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MANAGING FORESTS FOR MULTIPLE TRADEOFFS: COMPROMISING ON TIMBER, CARBON AND BIODIVERSITY OBJECTIVES

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Abstract

In this paper, we develop a multiple objective, decision-making model that focuses on forest policies that simultaneously achieve carbon uptake and maintenance of ecosystem diversity objectives. Two forest carbon measures are used – a nominal (undiscounted) net carbon uptake as a proxy for long-term carbon sequestration and discounted net carbon uptake that captures the "fast" carbon accumulation aspect. Ecosystem diversity is expressed in terms of desired structures for forest and afforested agricultural land. Economic effects of possible strategies are examined by comparing attainment of these objectives with the net discounted returns from commercial timber harvests and agricultural activities. The tradeoffs between timber and non-timber objectives are obtained by means of compromise programming. Two measures of distance between the current objective values and the ideal ones are used to assess attainment of multiple goals. We explore how the choice of a measure affects the decisions and overall performance. The model is applied to the boreal forest and accompanying marginal agricultural lands in the Peace River region of northeastern British Columbia.

Keywords: biological and ecosystem diversity; compromise programming; forest carbon sequestration; forest management; multiple objectives

MANAGING FORESTS FOR MULTIPLE TRADEOFFS: COMPROMISING ON TIMBER, CARBON UPTAKE AND BIODIVERSITY OBJECTIVES

1. Introduction

Climate change and loss of biological and ecosystem diversity are considered to be among the world's most important environmental policy issues. Changes in land use, particularly from forestry to crop cultivation, have a major impact on the amount of CO_2 entering the atmosphere and on the loss of forest biodiversity (IPCC 2000). One strategy for reducing atmospheric concentrations of CO_2 is to increase forest biomass production through better forest management and by planting trees on agricultural lands. Terrestrial carbon sinks of this kind are permitted in lieu of CO_2 emission reductions under Kyoto's Marrakech Accords (van Kooten 2004). One aspect that has been overlooked in much of the discussion concerning carbon forest sinks, but recently has been the subject of increase attention, is the impact that forest management for carbon uptake might have on biodiversity (Noss 2001, UNCBD 2004). Likewise, forest planning with the sole objective of protecting or enhancing biodiversity could have negative effects on carbon benefits. However, there remains a lack of information and understanding concerning the interactions between forest management for carbon and for maintenance of biodiversity.

In this paper, we investigate maintenance of biodiversity and carbon sinks as environmental functions to be taken into account in land-use planning in addition to socioeconomic objectives. Objectives that we classify as economic and environmental are in conflict and not measured in the same units. Therefore, we apply a broad modeling approach known as multiple-objective decision making (MODM) to analyze the multidimensional aspects of proposed policies and suggest a methodology for managing conflicts between policy objectives. The major strength of MODM is its 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.

The problem we deal with is described in more detail in the next section, while an integrated economic and ecological framework for multiple objective conflict management is developed in section 3. Tradeoffs among financial, carbon uptake and biodiversity objectives are examined using a compromise programming approach. In Section 4, we apply this approach to a case study in northeastern British Columbia. The study region consists of publicly owned boreal forestland and private lands in agricultural production. Model outcomes are presented in section 5, followed by conclusions in section 6.

2. Problem description

Forest policies often focus on ecological services in isolation, or reflect the tradeoff between a single ecological objective and an economic one. However, there are many objectives that need to be considered in forest management, with one possibly affecting some or all of the others (Alig et al. 1998). As a result, assessment of multiple ecological and social objectives is important in forest planning processes.

Krcmar et al. (2000), van Kooten et al. (2000), Diaz-Balteiro and Romero (2002) have investigated the tradeoffs between timber and carbon benefits. Kant (2002), Holland et al. (1994), and Buongiorno et al. (1994) have examined tradeoffs between timber benefits and biological diversity, using either an optimization or goal programming model. Their results suggest that increased carbon uptake and biological/ecosystem diversity can be attained only at significant costs in terms of forgone timber harvest and financial returns. Boscolo and Buongiorno (1997) explored forest management with financial, carbon-storage and biodiversity objectives. Each objective was maximized in isolation, with compromise policies derived by maximizing carbon uptake or diversity subject to a specific requirement on financial returns. When each objective function was maximized in isolation, outcomes indicated that the same forest policy could be used to satisfy the carbon uptake and diversity objectives. More recently, however, concerns have been raised about possible conflict between carbon storage strategies and management for biodiversity (IPCC 2002). These concerns have focused particularly on the species used in reforestation and afforestation. The choice of species may have a significant impact on both carbon accumulation and maintenance of biodiversity.

Different species grow and sequester carbon at different rates (Korn et al. 2003). The total forest carbon pool, the rate of change of the carbon pool, and the time that carbon will remain sequestered in the system depend on the dominant tree species in the ecosystem, among other factors (Paul et al. 2003; Vestedal et al. 2002). Species selection in reforestation and afforestation results in a tradeoff between fast carbon sequestration and subsequent release, and slower carbon sequestration with longer retention time. Although both the sequestration rate and the amount of sequestered carbon may be concurrently high at some stages, they cannot be maximized simultaneously (Carey et al. 2001). From a biodiversity perspective, the choice of tree species can greatly affect understory plant and associated wildlife species. Long-lived tree types and associated forest ecosystems support more complex relationships than do short-lived forests (Thompson et al. 2003).

In this paper, the economic criterion consists of net discounted returns to forest management on forestland plus net returns to agricultural land, whether used in forestry or in agriculture. To measure the success of forest management in accomplishing carbon uptake and biodiversity maintenance goals, indicators for carbon uptake and biodiversity are needed. We employ (1) cumulative nominal (undiscounted) net carbon sequestration (uptake minus emissions) over the time horizon as an indicator of long-term carbon uptake, and (2) cumulative discounted carbon sequestered to measure the success of fast carbon uptake strategies. Carbon flux is defined as the change in the amount of carbon stored between two consecutive periods. Changes in the amount of carbon stored in a terrestrial ecosystem are the result of tree growth, timber harvest and changes in land use, plus the change in soil carbon that accompanies changes in land use. Carbon entering wood products is also taken into account (although not currently allowed under the Kyoto Protocol), as is the subsequent release of carbon as products decay. The use of wood for biomass burning is not considered at this time.

As biodiversity indicators, we employ (1) the proportions of the public forestland in different tree species and tree size classes, and (2), for afforested agricultural land, the proportion planted to native and non-native species. The biodiversity indicators are calculated relative to specific targets. To define specific management targets in maintaining biodiversity, we take into account the following biodiversity considerations (Noss 2001; Thompson et al. 2003; Carnus et al. 2003):

- Forests that are similar to historical (undisturbed) conditions in terms of forest types and size maintain more biodiversity than those that are highly managed.
- Planted forests that are structurally diverse maintain more plant and animal species than those with a simple structure (e.g., monoculture).
- Forests planted to native species conserve local and regional animal species better than do plantations of exotic tree species or monocultures of native species.

Thus, we specify the forestland target as that of the natural forest, while the afforestation target involves equal proportions of three native and one non-native tree species.

A typical modeling approach when dealing with multiple management goals is optimizing a selected objective, either an economic or environmental one, while imposing restrictions on remaining goals and taking into account the usual technical constraints. This framework has often been used for analyzing the tradeoffs between economic and biological diversity objectives, with studies differing by whether or not they optimize a biodiversity objective (Carlsson 1999; Onal 1997) or maximize economic performance given restrictions on some indicators of biological diversity (Holland et al. 1994; Kant 2002).

This way of handling multiple goals may not be satisfactory because representing objectives by constraints is very rigid; setting unrealistic goals expressed in terms of constraints easily leads to infeasibilities. Further, representing some goals as constraints implies that they are given higher priority than the goal in the objective function. Therefore, we employ another approach that includes environmental and economic concerns directly as objectives within a multiple-objective programming framework.

3. Modeling multi-objective forest management problems

We now develop a multiple objective decision-making (MODM) model to analyze tradeoffs among economic, carbon and biodiversity objectives. The model incorporates various forest management practices on publicly owned forestland and tree planting (afforestation) activities on private agricultural lands. Financial and carbon benefits depend on the end use of the wood; hence, we consider the whole life cycle of a tree, from planting or natural regeneration to its use in products after harvesting or natural disturbance.

The specific objectives are to:

1. maximize the cumulative discounted net returns from forest and agricultural activities;
2. maximize cumulative nominal (undiscounted) carbon storage (uptake minus emissions);
3. maximize cumulative discounted carbon storage (uptake minus emissions); and
4. maintain ecosystem diversity.

Multi-Objective Model Formulation

The problem of land-use allocation and scheduling of management treatments to meet several objectives simultaneously is modeled as a multi-objective linear program. The model elements are defined as follows. Suppose that the planning horizon is divided into periods $t \in T$ and let M be the set of management strata. A management stratum $m \in M$ is defined in terms of species, site quality and age class. If specific forest characteristics are to be emphasized in the model, M can be partitioned accordingly. Here we consider forest diversity in terms of distributions of tree species $g \in G$ and size classes $s \in S$, where G and S are the index sets of tree species and size classes, respectively. Denote by $M_g \subseteq M$ a partition of M by species $g \in G$ such that $M_i \bigcap M_j = \varnothing$, $M = \bigcup_i M_i$, $i, j \in G$. Other partitions of the set M are possible if needed. $P(m,t)$ is the set of management treatments appropriate to stratum m and period t. Treatments include forestry activities (harvest and reforestation, both natural and artificial) and tree planting of private (marginal) agricultural lands.

Let nvf_{mpt} be the net value (\$/ha) of timber harvested on forestland, nva_{mpt} be the net value (\$/ha) of timber from afforested agricultural land and ag_b be the net value (\$/ha) of agricultural activity b. Denote by cf_{mpt} the carbon uptake (t/ha) in period t from one hectare of forestland of stratum m managed by treatment p, by ca_{mpt} the carbon uptake (t/ha) in period t from one hectare of afforested agricultural land of stratum *m* and managed by treatment *p*, and cag_b be the carbon uptake (t/ha) in any period from one hectare of agricultural land in activity *b*. Financial returns are discounted at rate α, while carbon is discounted at rate β (see van Kooten 2004, pp.77-78 for a discussion of carbon discounting). Decision variable $x = x_{mpt}$ represents the area (ha) of forestland of stratum *m* managed by treatment *p* in period *t*, $y = y_{mpt}$ represents the area (ha) of agricultural land planted with trees of stratum *m* managed by treatment *p* in period *t* and $z = z_{bt}$ represents the area (ha) of agricultural land in agricultural activity *b* in period *t*.

Objective **N** represents maximization of financial benefits to land and is expressed in terms of the cumulative net present value of forestry plus agricultural production over the horizon, $N(x,y,z) = \sum_{m\in M}\sum_{p\in P(m,t)}\sum_{b\in B}\sum_{t\in T}(1+\alpha)^{-t}[nvf_{mpt}\, x_{mpt} + nva_{mpt}\, y_{mpt} + ag_b z_{bt}]$.

Carbon benefits are modeled in terms of a flux, $CF_t(x,y,z) = C_t(x,y,z) - C_{t-1}(x,y,z)$, $t \geq 2$, or average change in carbon stock over the period *t*, where $C_t(x,y,z) = \sum_{m\in M}\sum_{p\in P(m,t)}(cf_{mpt}\, x_{mpt} + ca_{mpt}\, y_{mpt}) + \sum_{b\in B} cag_b z_{bt}$ is carbon stored in forest biomass and soil in period *t*. Objective **C** expresses maximization of cumulative net carbon uptake $C(x,y,z) = \sum_t CF_t(x,y,z)$, which represents a proxy for long-term carbon sequestration without regard to when net uptake occurs. To capture the temporal aspect of carbon management, we add objective **DisC**, which is to maximize cumulative discounted net carbon uptake, $DisC(x,y,z) = \sum_t DisCF_t(x,y,z)$. Here $DisCF_t(x,y,z) = DisC_t(x,y,z) - DisC_{t-1}(x,y,z)$ is a discounted flux, or average change in discounted carbon stock between two consecutive periods, where $DisC_t(x,y,z) = (1+\beta)^{-t}[\sum_{m\in M}\sum_{p\in P(m,t)}(cf_{mpt}\, x_{mpt} + ca_{mpt}\, y_{mpt}) + \sum_{b\in B} cag_b z_{bt}]$. The objective **DisC** represents a proxy for short-term carbon sequestration.

The last objective (**D**) concerns maintenance of biological and ecosystem diversity. This objective is expressed in terms of minimization of the sum of (1) maximum deviation of the forestland structure from a desired target and (2) maximum deviation of the afforestation structure from its desired target. Here $DF(x) = \max_{g,s} | F_{g,s}(x) - TF_{g,s} |$, $g \in M_g$, $s \in M_s$ is the maximum of absolute differences between the actual $F_{g,s}(x)$ and target $TF_{g,s}$ structure by tree species g and size classes s. Maximum deviation over the afforested land is expressed as $DA(y) = \max_{g} | A_g(y) - TA_g |$, $g \in M_g$, which is the maximum of the absolute differences between the actual $A_g(y)$ and target TA_g structure of tree species g on afforested agricultural land. We describe a target structure in terms of the area (in hectares) in specific tree species and size classes. The same approach can also be applied to other representations of diversity (e.g., age, canopy height).

The feasible set FS consists of constraints on land availability and conversion of land from agriculture to forestry, forest management and silvicultural investment options, initial and terminal timber and carbon inventories, and non-negativity constraints. The mathematical representation of the multi-objective linear programming model is as follows:

MOLP model

N Max $N(x,y,z)$ $$N(x,y,z)=\sum_{m\in M}\sum_{p\in P(m,t)}\sum_{b\in B}\sum_{t\in T}(1+\alpha)^{-t}[nvf_{mpt}\,x_{mpt}+nva_{mpt}\,y_{mpt}+ag_b z_{bt}]$$

C Max $C(x,y,z)$ $$C(x,y,z)=\sum_t CF_t(x,y,z)$$

DisC Max $DisC(x,y,z)$ $$DisC(x,y,z)=\sum_t DisCF_t(x,y,z)$$

D Max $D(x,y)$ $$D(x,y)=\max_{g,s}[|F_{g,s}(x)-TF_{g,s}|+|A_g(y)-TA_g|]$$

$(x,y,z)\in FS$

Compromise programming

It is highly unlikely that there is a single management strategy that achieves the best (minimum or maximum) value for each of the *MOLP* model's objectives. The best objective values are incorporated into an 'ideal' that is often used as a reference point. Compromise programming (Yu 1973; Zeleny 1982) is an approach that seeks management strategies for which objective values are 'closest' in some sense to the ideal, an idea successfully used in other MODM applications (Jones and Tamiz 2003).

Any feasible forest management strategy $(x,y,z)\in FS$ can be evaluated in terms of the model criteria. Such an evaluation can be represented by the scores $f_q(x,y,z)$, $q\in Q$ = {**N**,**C**,**DisC**,**D**}, where $f_N(x,y,z) = N(x,y,z)$, $f_C(x,y,z) = C(x,y,z)$, $f_{DisC}(x,y,z) = DisC(x,y,z)$and $f_D(x,y) = D(x,y)$. Let

(1) $$L_\pi(w,x,y,z)=\{\sum_{q\in Q}w_q^\pi[d_q(x,y,z)]^\pi\}^{1/\pi},\ \pi\geq 1,$$

denote a family of L_π metrics that evaluate distances between points in the criteria space. Here

(2) $$d_q(x,y,z) = \frac{f_q^* - f_q(x,y,z)}{f_q^* - f_{q*}},\ q \in Q = \{\mathbf{N}, \mathbf{C}, \mathbf{DisC}, \mathbf{D}\},$$

is the distance of the current objective value from its 'best' value, normalized by the range of values $f_q^* - f_{q*}$. We define $f_q^* = \max_{x \in X} f_q(x,y,z)$, $q\{\mathbf{N}, \mathbf{C}, \mathbf{DisC}\}$ and $f_q^* = \min_{x \in X} f_q(x,y) = 0$, $q \in \{\mathbf{D}\}$, and f_{q*} as the worst value of the objective q determined over the set of optimal solutions for the remaining objectives. This approach requires first that each objective function be optimized separately to determine f_q^* for all $q \in Q$. This is done using a series of linear programs coded in GAMS and solved using the CPLEX solver (Brooke et al. 1998). Weights $w_q \in (0,1)$, $q \in Q$ reflect the relative importance of objectives and π is a distance parameter, $1 \le \pi \le \infty$.

The solution to the program

(3) $$\min_{(x,y,z) \in FS} L_\pi(w,x,y,z)$$

is the *compromise* solution to the *MOLP* model with respect to π and w. The choice of π indicates a particular form of conflict management between the competing objectives. For $\pi=1$, the problem becomes

(4) $$\min_{(x,y,z) \in FS} L_1(w,x,y,z) = \sum_{q \in Q} w_q d_q(x,y,z)$$

and searches for a strategy to minimize the weighted sum of $d_q(x,y,z)$. We refer to (4) as the compromise *min sum* or compromise *average* program. The associated strategy will be called an *average strategy*.

As π increases, more weight is given to the largest $d_q(x,y,z)$. Ultimately, the largest distance completely dominates and, for $\pi=\infty$, it becomes $\max_{q\in Q} d_q(x,y,z)$.

(5) $$\min_{(x,y,z)\in FS} L_\infty(w,x,y,z) = \max_{q\in Q} d_q(x,y,z)$$

The solution, in this case, balances all objectives in terms of their normalized distances from the best values. We refer to (5) as the compromise *min max* or compromise *balanced* program. The associated strategy will be called a *balanced strategy*.

The model is implemented as follows: we minimize $L_\pi(w,x,y,z)$ for $\pi=1$ and $\pi=\infty$ and equal weights over the set of feasible management alternatives. The metric L_π has an important practical feature for both $\pi=1$ and $\pi=\infty$, namely, that it preserves the model's linearity. This is important given the model's size and complexity. Another significant feature is that the two-objective model solutions for L_π, $1<\pi<\infty$ lie between the solutions for L_1 and L_∞. We explore the potential impact of the parameter π on management strategies determined by compromise programming.

4. Case study

The compromise programming approach is applied to integrated land management in the boreal forest region of northeastern British Columbia (BC). This region includes a well-developed forestry sector within the Dawson Creek Timber Supply Area (TSA) and agriculture on adjacent lands of the South Peace River region. Some 1,083,890 hectares of the TSA is suitable for commercial timber harvesting and management. Of this, coniferous forests cover 724,070 ha and deciduous forests 359,820 ha. In addition, agricultural land totals 152,500 hectares. Spruce and lodgepole pine dominate the coniferous timberland base in the Dawson Creek TSA, while trembling aspen dominates the deciduous species. Currently, 75% of the coniferous forest and 50% of the deciduous forest are mature. This is attributed to the paucity of past harvesting. Current land uses are shown in Table 1.

<Insert Table 1 about here>

The model for the study region assumes that decisions occur at the end of twenty-year time periods. The planning horizon is 120 years beginning in 1980, with the first period needed to set up the initial conditions, which are based on actual land use. Forest activities for the 1980-2000 period are scheduled to meet the annual allowable cut for the TSA. Different land types are identified by such characteristics as site index, age and species types.

Once denuded by natural disturbance (fire, pest or disease) or harvesting, forestland can be replanted or left to regenerate naturally. We assume that denuded forestland is regenerated to the original species. The only exceptions are aspen stands for which reforestation by hybrid poplar is considered as an alternative. Since forest land is publicly owned and designated for timber production only, we do not consider the possibility of forestland conversion to agriculture. This is easily incorporated into the model and might prove useful if strategies for adapting to potential climate change are to be examined.

Yield and growth estimates are functions of management, site quality and tree species. Inventory numbers and economic data are generated from BC Ministry of Forests estimates for the Dawson Creek TSA (BC MoF 1994), whereas cost and return estimates for deciduous products are from BC Ministry of Agriculture, Fisheries and Food, (BC MoAFF 1996) estimates.

Both revenues and the recovery rates of lumber are a function of the species harvested and site quality.

The agricultural sector of the model includes tame pasture, forage and crop production. Tame hay is a mixture of alfalfa and grass-legume hay representative for the region. Various afforestation options of marginal agricultural land are considered – monoculture plantations of either native species or hybrid poplar and mixed-species plantations. No particular hybrid subspecies is considered, but rather a general one based on results from a study of afforestation for western Canada (van Kooten et al. 2000). Land available for afforestation by hybrid poplar is set at 50% of the total land currently in tame pasture and forage production.

In this study, forest ecosystem diversity is measured by its closeness to a desired target. Probably the best way of establishing the desired target is to rely on expert opinions and/or public expectations for a mix of desired future conditions or desired levels of ecosystem services. Alternatively, one can employ the diversity that would be expected in a natural forest (Hunter 1990). In either case, a forest could be managed to meet these requirements. Lacking clearly defined targets of forest structure for the study region, we use the target expressed in terms of species and tree size diversity of the natural forest. This target is attained when no harvests are permitted after the initial period harvest, with only natural regeneration afterwards.

Three native species (spruce, pine and aspen) and ten size classes are used to characterize ecosystem diversity, with deviations from the target expressed in terms of the number of hectares in each size-species class. Dawson Creek TSA has mostly mature forests, so that the targeted natural structure in each period consists of an old forest with large trees and younger forest with smaller trees on areas naturally disturbed (due to fire and pests), with natural disturbances being significant events in boreal forests. Deviation from the natural target is negative if the current area of a size class is smaller than the target area; it is positive if the current area of a size class is greater than the target area. After harvesting, the next period will have a surplus of young forest (small tree sizes) and shortage of mature forest (big tree sizes). In the model, we treat positive and negative deviations equally and minimize maximum absolute deviation from the target structure. Both deviations reflect human intervention and are not desirable from the perspective of ‘natural’ forest, but they are essentially different. For instance, reforestation by planting may be beneficial from the carbon and timber production perspectives, but it implies positive deviation from the target in the small size classes.

For (marginal) agricultural land, there is no clearly defined target for planting. Our selection of a target is guided by general consensus that mixed-species plantations maintain more plant and animal species than monoculture plantations, and that plantations of native species conserve local and regional animal species better than do plantations of exotic tree species (Noss 2001; Carnus et al. 2003; Korn et al. 2003). We set the afforestation target to be equally distributed between four tree species – in addition to hybrid poplar, three native tree species. It is not realistic to assume that afforestation of all available agricultural land will occur in the first period. Therefore, we set up the afforestation target in such a way that one-eighth of the total area made available in the model for planting is planted to each tree species type in the periods 2 and 3 of the planning horizon. The plantations are left to grow undisturbed (except for fire and insects) after that.

5. Analysis of model outcomes

The *MOLP* model is first solved for each of the objectives separately with all constraints that define the feasible set X in place. That is, we optimize each objective function individually and then compute the values of the remaining criteria at that optimal solution. The results are provided in Table 2, where each row consists of objective values calculated at the solution for the optimization problem indicated on the left. For example, the elements of the first row are the various objective values when net present value alone is optimized. The first three objectives are the cumulative net present value and nominal and discounted carbon sequestered over the planning horizon, while the last one refers to the sum of maximum deviations from the targeted forestland and afforestation structures, respectively. The ideal objective values are provided along the diagonal of the payoff matrix (Table 2) in boldface. These are the maximum possible value of each objective, but attainment of all maximum values at the same time is certainly not possible. The underlined figures correspond to the worst objective values and they are the coordinates of the nadir point. It is apparent from the payoff matrix that the four objectives are in conflict.

<Insert Table 2 about here>

Not surprisingly, the conflict is especially marked between timber and non-timber benefits, but there is also significant competition between short- and long-term carbon benefits and between carbon benefits and the diversity target. The strategy of maximizing net present value of timber production over the planning horizon leads to the worst value for long-term carbon accumulation. For example, in order to attain the maximum net present value of C$1.9 billion, 13.8 million tons of carbon from the forestland and neighboring agricultural land should be released, which means emissions of 6.5 million tons of carbon discounted at 4% over the horizon. At the same time, maximum deviation from the desired forestland structure is 137 thousand hectares and 14 thousand hectares from the afforestation target. Maximization of long-term carbon benefits leads to the lowest NPV – only C$1.3 billion – and a negative discounted net carbon uptake – 2.7 million tons of discounted carbon emissions. On the other hand, attainment of short-term carbon goals is significantly less in conflict with the economic and long-term carbon uptake goals. In order to accumulate 6.9 million tones of discounted carbon, long-term carbon accumulation is kept at 20 million tons and the NPV is C$1.7 billion. The short-term carbon goal is in greatest conflict with attainment of a desired forestland and plantation structure. Short-term carbon accumulation is possible only by significantly violating the diversity goals.

The strategy that fully meets the diversity goals results in the lowest discounted net carbon uptake and low (even negative) nominal carbon accumulation. In addition, the strategy to regulate the landscape for a desired structure implies low net present value – the second lowest after the short-term carbon accumulation strategy. Preservation of natural forests and multi-species plantations do not contribute much to short-term carbon uptake in Canada's boreal region.

The Compromise Strategies

Since none of the management strategies that optimize a single objective function is acceptable, changes in the environmental, economic and timber supply conditions are examined using compromise programming. The compromise strategy seeks to manage the conflict between the objectives by solving programs (4) and (5). We assume that equal weights are assigned to each objective in program (4). The 'balanced' and 'average' values are the objective values obtained for the balanced and average management alternatives, respectively. The 'balanced' and 'average' values are provided in Table 3. Figures in the parentheses indicate the extent to which the range between the nadir and ideal value is narrowed by the compromise program.

<Insert Table 3 about here>

For all objectives, the balanced values attain 60% of the objective range. While this level may seem acceptable for economic, long-term carbon and landscape diversity goals, it results in short-term carbon emissions. Objective values under the average strategy achieve between 34% and 87% of their corresponding best values. Deviation from the target diversity structure attains only 34% of its range, while short-term carbon uptake is at the 87% of its best value. Note that the average compromise values are obtained under equal weighting of the objectives with metric L_1. By varying weights associated with different objectives, stakeholders may explore tradeoffs between several objectives.

Land-use strategies

There are several land-use strategies that can be employed to meet objectives within the model. The first includes harvest alternatives that differ by species harvested and timing of harvesting; the second is reforestation of denuded forestlands by planting or natural regeneration. Finally, marginal agricultural land can be afforested with (three different) native species or fast-growing hybrid poplar or a combination of these. Since this option is considered one of Canada's alternatives for meeting Kyoto targets, we explore its potential economic and environmental impacts.

The optimal land use strategies are compared in Table 4 for scenarios that maximize net present value of forestry and agricultural activities and long- and short-term carbon accumulation, respectively, and minimize the maximum combined deviation from the target structure of managed forests and afforested land. In addition, Table 4 provides the balanced and average compromise land-use strategies when all four objectives are considered simultaneously.

As indicated in the table, a high level of early harvest of native species, reliance on natural regeneration by spruce and pine, reforestation of harvested aspen sites with hybrid poplar, and lack of afforestation are characteristics of the strategy that maximizes economic benefits (max NPV column). Management for long-term carbon accumulation, expressed by maximization of the cumulative net carbon uptake, leads to abandonment of early harvest of pine and spruce (except for the preset levels in the initial period), modest late harvests of conifers, and intensive late harvest of native and fast growing hybrids. Artificial regeneration is a dominant regeneration strategy, with both native and non-native tree species being planted. The total area of agricultural land available for afforestation is planted with a combination of pine and hybrid poplar. Medium quality agricultural lands are afforested by hybrid poplar and good ones by pine.

In contrast, when the focus is on short-term carbon uptake (maximization of discounted net carbon uptake), both coniferous and deciduous tree species are harvested in the second period, followed by intensive deciduous harvests in periods 3 and 4. This strategy is also characterized by intensive artificial regeneration with native and fast-growing hybrids whenever the latter option is possible. All agricultural lands available for afforestation are planted as early as possible with the hybrid poplar. Finally, harvesting does not occur if the management focus is only on achieving a natural forest structure. Agricultural land available is afforested in equal portions by all four species.

<Insert Table 4 about here>

Land-strategies that aim to reconcile conflicting objectives represent combinations of the previous extreme strategies. The balance land-use strategy focuses on minimizing the maximum deviation of objective values from their ideals. As diversity values are furthest from their best ones, the balanced land-use strategy recommends planting equal proportions of all tree species, reducing harvesting in the second half of the planning horizon and significantly decreasing artificial regeneration. Consequences of this management strategy include zero deviations from the afforestation diversity target and reduced deviations from the forestland diversity target. This strategy has the strongest negative impact on short-term carbon uptake. Unlike the balance strategy that focuses on avoiding extreme under-performers among multiple objectives, the average strategy may result in poor values of certain objectives. Unlike the balanced strategy, the average land-use strategy retains the high harvest levels in the first half of the horizon coupled with intensive artificial regeneration and afforestation with pine and hybrid poplar.

Comparison of Projected Outcomes over Time

An analysis of projected outcomes for each of the single-objective strategies and the balanced strategy may help understand sources of conflict. For this purpose, we chose to compare nominal carbon storage (in standing biomass and wood products) and maximum deviation from the target structure over time. We compare selected outcomes for four extreme scenarios and related land management strategies – those maximizing cumulative net present value (NPV) and nominal (Long-term C) and discounted carbon uptake (Short-term C), and preserving landscape diversity (Diversity) – and ones that balance (Balance) objectives and average (Average) objectives.

The distribution of net carbon uptakes over time for these six scenarios is presented in Figure 1. For the NPV and diversity scenarios, net carbon uptake falls in period 2 relative to the initial period. This is explained by the lack of artificial regeneration undertaken. For the diversity scenario, net carbon uptake reaches a long-term equilibrium starting in period 3, which is attributable to non-harvest of native forests and afforestation of agricultural land. On the other hand, the NPV strategy leads to a further decrease of carbon uptake in period 3 that is caused by intensive harvesting and lack of planting on both denuded forestland and agricultural land. This decline of carbon uptake for the NPV scenario stops after period 4 when intensive harvest is reduced because it is no longer profitable.

Short-term carbon uptake is the only single objective scenario that shows a non-declining trend of carbon uptake over the horizon. This is achieved through a high level of artificial regeneration and early afforestation using fast growing hybrid poplar. In contrast, the long-term carbon scenario is characterized by declining carbon uptake in period 2 relative to the initial period and a steep rise in carbon uptake for the rest of horizon. This pattern is mainly achieved by to afforestation using a mix of slow growing pine and fast growing hybrid poplar. The compromise scenarios accumulate carbon at rates somewhere between two contrasting scenarios – NPV and diversity on one hand, and long- and short-term carbon uptake on the other. Although no dramatic differences between two compromise scenarios are evident in terms of net carbon uptake over time, the balanced strategy favors long-term carbon uptake while the average strategy is more inclined toward meeting short-term carbon uptake goals.

An economic benefits scenario relies 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 60 years or older, the NPV strategy implies a drastic shortage of forest available for harvesting in later periods. Simultaneous harvests of newly established deciduous plantations only partially offset this shortage. The harvest intensity of the NPV scenario implies reduced carbon storage over the whole horizon (Figure 1).

< Insert Figure 1 about here>

The carbon uptake patterns under various management scenarios are closely related to the temporal distribution of deviations from the target structure (Figure 2). In Figure 2, the short-term carbon uptake strategy provides the greatest deviation from a desired landscape target. While it is mainly due to plantations of harvested aspen stands with hybrid poplar in periods 2 and 3, in later periods both forest harvests and afforestation by hybrid poplar contribute to high cumulative deviation from the target structure. The long-term carbon strategy really does not conflict with diversity preservation for the first five periods, but a big spike in deviations from target diversity occurs in period 6 due to intensive harvesting in the last period. A disadvantage of the NPV strategy 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 period 3 (Figure 2). Since most of the mature forests are cut in the first period, this implies a large deviation from large-diameter, older trees that characterize natural forests. This feature could also have a negative implication for wildlife dependent on late-successional stage forest habitat.

< Insert Figure 2 about here>

The two compromise strategies keep deviations from the diversity target at the constant level over the horizon – at 83,000 hectares and 135,000 hectares for the balance and average strategy, respectively. Strategies to achieve carbon or structural diversity targets, on the other hand, perform badly in terms of both timber benefits and remaining environmental services. For this case study, 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 afforestation of agricultural lands. These strategies create large areas of young forest, resulting in deviations that 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 can be achieved only by sacrificing ecological benefits – both diversity and carbon uptake (Figures 1 and 2, NPV strategy). 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 already indicated, this implies significantly reduced net returns and harvests, especially in period 2.

Carbon and biodiversity objectives can be in conflict depending on the biodiversity target and how biodiversity is measured**,** and on how the carbon objective is measured. This emphasizes the need to provide group expertise and public input when setting a target on forest structure. Policy makers, public and corporate, should be prepared for the loss of economic benefits due to reduced harvest volumes and increased management costs if long-run sustainable management is to be achieved.

In general, different measures of distance between the current objective values and the ideal ones used in the compromise programming approach lead to significantly different land-use and forest management strategies and associated objective values. Applying the measure that maximizes the worst objective value deviation from the ideal one leads to the balanced strategy that satisfies diversity targets as close as possible. This leads to significant underachievement of both the economic and carbon objectives. This strategy balances all objective values at 60% of their best values. The latter approach could be interpreted as a faire share of the costs of meeting multiple objectives simultaneously. Although all objectives equally underachieve the ideal, stakeholders may prefer a different solution. Maximization of the weighted sum of objective value deviations results in a strategy that attains nominal and discounted carbon objectives at the 77% and 87%, respectively, while significantly sacrificing the diversity objective. This occurs when equal weights are assigned to all deviations. Different average strategies can be generated by varying the weighting factors so that the stakeholders can explore tradeoffs between several objectives and choose an acceptable strategy. A lesson learned from the balanced strategy is that it is not possible to improve any objective to closer than 60% of its best value without worsening at least one of the remaining objectives.

6. Conclusions

Decisions regarding land-use and forest management are often made under multiple, inherently conflicting objectives. The approach often taken to deal with multiple objectives is to optimize a selected objective while imposing targets or restrictions on remaining goals. It assumes that decision-makers have a good knowledge of the objective targets, which often is not the case because many policy issues have not been adequately resolved.

In this paper, we developed a land-use and forest management model that incorporates explicitly multiple objectives. We included an economic objective and the three objectives that reflect ecological benefits associated with land-use and forest management. As it is highly unlikely that there is a single management strategy that attains the best or 'ideal' value for each of the multiple objectives, we applied compromise programming to find strategies for which objective values are closest to the ideal ones.

As illustrated in the paper, compromise programming provides a useful tool for both multi-objective conflict analysis and management, and quantification of the tradeoffs between economic and ecological benefits. Two measures of distance between the current objective values and the ideal ones are used in the paper to assess the attainment of multiple goals. The choice of distance enables the incorporation of the decision-makers' attitude toward simultaneous attainment of multiple objectives without the need to elicit explicitly their preference information.

The approach employed makes it possible to determine which management strategy best balances competing objectives and which leads to an average score for all objectives. These two strategies differ significantly in terms of land-use and forest management and associated economic and ecological benefits. The methodology can only help identify what impacts decision-makers' attitude regarding multiple objectives have on the final decision, but it cannot unequivocally point to the "best" strategy.

The approach described in this paper is general and allows for other land management strategies and concerns to be incorporated. For example, we addressed forest biodiversity in terms of tree species and size diversity, but the same approach can be used to explore other dimensions of ecological diversity and their tradeoffs.

The results of the case study prove that conflicts between the diversity objective and other objectives are primarily caused by the chosen target for structural diversity, namely, those of mimicking a ‘natural forest’ structure and tree plantations on agricultural land that have equal proportions of native and hybrid tree species. Nevertheless, similar outcomes could be expected for any other target that includes preservation of mature forests and diversity of the afforested landscape.

Acknowledgements

The authors want to acknowledge research support from the Natural Sciences and Engineering Research Council of Canada, the Sustainable Forest Management Network and BIOCAP/SSHRC.

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Table 1: Current land use (hectares)

Commercial Forestland		Agricultural Land	
Spruce	374,260	Tame Pasture	83,300
Pine	349,810	Forage	29,200
Aspen	359,820	Crops	40,000
Forest total	*1,083,890*	*Agricultural total*	*152,500*

Table 2: Objective values when each objective is optimized in isolation[a]

	Model objectives				**Biodiversity sub-objectives**	
	N(*x,y,z*) ($ '000)	*C*(*x,y,z*) ('000s t)	*DisC*(*x,y,z*)	Dev*F*(*x*)+ Dev*A*(y)[b] ('000s ha)	Dev *F*(*x*)	Dev *A*(y) ('000s ha)
max *N*(*x,y,z*)	**1,919,162**	-13,852	-6,462	151	137	14
max *C*(*x,y,z*)	1,328,639	**35,959**	-2,749	178	163	16
max Disc*C*(*x,y,z*)	1,655,889	20,158	**6,951**	205	163	42
min *D*(*x,y*)	1,447,138	-2,616	-10,569	**0**	0	0

[a] Best values are given in bold; worst values are underlined.

[b] Expressed as a deviation from the target.

Table 3: Objective values for the compromise strategies

	Model Objectives				**Biodiversity sub-objectives**	
Strategy	*N*(*x,y,z*) ($ '000)	*C*(*x,y,z*) ('000s t)	*DisC*(*x,y,z*)	Dev*F*(*x*)+ Dev*A*(y) ('000s ha)	Dev *F*(*x*) ('000s ha)	Dev *A*(y)
Balanced	1,681,119	15,880	-111	83		
	(60%)	(60%)	(60%)	(60%)	83	0
Average	1,651,522	24,282	4,749	135		
	(55%)	(77%)	(87%)	(34%)	121	14
IDEAL	1,919,162	35,959	6,951	0	0	0
NADIR	1,328,639	-13,852	-10,569	205	163	42

Table 4. Optimal and compromise land-use strategies

	Single Objective Strategies				Compromise strategies	
	max NPV	max Carb	maxDisc Carb	minMax Dev	Balanced	Average
			Harvest (1000 ha)			
Period 2						
Spruce	165	13	165		112	158
Pine	105		105		94	105
Aspen	10	2	49		47	47
Hybrid poplar	10	2	47		47	47
Period 3						
Spruce	28	1	28		28	3
Pine	12	1	12		1	12
Aspen	20	42	80		43	78
Hybrid poplar	20	42	78		43	78
Period 4						
Spruce	22		21			
Pine	9		24		9	
Aspen	40	69	64		17	21
Hybrid poplar	40	69	64		17	21
Period 5						
Spruce	8					
Pine						
Aspen	80	163	14		29	19
Hybrid poplar	80	163	14		29	19
Period 6						
Spruce		40	35		36	46
Pine		121	99		93	119
Aspen		23	14			
Hybrid poplar						
			Reforestation (1000 ha) by planting			
Spruce	1	118	135		79	80
Pine	1	153	270		90	148
Aspen		98	18			
Hybrid poplar	160	325	328		207	285
			Afforestation (1000 ha)			
Spruce				14	14	
Pine		30		14	14	28
Aspen				14	14	
Hybrid poplar		26	56	14	14	28

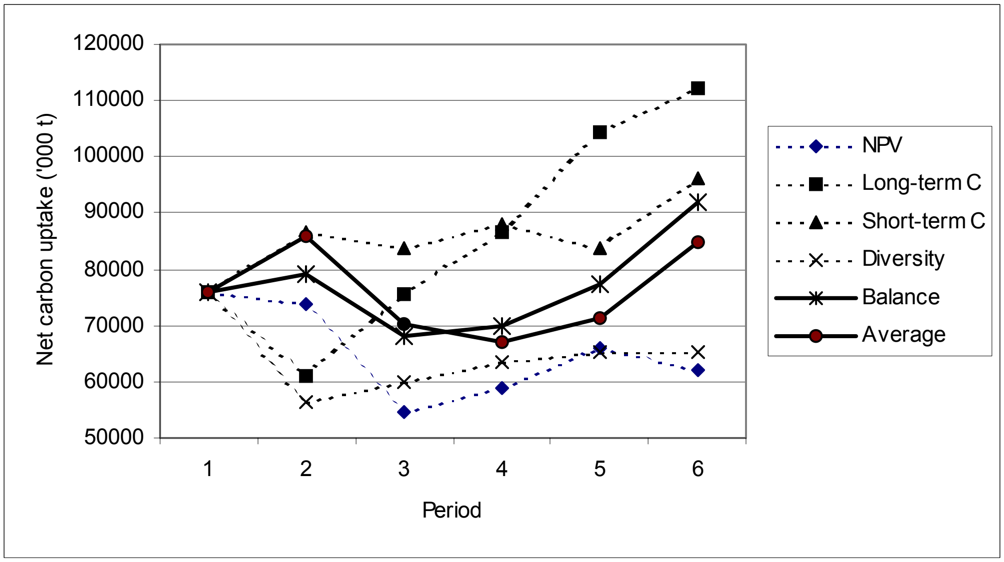

Figure 1. Net carbon uptake over time.

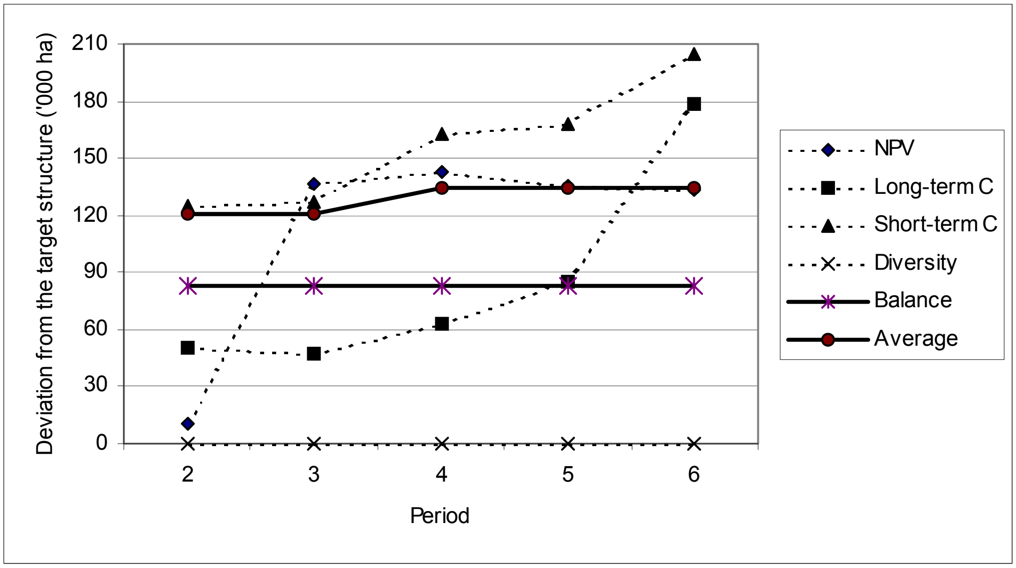

Figure 2. Deviation from the target structure over time.