DEFINING AND QUANTIFYING GOALS FOR MEASURING THE STATE OF AN ECOSYSTEM

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1. Background

The report which follows describes an attempt to determine and quantify preferences for a forest region in New Brunswick, Canada. The forest is subject to outbreaks of a pest called the Spruce Budworm which does great damage to the trees and thus to the logging industry, a major industry of the area. DDT has been sprayed extensively for the last twenty years so that now if the spraying were to stop an extensive outbreak would occur. The Ecology Project at IIASA spent some months studying possible strategies for handling the pest, the Methodology Project contributing to the study by creating a Dynamic Programming Optimization Algorithm [7]; and the study outlined here started when I attended a meeting of the Ecology and Methodology Projects together with some experts from the Canadian Forestry Commission. They were trying to establish an objective function for the optimization model by fitting values c_i to the linear formula

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*I would like to thank William C. Clark and George B. Dantzig for their helpful comments on this paper.

$$c_1(\text{Egg Density}) + c_2(\text{Stress})^1 + c_3(\text{Proportion of Old Trees}) + c_4(\text{Proportion of New Trees}) \quad . \qquad (1.1)$$

I was disturbed by this process for two reasons. Firstly, they did not appear to have a very accurate way of arriving at the parameters, and secondly the only concern of the experts seemed to be the monetary gains and losses to the logging industry whereas I had always supposed that our Ecology and Environment Project should be concerned with the protection of wildlife and scenery and so on. So I began this study with these two aims:

i) to derive the parameters c_i for the optimization model by different means as a comparison,

ii) to discover the true preferences of the members of the Ecology Project regarding trade-offs between profits, wildlife and the environment.

That was the motivation for the study. The motivation for this report is slightly different. It goes through the stages of analysis actually carried out. Nothing has been changed to make the analysts look less incompetent. There is a growing literature on techniques of decision analysis and reference to selected works which are appropriate to the study will be included even if few of the concepts in them were actually used here.

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[1] Stress is a measure of the health of the trees measured by the amount of defoliation in current and previous years caused by the budworm.

So why then with all these disclaimers was this lengthy piece written?

1) It was an important learning process for all those involved, including me as an analyst finding the stumbling blocks and learning some of the methodological problems involved. The Ecologists were forced to think about trade-offs (seemingly for the first time) between totally different quantities (how much logging profit is worth another 100 square miles of good recreational area) and to evaluate what they really want out of the forest. While these ideas are not new to people in the field of operations research, the Ecology group had not been exposed to them and perhaps some of the those who read this report will not have been either.

2) Potential analysts who may feel daunted by the imposing literature on decision analysis will possibly feel more inclined to try their own ideas after seeing this off-the-cuff approach.

2. The Analysis

I began by asking five of the participants to rank a list of states of the forest, exhibited in Figure 1, by preference and when they had done this, asked them to give a value 0-100 to each state indicating its "worth." They were to rank the list by taking any pair of forest states (summarized by the five data points) and deciding which state they would prefer the forest to be in,

	Prop. of Young Trees	Medium Age Trees	Old Trees	Stress	Egg Density
1	.10	.3	.6	0	0.3
2	.15	.35	.5	0	0.6
3	.10	.4	.5	0	0.5
4	.20	.5	.3	20	1.0
5	.10	.3	.6	10	0.1
6	.10	.3	.6	40	0.1
7	.10	.4	.5	0	0.5
8	.15	.35	.5	0	0.6
9	.5	.1	.4	0	2.0
10	.2	.5	.3	20	1.0
11	.2	.2	.6	20	10
12	.1	.3	.6	50	10
13	.2	.3	.5	20	10
14	.2	.3	.5	50	10
15	.2	.4	.4	20	10
16	.2	.4	.4	50	10
17	.3	.4	.3	20	10
18	.2	.5	.3	50	10
19	.3	.4	.3	30	80
20	.3	.3	.4	0	50
21	.2	.2	.6	0	150
22	.1	.6	.3	10	200
23	.2	.2	.6	0	500
24	.1	.3	.6	40	500
25	.3	.3	.4	40	500
26	.3	.4	.3	0	500
27	.3	.4	.3	40	500

Figure 1. Forest States.

assuming that from then on nature and man would be required to deal normally with it. The value they gave to each state could be derived by any reasoning they wished save that the ordering of preferences and of values should be the same.

I then used a statistical software package to obtain egression coefficients [e.g. 2] for the linear formula (1.1) by using Egg Density, Stress, Proportion of Old and Young Trees as independent variables and the value as the dependent variable, deriving one formula for each of the five participants.

The formulas I devised from the rankings of the two Forestry Commission members were very close to the parameters c_i actually obtained at the meeting (despite my misgivings) but those of the three Ecology Project members were quite different from the other two and from each other.

I discussed with them the reasons for their differences. The feeling emerged that the states in Figure 1 were meaningless because the whole forest could not be composed uniformally.[2] Indeed, if it were, all the twenty-seven states would be equally terrible. So I asked them whether they could describe a new state vector which would be meaningful.

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[2]The forest covers about 15,000 square miles.

2.1 Defining a Meaningful State Description

Professor Holling then devised a list of seven typical endemic conditions of a sub-forest (Figure 2) together with their appropriate vector state classification as in Figure 1. Then a new list was drawn up (Figure 3) where the states of the forest were described by seven parameters (summing to 1) giving the proportion or mix of the total forest in each condition category.

All four members of the Ecology group were then asked for their rankings of these twenty states. In addition I calculated the ranking implied by the objective function from the stand model used in the Dynamic Programming formulation which used the maximization of forest products as the objective. This is labeled "Forest Industry" in Figure 4 which gives the correlation between the five rankings. The marked difference between the ecologists and the "Forest Industry" partly reflects the fact that the experts were asked to think only in terms of the immediate future whereas the members of the Ecology group were thinking of the long term implications of the various states.

However, there were still differences in preferences within the group. Those of Holling and Clark were essentially the same, though they arrived at their orderings in completely different ways. Holling first created seven functions $v_1(p_1), v_2(p_2), \ldots, v_7(p_7)$ which gave his subjective "value" to having a proportion p_i of the forest in condition i.[3] Hence he gave a value of

$$v_1(.0023) + v_2(.0061) + \cdots + v_7(0)$$

to forest state 2 in Figure 4, and then used these values to obtain his ranking. Clark fixed his sights on having about 5-10% of forest in condition 4 (outbreak) and on keeping the predictability of the forest high (by having the proportions in conditions 3 and 7 low). He was aiming for a manageable forest.

This led to a general discussion of what was desirable. Predictability seemed to be one preference. Another was a desire to take the observed historical budworm outbreaks over time (a cycle of the forest moving through conditions 1-6 sequentially) into the same pattern over space that is, have the same proportion of the forest in each condition at any given time: "Controlled Outbreaks."[4]

It was decided that the seven statistics used were not sufficient to describe the state of the forest and Holling set to work to come up with a more comprehensive list of indicators. The aim was to devise a system whereby we could

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[3]Note that he has thus made some assumption of independence between the parameters. For a discussion on this topic see [5].

[4]I received a new perspective to the problem when I asked Holling why he ranked Forest Mix Number 20 in Figure 4 last. "Worst thing that could possibly happen," he said.

Condition of Sub Region	State No.	Proportion 0-9 Yrs.	10-30 Yrs.	30-70+ Yrs.	Stress	Eggs
Post Outbreak Endemic	1	.5	.3	.2	40	.03
Mid-Endemic	2	.4	.4	.2	0	.03
Potential Outbreak	3	.15	.35	.5	0	.03
Triggered Outbreak	4	.15	.35	.5	0	2
Mid-Outbreak	5	.2	.4	.4	40	500
Disaster	6	.3	.4	.3	.6	100
Budworm Extinct	7	.15	.35	.5	0	0

Figure 2. Classification of Possible Stand Conditions.

Forest Mix No.	Proportion of Land In Condition Category 1	2	3	4	5	6	7
1	0	0	1.0	0	0	0	0
2	.0023	.0061	.975	.0016	.0083	.0017	0
3	.0047	.0122	.96	.0033	.0165	.0033	0
4	.0122	.0122	.95	.0033	.0165	.0033	.0025
5	.04	.04	.85	.01	.05	.01	0
6	.045	.05	.80	.02	.06	.02	.005
7	.08	.08	.70	.02	.10	.02	0
8	.026	.226	.70	.007	.033	.007	.001
9	.06	.04	.66	.08	.10	.02	.02
10	.08	.04	.66	.08	.10	.02	0
11	.03	.27	.53	.06	.15	.03	0
12	.12	.10	.53	.06	.15	.03	0
13	.0244	.48	.48	.0033	.0165	.0033	.0025
14	.04	.44	.45	.01	.05	.01	0
15	.045	.42	.43	.02	.06	.02	.005
16	.052	.41	.41	.041	.058	.012	.001
17	.16	.16	.4	.04	.2	.04	0
18	.35	.08	.35	.08	.10	.02	0
19	.08	.35	.35	.08	.10	.02	0
20	0	0	0	0	0	0	1

Figure 3. Types Of Forest Mixes .

	Rashid	Clark	Holling	Jones	Forest Industry
Rashid	1.00	.69	.40	.21	-0.52
Clark		1.00	.80	.39	-0.80
Holling			1.00	.63	-0.46
Jones				1.00	-0.34
Forest Industry					1.00

Figure 4. Correlation Matrix.

place a decision maker in a chair where he could wave a magic wand and place the forest in condition A or condition B, where A and B were described by a set of summary statistics. Which statistics would he like to see to enable him to make a decision?

If he were a logger he would want to know the amount of wood in good condition for logging and the forest's potential for the next few years indicated by the level of budworm and so on.

For a given decision maker we would like to build up a set of statistics (indicators) which tells him all (or virtually all) that he wants to know in order to choose between A and B from his point of view.

To put this into practice Bill Clark was appointed decision maker. After Holling had drawn up a long list of possible indicators we three had a meeting to discuss this list with Clark. Which ones was he interested in?

We then ran into a problem. When a decision maker evaluates the state that the forest is in now, he has to look to the future. He has to predict how the forest will behave, keeping in mind the present number of budworm, for example. Hence when he evaluates the forest condition he amalgamates in his mind how the forest will develop in the future. Now the way in which the forest develops depends on the method of treatment, that is, on the policies being used for logging, spraying and the like.

Now recall that we are looking for an objective function which we can optimize to find a best policy for treating the forest. But if the decision maker had known of this "best policy" he might have evaluated the forests differently, which changes the best policy. Right? As an example suppose that a simple device is discovered which removes all possibility of a budworm outbreak. The forest preferences of the decision maker will be altered. Although the result of the optimization procedure may not be as good as this "device" it nevertheless may change his preferences. What is needed is a <u>set of statistics</u> such that preferences for their values are <u>independent of the policy being used</u>.

This was achieved by letting the decision maker view a <u>stream</u> of statistics about the conditions of the forest over a sufficiently long time horizon. Hence the decision maker need not predict anything. He is to evaluate the stream of statistics as one single finished product and is not to worry about how likely they are or to wonder what policy achieved them. Then it is the job of the simulator to adjust its internal policies to maximize the value assigned by the decision maker.

Note then that now the type of statistics required has changed. It is not necessary to know the density of budworm at any given time, for example; that was only necessary to get an idea about the future state of the trees. Since we can also see the quantity of lumber obtained for the next 100 years and the amount spent on spraying, it is irrelevant to know how much budworm there is. (Indeed it is probably irrelevant to know how much was spent on spraying--a simple net profit or loss may be sufficient.)

2.2 Finding the Attributes Relevant to our Decision Maker

Clark went through Holling's list of indicators deleting, adding and modifying. Some were discarded for being too minor, that is, not likely to influence his decisions, others because their implications were too difficult to understand (particularly standard deviations of data over space). The following list emerged of statistics for each year which Clark felt would affect his decisions.

Financial

X_1 = Profit of logging industry

X_2 = Cost of logging

X_3 = Cost of spraying

Logging Potential of Forest

X_4 = Amount of harvestable wood

X_5 = Percent of X_4 actually harvested in the given year.

Forest Composition

X_6 = Diversity, a measure of the mixture of differing classes, age type of trees for recreational purposes. The higher the diversity the better.

X_7 = Percentage of old trees

Observable Damage

X_8 = Percentage of defoliated trees

X_9 = Percentage of dead trees

X_{10} = Percentage of logged areas (no trees, stumps etc.)

Social

X_{11} = Unemployment (measured by taking a certain logging level as full mill capacity).

Insecticide

X_{12} = Average dosage per sprayed plot.

In addition to the list above, a variance for these statistics taken over the 265 states was also included in some cases.

Ignoring the variances for a moment this still leaves 12 x T statistics for a history of T periods. Indeed, eight of these statistics were originally intended for each site which would have given (4 + 265 x 8) T statistics.

Two fifty-year histories were generated by the simulation model with an initial set of internal policies and these statistics generated. Clark studied these listings and, following his earlier procedure for ordering the listing on Figure 3, essentially picked a few key statistics which he desired to maintain at a certain level and then checked to see that the others were not seriously out of line.

The idea at this stage was to give him a sequence of twelve or so such fifty-year listings of statistics and ask him to order them. Then he would be given the complete simulation outputs and asked to rank those; then the two lists would be compared. In this way the list of statistics would be modified and he would learn better what were their implications, so that eventually he would be able to arrive at the same orderings for the complete listings and the reduced set of statistic listings.

Owing to the mechanical difficulty of keeping IIASA's computer in operation and lack of time this was not done. For the sake of outlining the full procedure, let us assume that this was done.

We then set about the remaining list of statistics (X_1 to X_{12}) to reduce it to a manageable size of at most five or six per year.

I successfully argued that the potential wood, potential wood harvested, cost of spraying and insecticide (X_4, X_5, X_3, X_{12}) were given over all periods, and if these four attributes were going seriously wrong it would show up eventually somewhere else. The cost of logging could be deduced approximately from the profit figure and the unemployment level (which is proportional to wood harvested).

This left Profit, Diversity, Old Trees, Defoliation, Dead Trees, Logging Effects and Unemployment. It seems clear that all but the first and last are related to recreational, visual and environmental considerations. Could not these five statistics be amalgamated into a single statistic of recreation? Then we would have:

P = Profit

U = Unemployment

R = Recreational Value of Forest

for each time period.

'he general plan for producing a recreational value index .s shown in Figure 5.

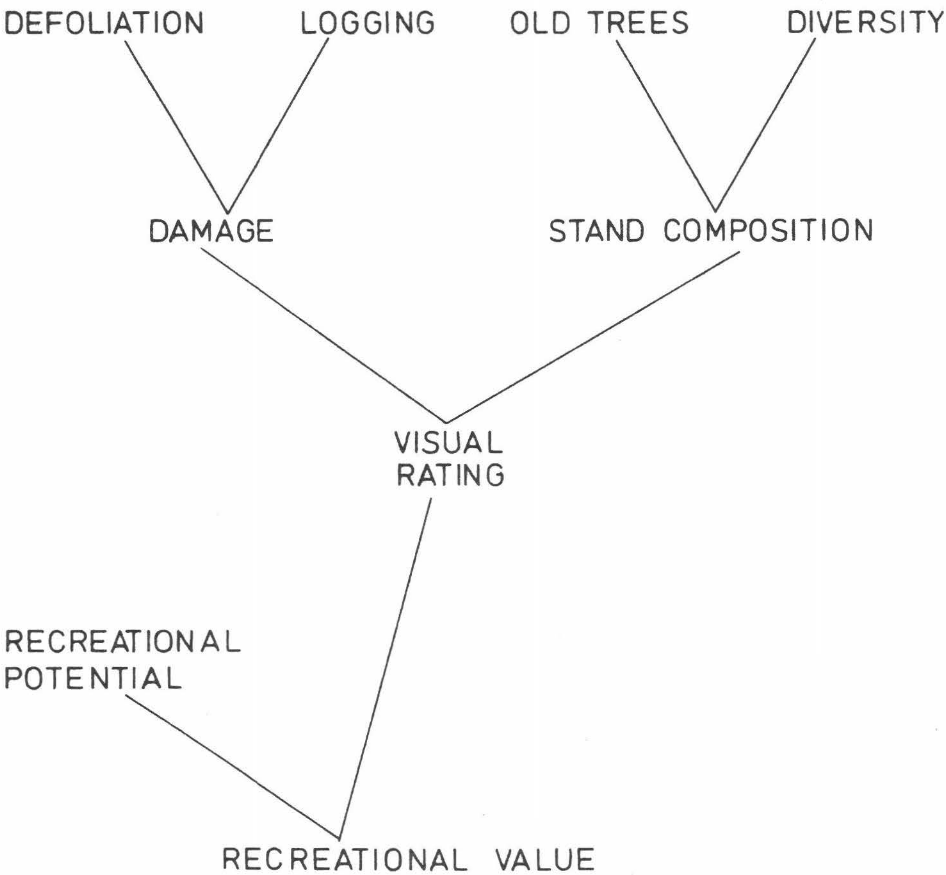

Figure 5.

The recreational potential is a value assigned by the Canadian Forestry Commission to each region of the forest, indicating its accessibility to tourists and quality of surroundings (streams, lakes, gorges). Each region has a value 0, 30, 70, 100.

For all the attributes in Figure 5 Clark divided the possible range into three classifications, for example, for defoliation a stand with 0-15% defoliation was good, 15%-45% medium, 45%-100% bad. Then where two attributes were combined in Figure 5 he used the rule displayed in Figure 6.

1 / 2	GOOD	MEDIUM	BAD
GOOD	GOOD	MEDIUM	BAD
MEDIUM	MEDIUM	MEDIUM	BAD
BAD	BAD	BAD	BAD

Figure 6.

Hence a stand would be given a visual rating equal to the worst rating of its components. The final composition of recreational potential and visual rating was achieved by Figure 7.

	0	30	70	100
GOOD	BAD	MEDIUM	GOOD	GOOD
MEDIUM	BAD	MEDIUM	MEDIUM	MEDIUM
BAD	BAD	BAD	BAD	BAD

Figure 7.

Because some of the regions of the forest are not suitable for recreation even under the best of conditions, the following are the number of regions possible in each recreation category.

$$0 \leq \text{GOOD} \leq 38$$
$$0 \leq \text{MEDIUM} \leq 262$$
$$3 \leq \text{BAD} \leq 265.$$

Since the total number of regions is fixed (265) it is only necessary to specify two of the above classifications; hence the final list of statistics to be tabulated for each period is:

P = Profit

U = Unemployment

G = Number of Good Recreational Regions

B = Number of Bad Recreational Regions.

2.3 A Value Function

The aim now is to derive a formula which takes the statistics (P_t, U_t, G_t, B_t) t = 0,1,2,..., and produces a value V such that if forest history α is preferred to forest history β then

$$V(\alpha) > V(\beta) \quad .$$

Over recent years a great deal of research has gone into devising good techniques for the assessment of value functions [6, 4]. To date these techniques have not been tried on this problem. At the time of the study the methodology group at IIASA was experimenting with linear programming (L.P.) software and was eager for examples with which to work. I combined our two aims and used the following linear programming approach to find value functions.

Consider a value function V having two variables x, y. Suppose the decision maker has said that in the following pairs the first one in each is preferred by him to the second:

$$(2, 5) \quad , \quad (3, 0)$$
$$(3,-7) \quad , \quad (1, 1)$$
$$(0, 2) \quad , \quad (-1,2) \; .$$

Thus

$$V(2, 5) - V(3, 0) > 0$$

$$V(3,-7) - V(1, 1) > 0 \qquad (2.1)$$

and

$$V(0, 2) - V(-1,2) > 0 .$$

Suppose we approximate V with a quadratic polynomial

$$V(x, y) = ax + by + cxy + dx^2 + ey^2 ;$$

then we have that

$$\begin{aligned} -a + 5b + 10c - 5d + 25e &> 0 \\ 2a - 8b - 22c + 8d + 48e &> 0 \qquad (2.2) \\ a + 2c - d &> 0 \end{aligned}$$

are necessary requirements for V to be a valid function. Examples of polynomial expressions whose coefficients satisfy (2.2) are:

$$\begin{aligned} V_1(x,y) &= xy + y^2 \\ V_2(x,y) &= x + y^2 \qquad (2.3) \\ V_3(x,y) &= -x^2 + y^2 . \end{aligned}$$

By obtaining more pairs of preference orderings, the possible set of coefficient values (a,b,c,d,e) may be reduced, for example, if we now find that in addition

$$(3, 2) > (0, 3)$$

then only the first of the three examples above is still valid.

If there are many alternative value functions for a given data set an L.P. algorithm will arbitrarily choose one of them unless it is given some selection criterion. Supplying an objective function for the L.P. problem gives the advantage that given the same data set the L.P. will always choose the same value function; hence as the data set alters slightly (because of new orderings) it is easier to see its effect on the resulting value function.

Note that if (a,b,c,d,e) is a solution of (2.2) then so is any positive multiple of it; hence the arbitrary constraint

$$|a| + |b| + |c| + |d| + |e| = 100$$

was added to bound the problem.[5]

The objective criterion used was to maximize the minimum gap between preference rankings. In the example used above the gaps between the left hand side of (2.1) and the right hand side (zero) using V_1 are 35, 26, 2; for V_2 are 24, 51, 1; and for V_3 are 30, 40, 1. Hence the minimum gap in each is 2, 1, 1, and so the maximum minimum gap is 2 and V_1 would be the preferred polynomial from that list.

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[5] $|a|$ means $+a$ if $a > 0$, $-a$ if $a < 0$. Later I used the simpler constraint $a + b + c + d + e = 1$ as this too effectively bounds the problem.

In general, for a list of preferences

$$x_i^1 > x_i^2 \quad , \qquad i = 1,2,3,\ldots,k$$

(> reads "is preferred to")
the full linear program would be

$$\begin{aligned} & s^* = \text{Max } s \\ \text{s.t.} \quad & V(x_i^1) - V(x_i^2) \geq s \qquad i = 1,\ldots,k \qquad (2.4) \\ & a + b + c + d + \cdots = 1 \quad . \end{aligned}$$

Note that a valid function exists if and only if $s^* > 0$. Otherwise the solution to (2.4) at least gives a solution with a "minimum error" in some sense. If $s^* \leq 0$ the decision maker would be questioned more closely on doubtful orderings, or if he is resolute, a higher order approximation should be taken.

Returning to our study, with four attributes (P, U, G, B) per time period two qualitative assumptions were made by Clark (with my prompting) that were felt to be reasonable (in the first case) or necessary (in the second).

a) Preferences for profit and unemployment were "independent" from those of recreation. If for some particular values

$$(P^*, U^*, R^*) > (P^0, U^0, R^*) \quad ,$$

and then if R* is replaced by some other level, say R^0, then

$$(P^*, U^*, R^0) > (P^0, U^0, R^0) \quad .$$

That is, the relative orderings of (P, U) pairs, are independent of the level of the recreation so long as it is the same in each case.[6] The reverse was also felt to be true, that preferences for recreation alternatives were independent of profit/unemployment levels so long as these remained constant.

b) Clark's preferences for profit and unemployment levels in a year depended on what those levels were last year and would be next year. For example, a drop in profits to gain fuller employment is not too serious if compensatingly larger profits are made in the surrounding years. Also, an unemployment level of 10% is worse if it follows a year of full employment than if it follows a year of 10% unemployment; that is, he prefers a steady level to one which oscillates. These were (and still are) serious methodological problems and it is intended to study them at IIASA in the near future. We need to study setting up a value function involving attributes over time when preferences for an attribute in one year depend on its levels in other years.

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[6] Preferential Independence, see [4]

Clark felt that if we replaced P_t as a statistic by

$$Q_t = \frac{P_{t-1} + P_t + P_{t+1}}{3} ,$$

we might better justify a separable value function such as

$$V = \Sigma \; V_t(Q_t, U_t, G_t, B_t)$$

where V_t is a value function based on the figures for year t alone.

Assumption a) enabled us to work with a value function

$$V_t(Q_t, U_t, G_t, B_t) = V_t(X(Q_t, U_t) \; , \; Y(G_t, B_t)) ,$$

allowing us to calculate a value function for recreation independently of that for profit and unemployment.

Figure 8 shows the rankings given by Clark for the two value functions X, Y for any time period. Note that for (Q, U) it is an ordered list and the rankings for recreation include some equalities.

These rankings produce the following value functions (a cubic polynomial approximation being used):

$$X = 76Q^3 + 3.3QU^2 - 12QU - 5Q^2 - 2.2U^3 - 0.5Q^2U \; ;$$

and

$$Y = 21.3GB + 19.7G^2 + 53.7G^3 + .01B^3 + 0.08GB^2$$
$$- 4.66B^2 - 0.62G^2B \; .$$

(Q, U)	(G, B)
(10,0) >	(15, 50) > (14, 0)
(0, 0) >	(25, 50) > (24, 0)
(7, 8) >	(34, 0) > (35, 50)
(20,10)>	(26, 0) > (38,100)
(0, 5) >	(28,100) = (22, 0)
(4, 8) >	(28,130) = (16, 0)
(7,10) >	(38,227) = (22, 50)
(-5,0) >	(26,200) = (20,150)
(30,15)>	
(-5,10)>	
(25,25).	

Figure 8.

Then Clark gave the following orderings for sets of all four attributes (Figure 9). The groups are lists with each member of a group being preferred to the one below it.

10, 0, 16, 30	10, 10, 16, 30
25, 0, 16, 100	25, 10, 16, 100
0, 0, 16, 0	0, 10, 16, 0
-5, 0, 16, 50	-5, 10, 16, 50
-5, 0, 0, 50	
	5, 0, 10, 50
5, 4, 16, 50	10, 0, 10, 100
5, 7, 16, 30	0, 0, 10, 30
5, 0, 16, 100	-5, 0, 10, 0
5, 10, 16, 0	
0, 10, 16, 0	
	5, 0, 10, 40
	10, 0, 2, 40
	0, 0, 16, 40
	-5, 0, 25, 40

Figure 9.

Now with the aid of the functions X, Y these lists may be reduced to lists of two attributes; for example the first list becomes:

$$\begin{array}{lcl} X(10, 0) & , & Y(16, 30) \\ X(25, 0) & , & Y(16, 100) \\ & \vdots & \\ X(-5, 0) & : & Y(0, 50) \ . \end{array}$$

The same cubic approximation technique was used to find a combined value function of

$$\begin{aligned} V(x, y) = {} & 0.39x + 0.0003y^2 + 0.87x \\ & + 0.013x^2y + 0.014xy^2 \\ & - 0.02y^2 - 0.002x^3 \\ & - 0.07x^2 - 0.20xy \ . \end{aligned}$$

2.4 <u>The Time Problem</u>

So far the analysis has reduced the simulated history of the forest into a time stream of values, one per year. For two simulated histories with output values

$$(V_1^1, V_2^1, V_3^1, V_4^1, \ldots)$$

and

$$(V_1^2, V_2^2, V_3^2, V_4^2, \ldots) \quad ,$$

we can only be sure that the decision maker prefers the first history to the second if $V_k^1 \geq V_k^2$ for all k and if this inequality is strict for some k.

To emphasize the point it is not possible at this stage for the analyst to say whether Clark would prefer a five year history

$$(2, 3, -1, 999, 7)$$

to one of

$$(2, 3, -1, 4, 8)$$

because we have no rules for intertemporal trade-offs.[7] The only manageable model for such trade-offs is a linear assumption that

$$V = \Sigma \alpha_t V(Q_t, U_t, G_t, B_t)$$

for some coefficients α_t, where presumably $\alpha_t \geq \alpha_{t+1} \geq 0$ for all t.

Had time permitted[8] we could have found viable values for the coefficients α_t by using the same technique which led to the coefficients in the second value function

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[7]This is true in general. With the possible exception of purely financial investment problems, no satisfactory progress has been made on the problem of intertemporal value trade-offs.

[8]Bill Clark returned to Canada in July 1974.

$$V(X(Q, U) \quad , \quad Y(G, B)) \quad .$$

However, for the moment the simulation model is generating different histories using a variety of policies and calculating the value

$$V = \Sigma \, \alpha^t \, V(Q_t, U_t, G_t, B_t)$$

for a range of constants α, $0 < \alpha < 1$.

2.5 What Next?

The idea now is to see whether, when Clark ranks a set of simulation model histories, the value function is in agreement, or at least if it is "close." If it is close then by testing a range of different policies into an adaptive simulation model, a locally best solution will emerge by adjusting the decision parameters of the simulator so as to maximize the value function.

Since we have assumed a value function which is separable over time it could be used in a dynamic programming model of the forest. If so, the optimization routine will yield a policy which **is globally** optimal with respect to that one decision maker's preferences.

3. Conclusions

No pretence is made that the preceding work was anything better than downright crude. The narrative was included in detail more for completeness sake than as a shining example for others to follow. Nor should the preferences expressed by our decision maker be interpreted as anything more than one man's preferences. (His disregard for profits was finally moderated somewhat over the period of the analysis but can be seen even now to be rife. Note that that was true even in the original list. Figure 3 shows him with a correlation of -.80 with the logging industry.)

The really interesting aspects of this study were never completed, due mostly to computer difficulties. These were the education process of the decision maker via the simulation model training to understand the physical implications of statistics and the gradual revision of the statistics used. The assessment qualitatively of a value function or more boldly a utility function [6] was not attempted.

But what did the study achieve?.

1. I feel that my main original aim of discovering what the Ecologists really wanted out of the forest was achieved, principally because they were forced[9] to think positively and articulate on paper what before had only been vague ideals. I would claim that many of the ideas connected with the budworm study were only revealed through this study (e.g. controlled outbreaks over space as opposed to time). If that claim is a little strong I would certainly assert that communication of these ideas between the members of the Ecology group was improved as a result.

2. From a methodological point of view the reoccurrence

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[9] That is to say they participated willingly and put some effort into it.

of the problem of intertemporal trade-offs serves to emphasize the <u>critical lack of methodological tools presently available for this problem</u>. If the only lasting result of this study is to further advertise this point, I will be satisfied.

3. A question arises concerning the traditional study in decision analysis of finding a value function $V(x_1,\ldots,x_n)$ to maximize over a region of possible values defined by some constraints $g_i(x_1,\ldots,x_n) \leq 0 \quad i = 1,\ldots,k$, say. That is maximize $V(x_1,\ldots,x_n)$ s.t. $g_i(x_1,\ldots,x_n) \leq 0 \quad i = 1,\ldots,k$. What Bill Clark was usually doing was dividing the attributes into two classes of "important" and "important if they get far away from normal" suggesting the following problem:

$$
\begin{aligned}
&\text{maximize } \bar{v}(x_1,\ldots,x_s) \\
&\qquad g_i(x_1,\ldots,x_n) \leq 0 \qquad i = 1,\ldots,k \\
&\qquad a_i \leq x_i \leq b_i \qquad\quad i = s+1,\ldots,n\ ,
\end{aligned}
$$

where (a_i, b_i) represents a sensible interval for the attribute x_i and $\bar{v}$ is a value function over only the "important" attributes. This would be a useful technique where n, the number of alternatives, was large, or in any case where the decision maker finds it difficult to make trade-offs between more than two or three attributes, and no independence assumptions hold.

Clark also "kept things simple" in other ways. Figures 5, 6, 7 show the very unsophisticated way in which a recreational index was obtained. I tried to have him adopt a continuous function of the continuous variables of defoliation, logging, etc. Quite reasonably he argued that he could not do that because then the resulting recreation numbers would mean nothing concrete to him. Agreed the "education process" mentioned earlier was not carried out but nevertheless this is something to be kept in mind by analysts.

4. Recall the way in which we sidestepped the problem of the optimal management policy being dependent on the present perception of the future which is in turn dependent on the success of the present non-optimal policy. We generated indicators over all years thus eliminating the need to perceive the future. This was merely trading one problem for another as we now have the problem of collapsing values over time.

My guess is that it would have been better (after all) to have used the former method and used successively better policies to revise the decision makers perception of the future consequences of a present state of the forest.

5. Figure 10 shows a result of the optimization algorithm (using (1.1) as an objective criterion) using the number of recreational bad areas as defined by Bill Clark as a guide. It can be seen that any inaccuracies in the assessment of the value function for preferences is likely to be of little consequence compared with the improvement made by the optimization. With this kind of improvement made by an optimization using a different objective criterion

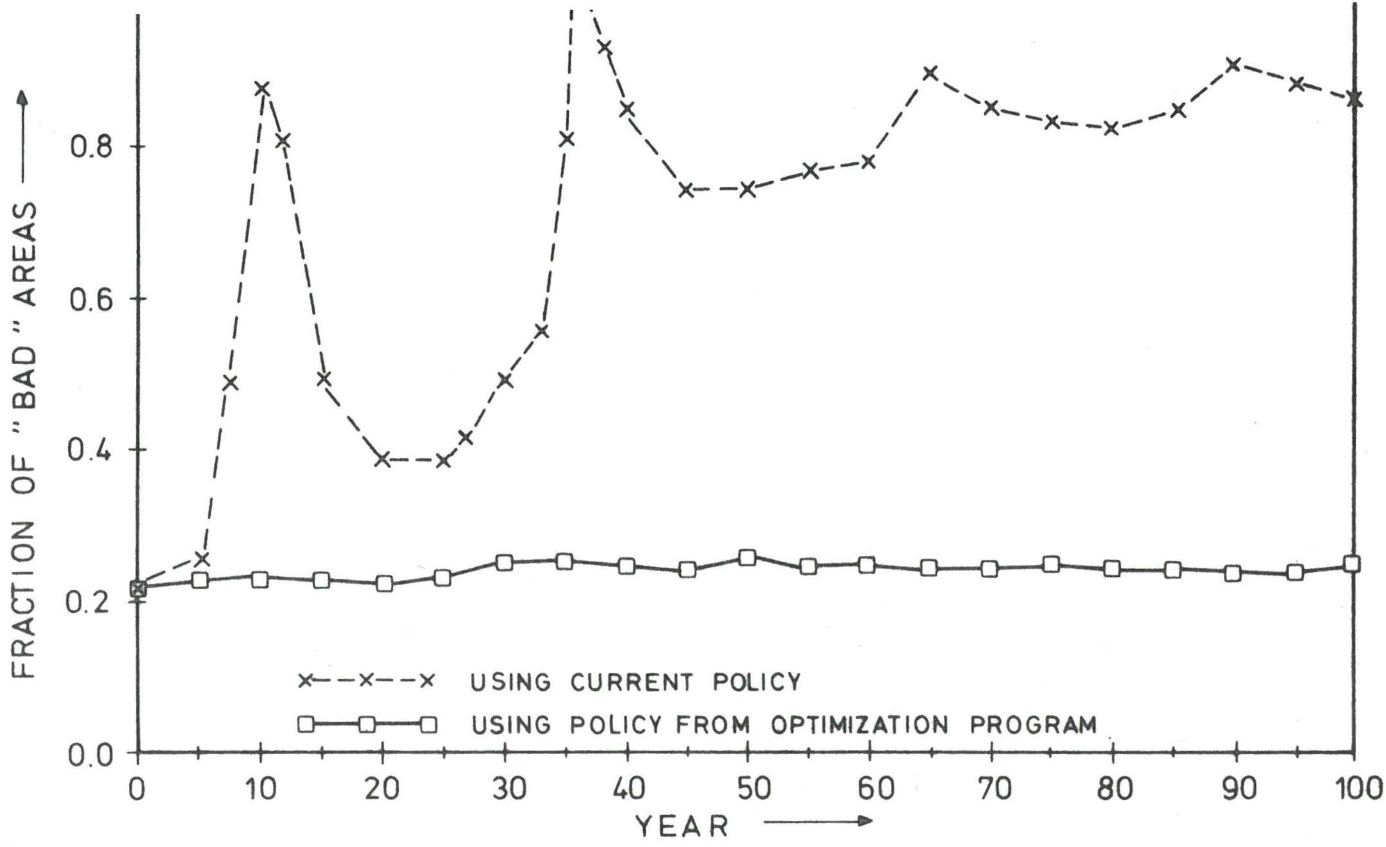

FIGURE 10. FRACTION OF "BAD" AREAS VS. YEAR OF SIMULATION

we can speculate on the vast improvement which would be likely if the correct (that is Clark's) value function were used in its place.

4. Implications

I would suggest that much progress can be made when studying an applied problem by attempting to quantify preferences of the project members over relevant attributes. Indeed I would say that the major benefits may be had even if the final quantative results are thrown in the waste basket because in the course of the analysis, communication with oneself as well as with other team members will have been improved with regard to the issues to be faced.

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