Journal of Forest Products Business Research
Volume No. 5, Article No. 7

A Multi-Criteria Timber Allocation Model Integrating Sawmilling Decisions

Marian V. Marinescu and Thomas C. Maness

The authors are, respectively, Assistant Professor, Forest Utilization, School of Forest Resources and Conservation, University of Florida, Milton, FL, email: marinescu@ufl.edu and Professor, Faculty of Forestry, University of British Columbia, Vancouver, BC, email: thomas.maness@ubc.ca.

ABSTRACT

A multi-criteria timber allocation model was developed using a mixed integer goal programming methodology to analyze tradeoffs between sustainable forest management criteria. By integrating the sawmilling decisions into the model, the effects of sawmilling operations on sustainability criteria could be analyzed. The multi-criteria timber allocation model was demonstrated with five sustainable forest management criteria: profit, employment, wildlife, recreation, and visual quality. In a case analysis, timber in 463 forest stewardship units was optimally allocated to either of three forest products companies (sawmills) or to reserve. To model the sustainable forest management conditions (SFM Case), equal relative weights were assigned to the five criteria. The SFM Case provided optimal allocation results which, in contrast with the current, profit-based allocation policy (Base Case), considered both the efficiencies of the three sawmilling operations and the sustainability of the regional forest ecosystem. The study concluded with a summary of the findings and future research to overcome the model assumptions and limitations.

Keywords: timber allocation, multi-criteria optimization, sustainable forest management

Introduction

In the Province of British Columbia, Canada, the practice of forest management has changed dramatically with the adoption of sustainable forest management practices. Sustainable forest management (SFM) refers to the way a forest is managed to maintain and enhance the long-term health of forest ecosystems for current and future generations (Montreal Process 1995). Forestry researchers, managers, and analysts are dealing with increasingly complex forest management plans that must ensure a stable regional economy and a non-declining relationship between all of its ecological features. Although progress has been made, there is still debate about the definition of sustainability and its applicability (Floyd et al. 2001).

For many years, analysts have used timber allocation models to study the effects of management actions, both on the forest ecosystems and on the processing operations to which the timber was allocated. The capability of timber allocation models to integrate the decisions along forest to product value chains is well documented. The works of Mendoza (1980), Hay and Dahl (1984), Maness and Adams (1991), and Maness and Norton (2002) are examples of models that integrate timber allocation with processing activities, but each had just one goal of maximizing the profits generated by converting the allocated timber into lumber products.

To provide an adequate measure of sustainability, forest management plans need to include a wide range of forest management values that cover environmental, biological, and physical factors (Mendoza and Prabhu 2002). Consequently, the development and application of multi-criteria timber allocation models has become paramount. Of all the multi-criteria procedures, goal programming has been one of the most preferred methods in forestry (Tarp and Helles, 1995). Studies by Arp and Lavigne (1982), Ludwin and Chamberlain (1989), Van Kooten (1995), and Bertomeu and Romero (2001) demonstrate the applicability of multi-criteria allocation models in land-use planning and wildlife habitat selection. Lately, goal programming models are emerging that include SFM criteria directly as goals (Diaz-Balteiro and Romero 2004). None of these studies, however, integrated sawmilling decisions into their formulations.

This integration is important because the effects of SFM policies on downstream operations (harvesting, sawmilling, and value-added manufacturing) are not always obvious. For example, regional SFM policies could change the attributes of the allocated timber to the point where sawmills would have to significantly restructure or even discontinue their operations. Multi-criteria timber allocation models can reveal tradeoffs between social, ecological, and economic criteria that could point to solutions on how wood processing facilities may better adapt to SFM practices.

The research described in this study took place in the Kootenay-Columbia Region of British Columbia, Canada. There, the Provincial Government leased large areas of forest, called charts, to forest products companies. Each year, companies requested cutting permits to harvest timber in their own chart areas. The allocation of timber rights considered only the potential profit generated from the sales of lumber products. But, forest products companies have unique economic, ecological, and social footprints, defined by their specific products and markets, effects on the environment, and regional employment levels. In the context of SFM, the allocations of timber to these companies should optimally match these footprints, while reaching the highest possible levels of sustainability. Recent studies in this region were successful in identifying criteria and indicators for SFM (BC Journal of Ecosystem Management 2006) and evaluating their use in SFM land-use plans (Maness and Farrell 2004, Marinescu 2004, Marinescu et al. 2005).

A multi-criteria timber allocation model was developed using a mixed integer goal programming formulation that integrated sawmilling decisions. The model allocates forest tracts, called stewardship units, to either forest products companies (sawmills) or to reserve, over a medium-term planning horizon (5 years). To demonstrate the model, five SFM indicators were included as objectives: profit, employment, wildlife habitat, visual quality objective, and recreation. In the following sections, the formulation of the multi-criteria timber allocation model is presented, followed by a case analysis, a sensitivity analysis, and a summary of the findings. The paper concludes with proposed future research.

The Multi-Criteria Timber Allocation Model

The multi-criteria timber allocation model is a multi-period, tactical (5-year time horizon) model developed on a mixed integer goal programming formulation (Charnes and Cooper 1962, Williams 1991). The model generates optimal allocations of timber located in areas, hereafter called stewardship units (SUs), to either forest products companies (sawmills) or to reserve. The goal is to minimize the sum of weighted negative deviations of profit, employment, recreation, visual quality, and wildlife goals from their targets. The multi-criteria timber allocation model has the following formulation:

$$Min\ z = \frac{w_P^-}{G_P} P^- + \frac{w_E^-}{G_E} E^- + \frac{w_V^-}{G_V} V^- + \frac{w_R^-}{G_R} R^- + \frac{w_W^-}{G_W} W^- \quad [1]$$

Subject to:

$$\sum_{ijkt} (Vol_{ijkt}^{\%} \cdot P_{ijkt}) + P^- = G_P \quad [2]$$

$$\sum_{ijkt} (Vol_{ijkt}^{\%} \cdot E_{ijkt}) + E^- = G_E \quad [3]$$

$$\sum_{ijkt} (Vol_{ijkt}^{\%} \cdot V_{ijkt}) + \sum_{j} (Res_j\% \cdot V_j) + V^- = G_V \quad [4]$$

$$\sum_{ijkt} (Vol_{ijkt}^{\%} \cdot R_{ijkt}) + \sum_{j} (Res_j\% \cdot R_j) + R^- = G_R \quad [5]$$

$$\sum_{ijkt} (Vol_{ijkt}^{\%} \cdot W_{ijkt}) + \sum_{j} (Res_j\% \cdot W_j) + W^- = G_W \quad [6]$$

$$-TotVol_j^{\%} - M \cdot binS_{ij} + \sum_{kt} (Vol_{ijkt}^{\%}) \geq -M \text{ for each } i,j \quad [7]$$

$$-TotVol_j^{\%} - M \cdot binRes_j + Res_j\% \geq -M \text{ for each } j \quad [8]$$

$$\sum_{i} (binS_{ij}) + binRes_j = 1 \text{ for each } j \quad [9]$$

$$\sum_{ikt} (Vol_{ijkt}^{\%}) + Res_j\% = TotVol_j^{\%} \text{ for each } j \quad [10]$$

$$\sum_{jk} (Vol_{ijkt}^{\%} \cdot Vol_{ijkt}) \leq MaxV_{it} \text{ for each } i,t \quad [11]$$

$$TotVol_j^{\%} = 100\% \text{ for each } j \quad [12]$$

$$0 \leq binS_{ij}; binRes_j \leq 1 \text{ interger binary variables} \quad [13]$$

All variables are positive.

Variables:

P^-, E^-, V^-, R^-, W^-	Negative deviations of the profit, employment, visual, recreation, and wildlife goals from their targets.
$Vol_{ijkt}^{\%}$	Percent of volume of SU *j* allocated to company *i* and harvested with treatment *t* in period *k*.

$Res_j^{\%}$	Percent of volume of SU *j* allocated to reserve throughout the entire time horizon.
$binS_{ij}$	Binary variable indicating if SU *j* was allocated to company *i*.
$binRes_j$	Binary variable indicating if SU *j* was allocated to reserve.
$TotVol_j^{\%}$	Percentage of volume in SU *j* allocated.

Parameters:

G_P, G_E, G_V, G_R, G_W	Profit ($), employment (person years), visual, recreation, and wildlife (incommensurate) goal targets.
$\frac{w_P^-}{G_P}, \frac{w_E^-}{G_E}, \frac{w_V^-}{G_V}, \frac{w_R^-}{G_R}, \frac{w_W^-}{G_W}$	Relative weights associated with the profit, employment, visual, recreation, and wildlife goal targets. The weights indicate the relative importance of deviating by 1 percentage point from the respective goals. The weights could take values between 1 and 100.
P_{ijkt}	Profit ($) generated by allocating SU *j* to company *i* in period *k* and harvested with treatment *t*. Profit values are generated by a sawmilling sub-model (FTP Analyzer,®(1) described in the Data section of this paper) for each company and SU, in each period. For partial cut treatments, the profit values are reduced according to the volume intensity of the partial cut.
E_{ijkt}	Employment (person years) generated by allocating SU *j* to company *i* in period *k* and harvested with treatment *t*. For partial cut treatments, the employment values are reduced according to the volume intensity of the partial cut.
V_j, R_j, W_j	Visual, recreation, and wildlife indicator values (incommensurate) for SU *j* when allocated to reserve. These indicators have values between 0 and 1.
$V_{ijkt}, R_{ijkt}, W_{ijkt}$	Visual, recreation, and wildlife indicator values for SU *j* when allocated to company *i* in period *k* and harvested with treatment *t*. These indicators have values between 0 and 1 and depend on the treatment intensity used by each company in each SU and period.
Vol_{ijkt}	Volume (m^3) of timber in SU *j* available to company *i* in period *k* and harvested with treatment *t*. For partial cut treatments, the volumes are reduced according to the volume intensity of the partial cut.
$MaxV_{jt}$	Maximum volume capacity (m^3) of company *j* in period *t*.
M	Large number. This number should be greater than $TotVol^{\%}_j$ (i.e., greater than 1, or 100%).

(1) The Forest to Product (FTP) Analyzer model was developed by WoodFlow Systems Corp., Vancouver, BC, Canada. The mathematical formulation can be found in Maness and Adams (1991) and Maness and Norton (2002).

The objective [1] of this model is to find an optimal allocation of SUs to companies and reserve that will minimize the sum of weighted negative deviations of profit, employment, recreation, visual, and wildlife goals from their targets. No positive deviation variables were included because positive deviations from targets (i.e., exceeding target levels) are desirable.

Constraints [2] to [6] set the targets for each of the goals and connect the allocation variables $Vol\%_{ijkt}$ to the deviational variables in the objective function.

Constraints [7] and [8], in combination with constraint [9], connect the binary variables to the SUs to which they refer. According to Williams (1991), their formulation includes the big number *M*, which forces the model to allocate each SU to either one company or to reserve.

Constraint [10] requires that the sum of volumes allocated to either sawmilling or to reserve does not exceed the maximum volume available in SU *j*.

Constraint [11] sets the timber volume capacity (m^3) of company *i* in period *t*.

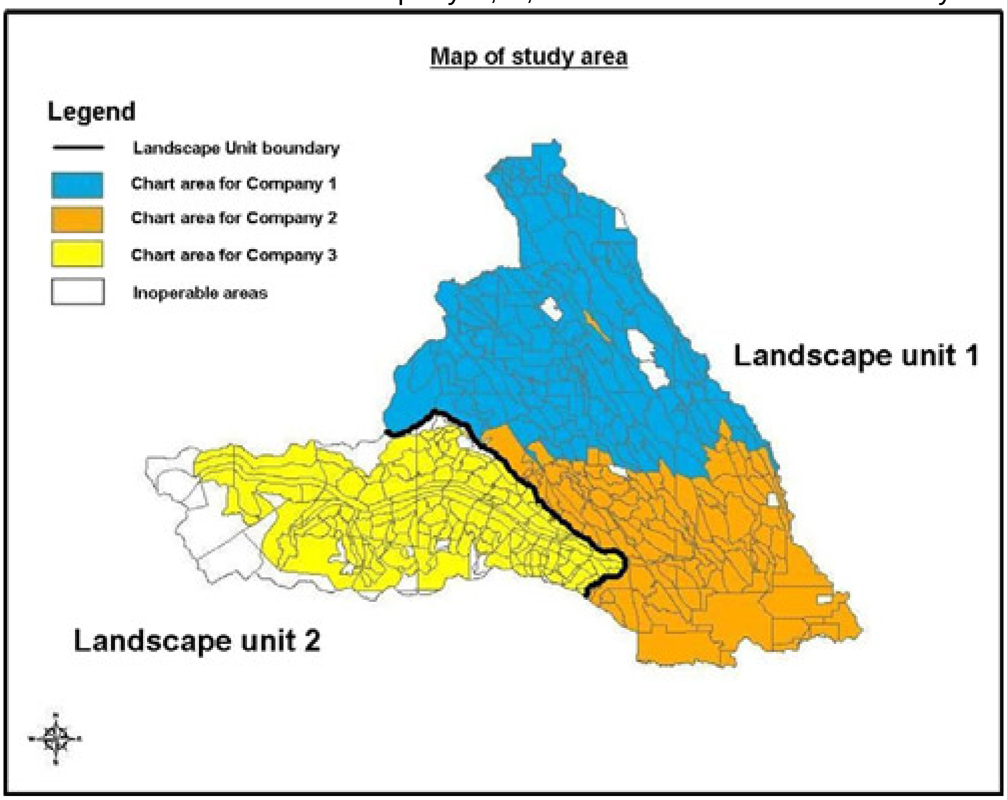
Constraint [12] is an upper bound on the timber volume (m^3) available for allocation in each SU. It forces the entire timber volume in the SU to be allocated to either a company or to reserve.

Constraint [13] sets the values of integer variables to 0 or 1 (i.e., binary).

Data

The study area presented in **Figure 1** consists of two landscape units with a total area of 45.8 thousand hectares and a total volume of spruce, pine, and fir (SPF) timber of 7.75 million m^3, divided into 463 SUs.

Figure 1. The map of the two landscape units considered in the study, indicating the chart areas for Company 1, 2, and 3. SUs are demarcated by thin lines.



Three forest products companies(2) rely on timber harvested in this area. **Table 1** shows their differences in products, markets, and employment levels. Company 2 manages a high-speed, low-cost stud mill, and it employs the least number of people. The other two companies manage sawmills with similar production parameters. But, there are some differences between these two companies regarding their machine centers, product structures, and ages. Company 1 has an older, less diverse, and less automated operation than the other companies. By contrast, Company 3 produces a large number of many types of products targeting a variety of markets (domestic, U.S., Japanese).

(2) In this study, companies were named Company 1, 2, and 3 to protect their identities.

Table 1. Production and market parameters for Companies 1, 2, and 3.

	Company 1	Company 2	Company3
Product type	SPF boards and dimension lumber	SPF studs	SPF dimension lumber (Japanese grades)
Markets	Canada and the United States	Canada and the United States	Canada, the United States, and Japan
Employment (avg. persons/yr.)	70	23	46

SFM criteria values for each SU were taken from the Geographic Information System (GIS) database developed by Maness and Farrell (2004). The GIS data was imported into an MS Access database, where a series of queries were performed to determine the criteria and indicator attributes for each SU. The values for recreation (hiking), visual quality (VQO(3)), and wildlife (ungulate winter range) indicators (R_j, V_j, W_j) were taken from the GIS Access database and reflect the current, unaltered condition of each SU. **Table 2** shows an example of the data for these indicators.

(3) Visual quality objective (VQO) or is a resource management objective that reflects the desired level of visual quality based on the physical characteristics and social concerns for an area. They are the results of visual quality assessments.

Table 2. An example of the recreation, visual, and wildlife indicator values in the GIS database. Note: These values are incommensurable.

SU no.	Recreation coefficient	Visual coefficient	Wildlife coefficient
1	0	0.6	0
2	0	0.8	1
3	0	0.8	1
4	0	0.6	0
5	0	0.6	0
6	0	0.8	0
7	1	0	1
8	0	0.6	1

9	1	0.6	0
10	0	0.6	0
11	0	0	1
12	1	1	1
13	0	0.8	1
14	1	0.6	0
15	0	0.8	1
16	1	0.8	0
17	1	0.8	1
18	0	0.8	1
19	0	0.6	0

Both recreation and wildlife criteria have values of 1 when the SU contained hiking trails, or winter ungulate winter range, respectively, and 0 otherwise. The visual quality criterion has values of: 1 for preservation, 0.8 for retention, 0.6 for partial retention, 0.4 for modification, 0.2 for maximum modification, and 0 for no VQO objectives. If allocated to reserve, the SUs preserved their criteria values. If allocated to companies, the SUs were assigned residual criteria values, V_{ijkt}, R_{ijkt}, W_{ijkt}, that depended on the intensity of the harvesting treatment (**Table 3**) set by each company, in each period.

Table 3. Treatment intensities for the three companies in each period.

Company	Period	Treatment	Intensity
1	1	Clearcut	100%
	2	Clearcut	100%
	1	Partial cut	40%
	2	Partialcut	40%
2	1	Clear cut	100%
	2	Clear cut	100%
	1	Partial cut	47%
	2	Partial cut	47%
3	1	Clear cut	100%
	2	Clear cut	100%
	1	Partial cut	37%
	2	Partial cut	37%

In this study, these residual indicator values were assumed to have an indirect linear relationship to the treatment intensities: the larger the harvesting intensities, the smaller the residual indicator values. The model, however, allows the inclusion of different relationships between these values and treatment intensities, if known. For example, users could assign a certain indicator value when the treatment intensity is within a certain interval, or could set it to zero if the intensity is above a threshold.

Table 4. Employment levels of the three forest products companies considered in the study (from *Timber Supply Review*).

Employment sources	Employment								
	Company 1			Company 2			Company 3		
	High	Medium	Low	High	Medium	Low	High	Medium	Low
	(persons per yr./1,000 m^3)								
Harvesting/administration	0.71	0.59	0.47	0.15	0.12	0.09	0.50	0.46	0.41
Transportation	0.11	0.08	0.06	0.07	0.07	0.06	0.17	0.15	0.14
Road	0.33	0.28	0.23	0.02	0.02	0.02	0.08	0.07	0.06
Silviculture	0.03	0.03	0.03	0.06	0.05	0.04	0.03	0.03	0.03
Processing	0.69	0.64	0.59	0.46	0.43	0.39	1.49	1.26	1.02

Employment values (E_{ijkt}) were calculated from the socio-economic analysis of *Timber Supply Review* (BC Ministry of Forests 2002). Employment values in **Table 4** indicate the average employment per thousand m^3 of harvested timber for each company. In order to differentiate the employment generated by each SU, three classes (high, medium, low) were developed specific to average slope (<10%, 10% to 30%, >30%), distance to sawmill (<10 km, 10 to 30 km, >30 km), volume (<10,000 m^3, 10,000 to 20,000 m^3, >20,000 m^3), and area (<50 ha, 50 to 100 ha, >100 ha) of the SUs considered in the analysis. By matching these classes with the appropriate employment levels for each activity, the total employment values were calculated for each SU and each company.

Profit values (P_{ijkt}) were calculated with a sawmilling sub-model (FTP Analyzer) for each SU and company according to its production settings, product mixes, and markets. The timber data was taken from the stand and stock tables contained in the GIS database for each SU. **Table 5** shows an example of the stand and stock table indicating the values for species, height, diameter at breast height (DBH), and number of trees per hectare in SU #1. The stand and stock data was then input as raw material data in the FTP Analyzer model.

Table 5. An example of the stand and stock data in the GIS database for SU #1.

Height (m)	Species	DBH (cm)	Number of trees
26.1	Pine	20	475.34
25.0	Fir	45	97.05
25.1	Pine	15	180.65
25.5	Pine	40	42.33
25.1	Pine	35	80.56
27.4	Pine	30	131.38
15.5	Pine	30	22.22
25.1	Spruce	30	182.77
15.5	Pine	25	27.58
25.1	Pine	35	45.44

15.5	Pine	20	143.39
25.1	Pine	15	706.61
15.5	Pine	15	154.88
25.1	Fir	60	36.11
25.1	Fir	55	36.14

The FTP Analyzer is a combined linear and dynamic programming optimization model. The model detemines the optimum set of bucking policies, cutting patterns, and production parameters that maximizes the profit generated from manufacturing lumber products for each company. The inputs into the model are raw materials (timber classes), cut programs, lumber products, markets, lumber prices, and plant configuration specific to each company. One thousand three hundred and eighty nine runs were performed (i.e., 463 SUs × 3 companies).

Table 6. The target values for the profit, employment, wildlife, visual, and recreation goals. Note: The values for the wildlife, visual, and recreation targets are incommensurable.

Objectives	Targets
Profit (million $)	266
Employment (persons-yr)	6,573
Wildlife	140
Visual	145
Recreation	133

The goal targets (G_P, G_E, G_V, G_R, G_W) were calculated, as suggested in Mendoza (1985), by running the multi-criteria timber allocation model for each goal, separately (**Table 6**). Consequently, this procedure guaranteed feasible (attainable) goal targets. This procedure was employed before the actual run of the model and set the appropriate goal targets.

The model considered two periods, 1 year and 4 years, respectively. To adjust for the time preference of money, the profit values were increased by 5 percent in the first period.

Data Handling

The multi-criteria timber allocation model was developed on an MS Access platform. The connection of the model with the GIS database allowed automatic data input/output and generation of allocation maps. XA® software by Sunset Technologies was utilized to solve the multi-criteria integer problem. The model was run on an Intel® Pentium 2.2 GHz, 1.99 GB RAM, dual processor PC. Processing time was approximately 60 seconds.

Model Assumptions and Limitations

Due to the use of linear goal programming, the relationships among all variables were assumed to be linear. Some operational costs, such as costs of dispersed operations and stand tending costs, were not considered. The relationships between the wildlife, recreation, and visual indicators values and the volume intensities of different treatments were assumed to be linear. A non-linear relationship would have a direct effect on the timber volumes allocated to clear-cut and partial-cut treatments. The volume of timber was assumed uniformly distributed across the SUs. When parts of the SUs were allocated, the resulting timber volume was assumed to be equally divided among all log classes. Data taken from the GIS database was assumed to reflect the real forest characteristics of each SU. In this model, only SPF were considered.

The multi-criteria timber allocation model has some limitations. First, due to the time horizon (medium-term planning) and the scope (timber allocation to different companies) of the model, the spatial layout of different treatment activities was not considered. Implementation of spatial constraints would likely result in increased computational time. Second, the model dealt concomitantly with forest management (medium-term planning) and wood processing (operational) issues, which could result in implementation problems. Finally, the goal programming procedure requires users to generate a series of allocation scenarios, using different weights, until a practical solution is reached (i.e., acceptable trade-offs between the allocation criteria). This, as with all multi-criteria methods, could likely increase decision-making time.

Case Study

Currently, the three forest products companies in this study operate in their own timber supply areas, called charts. To harvest timber, each company must apply for a permit in its own chart. The potential profit generated from lumber sales, specific to each company, is the only criterion considered in the allocation of SUs. To model this allocation policy, herein referred to as the Base Case, the multi-criteria timber allocation model was run with the sole objective of maximizing the profit criterion. By comparison, an SFM Case modelled a SFM policy in which the preference relative weights of the five allocation criteria (profit, employment, wildlife, recreation, and visual quality) were all set to 1. Also, to take full advantage of the resources in the two landscape units, companies were allowed to harvest timber located outside their own charts.

Results

Figure 2 presents a comparison between the profit values obtained in the SFM and Base Cases. The graph indicates that the total profit value in the Base Case was $235 million (7% higher than that of the SFM Case). In the Base Case, Company 1 contributed the most profit to the total profit value (41%), followed by Company 3 (39%) and Company 2 (20%). In the SFM Case, however, Company 3 generated the most profit (42%), followed by Company 1 (39%) and Company 2 (19%).

Figure 2. Comparison between the profit values (million $) generated in the Base Case and the SFM Case for each company and in total.

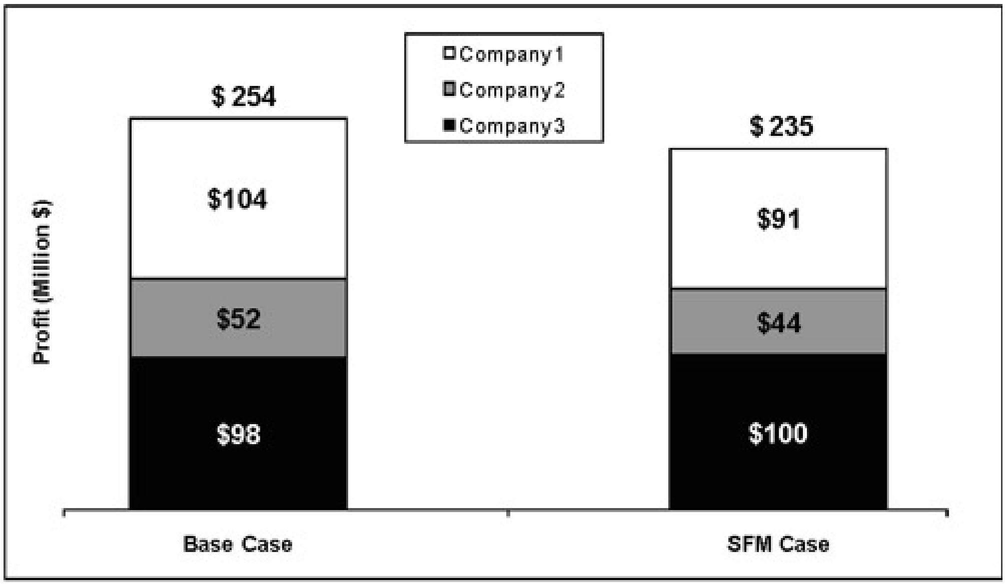


Figure 3 shows that in the SFM Case total employment reached 6,409 person years (3% larger than the values obtained in the Base Case). Company 1 generated the highest employment values (47% of the total employment in the Base Case and 46% in the SFM Case), followed by Company 3 (42% of the total employment in the Base Case and 43% in the SFM Case), and lastly Company 2 (11% of total employment in the Base Case and the SFM Case).

Figure 3. Comparison between the employment values (person years) generated in the Base Case and the SFM Case for each company and in total.

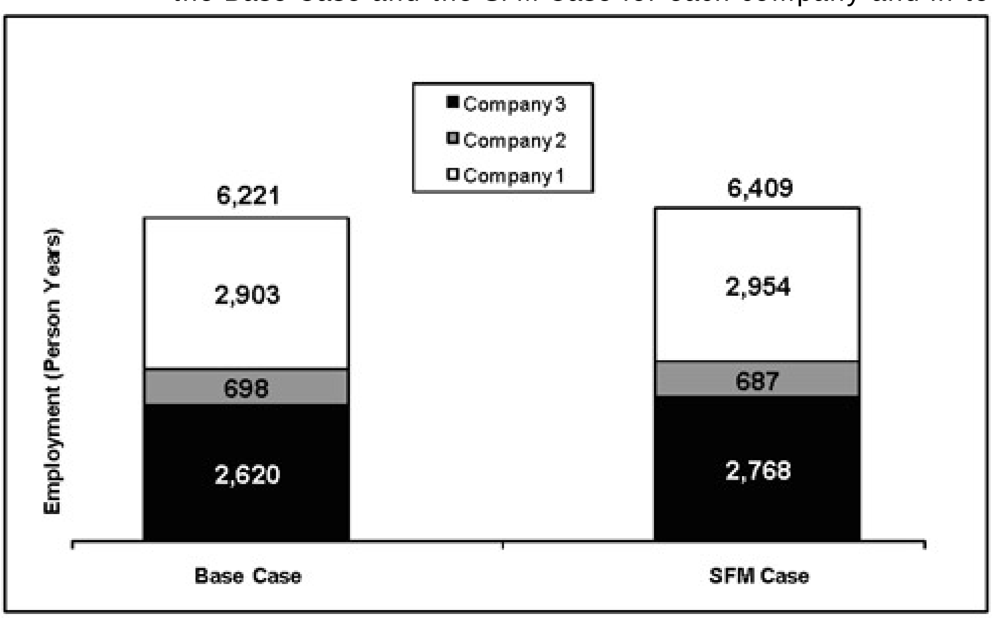
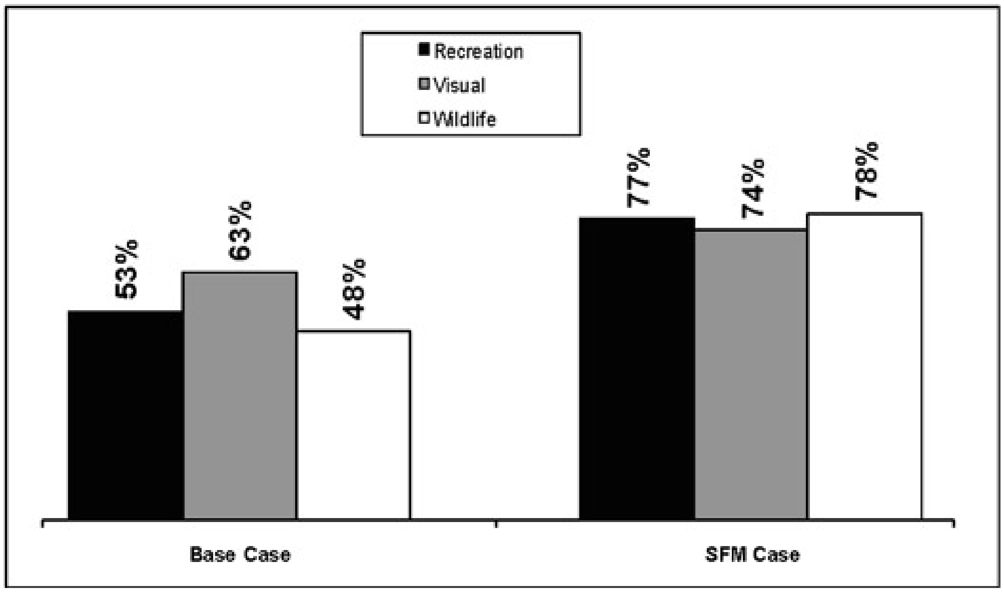


Figure 4 emphasizes that the values of recreation, wildlife, and visual criteria were considerably closer to their targets in the SFM Case than in the Base Case. In the SFM Case, all three criteria achieved values around 75 percent of their targets (30% wildlife, 11% visual, and 24% recreation levels larger than those obtained in the Base Case).

Figure 4. Comparison between achievement levels (% of target) for the recreation, visual, and wildlife criteria in the Base Case and the SFM Case.



The map in **Figure 5** shows the SUs allocated in the Base Case to companies from their own chart areas. By contrast, the map in **Figure 6** shows that, in the SFM Case, in addition to modelling the SFM conditions, the allocation was unconstrained by chart areas.

Figure 5. Map of the allocated SUs in the Base Case.

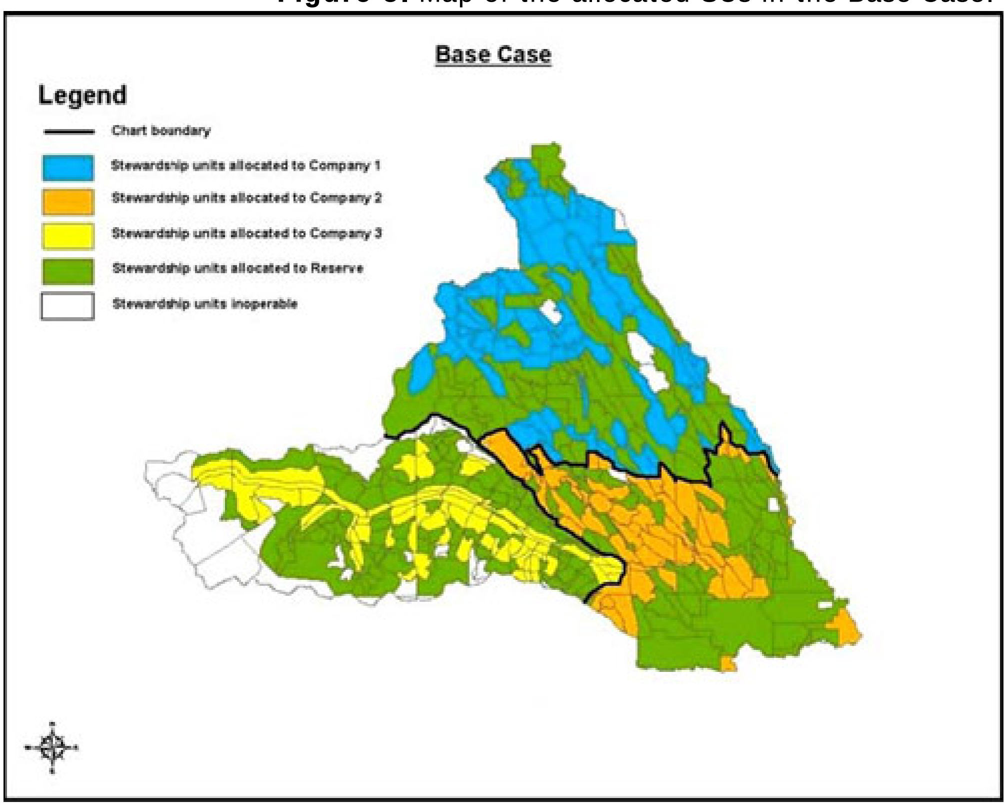
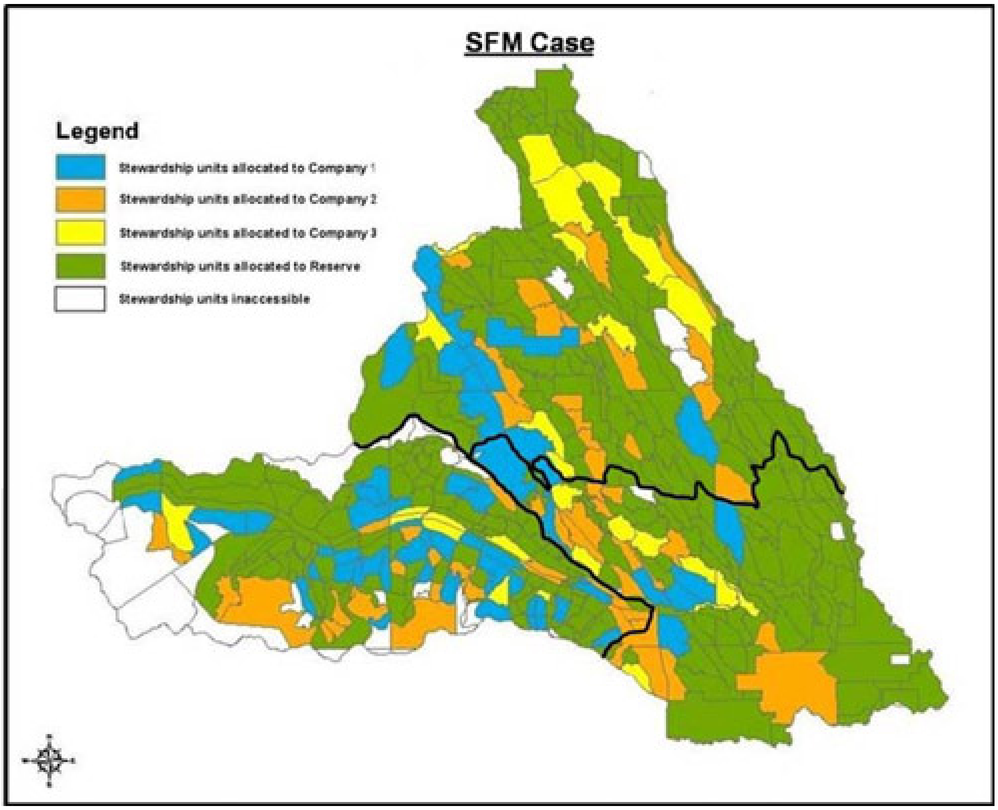


Figure 6. Map of the allocated SUs in the SFM Case.



Sensitivity Analysis

Because goal programming models do not generate unique solutions, rather non-dominated solutions(4), the user must evaluate a number of scenarios before finding a suitable solution for the multi-criteria decision problem. These scenarios depend on the relative weights that the user assigns to the goals. To overcome this limitation, the computer model was designed to construct graphical non-dominated solution sets between pairs of criteria (i.e., pair-wise comparisons). In these graphs, achievement levels for each preference level can be visualized and a decision can be rendered to select the most desirable timber allocation solution. In this study, profit(5) was chosen as the criterion against which all of the other criteria values were plotted.

(4) A non-dominated or non-inferior solution to a multi-objective problem is that solution in which none of the objectives can be improved without adversely affecting at least one of the other objectives.

(5) Profit was chosen because it is well understood by analysts and commonly used in trade-off analyses.

To construct the non-dominated solution set, the results of 29 scenarios presented in **Table 7** were generated with the multi-criteria timber allocation model. Each goal was first allowed to reach its target (maximum achievement). The weight of the profit goal was then kept at 100, while each of the other goals was given an incrementally higher value. Scenario number 7 (shaded row of data in **Table 7**) is the SFM Case.

Table 7. Scenarios used in the estimation of the non-dominated solution set. Shaded area indicates the values generated in the SFM Case.

Scenario	Weights					Achievement Values				
	Profit	Employment	Recreation	Visual	Wildlife	Visual	Wildfire	Recreation	Employment (persons-yr)	Profit (million $)
1	1	1	100	100	100	145	140	133	2,126	74
2	1	1	1	100	1	145	113	105	5,231	171
3	1	1	1	1	100	118	140	120	5,901	202
4	1	1	100	1	1	117	122	133	6,144	213
5	100	1	1	500	1	144	77	63	6,045	226
6	1	100	1	1	1	111	118	109	6,566	227
7	**1**	**1**	**1**	**1**	**1**	**119**	**126**	**123**	**6,409**	**235**
8	100	1	100	1	1	96	85	132	6,255	246
9	100	1	1	100	1	139	86	73	6,214	250
10	100	1	1	1	100	101	138	72	6,244	252
11	100	1	50	1	1	97	88	127	6,267	255
12	100	1	1	1	50	103	134	75	6,282	256
13	100	1	1	50	1	134	92	76	6,234	257
14	100	50	1	1	1	108	104	87	6,484	258
15	100	1	20	1	1	100	89	118	6,272	260
16	100	1	1	1	20	106	127	79	6,266	262
17	100	100	1	1	1	103	93	83	6,438	262
18	100	1	1	20	1	126	94	79	6,276	262
19	100	1	10	1	1	104	93	109	6,265	263
20	100	1	1	1	10	106	120	80	6,260	264
21	100	1	1	10	1	119	96	81	6,247	264
22	100	50	1	1	1	105	96	86	6,347	265
23	100	1	1	2	1	108	96	83	6,237	266
24	100	1	2	1	1	106	94	88	6,244	266
25	100	1	1	1	2	106	99	82	6,243	266
26	100	20	1	1	1	105	94	85	6,294	266
27	100	1	1	1	1	104	94	84	6,243	266
28	100	10	1	1	1	105	95	84	6,269	266
29	100	2	1	1	1	106	97	86	6,241	266

Figure 7 presents the values of the visual criterion achieved by the timber allocation model when the weights in **Table 7** were applied. The shaded area in the graph represents the estimated set of non-dominated solutions. This is the area in which all of the solutions generated by the multi-criteria timber allocation model are expected to lie. The dotted area is the trade-off area, in which the visual criterion values decrease with every increase in profit values. The results of the scenarios plotted in the trade-off area indicate that the visual indicator achieved maximum values and remained constant when low

profit values were achieved and decreased slowly between a profit value of $171 million and $226 million and more abruptly after that.

Figure 7. The area of non-dominated solutions and the trade-off area for the visual-profit criteria pair. The large dot indicates the SFM Case. The numbers indicate scenarios that delimit the area of non-dominated solutions (**Table 7**).

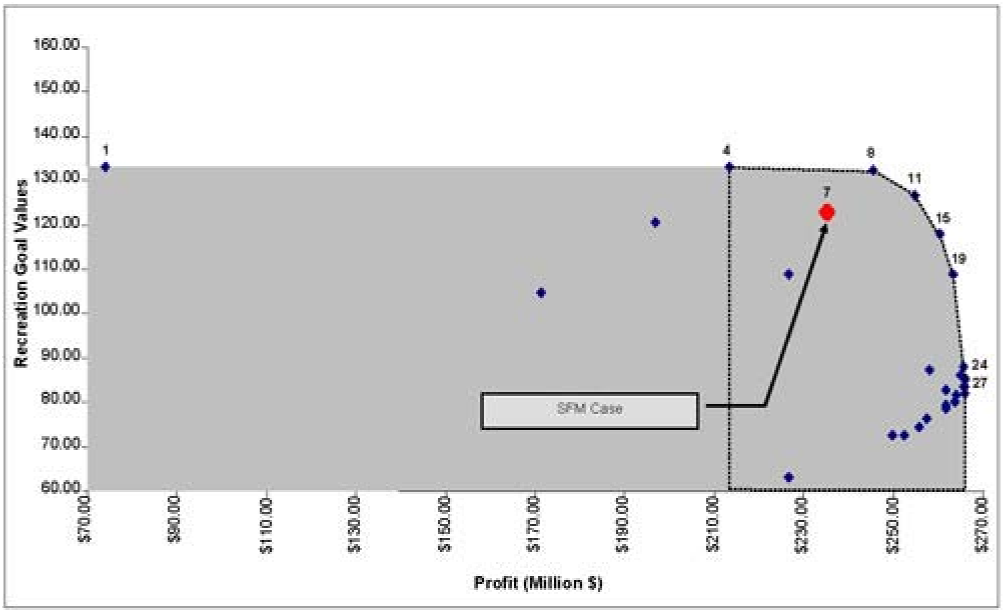


Figure 8. The area of non-dominated solutions and the trade-off area for the wildlife-profit criteria pair. The large dot indicates the SFM Case. The numbers indicate scenarios that delimit the area of non-dominated solutions (**Table 7**).

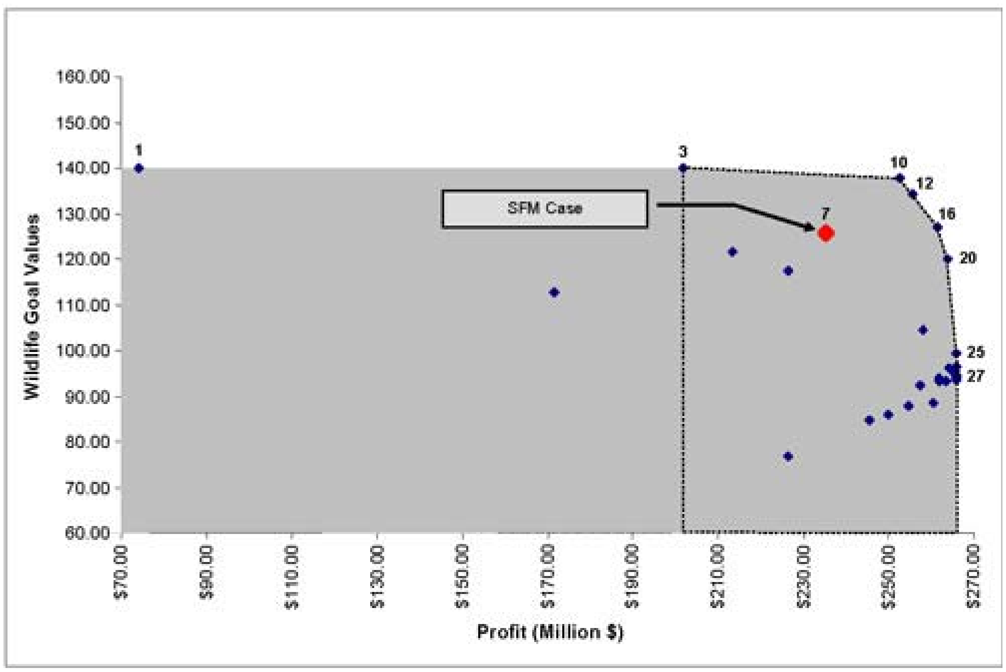


Figure 8 presents the area of non-dominated solutions and the trade-off area for the wildlife criterion. For this criterion, the results generated a narrower trade-off area than that of the visual criterion. This implied that a larger emphasis on profit could have a stronger influence on the wildlife

than on the visual criterion. The graph shows that the wildlife criterion values achieved the maximum wildlife goal of 140 until the profit equalled $202 million, after which they started decreasing slowly between a profit value of $202 million and $262 million and more abruptly thereafter.

Figure 8. The area of non-dominated solutions and the trade-off area for the wildlife-profit criteria pair. The large dot indicates the SFM Case. The numbers indicate scenarios that delimit the area of non-dominated solutions (**Table 7**).

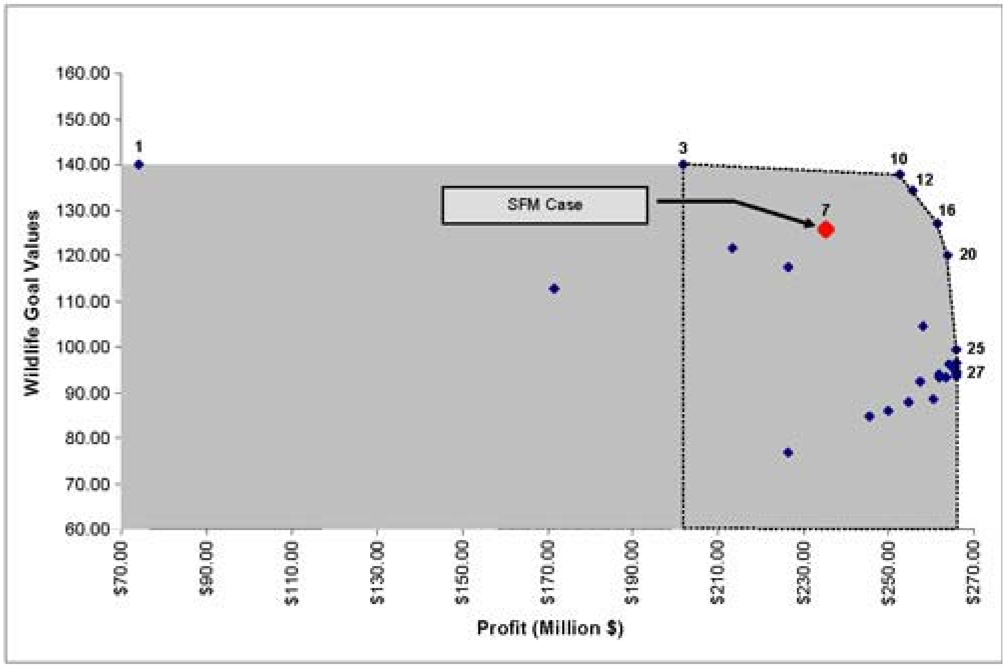


Figure 9 presents the estimated set of non-dominated solutions and the trade-off area for the recreation criterion. It is notable that the trade-off area for this criterion is narrower than those of visual and wildlife criteria which suggests that an increasing emphasis on profit triggers a stronger effect on this criterion than the other two. The recreation criterion values, however, did not drop as steeply as those of the previous two criteria. A very slow decrease in the recreation criterion values was registered between a profit of $213 million and $246 million and the decline became steeper after that (as opposed to $262 million in the wildlife criterion case).

Figure 9. The area of non-dominated solutions and the trade-off area for the recreation-profit criteria pair. The large dot indicates the SFM Case. The numbers indicate scenarios that delimit the area of non-dominated solutions (**Table 7**).

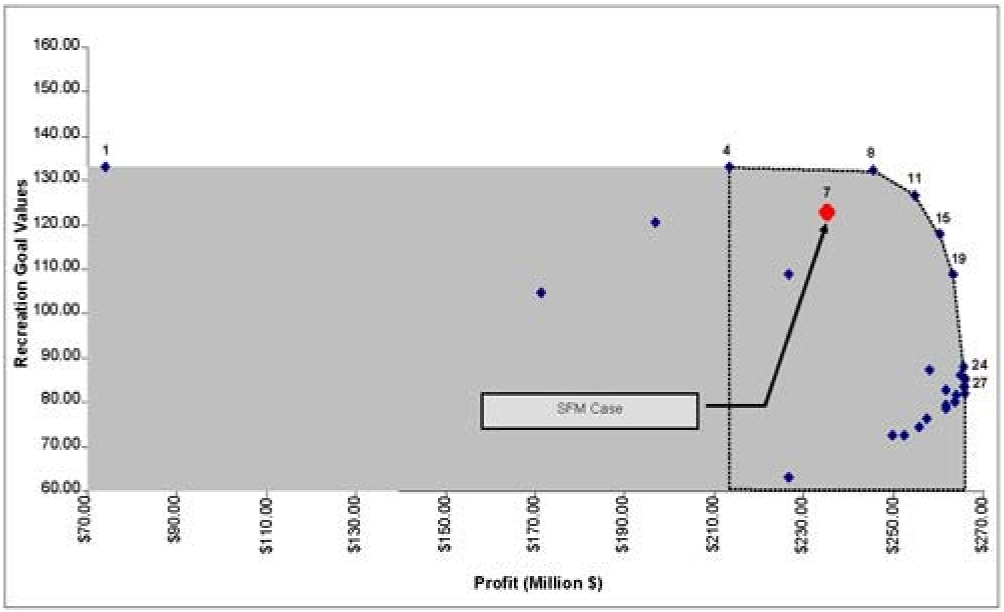


Figure 10 represents the non-dominated set and the trade-off area for employment criterion. The shape of this set was different than those of wildlife, recreation, and visual criteria, which suggests a different type of relationship between the employment and profit criteria. The employment criterion values presented a steady increase with increases in profit and a very slow decrease after the profit reached $227 million. The employment criterion values tended to decrease much faster when the profit reached its