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Climate Change, Canadian Policy and Terrestrial Ecosystems: Economic Considerations

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Climate Change, Canadian Policy and Terrestrial Ecosystems: Economic Considerations

SFM Network Project: Economic, Biodiversity and Carbon Uptake Tradeoffs in Forest Management: An Application of Fuzzy Methods to Vague Concepts and Imprecise Data

by

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EXECUTIVE SUMMARY

The SFM Network has sponsored research into the economics of climate change with a focus on carbon uptake and storage in forest ecosystems. One purpose of this research was to investigate the prospects of forestation and afforestation projects in meeting some of Canada's international obligations to mitigate global warming. Some conclusions regarding the cost-effectiveness work are as follows:

- Silvicultural investments to enhance growth in existing forests for the purposes of enhancing carbon uptake are not cost effective, with some exceptions.
- Afforestation projects are not cost effective if native tree species are planted. If fasting-growing species are used, afforestation may be cost-effective, and certainly competitive with CO_2-emissions reduction options.
- The cost-effectiveness of the terrestrial sinks option is highly sensitive to the rate, and associated (marginal) cost, at which agricultural land can be converted to forest and transaction costs associated with the mechanisms used to entice landowners to plant trees.
- The effectiveness of the forestry option is enhanced if carbon in wood product sinks and other forest ecosystem sinks (such as soil sinks) are taken into account (although this was not yet allowed under Kyoto). Yet, biomass burning may be preferred to the use of timber for wood products because it lessens the possible carbon leakage associated with the effect of reduced stumpage values (lees land in forests) that is associated with the latter.
- At best, Canada can rely on afforestation to meet some 7-10% of its annual obligations to mitigate climate change, much less than the hope for 22%.

We also developed the TECAB model to examine tradeoffs among economic, carbon uptake and biodiversity objectives. TECAB uses compromise programming to find a balance strategy. Compared to the maximum for each objective, which would be unattainable in any event because of real world constraints, the balance strategy achieves what we consider to be an excellent compromise (see Table 6).

Finally, we investigated the use of fuzzy logic to treat uncertainty in forest management and uncertainty about (non-market) valuation of environmental amenities. In the case of forest management, we show that outcomes are highly sensitive to whether a decision maker is optimistic or pessimistic about whether a particular management strategy is or is not successful in achieving carbon uptake goals, for example. In the case of fuzzy logic applied to valuation, our results suggest that traditional methods of valuation might overstate the true value of an environmental amenity. We caution that substantially more research is required before anything definitive can be said.

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1. BACKGROUND

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. At COP3 in Kyoto, December 11, 1997, industrialized (Annex I) countries agreed to reduce CO_2 emissions by an average 5.2% from the 1990 level by the commitment period 2008-2012. The Kyoto Protocol is seen as a necessary step to get nations to take the threat of global climate change seriously, as it was recognised already in 1995, at the first Conference of the Parties in Berlin, that the 1992 Rio commitments might not be enough. The Berlin Mandate began a process that would lead to a strengthened international accord with legal instruments. The Kyoto Protocol was ratified only by Romania and, as a result of the breakdown of COP6 in The Hague in Fall 2000, the United States withdrew its support for the Protocol. Nonetheless, the FCCC process will continue and COP7 is planned for Berlin in July 2001.

At Kyoto, Canada committed to reduce CO_2-equivalent greenhouse gas emissions by 6% of the 1990 level by 2008-2012. Canadian CO_2-equivalent GHG emissions by sector are provided in Table 1. In 1990, Canada produced 601 million tonnes (Mt) of CO_2-equivalent emissions, with the industrial sector, including fossil fuel production but excluding electrical generation, accounting for 33% of the total. By 1997, after a period of economic expansion, Canada's GHG emissions had increased by 13% to 682 Mt. Business-and policy-as-usual emissions are projected to reach 764 Mt annually by 2010, while Canada's Kyoto commitment requires that they not exceed 565 Mt. Emissions are further projected to increase to nearly 850 Mt annually by 2020, although this projection is sensitive to assumptions about population and economic growth, changes in energy prices, the rate of adoption of energy-saving technologies, and other factors (see Natural Resources Canada 1999). To meet this target, emissions need to be reduced by 199 Mt annually within the next decade, or by 26% of policy-as-usual emissions. Clearly, considerable effort will be required, within a very short time frame, to achieve the emissions reduction objective.

Table 1: CO_2-equivalent greenhouse gas emissions by sector, actual 1990, projected 2010 and Kyoto target, Mt

Sector	Actual 1990	Projected 2010	Kyoto Target	Difference[a]
Residential	49	48	46	2
Commercial	26	34	24	10
Industrial	125	138	118	20
Transportation	147	197	138	59
Fossil Fuel Production	75	123	71	52
Electricity	95	119	89	30
Agriculture	61	72	57	15
Other	23	34	22	12
TOTAL	**601**	**764**	**565**	**199**

[a] Projected 2010 minus Kyoto target. Column entries may not sum to total due to rounding.
Source: Natural Resources Canada (1999) and calculation

Prior to Kyoto, Canada's policy response, which is incorporated in its policy-as-usual scenario, consisted of the 1995 National Action Program on Climate Change (NAPCC). The NAPCC's main components are the Voluntary Challenge and Registry (VCR) program, Joint Implementation, a national communication program, and international co-operation. The NAPCC's main focus is to encourage voluntary action by individuals, industry and non-profit organisations (UN FCCC 1996, paragraph 31).[1] The NAPCC is essentially oriented towards principles and broad strategy and makes little reference to specific measures to achieve the pre-Kyoto commitment. As a result of the national strategy set up for implementing the Kyoto Protocol, voluntary action again features prominently in Canada's policy arsenal, particularly as it relates to the industrial sector.

We conducted a survey of Canadian industrial firms and firms in fossil fuel production as part of this SFM project to determine participation in voluntary programs and the ability of firms to meet the Kyoto target (Takahashi et al. 2001). While the sample of firms chosen focused on larger firms, only 35% of responding firms indicated some familiarity with the VCR, while 22% of firms participated in the VCR and 14% had actually submitted an action plan. Survey respondents also indicated that, on average,

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[1] Industry responded with the Canadian Industry Program for Energy Conservation, a "motherhood and apple pie" initiative to encourage firms to invest voluntarily in new energy-efficient technologies.

they could realistically reduce CO_2 emissions by no more than 2% below what they were in 1990 by 2010. (Growth in emissions will continue in this sector as new firms enter and/or smaller firms expand because of economic growth.) The results suggest that firms are not prepared to reduce emissions, and any steps they take to reduce emissions do not go beyond business-as-usual practices. Indeed, Canada's largest companies lobbied the government in early 2000 to delay emissions reduction (Mittelstaedt 2000; see also Canadian Pulp & Paper Association, hereafter CPPA, 2000). Voluntary action is clearly untenable and stronger measures such as taxes or regulation will likely be required if more substantial results are to be achieved.

The second major plank in Canada's policy response is reliance on terrestrial carbon (C) sinks particularly forest sinks. Forests are important because they sequester more carbon at a faster rate than agricultural sinks, with further benefits possible if account is taken of wood product sinks (e.g., construction lumber, paper in landfills) or wood biomass used to produce energy in place of fossil fuels. Forests store C by photosynthesis, with each m^3 of wood storing approximately 200 kg of C. For every tonne (t) of C sequestered in forest biomass, 3.667 t of CO_2 is removed from the atmosphere. Countries that have a large forest sector are interested in C credits related to reforestation, and those with large tracts of (marginal) agricultural land are interested in afforestation as a means for achieving some of their agreed upon CO_2-emissions reduction. Canada falls into both these categories.

The primary focus of the research conducted under the auspices of SFM Network funding was on the economics of forest carbon sinks in Canada. The current project was a continuation of our previous SFM Network funded project on climate change and forestland use (Krcmar et al. 2001; Stennes 2000; van Kooten et al. 1999, 2000; van Kooten and Hauer 2001). Although the results of the preceding project (some of which was completed under the current project) suggested that afforestation of marginal agricultural lands is a competitive C-uptake strategy, a number of issues had remained unresolved.

1. The first of these concerned the approach dynamics: How long was it likely to take to implement a large-scale, tree-planting program in Canada? Even if hybrid poplar has a rotation age of 12-15 years, could enough be planted to contribute to the Kyoto-mandated target?
2. In the afforestation literature, transaction costs have been ignored and there has been little attention on economic incentives and institutions. Could transaction costs be an unanticipated cost that creates a significant barrier to tree planting? How do transaction costs affect the instruments needed to "entice" farmers to transfer

marginal land into forestry? In particular, will farmers be willing to accept large-scale hybrid poplar plantations? Do farmers need compensation for reductions in biodiversity and scenic amenities?

3. What impacts might forest management for C uptake have on forest biodiversity?
4. Finally, how can uncertainties inherent to forestry and carbon uptake be incorporated into forest management models? And how might uncertainty and ambiguity regarding environmental valuation be incorporated into economic models of forest conservation?

In section 2, we focus on the role of forest sinks in Canada's policy arsenal for achieving CO_2-emissions reduction targets. Then, in section 3, we present our research on the potential impacts of carbon-uptake policies on timber and non-timber values. In section 4, we discuss our research on uncertainty in forest management related to climate change, and on uncertainty in valuing environmental or non-market amenities. In this research, we employed fuzzy set theory and related possibility theory, demonstrating its potential applications to forest management and environmental valuation. Our conclusions follow in section 5.

2. ROLE OF TERRESTRIAL ECOSYSTEMS IN MITIGATING CLIMATE CHANGE

A country can obtain carbon credits at home by planting trees where none grew previously, increasing the rates at which trees grow through enhanced forest management, or potentially other land-use activities that increase carbon in soils or growing plants. The Kyoto Protocol permitted C sequestration in trees planted as a result of an afforestation or reforestation program to be counted as a credit, while C lost by deforestation was counted as a debit (article 3.3). While only C sequestered in wood biomass was initially counted, the Protocol left open the possibility for including other components, such as wood product C sinks, wetlands and soil C sinks (article 3.4). This possibility will remain in any future climate/emissions-reduction negotiations. Carbon credits could also be obtained for activities in developing countries and economies in transition. Kyoto's Clean Development Mechanism (CDM) enabled industrialized countries to purchase certified offsets from developing countries by sponsoring projects that reduce CO_2 emissions below business-as-usual levels in those countries. Likewise, emission reduction units could be produced through Joint Implementation (JI) projects in countries whose economies are in transition. Projects that prevent or delay deforestation and land-use change, or result in the establishment of plantation forests, were eligible under the CDM and JI.

Collectively the terrestrial carbon sink projects described above are referred to as land use change and forestry (LUCF) projects. What was strange about the Kyoto Protocol is that the 1990 baseline for greenhouse gas emissions does not include terrestrial C flux, but the calculations for determining compliance for 2008-2012 did. Baseline emissions were founded on gross emissions, while compliance was based on net emissions. A country could conceivably meet its emissions reduction target even though its gross emissions have increased. It could do this, say, through domestic LUCF projects and/or foreign ones under the CDM or through JI. This oddity is unlikely to disappear in a future accord, although the exact form it may take is uncertain.

The role of terrestrial sinks and whether market mechanisms should treat carbon offsets the same as emissions reduction are a source of dispute. An attempt to reach an agreement on these and other outstanding Kyoto issues was made at the sixth COP in The Hague, Netherlands, during November 2000. COP6 failed partly because European countries took the view that there should be limits to the role of sinks (a cap) and LUCF projects so that countries would be forced to address emissions reduction. Europeans fear that LUCF projects are ephemeral and do not help to reduce the long-term, upward trend in CO_2 emissions. The opposite view is that CO_2 emissions reduction and carbon sinks are no different in their impact and should be treated the same on efficiency grounds (Chomitz 2000).

A second reason why COP6 failed and the Americans eventually scuttled Kyoto has to do with the role of market instruments. The U.S. and some other countries hope to achieve future CO_2-emissions reduction targets in part by purchasing carbon offsets abroad, thereby lessening the “pain” at home. From an economic efficiency point of view, it makes sense that the least cost means of reducing atmospheric CO2 be pursued, but, again, the Europeans feel that the Americans are not serious about addressing their own high-levels of emissions. They also fear that payments by private or public agents to those in developing countries will drive out current development aid. While this may be true, to some extent, it appears that developing countries can benefit from sale of C credits/offsets because they benefit from more efficient technologies, a cleaner environment and reduced levels of deforestation.

In principle, a country should get credit only for sequestration above and beyond what occurs in the absence of C-uptake incentives, a condition known as “additionality” (Chomitz 2000). Thus, for example, if it can be demonstrated that a forest would be harvested and converted to another use in the absence of specific policy (say, subsidies) to prevent this from happening, the additionality condition is met. Carbon sequestered as a result of incremental forest management activities (e.g., juvenile spacing, commercial thinning, fire control, fertilisation) would be eligible for C credits, but only if the activities would not otherwise have been undertaken (say, to provide higher returns or maintain market share). Similarly, afforestation projects are additional if they provide environmental benefits (e.g., regulation of water flow and quality, wildlife habitat) not captured by the landowner and would not be undertaken in the absence of economic incentives, such as subsidy payments or an ability to sell carbon credits (Chomitz 2000). Which LUCF projects meet the additionality requirement?

2.1 Land Use Change

Consider first the role of tropical deforestation.[2] Tropical forests generally contain anywhere from 100 to 400 m^3 of timber per ha, although much of it may not be commercially useful. This implies that they store some 20-80 tonnes of C per ha in wood biomass, ignoring other biomass and soil C. An indication of total C stored in biomass for various tropical forest types and regions is provided in Table 2. The C sink function of soils in tropical regions is even more variable across tropical ecosystems (see Table 3, col. 2). This makes it difficult to make broad statements about carbon loss resulting from tropical deforestation. Certainly, there is a loss in C stored in biomass (which varies from 27 to 187 t C ha^{-1}). There may or may not be a significant loss in soil C depending on the new land use (agricultural activity) and the tropical zone. While conversion of forests to arable agriculture will lead to a loss of some 20-50% of soil C within 10 years, conversion to pasture may in fact increase soil C, at least in the humid tropics (see Table 3). One thing is clear, conversion of forestland to agriculture leads to a smaller carbon sink, with a greater proportion of the ecosystem's C stored in soils as opposed to biomass (Table 4). To address this market failure (release of C through deforestation), policies need to focus on protection of tropical forests.

Table 2: Carbon Content of Biomass, Various Tropical Forests and Regions

Country/Forest	Wet Tropical	Dry Tropical
Africa	187 t C ha^{-1}	63 t C ha^{-1}
Asia	160 t C ha^{-1}	27 t C ha^{-1}
Latin America	155 t C ha^{-1}	27 t C ha^{-1}

Source: Papadopol (2000)

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[2] Evidence indicates that forested areas are increasing in developed countries, particularly those in the northern latitudes, so the focus is only on deforestation in tropical regions.

Table 3: Depletion of Soil Carbon following Tropical Forest Conversion to Agriculture

Tropical Region	Soil Carbon in Forest	New Land Use	Loss of Soil Carbon with New Land Use
Semi-arid	15-25 t C ha^{-1}	Shifting cultivation (arable agriculture)	30-50% loss within 6 years
Subhumid	40-65 t C ha^{-1}	Continuous cropping	19-33% loss in 5-10 years
Humid	60-165 t C ha^{-1}	Shifting cultivation pasture	40% loss within 5 years 60-140% of initial soil C

Source: adapted from Paustian et al. (1997)

Table 4: Total Carbon in Tropical Ecosystems by Sink, Percent [a]

Land Use	Tree	Understorey	Litter	Root	Soil
Original Forest	**72**	**1**	**1**	**6**	**21**
Managed & logged over-forest	72	2	1	4	21
Slash & burn croplands	3	7	16	3	71
Bush fallow	11	9	4	9	67
Tree fallow	42	1	2	10	44
Secondary forest	57	1	2	8	32
Pasture	<1	9	2	7	82
Agroforestry & tree plantations	49	6	2	7	36

[a] Average of Brazil, Indonesia and Peru
Source: Woomer et al. (1999)

It may be difficult, however, to prevent tropical deforestation from occurring. While mechanistic causes of land use change (logging, road construction, illegal land clearing by peasants, etc.) are often easy to identify, as are possible domestic policies for correcting these forms of market failure, the underlying or ultimate factor is government policy related to revenue and foreign exchange needs, and urbanisation and population control (Bromley 1999; van Kooten et al. 2000b). Income and/or the foreign exchange generated from logging concessions (e.g., SE Asia) or the new land use (cattle ranching in Brazil) are important for some Governments in tropical regions. Governments may also permit or even encourage land-use changes as part of an overall policy to address urbanisation pressure and general over-population in certain areas. Indonesia has moved peasants into outlying forested regions as a means of addressing over-crowding in Java, for example, while Brazil has promoted development of the Amazon in order to encourage migration into the region and away from more urbanised areas to the South.

2.2 Enhanced Management of Existing Forests and Afforestation

There remains disagreement about what is meant by reforestation and afforestation; some countries interpret reforestation to mean that any growth in trees planted on forestland denuded after 1990 is eligible for carbon credits. In effect, they want C credits for replanting forests that have been logged, thereby violating additionality. The Intergovernmental Panel on Climate Change (IPCC 2000) interprets reforestation as tree planting on land that had at some time in the past been in forest, but has recently been in agriculture; Canada and some other countries interpret this as afforestation. According to the IPCC, afforestation refers to tree planting on lands that have never been and would not naturally be in forest. These disparate views are rooted in Kyoto's failure to take proper account of carbon in wood products. Canada and other major wood product exporters feel that their definition of reforestation simply recognises the fact that much of the C in harvested timber gets exported and that the debit from logging should therefore be charged to the importing country.

Reforestation needs to take into account the C debit from harvesting trees, but it also needs to take into account C stored in wood product sinks (and exported C) and additional C sequestered as a result of forest management activities (e.g., juvenile spacing, commercial thinning and fire control). Even when all of the C fluxes are appropriately taken into account, it is unlikely that "additional" forest management (enhanced or incremental silviculture) will be a cost-effective and competitive means for sequestering carbon (Caspersen et al. 2000).[3]

Evidence from Canada, for example, indicates that basic silviculture (reforestation) does not pay even when C uptake benefits are taken into account, mainly because northern forests tend to be marginal (van Kooten et al. 1993). The reason is that such forests generally regenerate naturally, and returns to artificial regeneration accrue in the distant future. Only if short-rotation, hybrid poplar plantations replace logged or otherwise denuded forests might forest management be a competitive alternative to other methods of removing CO_2 from the atmosphere. As demonstrated in the SFM-funded research, hybrid poplar plantations may also be the only cost-effective, competitive alternative when marginal agricultural land is afforested (van Kooten et al.1999, 2000a).

Surprisingly, despite the size of their forests and, in some cases, large areas of marginal agricultural land, our research suggests there remains only limited room for forest sector policies in the major wood producing countries (Canada, Finland, Sweden, Russia). We illustrate this using the TECAB model that we developed for northeastern British Columbia (Stennes 2000; Krcmar and van Kooten 2001). The model consists of tree-growth, agricultural activities and land-allocation components, and is used to

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[3] Global data on the potential for C uptake via forest management is provided in Appendix Table A.1.

examine the costs of C uptake in the grain belt-boreal forest transition zone of BC. These estimates, extended to similar regions, provide a good indication of the costs of an afforestation-reforestation strategy for C uptake for Canada as a whole, and likely for other boreal regions as well. The study region consists of 1.2 million ha, of which nearly 10.5% constitute marginal agricultural land, with the remainder being boreal forest. The boreal forest is composed of spruce, pine and aspen. For environmental reasons and to comply with BC's Forest Practices Code, the area planted to hybrid poplar in the model is limited only to logged stands of aspen and marginal agricultural land. Other harvested stands are replanted to native species or left to regenerate on their own, depending on what is economically optimal. Carbon fluxes associated with forest management, wood product sinks and so on are all taken into account. An infinite time horizon is employed, land conversion is not instantaneous (as assumed in some models), C fluxes associated with many forest management activities (but not control of fire, pests and disease) are included, and account is taken of what happens to the wood after harvest, including their decay (see Table A.2 for data on decay of forest ecosystem components). The model also addresses uncertainty using fuzzy logic (see section 3).

The study results are summarised in Figure 1. These indicate that upwards of 1.5 million tonnes of discounted C (discounted at 4%) can be sequestered in the region at a cost of about $40 per t or less. This amounts to an average of about 1.3 t ha^{-1}, or about 52 kg ha^{-1} per year over and above normal C uptake. If this result is applied to all of Canada's productive boreal forestland and surrounding marginal farmland, then Canada could potentially sequester some 10-15 Mt of C annually via this option. This amounts to at most 7.5% of Canada's annual Kyoto-targeted reduction, well below the 22% that had been envisioned (CPPA 2000). This is a rather pessimistic conclusion given that, in general, plantation forests are considered a cost-effective means of sequestering C (Sedjo et al. 1995; Adams et al. 1999). Again, the reason is that boreal forests are globally marginal at best and silvicultural investments simply do not pay for the most part, even when C uptake is included as a benefit of forest management (van Kooten et al. 1993; Wilson et al. 1999).

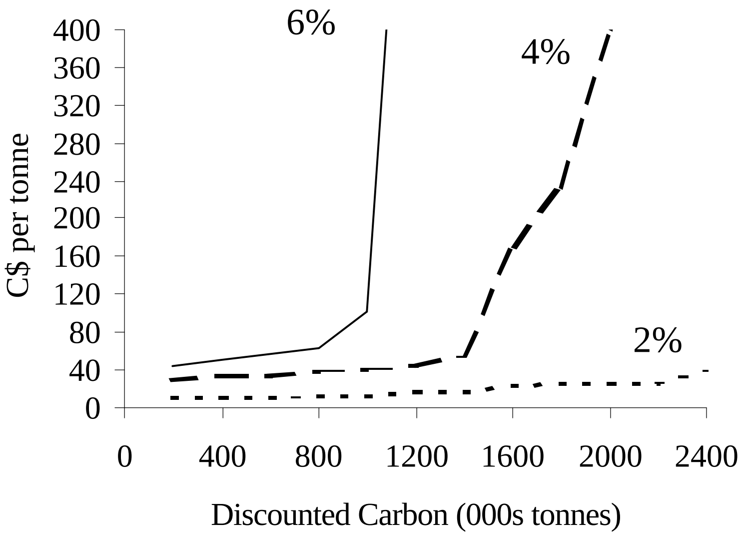

Figure 1: Marginal Costs of C Uptake in a Boreal Forest Ecosystem, NE British Columbia

There remains a great deal of uncertainty about planting hybrid poplar on a large scale because it has not been done previously. There are drawbacks that limit its viability:

1. Relative to native species, hybrid poplar plantations have negative environmental impacts related to reduced biodiversity and susceptibility to disease (see Callan 1998).
2. If there are transaction costs associated with afforestation, this will increase C-uptake costs above what has thus far been estimated.
3. There is uncertainty about (current and future) stumpage values and prices of agricultural products, and this makes landowners reluctant to convert agricultural land to forestry.
4. Little is known about the potential of wood from afforested land as a biomass fuel.
5. Research suggests that planting trees where none existed previously decreases surface albedo that offsets the negative forcing expected from C uptake (Betts 2000). Indeed, in some cases, a forestation program may even contribute to climate change rather than mitigating it as expected. This is more of a problem with coniferous than deciduous species, however, although it would not be entirely absent in hybrid poplar plantations.
6. There is the problem of leakages: Large-scale afforestation and/or other forest plantations are bound to lower wood fibre prices, with current woodlot owners (say in the US South) reducing their forest holdings by converting land back to agriculture in

anticipation. These are generally ignored in calculating the costs of individual afforestation or reforestation projects. Yet, such leakages can be substantial, even as high as one-half of the C sequestered by the new plantations (Sohngen and Sedjo 1999).

2.3 Wood Product Sinks and Biomass Burning

By producing energy from wood biomass rather than fossil fuels, countries are able to reduce their overall CO_2 emissions by an amount approximately equal to the savings in emissions from the fossil fuels that are replaced. This is because any CO_2 released by burning wood biomass is claimed as a credit by growing the trees that are subsequently burned. Our early research suggested that, for a realistic cost of C uptake of less than $20 per tC, 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 (van Kooten et al. 1999). We also showed that, if wood is harvested and account is taken of carbon that enters wood product pools, afforestation of marginal agricultural land could be a useful component of Canada’s policy arsenal. We concluded that, for carbon uptake costs of $20 per tC or less (in the mid-range of 2001 carbon trading), it may be worthwhile to plant hybrid poplar (but not native species) on maybe one-third of the agricultural land that a non-economist might identify as suitable for afforestation. We identify that, in a steady state, it may be optimal to plant 3 million ha in western Canada to hybrid forests if the problems mentioned above and transaction costs (see section 2.5 below) are ignored (van Kooten 2000).

Because wood product sinks were disallowed under Kyoto and, in any event, could lead to significant leakages (as stumpage prices were driven down), biomass burning may be a better option for countries with vast forest/agricultural areas to pursue. The benefits of C uptake through afforestation are enhanced when there exist opportunities to use forest biomass in conjunction with wood waste to produce energy that substitutes for energy from fossil fuels (with the reduction in GHG emissions from fossil fuel consumption constituting a credit). In terms of carbon balance, the benefits of burning biomass to produce energy include the maintenance of an emission-uptake equilibrium (no net flux), the one-time gain in C uptake from initial establishment of a tree plantation, and finally the annual fossil-fuel offsetting emissions.

For some countries, biomass burning may be important if the nuclear, wind (turbines can kill birds) and hydropower options are thought to be environmentally unsound and solar power too expensive. In Canada, the forest sector is a large consumer of electricity, much of it purchased from the local/regional provider. The purchased electricity is generated from a variety of sources, including primarily natural gas, coal and hydropower. The forest sector self-generates about half of the power that it uses (Forest Sector Table 1999), but is constrained in many cases from achieving economies of size in power generation by an inability to sell excess power into the provincial grid and/or a lack of fibre (CPPA 2000). In British Columbia, for example, BC Hydro restricts sale of privately generated power into the provincial grid because this would reduce prices and the revenues that the government-owned company could generate. Until recently, sawmills in the Province burned sawdust in beehive burners, but, when this was no longer permitted on environmental grounds, the sawdust was simply put into landfills. A small number of cogeneration plants have been built since the ban, primarily in areas where disposal costs and wood waste volumes are highest. With increased demand for energy and greater environmental consciousness, policies that discourage alternative, environmentally friendly forms of power generation should be a thing of the past.

Firms do not currently pay for wood waste, but its availability may prevent economies of scale in biomass burning. If carbon taxes/subsidies or government regulations cause firms to take biomass burning more seriously, demand for industrial wood waste will increase beyond current supply, and wood waste will take on value. This, in turn, will encourage production of wood fibre from fast-growing energy plantations. If biomass power generation is determined to be economically profitable, farmers may be able to sell biomass at a profit; at least, it might reduce the compensation (private or public) paid to farmers for establishing and maintaining tree plantations, and increase the area economically feasible for afforestation. We are currently investigating this as part of the unfinished research associated with the SFM-funded research (see Graham 2001).

Besides the reduction in CO_2 emissions, biomass burning can provide opportunities for industry and communities to reduce their electricity costs if power generators are scaled to their particular requirements. The establishment and operation of biomass systems will increase employment, with most of the jobs created in rural areas where jobs are most threatened by ongoing forest protection measures and mechanisation of factors of production.

Wood fuel conversion technologies include direct combustion, cogeneration, gasification, and conversion to liquid fuels. The efficiency of the conversion system determines the reduction in CO_2 emissions through the displacement of fossil fuels. Estimates of emission savings range from 1.7 to 9.0 tC ha^{-1} per year depending on forest type, discount rates, energy conversion efficiency, and the particular fossil fuel being displaced (Wright et al. 1992; van Kooten et al. 1999). The cost of substituting wood biomass for coal in electricity production ranges from \$27.60 to \$48.80 per t C, based on a value of \$7.50 per m^3 for hybrid poplar on energy plantations, a substitution ratio of 2.6-4.6 m^3 of wood per t of coal to generate an equivalent amount of energy, and a carbon content of 0.707 tC per t of coal (Marland et al. 1995).

As shown in Table 5, energy from wood residues can compete with fossil fuels and purchased electricity. This conclusion needs careful scrutiny, however. First, wood residue prices are based on average and not marginal costs, and are only available for small-scale operations where wood is easy to come by. At a larger scale, one would expect much higher raw material (wood) costs. Second, wood fibre prices vary significantly by region depending on residue surpluses or shortages, and environmental regulations. Regional values are not currently available for comparison (Forest Sector Table 1999). If fast-growing plantations are included, estimated costs are \$2.82 per GJ, which is more expensive than fossil fuels, but still cheaper than purchased electricity.

Table 5: Energy Price Comparisons for British Columbia, Canada (\$1997)

Wood Residues (assumed conversion factor = 18 GJ per dry tonne)	
Wood residue from pulp and paper mills	\$1.0 GJ^{-1}
Wood residue from wood industry	\$0.56 GJ^{-1}
Wood waste plus plantation wood	\$2.82 GJ^{-1}
Fossil Fuels (based on natural gas, boiler efficiency of 85%, C emission factor of 0.050 t GJ^{-1})	
Fuel price	\$1.73 GJ^{-1}
Electricity (at \$0.039 per kWh)	\$10.84 GJ^{-1}

Source: Forest Sector Table (1999) and own calculations

Fossil fuel substitution on a global scale, using 10% of an estimated 3,454 million ha of forested area as a source for biomass energy, would replace an average of 2.45 GtC per year. This figure is based on 7 tC ha^{-1} yr^{-1}, while the average C capture rate can vary from less than 0.5 to 12 t C ha^{-1} yr^{-1} depending on the type of forestry being practiced – conventional or plantation. This amounts to some 40% of global fossil fuel emissions of carbon in 1990.

In Canada, the high capital cost of infrastructure, regulation of the electricity market, and the relatively low cost of fossil fuels restrict the economic viability of substituting biomass for fossil fuels in power generation. When we consider global climate change, future energy requirements, availability of supply, and social and environmental values, we find that the benefits of renewable energy sources such as wood biomass outweigh the costs in some, but not all situations.

2.4 Prognosis for Forest Carbon Sinks on Marginal Agricultural Land

Our research also addressed two issues unrelated to whether or not hybrid poplar or native tree species are planted on marginal agricultural land. First, in order to plant trees on the scale required to address internationally agreed-upon emissions targets, a large area will need to be planted. If marginal costs of planting rise as more area is planted during a given window of time (trees can only be planted at certain times of the year), then it could take some time before a sufficiently large area is planted. Planting at too fast a rate will simply increase the costs of C uptake, making this option less competitive relative to others in the economy or abroad. Using an optimal control model, we find that, while it may be optimal to plant a significant area of marginal agricultural land to trees, it could take as long as 40 years to achieve the scale needed to make a difference in Canada's annual emission-reduction needs (van Kooten 2000).

Second, using the results from a survey of landowners in western Canada that we conducted in July 2000 (208 completed surveys), we find that transaction costs may be a significant barrier to achievement of any federal afforestation target that might be set (Suchánek 2001; Suchánek et al. 2001). While landowners are in a position to help Canada achieve C offsets through large-block tree plantations, our results suggest that getting farmers to do so may be a hard sell. Even if they are fully compensated for lost agricultural revenues and tree planting costs, more than one-quarter of respondents would be unwilling to enter voluntarily into an afforestation program. Rather, the evidence suggests that landowners are content to change cropping practices in ways that provide some, albeit much smaller, C benefits, whether that consists of planting shelterbelts and individual trees or changing cropping practices so that more organic matter is stored in soils. Less than 1/4 of farmers even view large-block tree plantations to be an effective means for producing C credits, compared to much higher proportions citing other agricultural activities. Importantly, these other activities provide benefits, such as reduced wind erosion or greater soil fertility, in addition to those associated with C uptake. Even then landowners demand or expect to be compensated (see van Kooten et al. 2001).

It appears that there may be unaccounted for transaction costs that prevent large-scale tree planting on marginal agricultural lands in western Canada. Landowners are reluctant to change dramatically their land uses; they prefer to continue with what they know best, and current agricultural policies, programs and research (e.g., with respect to soil C sinks) entrench such behavior. Further, the empirical evidence indicates that farmers are actually hostile towards tree planting in areas where land clearing has been most pronounced (the black soil zone). Asset specificity, in the form of developed land and investments in combines, tractors, fencing and trucks, may also be an obstacle to afforestation. Finally, the great majority of farmers responding to our survey would not be willing to enter into tree-planting agreements that exceeded about 15 years, the rotation age for hybrid-poplar. This militates against programs to plant native tree species for biodiversity reasons, since such trees have a rotation age of some 40 years or more (van Kooten, Shaikh and Suchánek 2001).

As further evidence of farmers' reluctance to plant trees on a large scale, we estimated their average willingness to accept (WTA) compensation for planting trees (Suchánek et al. 2001). The average annual amount that farmers would need to be compensated to plant trees on marginal agricultural land turned out to be about $40 per acre, or nearly $100 per ha. This is over and above the actual afforestation and other association costs and is about six times the opportunity cost of the land. Of course, this does not include the transaction costs of a coordination mechanism for implementing large-scale tree planting. Landowners expressed a strong preference for contracting with state agencies (i.e., receiving government subsidies) as opposed to relying on carbon markets (van Kooten et al. 2001). While carbon markets result in the most cost effective trades (with the least cost land going into C plantations), they also impose the greatest risks on the individual landowner.

Does this imply that there is no room for domestic afforestation projects? Not at all, as much of the forgoing analysis is based on average and not marginal considerations. Indeed, at the margin there will undoubtedly be forest plantation strategies that make sense because they are competitive with projects elsewhere in the economy or abroad. Our research only cautions against willy-nilly adoption of large-scale projects without due consideration of the institutions and incentives provided landowners, because the nature of the coordination mechanism chosen can tip the scale against a project by unduly increasing its costs.

3. ECONOMICS, BIODIVERSITY AND CARBON UPTAKE TRADEOFFS IN FOREST MANAGEMENT

Forest policies often focus on ecological services in isolation, or examine tradeoffs between a single ecological objective and an economic one. Integrated assessment of multiple ecological and economic objectives is rare, even though policies that address one objective may affect some or even all of the other objectives (Alig et al. 1998; Englin and Callaway 1995).

Climate change and loss of biodiversity are considered to be among the world's most important environmental policy issues. Changes in land use, particularly from forestry to cropland, have a major impact on the amount of CO_2 entering the atmosphere and on the loss of forest biodiversity. One “no-regrets” strategy for reducing atmospheric concentrations of CO_2 is to increase forest biomass production through better forest management (silvicultural investment) and planting trees on agricultural lands (see above). Managing for C uptake has various impacts on biodiversity, a factor generally ignored in decision models, while forest planning with the sole objective of preserving biodiversity affects both timber and C benefits. Hence, our investigation (Krcmar and van Kooten 2001) includes preservation of biodiversity as an objective in addition to timber and C uptake, thereby extending our previous study on multiple-use of forests (Krcmar et al. 2001).

Difficulties in quantifying biodiversity, broadly defined as “the variety of life”, represent an obstacle for its successful incorporation into forest planning. While many measures of biodiversity have been proposed (Weitzman 1992), no universal measure has been adopted. Forest ecologists emphasize the importance of maintaining structural diversity of forests, because diversity of vertebrates is closely related to foliage height diversity (Bunnell 1998). Since the relationship between tree diameter and height is well defined, tree size diversity can serve as a proxy for foliage height diversity (Buongiorno et al. 1994). Managing forests for structural diversity avoids complex questions about what plant and animal species to protect or what habitat to favour.

While high evenness is often equated with diversity, an even distribution of species (or forest structure) is not always an appropriate measure of biodiversity. The diversity of an ecosystem may be better described in relationship to some desired “target” (Buongiorno et al. 1994). Structural diversity of a forest is then measured by its closeness to the target distribution, and the forest can be managed to meet these requirements.

Models that support the sustainable forest management policy process need to incorporate multiple objectives important to different stakeholders. Objectives, broadly classified as economic and environmental, are often in conflict and not measured in the same units. In many situations there is no adequate information to develop welfare functions and apply cost-benefit methodologies. The need to analyze the multi-dimensional performance of proposed policies and manage conflicts between policy objectives led to the development of a modeling approach known as multiple-criteria decision-making (MCDM). The major strength of MCDM methods is their ability to address conflicting interests, provide a comprehensive analysis of conflicts and make the tradeoffs more transparent to all policy participants, thus allowing for public negotiation.

We developed an integrated economic and ecological approach to multiple objective conflict management (Krcmar and van Kooten 2001). The method of compromise programming was applied, and tradeoffs between economic and other benefits were quantified. The multiple objective model that we developed, and refer to as TECAB, preserves the linear structure of the original model and makes it possible to determine which management strategy best balances competing objectives. Finally, the measure of structural diversity in terms of a fit to the desired forest pattern fulfills the requirements of flexibility and generality, and may include other dimensions of biological diversity.

The approach proposed is most suitable for strategic planning at the forest level. As a case study, we applied TECAB to northeastern British Columbia (see also above). The study region consists of boreal forest and a region of intensive (crop production) and extensive (grazing) agriculture. Five objectives are defined for land management in this region: 1) maximization of net discounted returns from forest and agricultural activities; 2) maximization of cumulative timber volume; 3) maximization of cumulative discounted carbon stored (uptake minus emissions); 4) maintenance of a stable flow of timber to the mills; and 5) attainment of a desired forest structure.

TECAB is first solved for each of the objectives separately, assuming that the remaining objectives are unimportant, but with all other constraints in place. The results are shown in Table 6. Each row of the table consists of objective values calculated at the solution obtained when the problem indicated in the first column is optimized. For example, the elements of the first row are the objective values at the optimal solution of the NPV objective. The first three objectives are the cumulative net present value (NPV), timber volume and carbon sequestered over the planning horizon, while the last two refer to the maximum deviation from the target timber flow and the target forest structure. Elements on the main diagonal in Table 6 are the best values for each objective, whereas the figures in bold correspond to their worst values.

Table 6: Objective values for various management strategies[a]

Management strategy	NPV ($'000s)	Volume ('000s m^3)	Carbon ('000s t)	Even Flow ('000s m^3)[b]	Structural Diversity (ha)[c]
NPV	1,084,858	137,659	0	39,269	-129,126
Timber volume	664,212	254,715	0	76,707	+162,214
C uptake	519,402	85,583	3,838	42,420	+162,214
Even flow	599,073	212,098	0	0	+143,560
Biodiversity	443,200	42,420	-476	42,420	0
Balanced	779,703	171,495	2,214	32,451	68,625

[a] Best values are found on the diagonal; worst values are given in bold.
[b] Expressed as a deviation between periods.
[c] Expressed as a positive or negative deviation from the target.

Obviously there is strong conflict among the five objectives. Not surprisingly, the conflict is especially marked between timber and non-timber benefits, but there is also significant competition between long-term economic benefits and supply of timber in terms of both cumulative and stable flow. In fact, the strategy of maximizing timber volume over the planning horizon leads to the worst values for even flow of timber, C uptake and attainment of the structural diversity target. A carbon driven land-use strategy is in substantial conflict with timber supply and economic benefits. The highest degree of conflict is between achievement of desired forest structure and timber benefits. Timber strategies, either for cumulative volume or even flow, generate high positive deviations from the structure of a “natural” forest. The areas of young forest created by reforestation of denuded forestlands in periods 2 and 3 are the source of these deviations. The strategy to regulate the landscape for a desired structure implies low net present value and timber volume. In addition, the structural diversity strategy results in low (and even negative) cumulative (discounted) carbon flux. Preserving natural forests without new growth does not contribute to carbon uptake. Conflicts between the diversity preservation objective and all other objectives are primarily the result of the diversity structure target that is chosen – natural forest. Nevertheless, similar outcomes could be expected for any other target that includes preservation of mature coniferous forest, unless additional management activities are undertaken.

Since optimization of a single objective, changes in the environmental, economic and timber supply conditions are examined for the case of the “balanced strategy”. This management strategy seeks to manage the conflict between the five objectives. The “balanced” objective values are provided in the last row of Table 6.

Comparing the balanced objective values with the best possible values shows that the balanced strategy provides 72% of the best cumulative net return, 67% of the highest cumulative timber harvest and 58% of the maximum amount of carbon that can be stored in wood and wood products. Although such reductions in economic returns and cumulative harvest volume (the source of government revenue) may seem unacceptable, one should not forget that the best values for these objectives are achieved by greatly violating the requirements on carbon uptake, maintenance of forest diversity and even flow of timber.

If a judgement is made between the balanced objective values and those obtained under an even flow strategy, a different picture emerges. Compared to the even flow strategy, the balanced strategy is about 30% better in terms of net present value and only about 19% worse in terms of reduced cumulative timber volume. The balanced strategy does not perform well in terms of stable timber flow, however. The maximum difference between period harvests is about 42% of the highest fluctuation between periods that occurs under the strategy that maximizes timber output. These results are consistent with the findings on downsizing effects of the non-declining or stable flow of timber on attainment of other objectives.

Under the balanced strategy, the diversity objective attains its lowest deviation of any other strategy, except for the case where the only concern of management is structural diversity. Intensive afforestation and moderate planting to reforest denuded lands are the main features of the balanced strategy. A balance between early and late harvesting of both native and hybrid species is achieved. Both high cumulative and stable flows of timber require intensive reforestation, which is very expensive. Unfortunately, such an investment to achieve timber harvest goals is neither economically nor environmentally justified. It is important to recognize that the choice of weights and the form of distance function could affect the outcomes of the “balanced strategy.” However, by assigning different weights according to the preferences of policy participants, the analyst can aid in demonstrating and hopefully reconciling tradeoffs among objectives.

An analysis of projected outcomes for each of the single-objective strategies and the balanced strategy over the planning horizon may better help reveal sources of conflict. For this purpose, we compare selected outcomes for five extreme scenarios and related land management strategies – those maximizing cumulative net present value (N), timber volume (V) and carbon uptake (C), maintaining stable timber flow (E), and preserving structural diversity of forest (D) – and the one that balances (B) objectives.

Nominal net returns to both forestry and agriculture in different time periods for these scenarios are presented in Figure 2. For all strategies, the distribution of nominal net returns over time falls significantly in periods 3 and 4 relative to the two initial periods. The only exception is the balanced strategy, which generates a high net return in period 4. The explanation for these patterns is found by examining harvest volumes over time. After the increases in harvest volume in period 2 for the N and V strategies relative to the initial period harvest, harvests drop sharply in periods 3 and 4. Harvests rise again in the very last period for the V strategy, but remain low for all other strategies, except for B. The balanced strategy provides a non-declining flow of harvest starting from period 2 after the sharp decline in timber supply relative to the initial period.

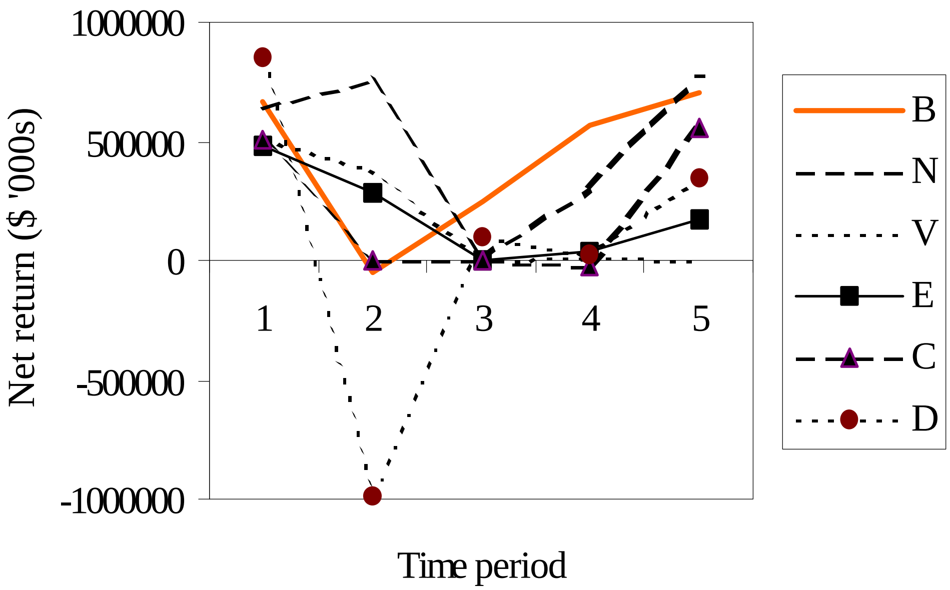

Figure 2. Nominal net returns by period for various strategies

Strategies oriented to economic benefits and timber volume rely on intensive harvesting of natural forests in period 2 (recall that harvests in period 1 are predetermined). Since harvesting is restricted to natural forests of age 60 years and over, the N or V strategies imply a drastic shortage of forest available for harvesting in periods 3 and 4. Simultaneous harvests of newly established deciduous plantations could only partially offset this shortage. The harvest intensity of scenarios N and V implies reduced carbon storage in periods 2 and 3 (Figure 3).

A disadvantage of the V and E strategies lies in the high number of young trees regenerated in the periods following harvesting. This creates an excessive positive deviation from the desired forest structure, especially in periods 2 and 3 (Figure 4). Unlike timber supply strategies, the N strategy generates high negative deviation from the target structure in periods 2 through 4. Since most of the mature forests are cut in the first period, this implies a large negative deviation from large-diameter, older trees that characterize natural forests. This feature could have a negative implication for wildlife dependent on late-successional stage forest habitat.

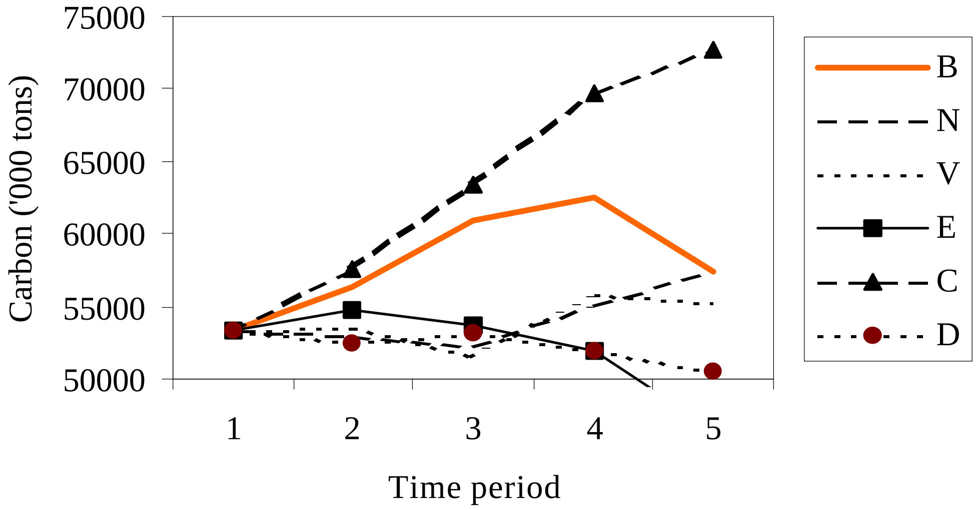

Figure 3. Nominal carbon storage by period for various strategies

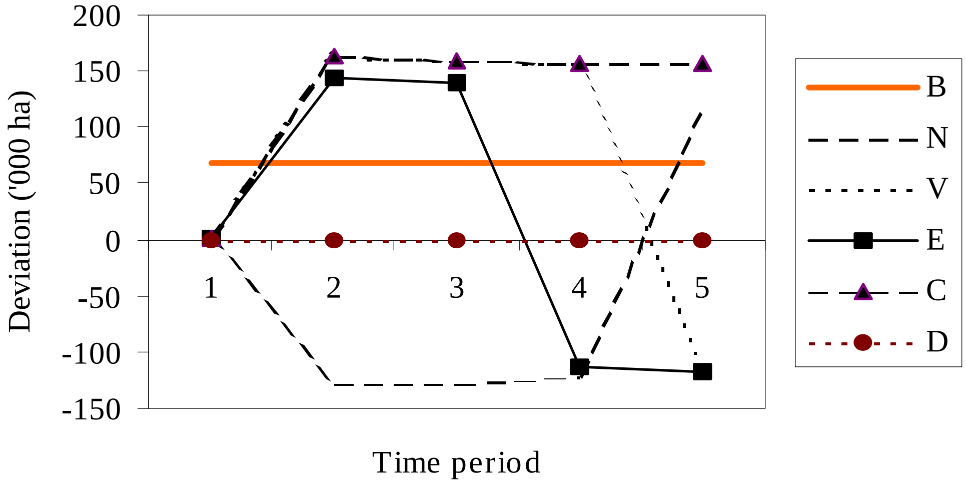

Figure 4. Deviation from the target forest structure by period for various strategies

On the other hand, strategies to achieve carbon or structural diversity targets perform badly in terms of both timber benefits and remaining environmental services. For this application, the target structure is preset to that of the “natural” forest with no human intervention. Carbon strategies rely on providing high amounts of biomass by artificial regeneration of denuded forestland or agroforestry. These strategies create large areas of young forest, resulting in (positive) deviations from the target structure, which are beneficial from a carbon uptake perspective. While such benefits could justify investments in (intensive) silviculture – plantations and reforestation – they lead to lower biodiversity.

A comparison of projected outcomes over time suggests that high cumulative net returns and harvest volume could be achieved only by sacrificing stable timber supply and ecological benefits. The balanced strategy offers a possibility for resolving or at least mitigating this conflict. For this strategy, carbon is sequestered every period, but then released through harvest in the final period. By postponing harvests of mature forests, the balanced strategy provides a forest structure that does not fluctuate much from the target over time. As we have already discussed, this implies significantly reduced net returns and harvests, especially in period 2.

Carbon and biodiversity objectives can be in conflict depending on the preset target on biodiversity and its measure**,** and on how the carbon objective is measured and formulated. This emphasizes the need to provide both group expertise and public input when setting a target on forest structure. Policy makers, public and corporate, should be prepared for short- to medium-term negative impacts in terms of reduced harvest volumes and increased management costs if long-run sustainable management is to be achieved.

The case study results do not give enough economic and environmental credits to hybrid poplar plantations for carbon sequestration. In order to justify large-scale forest plantations, it is necessary that they contribute significantly not only to the carbon uptake objective, but be a source of timber supply, thereby reducing pressure on harvests of mature native forests.

One natural extension of this research would be to study effective ways for eliciting stakeholders' preferences and constructing the weights to incorporate in the model. Various viewpoints about resolving conflicts among objectives can also be studied by varying the distance parameter. The approach described and applied in this paper is general and allows for other forest management strategies and concerns to be incorporated as well. For example, biodiversity is addressed in this paper in terms of species and tree size diversity, but the same approach can be used to explore other dimensions of ecological diversity and their tradeoffs.

4. FUZZY SET APPROACH TO VAGUE CONCEPTS AND IMPRECISE DATA

Uncertainties are inherent in economics related to climate change, projections of future climate, in determining the potential impact of strategies to mitigate climate change, in estimating the effects of land-use change and forestry, and, particularly, in setting targets and objectives dependent on stakeholders' values and preferences. Our research focused on some of the uncertainties related to land-use change and C-uptake related to forestry (Krcmar et al. 2001) and those related to the valuation of environmental amenities (van Kooten et al. 2001, Krcmar and van Kooten 2000). Sources of uncertainty include:

- variability of timber yields as a result of weather, climate, (possible) CO_2–fertilization and the intensity of silvicultural treatments;
- imprecise data on carbon sinks, especially with respect to the life cycle of carbon in wood and wood products; and
- vague and changing societal values and preferences.

Different approaches can be undertaken to cope with uncertainty. Challenges related to incorporating uncertainty explicitly in sustainable forest management decisions are well recognised. Traditional probabilistic approaches are most often used, but they assume a degree of knowledge that is not usually possessed by a decision-maker. Also, the use of probability for uncertain targets arising from multiple objectives is conceptually inappropriate. Uncertainty of stakeholders' preference information cannot be modelled stochastically since its source is vagueness and lack of knowledge about the problem under consideration.

Fuzzy set theory (Zadeh 1965) provides a useful alternative to probabilistic approach for interpreting vagueness and imprecision associated with complex issues of forest management under multiple social, economic and environmental objectives.

4.1 Carbon sequestration under uncertainty

Managing uncertainties related to climate change is a difficult task. The information we possess about many technical parameters related to climate change is scanty and not sufficient to assess probabilities. Even when it is possible to assess probabilities, the complexity of the resulting models often renders them computationally intractable. The problem is further complicated in the case of land-use change and forestry because many policy issues have not been adequately resolved and there remains uncertainty about the effects of terrestrial activities on carbon flux.

Policy makers often use alternative scenarios to depict uncertainty, with scenarios consisting of a combination of point estimates that produce representations of alternative possible states of the system. While scenario analysis helps increase awareness of uncertainty, decision-makers must decide which scenario is the most representative of reality. The approach often taken to deal with such complexities is scenario analysis. This approach assumes that the decision-maker may, by observing a range of solutions and consequences for alternative scenarios, choose one of them as the most likely and thus implement the corresponding solution.

The conceptual, data and computational problems associated with probabilistic formulations of forestland management and challenges related to scenario analysis led us to incorporate non-probabilistic measures in our models by treating uncertain parameters as fuzzy sets.

We consider several sources of uncertainty in the coefficients and parameters of our model. Although some of the coefficients, such as timber yield, may be considered random, it is difficult to provide probability distributions of yield under a changing climate and potential CO_2–fertilization effect. Incomplete information about net carbon storage in the understory and decay of wood products is the source of uncertainty in C coefficients, while targets in some of the constraints express vagueness of future regulations on timber production and targets set by the ongoing negotiations on C-uptake goals.

We developed alternative models to incorporate uncertainty explicitly in system parameters and uncertainty in the policy domain (i.e., uncertainty with respect to objectives) (Krcmar et al. 2001). Uncertainty is addressed using two measures of uncertainty: possibility and necessity. The choice of an uncertainty measure enables the incorporation of the decision-maker’s attitude toward uncertainty without fixing the values of uncertain parameters.

We apply fuzzy measures instead of probability to model imprecise timber yield and C–uptake coefficients and vague targets. This approach allows a broader interpretation of uncertainty to be addressed and the attitude of DM uncertainty to be incorporated (Dubois and Prade 1993). Two operators used for the aggregation of the model objectives and/or constraints express a difference in the DM's preferences. The results of the model formulations with alternative uncertainty measures and various aggregating operators are contrasted to those of traditional scenario analysis.

A model that incorporates various land management practices with certain commercial timber output and C flux objectives has a multi-period planning horizon with decisions in each period “best” meeting cumulative objectives over the planning horizon, as well as those for each period. Boundary conditions in terms of initial land availability, as well as targets on timber and C benefits at the end of horizon, are imposed. The objective is to maximize the cumulative NPV of products in forestry and agriculture, while meeting specific C sequestration targets in response to government climate policy and maintaining a stable timber flow to prevent mills from closing and employment from fluctuating widely. Economic and C-uptake benefits depend on the end-use of wood;

hence, we consider the whole life cycle of a tree, from planting or natural regeneration to its end use as a wood product.

Uncertainty in this paper is expressed in terms of fuzzy sets (Zimermann 1996). Depending on the DM's attitude to uncertainty, two fuzzy measures – possibility or necessity – can be used (Dubois and Prade 1989). The fuzzy measure Q is defined as a function from the power set $\mathbf{P}(U)$ to [0,1] with: (i) $Q(\emptyset) = 0$; $Q(U) = 1$; and (ii) $\forall A, B \in \mathbf{P}(U): A \subseteq B \Rightarrow Q(A) \leq Q(B)$. From property (ii), it follows $Q(A \cup B) \geq \max\{Q(A), Q(B)\}$. This limiting case is the possibility measure, $\Pi(A \cup B) = \max\{\Pi(A), \Pi(B)\}$. It expresses the degree to which a certain event A is possible. Following from $\Pi(A)$ is the necessity measure, $N(A) = 1 - \Pi(A^C)$. Necessity reflects the degree of impossibility of A^C, or certainty of occurrence of A.

The possibility measure reflects the ultimate in optimism. It seeks to avoid situations where achieving any specific objective constraint or target is impossible. Such optimism is conducive to situations involving multiple stakeholders, because it seeks to grant concessions to all without making it difficult to find a solution. The necessity measure expresses the impossibility of not attaining goals and, thus, it is a conservative or even pessimistic measure. Focusing on necessity means seeking more certainty in achieving objectives. The necessity measure achieves its maximum when an objective is attained with certainty; its minimum reflects situations where the possibility of not achieving goals is at a maximum.

Comparison of alternative model formulations

We compare the outcomes of three formulations of the model. The first one is a model with the "best" point estimates used for technical coefficients and the desired (allowable) values for targets. The model becomes a standard deterministic linear programming (LP) problem. This scenario is referred to as the "base case" for the remainder of the analysis.

The other two models involve the possibility and necessity measures of uncertainty. Early period harvest patterns of spruce, pine and aspen are pretty similar when the necessity and possibility formulations are used to make decisions. The possibility model produces strategies that rely on intensive early harvest of spruce and pine compared to the base case scenario. This results in a focus on NPV and prediction of the highest NPV among all model formulations. Large differences occur in late period harvests for all species. Spruce sites are aggressively harvested when the necessity measure is employed. If the decision-maker uses the possibility formulation, the lowest level of spruce is harvested in late periods. This can be explained by the priority of harvest in both the base case and possibility models to achieve high returns. Thus, these models select strategies that harvest valuable spruce on good and medium sites only. The necessity model, on the other hand, tries to attain carbon targets first. This results in focussing on costly reforestation by planting after non-profitable poor spruce sites had been harvested. For the late period pine harvests, the largest harvest area is in the base case model, and is lowest for the possibility formulation. All of the scenarios cease harvests of native deciduous species in period 2. In the late periods, the possibilistic model suggests harvesting native deciduous trees. The remaining formulations do not allow harvest of native deciduous species after the initial time period (which uses a constraint to force deciduous harvests).

Reforestation shows striking differences between the necessity and possibility formulations. An optimistic decision-maker applies the possibility formulation, which generates a strategy with highly satisfactory payoffs in terms of both timber and carbon benefits. These payoffs are easily reached without employing costly reforestation by planting.

Initial period planting of hybrid poplar on agricultural land occurs in all models. This enables fast C uptake and harvest volume. The only case in which native conifers are planted on agricultural land is under the necessity measure of uncertainty. These highly expensive agricultural plantings of native conifers are retained for carbon storage.

The model results show that the base case “best estimate” scenario differs substantially from cases that address uncertainty explicitly. Also, the models with fuzzy measures generate strategies that differ significantly from each other (depending on the policy maker’s attitude toward uncertainty) in terms of both projected objective values and recommended land management practices.

The optimism of the DM employing possibility measures results in early harvests and natural reforestation afterwards, and afforestation by fast-growing hybrid poplar. Satisfying the targets is highly plausible only if the most likely coefficient values occur.

The necessity formulation outputs differ most from the others. The DM who maximizes the minimum necessity of meeting the targets uses a strategy almost opposite to that used by the possibilistic DM. This may be explained by a cautious, even conservative, attitude toward uncertainty. The necessity model formulation minimizes the impossibility of not achieving targets. A conservative DM will almost certainly attain all targets to some extent even if the least plausible coefficient values occur. This is achieved by high spruce harvest and moderate harvests of pine and native deciduous species in late periods. In addition, reforestation of denuded forest sites by planting is very high, especially in early periods, which guarantees high biomass and carbon storage over the time horizon. Implications of such cautious strategies include lower harvest volume in the late periods. Another impact is a significant drop in NPV, which can be mainly justified by high costs of planting, afforestation by native conifers and harvests of non-profitable forest sites, rather than by decreasing harvest volume.

The objectives levels reached by the alternative formulations are provided in Table 7. The highest projected NPV occurs in the model that maximizes the minimum possibility of meeting the constraints. The possibility formulation attains an NPV of \$1066 million with a possibility (plausibility) of 0.95. This NPV is consistent with the aggressive harvest of quality sites, low reforestation by planting and complete avoidance of afforestation by native conifers. On the other hand, the necessity formulation that maximizes the impossibility of not achieving targets is less successful in terms of "achieving" economic objectives. It achieves an NPV of \$612 million with a necessity (certainty) of 0.12. Necessity maximization, as a conservative approach, aims to attain with certainty lower target bounds, so that harvest levels are consistently lower.

The base case scenario generates the highest cumulative carbon uptake because its underlying LP model requires that all constraint targets are fully satisfied. The lowest discounted carbon uptake is achieved by the necessity maximization strategy. This strategy guarantees an uptake of 0.840 million tonnes of carbon discounted at the 4% rate.

Table 7. Projections of objective values in different model formulations

	Base Case	Max-min Necessity	Max-min Possibility
NPV (million \$)	978.001	612.530	1066.460
Harvest volume (million m^3)			
Period 1	42.420	42.420	42.420
Period 2	38.180	36.310	38.750
Period 3	33.940	31.090	34.020
Period 4	29.700	25.740	29.330
Period 5	25.460	22.206	28.215
Total Harvest Volume	**169.700**	**157.765**	**172.735**
Discounted C flux (million tonnes)			
Period 2	0.911	0.046	1.243
Period 3	0.510	0.605	0.124
Period 4	0.129	0.192	0.095
Period 5	0.000	-0.003	0.021
Total discounted C uptake	**1.550**	**0.840**	**1.463**

In general, different approaches lead to significantly different land-use and forest management strategies. Base-case outputs track what we would expect forest management to look like if the government implements strategies based on fixed targets and best estimates for uncertain coefficients. Two other scenarios address uncertainty explicitly, including different views of the states of nature.

Similarities exist between the plans chosen by DMs in the base case and a possibility max-min in terms of reforestation by planting and afforestation, since both formulations focus on achieving timber benefits. If a more cautious view on the state of nature is taken, then strategies are dominated by the need to satisfy the C-uptake targets. When the possibility or necessity measures are used, the best strategies differ substantially in terms of both projected objective values and recommended land management practices.

We studied how decisions with respect to land management change given alternative models, and that land-use strategies are altered significantly with respect to problem formulation. The results of the case study prove that the interaction of the strategic features over time is complex and hard to predict. This makes the use of multiple scenarios for the climate change problem difficult. Indeed, the common heuristics of adjusting base case solutions do not work. Changes in the strategic mix are not monotonous along a continuum from pessimism to optimism. This implies that uncertainties in both objectives and parameters must be modeled explicitly. We conclude that, ultimately, the onus of clearly specifying all the parameters of the choice falls back on the DM. Our models can only help identify what impact their attitude toward uncertainty, policy targets and so on has on the final decision, but it cannot unequivocally point to the “best” strategy.

4.2 A fuzzy approach to environmental valuation

As part of the SFM project, we examined the use of fuzzy logic for valuation purposes (van Kooten et al. 2001; Krcmar and van Kooten 2001). The contingent valuation (CV) survey method is a widely used technique for valuing non-market environmental amenities. In forestry, for example, both commercial timber values and non-timber values are important for guiding policy. Commercial timber values are straightforward to measure using market data and the travel cost method can be used to find forest recreation benefits, but CV is generally required to provide estimates of preservation value, which may be the most important non-timber value.

Most CV surveys rely on a dichotomous choice question to elicit either willingness to pay (WTP) or compensation demanded. Calculation of the Hicksian compensating or equivalent welfare measure is based on the assumption that the survey respondent knows her utility function with certainty. The assumption of preference certainty is a strong one because CV seeks to elicit values for environmental resources from respondents who may lack the cognitive ability to make such assessments. These approaches rely on probabilistic interpretations of uncertainty. Our contention is that the apparent precision of standard WTP estimates (even as a mean value with confidence interval) masks the underlying vagueness of preferences and may lead to biased outcomes.

Fuzzy set theory addresses both imprecision about what is to be valued and uncertainty about values that are actually measured. In van Kooten et al. (2001), we focused on the most often used economic application of fuzzy set theory – modelling choices when preferences are vague. We distinguish between three types of uncertainty that could cause ill-defined preferences for environmental goods.

First, people may not be well acquainted with the alternatives they are being asked to value, and cannot easily express a preference for different combinations of income and the environmental amenity. For example, a survey of Scottish citizens revealed that over 70% of the respondents were completely unfamiliar with the meaning of biodiversity. Similarly, some respondents are likely not familiar with 'obscure' endangered species such as the striped shiner or the squawfish, yet are asked to value their survival (Bulte and van Kooten 1999). One straightforward means for mitigating this type of uncertainty is to provide more information or detail about the amenity to be valued.

Second, respondents may be truly uncertain about their preferences because they have never previously given such tradeoffs much thought. In a one-shot CV experiment, a respondent's stated WTP may be biased. One approach in this case is to use focus groups that enable stakeholders (as opposed to a truly representative group) to construct a preference function. Other approaches have also been proposed to address this type of uncertainty, all relying on a probabilistic interpretation of uncertainty.

Third, it may be the case that respondents *never* fully know their preferences. The concern is with a respondent's cognitive inability to rank commodities with diverse properties, even if the commodities themselves are well defined and their attributes completely known by the respondent. This type of uncertainty has been ignored in much of the economic valuation literature, and certainly in the valuation of non-market goods.

There is a fundamental and philosophical difference between the second and third approaches to uncertain preferences. The second approach assumes that respondents learn about their preferences over time and eventually 'know' their true utility function. In other words, respondents are uncertain about the location of their true indifference curve(s), but a time series of CV surveying would measure a shifting 'perceived' indifference curve that gradually approaches the true one. The third approach, in contrast, treats the utility function as a useful analytical construct, but acknowledges that certain trade-offs are inherently difficult, if not impossible, to make. How does one value ‘employment’ versus ‘endangered species conservation,’ or ‘children’s health’ versus ‘poverty alleviation’? While respondents will certainly have some preference over such choices, valuation at the margin is extremely difficult and it is obvious that some trade-offs cannot be represented by a true and unique indifference curve.

We introduced the notion of fuzzy set theory in a first attempt to employ it as an alternative approach for dealing with preference uncertainty within the standard contingent valuation framework (van Kooten et al. 2001). The fuzzy approach to contingent valuation that we developed should not be regarded as competing with, but rather as complementing, the standard approaches to preference uncertainty within a CV framework.

Our concern is with people who may have conflicting impulses about which goods they prefer; they may think that one good is better than another in some respect but worse in others. We consider respondents’ cognitive (in)ability to rank commodities with diverse properties, even if the commodities themselves are well defined or crisp, and information is perfect. An assumption of the DC approach in the CV context is that each respondent is able to determine which option is preferred, but there are situations when it may be difficult or impossible for the respondent to determine with certainty the preferred option.

Authors who studied preference uncertainty in the CV framework (Ready et al. 1995) interpret respondents’ difficulty in making a choice as uncertainty over the location of the indifference curve. Most CV studies assume that the respondent resolves such uncertainty through additional information about the amenity being valued. While additional information and knowledge of the amenity in question may narrow the preference uncertainty region, preference uncertainty remains as a result of strong conflicts between the objectives (Ready et al. 1995, Loomis and Ekstrand 1997). In such situations, a respondent typically adopts one of a variety of decision rules in order to provide a crisp answer to the DC question. Despite differences in the approaches, they are all based on Hanemann’s formulation of the utility difference model. The underlying assumption of this model and its modifications is that uncertainty in the model (respondent’s and/or observer’s) can and should be modelled probabilistically.

Unlike these approaches, we assume that a respondent’s utility is vague and can be represented by a fuzzy number $\tilde{u}$. Then, the indifference curve is fuzzy too. Graphical illustration of the DC model when utility is fuzzy is given in Figure 5. Income and the amount of the environmental amenity are assumed to be well defined or crisp.

Representative fuzzy indifference curves are provided in Figure 5 for two individuals (*A* and *B*) faced with the opportunity of paying an amount *W* to increase the availability of the environmental amenity from E_0 to E_1, or remaining at the status quo level K. Combinations of income and the environmental amenity located on the dark lines have memberships equal to 1.0 in the fuzzy utility sets, $\tilde{u}$ (*A*) and $\tilde{u}$ (*B*). Points located off the dark lines but in the respective shaded areas have a degree of membership in the fuzzy indifference level that is less than 1.0 but greater than 0. The outside boundaries of the indifference curve are given by dashed lines. For the respondent with fuzzy indifference curve $\tilde{u}$ (*A*), the new consumption set represented by β has a membership in $\tilde{u}$ (*A*) of 1.0. For the individual with fuzzy indifference curve $\tilde{u}$ (*B*), $\mu_{\tilde{u}(B)}(\gamma)=0.60$ say, while $\mu_{\tilde{u}(B)}(\beta) = 0$ and $\mu_{\tilde{u}(B)}(\pi)=1$.

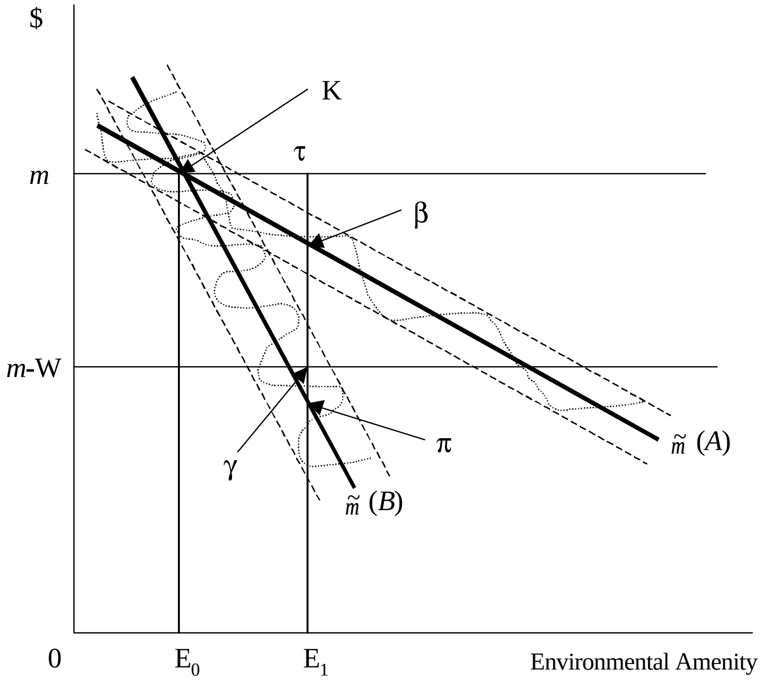

Figure 5. Interpretation of Dichotomous Choice Answers with Fuzzy Utility

When a respondent's utility is crisp (i.e., only the dark line), then *W* will be accepted ('yes' answer) when the indifference curve at E_1 is below the line *m–W*. This is the case for respondent B, but not for respondent A. Figure 5 illustrates the potential problems in answering a DC question regarding a given bid *W* when a respondent's utility is fuzzy. Respondent A will always reject the opportunity to pay *W* for more of the environmental amenity. Respondent *B*'s fuzzy indifference curve intersects the environmental amenity level E_1 at an interval that contains the *m–W* value. Consequently, some points of the intersecting interval are below and others are above the line *m–W*. Answers to the DC question are therefore subject to a decision criterion.

Although we emphasize the importance of allowing consumer preferences to remain uncertain, the estimation techniques that we employ are preliminary. Ultimately the fuzzy utility approach should lead to estimates of fuzzy willingness to pay derived from fuzzy utility maximization subject to (perhaps fuzzy) constraints. Perhaps, it requires the estimation of the fuzzy parameters of a probit or logit model, but fuzzy estimation techniques are generally in their infancy and are not yet available. Future research will need to include analyst's uncertainty explicitly together with a respondent's vague preferences, which would require incorporating both stochastic (expressing an analyst's uncertainty) and fuzzy (containing a respondent's vague preferences) components into the analysis of contingent valuation responses. Further research also needs to consider different methods for comparing fuzzy numbers and their impact on (fuzzy) CV estimates, and how to evaluate uncertain coefficients of the fuzzy utility function. Finally, it is necessary to develop an appropriate survey instrument that allows respondents to express their preference uncertainty qualitatively, rather than relying on data generated from CV surveys that essentially require crisp responses. Indeed, it is likely necessary to develop survey instruments that also treat fuzziness due to vagueness in classification.

At this stage, it is not possible to say that the fuzzy approach is somehow 'better' than standard approaches for evaluating environmental amenities. The fuzzy approach to contingent valuation interprets uncertainty in a fundamentally different way than the standard random utility maximization model. Our results indicate persistence of preference uncertainty over a wide range of bid values, thus suggesting that uncertainty cannot be treated only as a random phenomenon to be minimized by providing respondents with more information. In that case, the fuzzy approach needs to be seriously considered as a method for addressing preference uncertainty in non-market valuation.

In van Kooten et al. (2001), we used the fuzzy-utility framework of Figure 5 to construct a procedure to incorporate preference information to find estimates of non-market value. In particular, we estimated aggregated fuzzy WTP and willingness not to pay (WNTP), and illustrated our approach with an empirical application of the willingness to pay for forest preservation in Sweden, using data from Li and Mattson (1995).

In a subsequent study (Krcmar and van Kooten 2000), we focused on two individual rather than corporate fuzzy membership functions, and then aggregating the membership functions to find estimates of value. Unlike the previous approach, the focus is only on WTP and not on WNTP. This required an arbitrary transformation of responses to the uncertainty question in the survey. Thus, if a respondent stated she was only 40%

certain, say, of her response to a dichotomous choice, yes/no, question, the response was "flipped" – a "yes" response was changed to "no" with 60% certainty and vice versa for a "no" response. This is precisely what Li and Mattson (1995) did as well.

The individual membership functions we constructed were somewhat arbitrary because they assumed respondents would be WTP zero for forest conservation with membership value 1.0 (see van Kooten et al. 2001 in this regard), and that the response to the uncertainty question constituted another point on the membership function. Membership functions were aggregated into a single membership function, which is shown in Figure 6. In the figure, the alpha-level refers to the confidence of the estimated value of WTP for forest conservation. The estimates of van Kooten et al. (2001) fall within this membership function.

Both fuzzy methods for obtaining non-market values resulted in lower estimates of value than indicated by the traditional approach. However, since the results are based on a single study, no general conclusions can be drawn. Clearly, further research in this area is required.

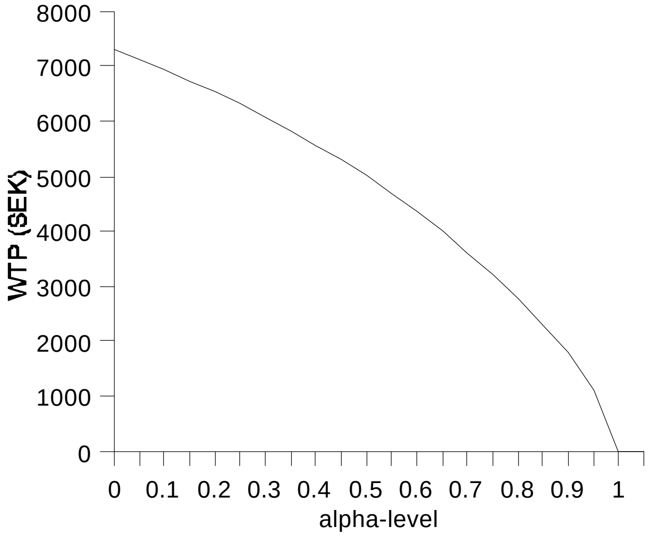

Figure 6. Fuzzy WTP for Continued Use of Forest Environment

5. CONCLUSIONS

One purpose of our research into the economics of climate change, with focus on carbon uptake and storage in forest ecosystems, was to investigate the prospects of forestation and afforestation in meeting some of Canada's international obligations to mitigate global warming. Our findings indicate, first off, that enhanced silviculture is not a cost effective means of sequestering carbon, and that, if silvicultural investments can not be justified on economic efficiency grounds (net present value is positive), it is unlikely that such investments will be profitable if carbon benefits are included. However, even where inclusion of carbon benefits makes them socially profitable, the additional carbon society gains is rather small.

Second, our research showed that afforestation projects are generally not cost effective if native tree species are planted. If fasting-growing hybrid poplar is planted, afforestation may be cost-effective, and competitive with CO_2-emissions reduction options. However, the cost-effectiveness of the terrestrial carbon sinks option is highly sensitive to a number of factors. These include the use to which timber is put at time of harvest (left standing, converted to wood products or burned for energy production), distances to mills, rates of tree growth, discount rates, and so on. We show that the effectiveness of the forestry option is enhanced if carbon gets stored in wood products, and other forest ecosystem sinks (such as soil sinks) are taken into account (although this was not yet allowed under Kyoto). Yet, biomass burning may be preferred to use of timber in wood products because there exists the possibility that, if timber from additional forest plantations is used for lumber or wood pulp, stumpage values are driven down and landowners reduce forest holdings elsewhere. The resulting carbon leakage could reduce the effectiveness of this approach by half.

Our research on afforestation also indicates that costs of carbon sequestration are affected by two factors often ignored in more simplistic, straightforward analyses of costs and benefits. All of the marginal agricultural land that might be considered optimal for conversion to plantation forest can not possibly be planted in one season. Attempts to do so will encounter rising marginal costs. Attempts to exceed some optimal rate at which agricultural land can be converted to forest will only raise carbon sequestration costs. Indeed, our research suggests that it could take 40 years to convert an area of some 3.3 million ha of farmland to forest. Any attempt to reduce this timeframe will only increase costs needlessly. Further, our latest research suggests that there may be unaccounted for transaction costs associated with the mechanisms used to entice landowners to plant trees. These transaction costs will increase overall afforestation costs and reduce Canada’s options with regard to terrestrial carbon uptake.

Based on our research to date, we estimate that, at best, Canada can rely on afforestation to meet some 7-10% of its annual obligations to mitigate climate change. This is well below the 22% identified by the Canadian Pulp and Paper Association and implicitly adopted by the Canadian government as a reasonable target.

We also developed the TECAB model to examine tradeoffs among economic, carbon uptake and biodiversity objectives. TECAB uses compromise programming to find a strategy that balances the various objectives of forest management (profitability, even flow, timber volume, carbon flux and biodiversity). The balance strategy does not attempt to achieve any maximum associated with an individual objective; individual objective maximums are unattainable in any event, because of real world constraints. The balance strategy achieves what we consider to be an excellent compromise (see Table 6).

Finally, we investigated the use of fuzzy logic to treat uncertainty in forest management and uncertainty about (non-market) valuation of environmental amenities. In the case of forest management, we show that outcomes are highly sensitive to whether a decision maker is optimistic or pessimistic about whether a particular management strategy is or is not successful in achieving carbon uptake goals, for example. In the case of fuzzy logic applied to valuation, our results suggest that traditional methods of valuation might overstate the true value of an environmental amenity. We caution that substantially more research is required before anything definitive can be said.

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APPENDIX

Table A.1: Global estimates of costs and potential carbon that can be removed from the atmosphere and stored by enhanced forest management, 1995 to 2050

Region	Practice	C Removed & Stored (Gt)	Estimated Costs ($US $\times 10^9$)
Boreal	Forestation[a]	2.4	17
Temperate	Forestation[a]	11.8	60
	Agroforestry	0.7	3
Tropical	Forestation[a]	16.4	97
	Agroforestry	6.3	27
	Regeneration[b]	11.5 - 28.7	44 - 99
	Slowing-deforestation[b]	10.8 - 20.8	
TOTAL		**60 – 87**	

[a] Refers primarily to reforestation, but this term is avoided for political reasons.

[b] Includes an additional 25% of above-ground C to account for C in roots, litter, and soil (range based on uncertainty in estimates of biomass density)

Source: Adapted from Watson et al. (1996, pp.785, 791)

Table A.2: Rates of decay of forest ecosystem components after harvest

End-use Category	Anthropogenic Time (years from felling until decay starts)	Decay Time (years until all fibre has decayed)
Bark in land fillings	0	8
Bark for burning	0	1
Needles	0	7 to 11
Branches, stumps, stems in forest	0	12
Root system after felling	0	100
Construction material	80	80
Furniture & interiors	20	50
Impregnated lumber	40	70
Pallets	2	23
Losses	0	1
Composites, plywood	17	33
Sawdust	1	2
Pulp/paper	1	2
Fuelwood	0	1

Source: Hoen and Solberg (1994)