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Ecological Modelling 185 (2005) 451–468

ECOLOGICAL MODELLING

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Managing forest and marginal agricultural land for multiple tradeoffs: compromising on economic, carbon and structural diversity objectives

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Received 20 April 2004; received in revised form 11 December 2004; accepted 20 December 2004

Abstract

In this paper, we use compromise programming to solve a multiple-objective land use and forest management planning model. Long- and short- (‘fast’) term carbon uptake, maintenance of structural diversity, and economic (net returns to forestry and agriculture) objectives are simultaneously achieved by minimizing the distance between current objective values and the ideal ones. Two distance metrics are used, representing a risk neutral and highly risk-averse decision maker. An application of the model to public forestland and adjacent private agricultural lands in the (boreal) Peace River region of northeastern British Columbia indicates that both short- and long-term carbon uptake, and maintenance of structural diversity, can be achieved only at the high financial costs. Contrary to earlier studies, we also find conflict between both short- and long-term carbon uptakes and maintenance of landscape structural diversity. Targeting short-term carbon uptake results in the greatest deviation from desired structural diversity, although the deviation is somewhat smaller with respect to the long-term carbon uptake goal. Further, risk neutral and risk-averse decision makers will employ significantly different land use and forest management strategies. Finally, the ‘balanced’ strategy (which underachieves attainment of the ‘ideal’ by the same degree for all objectives) attains diversity targets quite closely, but significantly underachieves economic and carbon objectives. Maximization of the weighted sum of objective deviations results in an ‘average’ strategy that performs much better in attaining carbon objectives, but diversity is sacrificed.

Keywords: Compromise programming; Carbon sequestration; Forest management and afforestation; Structural diversity

1. Introduction

Land use policies often focus on ecological services in isolation, or reflect the tradeoff between a single

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doi:10.1016/j.ecolmodel.2004.12.014

ecological objective and an economic one. But there are many objectives that need to be considered in land use planning, with one possibly affecting some or all of the others (Alig et al., 1998). Climate change and loss of biodiversity are considered to be among the world's most important environmental policy issues. Changes in land use have a major impact on the amount of CO_2 entering the atmosphere and on the loss of forest biodiversity, particularly the conversion from forestry to crop cultivation (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. One aspect of this strategy that has been overlooked in much of the discussion concerning carbon forest sinks, but has recently drawn more attention, is the impact that land management for carbon uptake might have on biodiversity (Noss, 2001; UNCBD, 2004). There still remains a lack of information and understanding concerning the interactions between land management for carbon and maintenance of biodiversity.

Since the adoption of the United Nations' Convention on Biological Diversity in 1992, conservation of biodiversity has been an important topic of the land use and forest planning literature. Biodiversity refers to the variety and abundance of species, their genetic composition, and the communities, ecosystems and regions in which they occur (Hunter, 1990; Burley, 2002). It also refers to ecological structures, functions and processes at each of these levels. The complexity of biodiversity makes it difficult to decide what to measure, although forest ecologists agree that some of the ecological processes influencing forest biodiversity depend on the maintenance of forest compositional and structural diversity at several spatial and temporal scales (Ferris-Kaan et al., 1998; Franklin, 1988). Some researchers have studied conflicts between timber production and maintenance of structural diversity using optimization models: Kant (2002) and Buongiorno et al. (1994) examined tradeoffs between economic returns and maintenance of structural diversity, which they modeled as a non-spatial composition of several tree-size classes.

In addition to non-spatial composition, there is a need to include spatial configuration of some attributes in forest management (Baskent and Jordan, 1995). Modeling difficulty is increased by the complexity of the objective function and the constraints that represent spatial requirements of wildlife habitat or green-up of adjacent stands, with this complexity often mitigating use of optimization techniques. Several studies have successfully applied heuristic techniques to find approximately optimal solutions to the spatial forest planning problem. Bettinger et al. (1997, 1998) developed two tabu search routines that combine timber production and maintenance of wildlife habitat goals. Ohman (2000) and Baskent and Jordan (2002) applied simulated annealing to obtain solutions to the multiobjective spatial forest planning problem.

Concern about anthropogenic emissions of CO_2, along with the adoption of the Kyoto Protocol in, 1997, triggered research focusing on the earth-to-atmosphere carbon cycle. The Kyoto Protocol allows countries to claim credits for carbon sequestered as a result of afforestation (planting trees on agricultural land), reforestation (planting trees on denuded forestland) and land management that enhances growth of vegetation, while carbon lost as a result of deforestation is a debit (van Kooten, 2004). While land use and forest management decisions impact the amount of carbon and its rate of accumulation in standing timber and product pools, the financial costs and benefits of such decisions must be balanced against their carbon fluxes when deciding upon appropriate forest carbon strategies. Classic methods based on the Faustmann formula have been applied for economic assessment of forest carbon uptake (van Kooten et al., 1995, 1999; McKenney et al., 2004), but another approach to economic assessment has been to incorporate a carbon benefit objective explicitly into a forest management optimization model. This was done by Hoen and Solberg (1994), Krcmar et al. (2001), and Diaz-Balteiro and Romero (2003), who examined tradeoffs between timber and carbon benefits using constrained optimization or goal programming approaches. In these models, dependencies among activities in adjacent areas are not important for carbon. This may explain why such models are of a non-spatial nature.

More recently, concerns have been expressed 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, which may have a significant impact on both carbon accumulation and maintenance of vegetative diversity. 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). Choice of species for reforestation and afforestation requires a tradeoff between fast carbon sequestration and subsequent release, and slower carbon sequestration with longer retention time. The choice of tree species can greatly affect biodiversity through understory plants 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).

There are a number of different ways for accommodating multiple objectives in land use and forest management planning models. One is to construct, from the multiple objectives, a single objective to be optimized. This is done by using fixed weights or penalties to combine objectives into a single aggregate expression. That is, the solution to the multiobjective optimization problem is obtained by optimizing a weighted sum of several objectives, with the weights representing the relative importance of each. For a fixed set of weights, the solution to the single-objective problem determines one among many possible tradeoffs among several objectives; others can be obtained by varying the weights. The difficulty with this method is determining appropriate weights to assign each objective. As a result, most researchers now eschew this approach.

An alternative approach is to specify one objective to be optimized while the others were included as constraints. By varying the target of an objective in the constraint set, tradeoffs between that object and the one chosen for optimization can be derived in parametric fashion, but it is not possible with this approach to examine tradeoffs among all objectives simultaneously. In the context of forest management, this methodology was used by Hoen and Solberg (1994), Buongiorno et al. (1994), Onal (1997), Boscolo and Buongiorno (1997), and Kant (2002). Using this approach, Boscolo and Buongiorno (1997) were the first to address the carbon, biodiversity and financial objectives in forest management planning, but they were limited to exploring only tradeoffs between two objectives at a time.

Finally, among the studies we reviewed, only Diaz-Balteiro and Romero (2003) and Krcmar et al. (2001) capture explicitly the multiobjective nature of the problem. The former incorporate carbon uptake with other objectives of forest planning – net present value (NPV), volume and area control, and ending forest inventory – into a goal programming model that seeks to get as close as possible to the specified objective targets. Krcmar et al. (2001) focused on the decision makers' attitudes toward uncertainty using two measures of uncertainty, possibility and necessity.

Although the multiobjective optimization framework has gained increasing popularity in land use and forest planning (Stewart et al., 2004; Pukkala and Pukkala, 2002), at some point, the application of multiobjective solution techniques requires specifying the decision maker's preference structure over the set of objectives. This subjective evaluation is crucial in the selection of one or more solutions from the many tradeoffs available. In the absence of information about decision makers' preferences for multiple objectives, one may opt to either generate all solutions of the multiobjective optimization problem (Steuer, 1986) or determine solutions associated with specific stakeholders' behavior. In the case of both economic and environmental objectives, a decision maker's risk attitude has proven to be an important driver in selecting the preferred solutions. Ballestero (1997) established a link between a parameter in compromise programming, one of the oldest solution techniques for multiobjective optimization, and a decision maker's risk attitude. This link is exploited in our paper to analyze different tradeoffs between economic, carbon and structural diversity objectives.

In this paper, we extend the work of Diaz-Balteiro and Romero (2003), Krcmar et al. (2001), Ballestero (1997), Boscolo and Buongiorno (1997), and other researchers in several important ways. First, we formulate a land use and forest management model that explicitly incorporates economic, structural diversity, and short- and long-term carbon uptake objectives. Our measure of structural diversity is based on Buongiorno et al. (1995) and Onal (1997). But, we emphasize not only the importance of tradeoffs among various objectives, but are the first to consider two carbon uptake objectives and quantify the tradeoffs between them. This is important to the Kyoto process as there are likely to be several commitment periods with different CO_2 emission reduction targets in each. Further, we quantify the tradeoffs among several objectives simultaneously using compromise programming, and demonstrate the applicability of this approach using a case study. The case study involves public and private lands, with this mix leading to a different ‘optimal’ than would be the case if all land were publicly owned. Finally, and importantly, we compare tradeoffs for different decision makers’ risk attitudes.

Our problem is described in more detail in the next section. Then, in Section 3, we develop a multiobjective optimization model with economic, carbon and structural diversity objectives. Tradeoffs among multiple objectives are examined using a compromise programming approach. In Section 4, we apply our model to a region in northeastern British Columbia (BC). The study region consists of publicly owned boreal forestland and private lands in agricultural production. Outcomes of the case study are provided in Section 5. Our conclusions follow in Section 6.

2. Problem description

The general scope of this paper is to explore tradeoffs between economic, carbon and structural diversity objectives in forest and marginal agricultural land management. To measure the success of land management strategies in accomplishing economic and environmental goals, we need economic, carbon-uptake and structural diversity indicators (measures). The economic criterion consists of the net discounted returns to management on forestland plus net returns to agricultural land, whether used in forestry or agriculture.

Our carbon measure is carbon flux, the change in carbon stocks associated with several carbon pools. For carbon accounting, we follow the methodology described in detail in several articles (van Kooten et al., 1999, 2000). Our carbon model is similar to the Carbon Budget Model of the Canadian Forest Sector (Kurz et al., 1992; Apps et al., 1999) and the recently developed regional carbon budget model of Song and Woodcock (2003), accounting for carbon fluxes in several components. These include standing trees affected by harvesting, decomposition of residual carbon left in the forest after harvesting, and carbon in harvested biomass that is converted to forest products and released to the atmosphere through decay. We also track changes in soil carbon after conversion of agricultural land to forestry.

Discounting is another important issue in multiple-period modeling of carbon uptake. If discounting is utilized for financial costs and returns but not for the physical carbon, there will be an obvious bias towards carbon sequestration in later periods. This has been well recognized in carbon sequestration research and the discounting of physical carbon has been used in a number of studies (Boscolo and Buongiorno, 1997; van Kooten et al., 2004). A social discount rate is assumed for discounting carbon uptake. This rate can be lower, equal, or greater than a rate used for discounting financial flows, although there is evidence to suggest that people might well discount environmental amenities at a lower rate than financial flows, and the more distant future at a lower rate than those less distant (Knetsch, 2000; Newell and Pizer, 2003).

To capture the temporal aspect of carbon benefits, we distinguish between two carbon measures: (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.

When designing the structural diversity objective, we considered two forest landscape attributes—tree size and tree species. Having varied size classes of trees enhances structural diversity of a managed forest. Big trees constitute a particularly valuable contribution to wildlife habitat. This size of trees can be achieved by natural aging and/or enhanced silviculture. Promoting a variety of different tree species also improves structural diversity within the managed forest (Franklin, 1988). High evenness is often equated with diversity leading to the application of diversity indices, such as the Shannon and Simpson indices. Several modeling approaches differ only in terms of the diversity index applied (Buongiorno et al., 1994; Kant, 2002). On the other hand, there are opinions that diversity may be better described in relationship to some desired ‘target’ (Buongiorno et al., 1995; Onal, 1997; Boscolo and Buongiorno, 1997). 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 forest structures—and these might differ significantly. 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.

Our indicators of structural diversity are calculated relative to specific targets. To define specific management targets in maintaining structural diversity of native and planted forests, we take into account the following 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.

Similar to Boscolo and Buongiorno (1997), we select the natural forest as an ideal (though not necessarily attainable) target for structural diversity objectives. If left unmanaged, forests are subject to natural disturbances; thus, fire is included in our modeling of the structure of natural forests, because it is the major natural disturbance in boreal forests. We model fire deterministically using the average incidence of fire in the study region and assuming natural regeneration afterwards.

When establishing the diversity target for afforested marginal agricultural land, we follow the principle of evenness, with the afforestation target involving equal proportions of native and non-native tree species.

3. Model formulation and solution approach

Our forest and marginal agricultural land planning problem is complex because of the presence of multiple objectives that have to be met by every management strategy. 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 structural diversity. These objectives conflict, they are of a different nature and measured in various units. Rather than optimizing a selected objective, either an economic or environmental one, while imposing restrictions on remaining goals, we formulate the forest and marginal agricultural land planning problem using a multiple-objective framework and linear programming. The model decision variables include 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 model elements are defined as follows. Suppose that the planning horizon is divided into $t \in T$ periods 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 $M_i \cap M_j = \emptyset$, $M = \cup_i M_i$, $i, j \in G$. 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, where $\alpha \geq \beta$. A distinction between financial and carbon discount rate allows for the analyses of the impact of temporal aspect on carbon management strategies. 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 as 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, $\mathrm{DisC}(x, y, z) = \sum_t \mathrm{DisC}F_t(x, y, z)$. Here, $\mathrm{DisC}F_t(x, y, z) = \mathrm{DisC}_t(x, y, z) - \mathrm{DisC}_{t-1}(x, y, z)$ is a discounted flux, or average change in discounted carbon stock between two consecutive periods, where

$$\mathrm{DisC}_t(x, y, z) = (1+\beta)^{-t} \left[\sum_{m \in M} \sum_{p \in P(m,t)} (cf_{mpt} x_{mpt} + ca_{mpt} y_{mpt}) + \sum_{b \in B} cag_b z_{bt} \right].$$

The objective **DisC** represents a proxy for short-term carbon sequestration.

The last objective (**D**) concerns maintenance of forest structural 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 multiobjective linear programming model is as follows:

MOLP model

N Max $N(x, y, z)$
C Max $C(x, y, z)$
DisC Max $\mathrm{DisC}(x, y, z)$
D Max $D(x, y)$
subject to
(x, y, z) ‘element’ FS

where:

$$N(x, y, z) = \sum_{m \in M} \sum_{p \in P(m,t)} \sum_{b \in B} \sum_{t \in T} (1+\alpha)^{-t}[nvf_{mpt} x_{mpt} + nva_{mpt} y_{mpt} + ag_b z_{bt}]$$
$$C(x, y, z) = \sum_t CF_t(x, y, z)$$
$$\mathrm{DisC}(x, y, z) = \sum_t \mathrm{DisC}F_t(x, y, z)$$
$$D(x, y) = \max_{g,s}[|F_{g,s}(x) - TF_{g,s}| + |A_g(y) - TA_g|]$$

3.1. Compromise programming

One of the most widely applicable approaches to obtain solutions to the multiobjective optimization problem is distance metric optimization (Jones and Tamiz, 2003). The distance metric framework was introduced in the context of compromise programming (Yu, 1973) and includes several well-known multiobjective techniques, such as goal programming and the reference point method (Romero et al., 1998). The distance metric approach seeks management strategies that minimize a distance function between the achieved levels of objectives and a reference point in the objective space. The multiobjective techniques differ in how they define the reference point and the distance function.

It is highly unlikely that there exists 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' point in the objective space. Compromise programming is characterized by the minimization of the distance between the achieved levels of objectives and the ideal ones. The distance function is formulated in terms of a metric in the objective space.

Let a feasible land management strategy $(x, y, z) \in FS$ be evaluated in terms of the *MOLP* model criteria, $f_q(x, y, z)$, $q \in Q = \{\mathbf{N}, \mathbf{C}, \mathbf{DisC}, \mathbf{D}\}$, where $f_N(x, y, z) = N(x, y, z)$, $f_C(x, y, z) = C(x, y, z)$, $f_{\mathrm{DisC}}(x, y, z) = \mathrm{DisC}(x, y, z)$, and $f_D(x, y) = D(x, y)$. Denote by

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

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

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

is the distance of the current objective value from its best value, normalized by $f_q^* - f_{q*}$. 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, $1 \leq \pi \leq \infty$. The choice of the distance parameter π expresses decision makers' attitudes toward simultaneous attainment of multiple objectives: $\pi = 1$ represents a risk neutral decision maker and $\pi = \infty$ a decision maker with extremely high risk aversion (Ballestero, 1997).

The solution to the program

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

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

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

and the solution algorithm 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 $\max_{q \in Q} d_q(x, y, z)$.

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

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. 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. About one million hectares of the area is suitable for commercial timber harvesting and management. Of this, coniferous forests cover some 70% and deciduous forests 30%. In addition, agricultural land totals approximately 152,000 ha. Spruce and lodgepole pine dominate the coniferous timberland base, while trembling aspen is a dominant deciduous species. Currently, 75% of the coniferous forest and 50% of the deciduous forest are mature. Current land uses and species distribution are found in Table A.1.

The model assumes that decisions occur at the end of 20-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 period 1980–2000 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, except for aspen stands for which reforestation by hybrid poplar is considered as an alternative. Since forestland is publicly owned and designated for timber production only, we do not consider the possibility of forestland conversion to agriculture.

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. Afforestation options of marginal agricultural land include plantations of native species and hybrid poplar. 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., 1999). Land available for afforestation by hybrid poplar is set at 50% of the total land currently in tame pasture and forage production.

Yield tables for each combination of regeneration type, species, site quality, and age were generated using the forest dynamics simulation model, TIPSY, version 1.3 (Mitchell and Grout, 1995). Volume estimates for three tree species are provided in Table A.2. To estimate the growth of hybrid poplar, we employed the Chapman–Richards function, $G(t) = A(1 - e^{-kt})^m$, where A is the maximum stem wood volume and k and m are parameters. Available data on growth rates have been obtained under various management regimes, including fertilization and irrigation. For the boreal region, we set $A = 329$, $k = 0.156$, and $m = 3.0$ (van Kooten et al., 1999).

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. Financial flows are discounted at 4%.

The carbon measure for this case study is the change in the carbon stock associated with the aboveground biomass of the forest, soil carbon, and forest products. The carbon stored in biomass is determined by the volume found in the bole (or commercial component of the tree), which is given by growth function $G(t)$, multiplied by an expansion factor equal to 1.57 for native species and 1.39 for hybrid polar to obtain total aboveground biomass. Root biomass (R) is related to aboveground biomass (G) as follows, with both measured in tonnes per hectare, $R = 1.4319G^{0.639}$.

The carbon content of timber in the study region averages 0.193, 0.221, 0.197, and 0.184 t/m^3 for spruce, pine, aspen, and hybrid poplar, respectively (van Kooten et al., 1993, pp. 243–245). To the carbon stored in biomass, we add the change of carbon in the forest product pool. Four forest product categories – coniferous lumber, coniferous pulp, deciduous OSB, and deciduous pulp – are considered in the model. Coniferous timber is cut into lumber with the remainder going to chips for pulp. Deciduous harvests are sold, as logs, for either pulp or OSB production. The amount of product from each pool that ends up in landfills is also taken into account. The use of wood for biomass burning is not considered at this time. The products decay and release CO_2 to the atmosphere at various rates. Estimates of the amount of carbon remaining in product pools over time are provided in Table A.3.

The last carbon component is the change of soil carbon. We assume that soil carbon associated with forests does not change as long as there is no change in land use. It was noted that forest soils in the boreal region store some 108 t of carbon/ha compared to cropland that stores some 60 t (van Kooten et al., 1999). Using this relation and assuming that 50% of the difference is sequestered in each of the first two periods after the land is converted from agriculture to forestry, 48 t of carbon/ha are added to soil during the 40 years required for a hybrid poplar ecosystem to achieve soil carbon equilibrium. Based on the methodology described, two

Table 1
Objective values when each objective is optimized in isolation[a]

	Model objectives				Diversity sub-objectives	
	$N(x, y, z)$ (Can$ 1000)	$C(x, y, z)$ (1000 t)	DisC(x, y, z) (1000 t)	Dev $F(x)$ + Dev $A(y)$[b] (1000 ha)	Dev $F(x)$[b] (1000 ha)	Dev $A(y)$[b] (1000 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(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.

carbon measures are calculated for each planning period: the nominal (undiscounted) carbon flux and discounted carbon flux. A rate of 4% is used to discount carbon—the same as that used to discount financial flows. The nominal and discounted carbon fluxes were added up for all planning periods to obtain measures of long- and short-term carbon uptake over the horizon.

In this case study, 3 native species (spruce, pine, and aspen) and 10 size classes are used to characterize structural diversity of existing forests. The forest structural diversity is measured by its closeness to the target expressed in terms of species and tree size diversity of the natural forest. The target would be attained if no harvests were permitted after the initial period harvest,[1] with only natural regeneration of forests denuded by the initial harvests or natural disturbance. Deviations from the target are 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 but regular 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 the 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 unrealistic 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 available planting area is planted to each tree species type in periods 2 and 3 of the planning horizon. The management targets for marginal agricultural land are provided in Table A.4. The plantations are then left to grow undisturbed (except for fire and insects).

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 1, 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

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[1] The initial period conditions are based on actual land use in period 1980–2000.

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 in boldface along the diagonal of the payoff matrix (Table 1). 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 lowest point. From the payoff matrix it is clear that the four objectives conflict.

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-run carbon accumulation. For example, to attain the maximum net present value of Can$ 1.9 billion, 13.8 million tonnes of nominal carbon from the forestland and neighboring agricultural land should be released, which translates into emissions of 6.5 million tonnes of carbon discounted at 4% over the horizon. At the same time, maximum deviation from the desired forestland structure is 137,000 and 14,000 ha from the afforestation target. Maximization of long-term carbon benefits leads to the lowest NPV – only Can$ 1.3 billion – and a negative discounted net carbon uptake – 2.7 million tonnes 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 tonnes of discounted carbon, long-term carbon accumulation is kept at 20 million tonnes and the NPV is Can$ 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 does not contribute much to short-term carbon uptake in boreal Canada.

5.1. 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 of the balanced and average management alternatives, respectively, and are provided in Table 2. Figures in the parentheses indicate the extent to which the range between the nadir (lowest or worst) and ideal value is narrowed by the compromise program.

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 cumulative carbon emission over the short horizon. 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 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 other possible tradeoffs between several objectives.

5.2. 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 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.

Table 2
Objective values for the compromise strategies

Strategy	Model objectives				Diversity sub-objectives	
	$N(x, y, z)$ (Can$ 1000)	$C(x, y, z)$ (1000 t)	DisC(x, y, z)	Dev $F(x)$ + Dev $A(y)$ (1000 ha)	Dev $F(x)$ (1000 ha)	Dev $A(y)$ (1000 ha)
Balanced	1,681,119 (60%)	15,880 (60%)	−111 (60%)	83 (60%)	83	0
Average	1,651,522 (55%)	24,282 (77%)	4,749 (87%)	135 (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

The optimal land use strategies are compared in Table 3 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 3 provides the balanced and average compromise land use strategies when all four objectives are considered simultaneously.

As indicated in Table 3, 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 hybrid poplar. Finally, harvesting does not occur if management focuses only on achieving a natural forest structure. Agricultural land available is afforested in equal proportions by all four species.

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

Table 3
Optimal and compromise land use strategies

	Single objective strategies				Compromise strategies	
	Max NPV	Max Carbon	Max DisCarbon	Min maxDev	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

horizon and significantly decreasing artificial regeneration. As a consequence, there are no 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.

5.3. *Comparison of projected outcomes over time*

An analysis of projected outcomes for each of the single-objective strategies and the balanced strategy

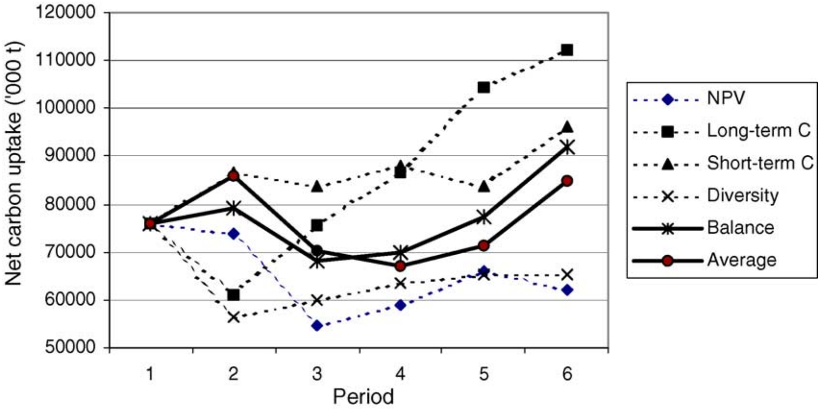

Fig. 1. Net carbon uptake over time for different land management strategies: maximizing net present value (NPV), nominal (Long-term C) and discounted carbon uptake (Short-term C), and preserving structural diversity (Diversity)—and ones balancing (Balance) objectives and averaging (Average) objectives.

may help understand sources of conflict. For this purpose, we compare nominal carbon storage (in standing biomass and wood products) and maximum deviation from the target structure over time. We contrast selected outcomes for four extreme scenarios and related land management strategies—those maximizing cumulative net present value and nominal (Long-term C) and discounted carbon uptake (Short-term C), and preserving structural 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 Fig. 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 through 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 dramatic downfall in timber available for harvest 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 (Fig. 1).

The carbon uptake patterns under various management scenarios are closely related to the temporal distribution of deviations from the target structure (Fig. 2). In Fig. 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

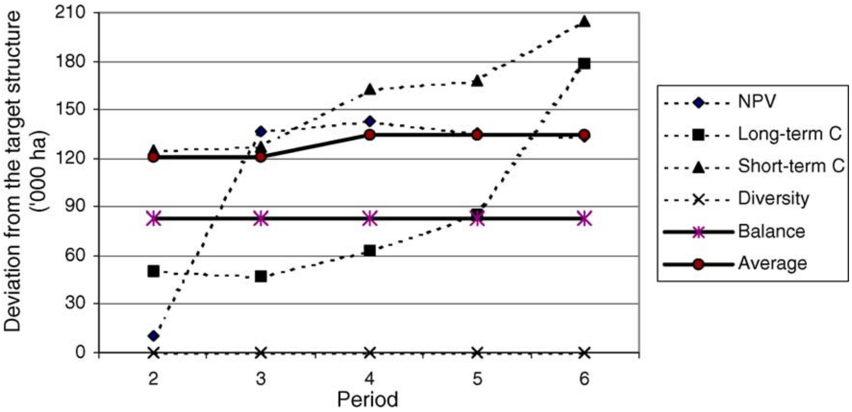

Fig. 2. Deviation from the target structure over time for different land management strategies: maximizing net present value (NPV), nominal (Long-term C) and discounted carbon uptake (Short-term C), and preserving structural diversity (Diversity)—and ones balancing (Balance) objectives and averaging (Average) objectives.

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 (Fig. 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.

The two compromise strategies keep deviations from the diversity target at the constant level over the horizon—at 83,000 and 135,000 ha 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 the 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 structural diversity.

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 (Figs. 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 structural diversity objectives can conflict depending on the structural diversity target and what structural elements are considered, 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 lower 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. By applying the measure that maximizes the worst objective value deviation from the ideal one, this leads to the balanced strategy that attains diversity targets as closely as possible. This leads to significant underachievement of 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 77 and 87% of the respective nominal and discounted carbon objectives, while significantly sacrificing the diversity one. 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. Discussion and conclusions

In this study, we developed a land use and forest management model that explicitly incorporates multiple objectives, particularly an economic objective and three others that reflect ecological benefits related to carbon sequestration and biodiversity. Since it was highly unlikely that a single management strategy could attain the best value for each of the objectives simultaneously, we applied compromise programming to discover strategies that might be regarded ‘acceptable’. To assess acceptability (or the extent to which multiple objectives are attained), two measures of the distance between the current and ideal objective values were used. The choice of the distance metric π enabled us to incorporate decision makers’ attitudes toward simultaneous attainment of multiple objectives: $\pi = 1$ was used to represent a risk neutral decision maker and $\pi = \infty$ a decision maker with extremely high risk aversion.

Our study built upon previous forest management research with multiple objectives, although our formulation, solution technique and underlying policy implications were significantly different from those of related studies. While Diaz-Balteiro and Romero (2003) incorporated objectives into a goal programming model, this required information about decision makers’ preferences in the form of weights and objective targets. Lacking this information, we used compromise programming, comparing the ‘ideal’ objective values to the results of the ‘best’ compromise solution. We did not need predetermined weights, although the method allows for this possibility. Rather, the decision maker’s risk attitude was taken into account through the choice of metric π.

Not surprisingly, previous studies indicate that increased carbon uptake can be attained only at a significant cost in terms of forgone timber harvest and financial returns, and that the cost of maintaining structural diversity of forest is high (Buongiorno et al., 1994; Hoen and Solberg, 1994; Onal, 1997; Boscolo and Buongiorno, 1997; Kant, 2002). Our results in this regard are similar: we find that both short- and long-term carbon uptake and maintenance of structural diversity are achievable only at a high financial cost. However, in contrast to Boscolo and Buongiorno (1997), who found that the same forest policy could be used to satisfy the carbon uptake and diversity objectives, we came to an opposite conclusion. Both short- and long-term carbon uptakes are in conflict with the maintenance of landscape structural diversity. Meeting the short-term carbon-uptake objective results in the greatest deviation from a desired forest and afforested land structure, while that deviation is somewhat smaller in the case of achieving long-term carbon uptake goal. This discrepancy may be explained by the fact that our management scenario included afforestation of marginal agricultural land and the possibility of plant fast-growing, hybrid species. Species selection in reforestation and afforestation may result in a tradeoff between fast carbon sequestration and subsequent release, and slower carbon sequestration with longer retention times. And choice of tree species affects structural diversity.

Compromise programming provides a useful tool for both multiobjective conflict analysis and management, and quantification of the tradeoffs between economic and ecological benefits. Since management strategies that *balance* competing objectives differ substantially in their economic and ecological implications from those that *average* the scores of all objectives, our methodology can only help identify what impacts decision-makers' risk attitudes have on the final decision, but it cannot unequivocally point to a 'best' strategy. The decision is ultimately a political one.

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 structural diversity 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. Nonetheless, the benefit of our approach is that it demonstrates very clearly that conflicts between diversity and other objectives are primarily caused by choice of target for structural diversity, namely, a forest structure that mimics a 'natural forest' 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.

Appendix A. The case study data

See Tables A.1–A.4.

Table A.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 A.2
Total volume per regeneration treatment, species, site class, and age (m^3/ha)

	Age							
	20	40	60	80	100	120	140	160
Natural reforestation								
Spruce.good	0	43	148	226	314	344	408	417
Spruce.med	0	0	70	124	211	265	317	339
Spruce.poor	0	0	18	45	85	94	129	210
Pine.good	0	46	161	217	279	321	370	376
Pine.med	0	42	96	148	197	245	305	309
Pine.poor	0	0	22	71	93	114	179	183
Popl.good	0	62	145	209	245	278	291	313
Popl.med	0	62	144	167	200	234	254	258
Popl.poor	0	0	62	94	134	167	201	209
Reforestation by planting								
Spruce.good	1	88	275	427	489	521	532	530
Spruce.med	0	18	119	245	349	427	463	483
Spruce.poor	0	1	5	26	72	130	191	244
Pine.good	10	146	281	368	417	447	467	475
Pine.med	3	60	150	216	279	317	345	364
Pine.poor	1	10	42	78	120	150	173	192
Popl.good	0	62	145	209	245	278	291	313
Popl.med	0	62	144	167	200	234	254	258
Popl.poor	0	0	62	94	134	167	201	209

Source: Yield data produced by TIPSY software (Mitchell and Grout, 1995).

Table A.3
Proportion of the original carbon remaining from forest products

Year	Lumber	Coniferous pulp	Deciduous pulp	OSB
0	0.98	0.48	0.38	0.78
20	0.92	0.41	0.33	0.74
40	0.84	0.33	0.26	0.67
60	0.74	0.24	0.19	0.59
80	0.61	0.15	0.12	0.48
100	0.47	0.11	0.09	0.38

Source: Based on Kurz et al. (1992).

Table A.4
Management targets for marginal agricultural land (hectares)

	Afforestation of marginal agricultural land	
	Period 2	Period 3
Spruce	7031	7031
Pine	7031	7031
Aspen	7031	7031
Hybrid poplar	7031	7031

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