023	3.0
Other hardwood prairie	228	0.034	3.0

[a] Boreal refers to the northern part of the study region (BC Peace River region and ARAs 6 & 7 in Alberta) using data for the boreal forest region of Quebec; prairie refers to the central and southern parts of the study region.

Source: Guy and Benowicz (1998)

Because large plantations of hybrid poplar are not aesthetically pleasing, trees are less valuable and biodiversity is reduced compared to the marginal agricultural activity, an alternative to planting only poplar on agricultural land is considered. Under this alternative, a mix of species consisting of 30% hybrid poplar, 50% softwood species and 20% other hardwood species is planted.

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) softwoods: $R = 0.2317\ G$ and

(3) hardwoods: $R = 1.4319\ G^{0.639}$.

Finally, the carbon content of timber in the study region averages 0.207 t per m^3 for softwoods and 0.187 t per m^3 for hardwoods (van Kooten, Thompson and Vertinsky 1993, p.244–45). Based on the above data, estimates of cumulative C uptake over a 50–

year time horizon are provided in Figure 1. The four scenarios in Figure 1 refer to the planting of hybrid poplar only in the northern (boreal) and southern (prairie) sub–regions of our study area, and the planting of a mix of species in these regions.

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, an additional 0.96 t of C per year per ha needs to be added to the amounts in Figure 1 (or 48 t ha^{-1} over the entire period). 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.

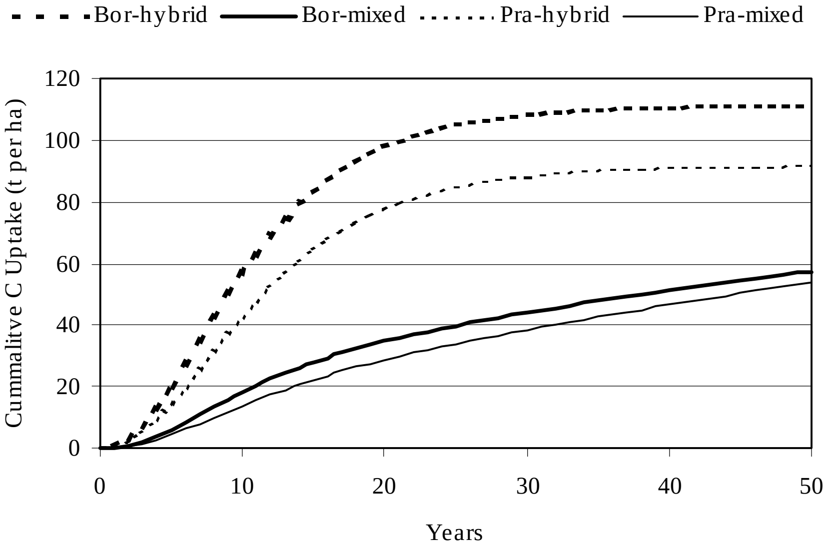

Figure 1: Carbon Uptake with Hybrid Poplar and Mix of Species, One–time Planting

Economics of One–time Tree Planting

For simplicity, we assume a one–time conversion of agricultural land to forest and a time horizon of 50 years. This is a bit troublesome as it takes time to afforest large areas and costs (forgone agricultural benefits) will continue to be incurred after 50 years if the land remains in forest. Thus, it is necessary to assume that, at age 50, by harvesting the trees, using the revenues to cover future costs of establishing new forests and storing C in wood products or by some other means, both the gains and losses in carbon and in monetary values are somehow balanced. With this in mind, the present value of C sequestration costs can be calculated.

The total costs of afforestation are the direct planting costs plus the annual forgone agricultural benefits, which are provided in Table 3 for various agricultural activities on marginal land. It is assumed that costs are discounted at a social rate of 4%. Three discount rate scenarios are employed for physical carbon, namely no discounting, discounting at 2% and discounting at the same rate as costs are discounted (4%). The results are provided in Table 5 and, for hybrid poplar, in Figures 2 and 3. In these figures, there is a noticeable "jump" at just over 5 million ha (about 750 Mt of undiscounted C), reflecting the higher opportunity costs of land in forage over land in pasture.

Table 5: C Uptake on Marginal Agricultural Land in Western Canada, Average Costs and Available Area[a]

	Rate at which physical carbon is discounted					
Item	0% no limit	0% $20 limit	2% no limit	2% $20 limit	4% no limit	4% $20 limit
Hybrid poplar						
Total C uptake (10^6 t)	1,036.6	768.1	1,036.6	661.9	1,036.6	258.3
–Discounted C (10^6 t)	1,036.6	768.1	764.6	487.5	591.8	149.3
Average Cost ($/t)	$18.82	$12.24	$25.52	$15.78	$32.97	$18.40
Area (10^6 ha)	7.03	5.24	7.03	4.52	7.03	1.68
Mixed species						
Total C uptake (10^6 t)	726.3	446.6	726.3	0	726.3	0
–Discounted C (10^6 t)	726.3	446.6	477.1	0	337.7	0
Average Cost ($/t)	$26.87	$16.35	$40.91	-	$57.78	-
Area (10^6 ha)	7.03	4.33	7.03	0	7.03	0

[a] Limit refers to the maximum cost tolerated for undertaking an investment in C uptake by planting trees on agricultural land.

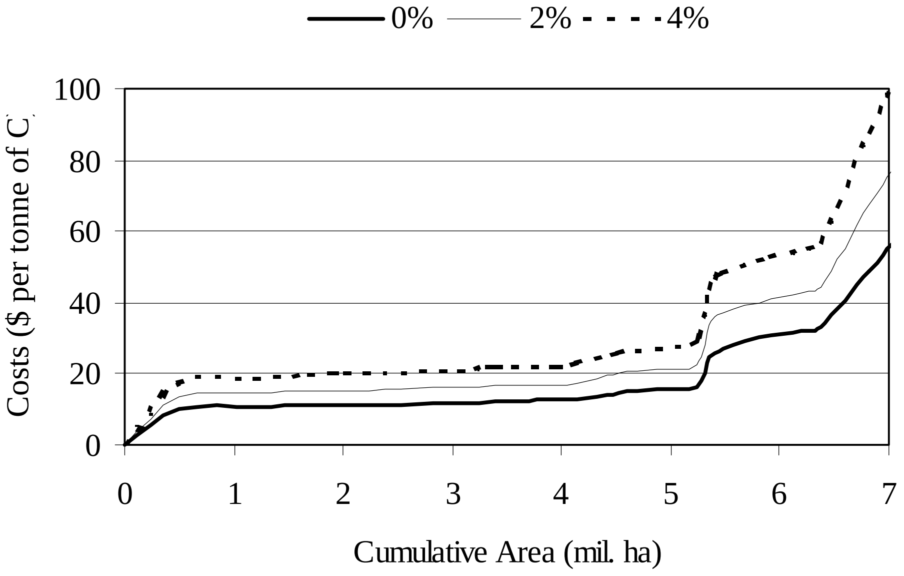

Figure 2: Costs of Carbon Uptake as a Function of Area, Western Canada, One–time Planting of Hybrid Poplar, 50–Year Horizon, Various Discount Rates

Average costs of sequestering C through planting hybrid poplar vary from $18.82 per tonne if C is not discounted to $32.97 per tonne if C is discounted at 4%. If a mix of species is planted, average cost per tonne of C is between $26.87 and $57.78 at 0% and 4% discount rate, respectively. As discussed below, marginal costs of C uptake are much higher, and it is marginal costs that are relevant for decision making.

Total land available for afforestation amounts to 7.0 million ha if no economic limitations are imposed. The maximum amount of C that can probably be sequestered through hybrid poplar afforestation in the Great Plains region of BC and Alberta over a 50-year time horizon is about 1 Gt, or some 20 Mt per year (Table 5). This would account for nearly 40% of Canada's needed reduction for the commitment period.

This optimistic result ignores many economic realities, however. It assumes that physical carbon is not discounted, that land can be teased out of agriculture and trees planted on it within a very short time frame with no social adjustment costs, and that tree growth is even over the entire period, which is akin to using MAI for determining C uptake during the commitment period. More importantly, it ignores the fact that C–uptake costs increase as more C is sequestered (as increasingly valuable agricultural land is converted to forest).

Carbon uptake costs in excess of $20 are likely unacceptable given that there surely exist cheaper ways to reduce CO_2 emissions (e.g., improvements in fuel efficiency may be had for low cost, while some utility companies already purchase C uptake services for less than $5 per t). If $20 is chosen as the cut off for socially desirable investments in afforestation, then 5.24 million ha of marginal agricultural land should be converted to forests when physical C is not discounted and hybrid poplar is selected for afforestation (see Figure 2 and Table 5). It is clear that, if carbon is discounted at 2%, no more than 662 Mt of C will be sequestered over the 50–year period (13Mt per year) if costs are to be kept below $20 per t. Even so, converting agricultural land to forests in BC and Alberta can account for more than 26% of Canada's Kyoto commitment. If the results for the study region are representative, and given that it constitutes about 30% of Canada's available area eligible for afforestation (Nagle 1990), large hybrid poplar afforestation programs have great potential to meet Canada's emission reduction targets. However, with regards to the specific Kyoto target, it may not be possible to entice and plant to trees an adequate amount of private agricultural land over the next 12 years to come close to meeting the objectives of C uptake through afforestation. Further, as the difference between business–as–usual emissions and targeted reductions increases, the contribution of forestry (at least in the absence of a long–term strategy) will decrease. Finally, we have calculated costs per tonne of undiscounted C (Figure 3) even when physical C was discounted. If costs are calculated on the basis of discounted C, many of the above results could well be turned on their head.

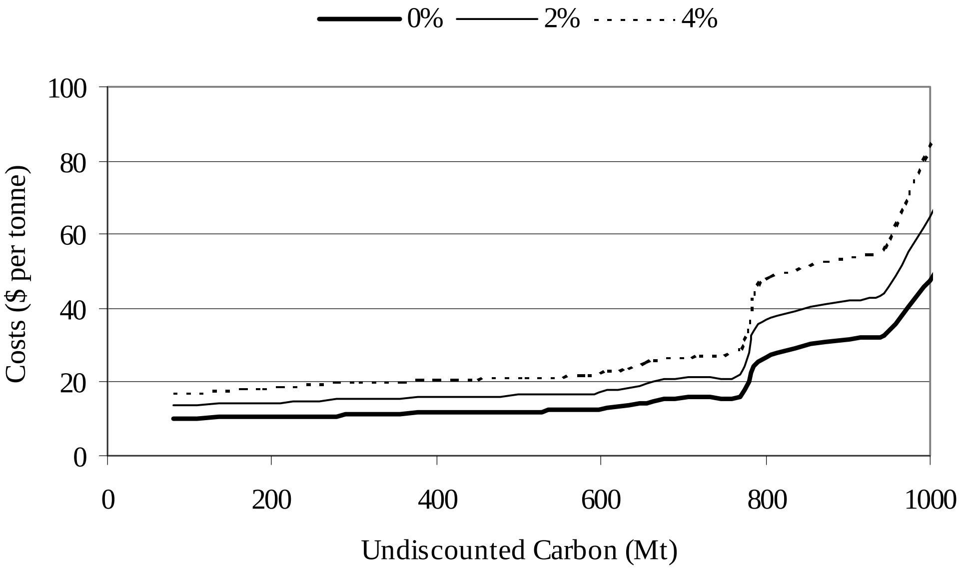

Figure 3: Marginal Costs of Carbon Uptake in Western Canada, One–time Planting of Hybrid Poplar, 50–Year Horizon, Various Discount Rates

Conclusion

The foregoing discussion was based on the assumption that plantations will consist of purely hybrid poplar species. More likely, a mix of species will be planted, in which case no C will be sequestered if a discount rate of 2% or more is used for discounting physical C and an upper limit for C–uptake costs of $20 is used. Changing the assumptions regarding tree–planting programs has dramatic consequences for the results. Hybrid poplar plantations seem to have great potential in terms of reducing atmospheric CO_2 concentrations. With more realistic assumptions about afforestation—planting mixed species, posing a limit of $20 on marginal carbon uptake costs and calculating costs per unit of discounted carbon—one must conclude that the potential of tree plantations as an economically viable C-sink is at least ambiguous for the case of one–time planting.

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