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Determining profitability for Ngati Whakaue Tribal Lands Inc. farms by developing a sustainable land management plan

Oliver Chikumbo[1], Hamuera Mitchell[2] and Richard Valance[2]

[1] *Scion, Private Bag 3020, Rotorua 3046, New Zealand*

[2] *Ngati Whakaue Tribal Lands Inc., 1176 Amohau Street, PO Box 12015, Rotorua, New Zealand.*

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*corresponding author: oliver.chikumbo@scionresearch.com

Abstract

It is a challenge for farmers to manage sustainable development in order to achieve financial, social and environmental objectives feasibly and simultaneously. This paper describes the use of a systems-approach framework for addressing such a complex problem. Three farms were evaluated using this framework. The model used simultaneously optimised financial, social and environmental objectives by selecting from a range of land use and management alternatives over a specified period of time. The result was a financial performance that could be linked to the environmental benefits rather than a simple balance sheet. It contained not only financial information but also an account of both environmental impacts and implicit social and cultural concerns of the farms' manager and owners. The results obtained from this evaluation are now in the process of being implemented to all three farms. These positive results indicate that a systems-approach framework could be successfully applied to resolving other complex land use situations.

Keywords: Metropolis algorithm; multi-objective optimisation; stakeholder participation; sustainability.

Introduction

The aim of this work was to identify a sustainable, environmental and economic scenario for three farms which complied with local environmental legislation and was acceptable to the owners. We used the Metropolis algorithm (MA) to solve this multi-objective land use and management problem, which is described in detail later. Use of the MA is certainly not new, but this paper demonstrates its application to a real world combinatorial optimisation problem, where the set of possible solutions is discrete and in many such problems exhaustive search is not feasible (Lee, 2004). This enabled land use (spatial information) and management alternatives (temporal information) to be optimised simultaneously.

A decision-making process is naturally based on comparison of different points of view, some in favour and some against an objective or point of view. Maximising some and minimising others can result in an acceptable compromise. Constructing a mathematical model representing this situation leads to a multi-objective optimisation formulation. To mimic the real world, conflicting and incommensurable objectives (Fonseca & Fleming, 1993) would have to be represented in the formulation.

Artificial Intelligence (AI) and Operations Research, coupled with computational innovation, makes it possible to find solutions to real world multi-objective optimisation problems (Csete & Doyle, 2002). For the land use and management problem addressed in

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this paper, the optimisation is further complicated by locational considerations. Locational considerations mean that assignment or non-assignment (i.e.variables are required to be 0 or 1) of a land use and/or management alternative is based on physical and environmental geography. This turns the problem into a combinatorial one because the space of possible solutions is discrete instead of continuous. Finding a solution for a combinatorial optimisation problem is nontrivial. Checking or enumerating all possible solutions of real-world problems may take thousands of years even when using optimisation techniques such as linear programming or specifically mixed-integer linear programming (for combinatorial optimisation) on the fastest supercomputers. Formulating the problem may be the easy part but computation (in searching for the solution) may present serious issues that Bellman (1957) referred to as the ‘curse of dimensionality’.

Combinatorial optimisation belongs to a class known as NP problems whose computation time for an exact solution increases with *N*, the number of variables, as *exp(constant * N)*, becoming rapidly prohibitive in cost as N increases. In complexity theory, NP denotes the set of decision problems solvable by a non-deterministic (i.e. permitting more than one choice of next move at some step in a computation) polynomial time algorithm as opposed to the P problems solvable by a deterministic (i.e. permitting at most one next move at any step in a computation) polynomial time algorithm. Such NP problems are considered ‘hard’ in the sense that they are not currently solvable in deterministic polynomial time (De Jong & Spears, 1989).

Heuristic search algorithms have been adapted to solve combinatorial optimisation problems because they are computationally efficient methods of exploring all the statistically sampled areas of importance in a solution space in AI. The minimal downside of heuristics is that they may sacrifice some quality of the solution. Some examples of heuristic search techniques include Tabu search (Glover, 1994), Metropolis algorithm (Press et al., 1992), simulated annealing (Kirkpatrick et al., 1983) and Lin-Kernighan search (Lin & Kernighan, 1973). These algorithms avoid converging on local optima by using heuristic methods that allow non-improving moves to be taken (Rana, 1999).

We firmly believe that no heuristic search algorithm is better than another over all possible problems, and that in fact there is often a good deal of problem specific information involved in the choice of problem representation and search operators (Quagliarelli et al., 1997). The Metropolis algorithm was used here because of comparatively fewer calculations required to determine moving from one state/configuration to the next. Each state defines a potential solution and an objective function is used to evaluate it. The fewer the number of calculations, the shorter the time required to reach convergence for large and complex problems. A greater depth of the method is given in the section on optimisation formulation.

Study area and problem definition

The Rotorua District of New Zealand is an area of 9065 km^2 that has an annual gross domestic product (GDP) of NZ$ 2.0 billion (APR Consultants, 2005). The main economic sectors are forestry, logging and wood processing (contributing 15% of the GDP), tourism (12% of the GDP), agriculture (10% of the GDP), and service industries (including retail, financial, education, health, cultural and recreational services) which contribute 63% of GDP. The main agricultural activities in the district include dairy, beef, sheep and deer farming (Richardson & Botherway, 2006). The Rotorua District has many lakes (see Figure 1), and there is a need to manage land use in order to balance utilitisation by these commercial interests and water quality.

A major environmental problem is that human activities in streams and lakes cause a decline in water quality which, in turn, causes eutrophication, toxic algal blooms, aquatic ecosystem stress, and risks to human health (EBOP, 2000). Nutrient inputs from various land uses include agricultural fertilisers, farm animals, discharge from septic tank soak fields and urban runoff. Water quality is measured using the Trophic Level Index (TLI) (Richardson & Botherway, 2006), which is a sum of four interrelated factors: phosphorus (P), total nitrogen (N), secchi disc depth (clarity) and chlorophyll *a* (amount of algae).

Water quality in the Rotorua lakes has been declining for 30 to 40 years, and toxic blue-green algal blooms have become a serious problem in some of them (Richardson & Botherway, 2006). Land uses in the Rotorua lakes catchments are stable but there is, as elsewhere in New Zealand, intensification of pastoral farming (Richardson & Botherway, 2006). Intensification of pastoral farming will always lead to more nutrient release, no matter how well the application of fertiliser is managed.

There are also substantial natural sources of nutrients in the lakes catchments. For instance, the water that flows into Lake Rotorua from perennial springs at Hamurana is high in phosphorus (Environmental Defence Society, 2007). This phosphorus is naturally leached from the underlying ignimbrite volcanogenic aquifer material (Morgenstern et al., 2004).

In 2003/2004, the yearly average TLI for Lake Rotorua reached the supertrophic lake classification (>5.0 TLI units) for the first time since monitoring by the regional council, Environment Bay of Plenty (EBOP) began in 1990. This resulted in the lowest water clarity seen in the lake in that time (EBOP, 2000). The causes were

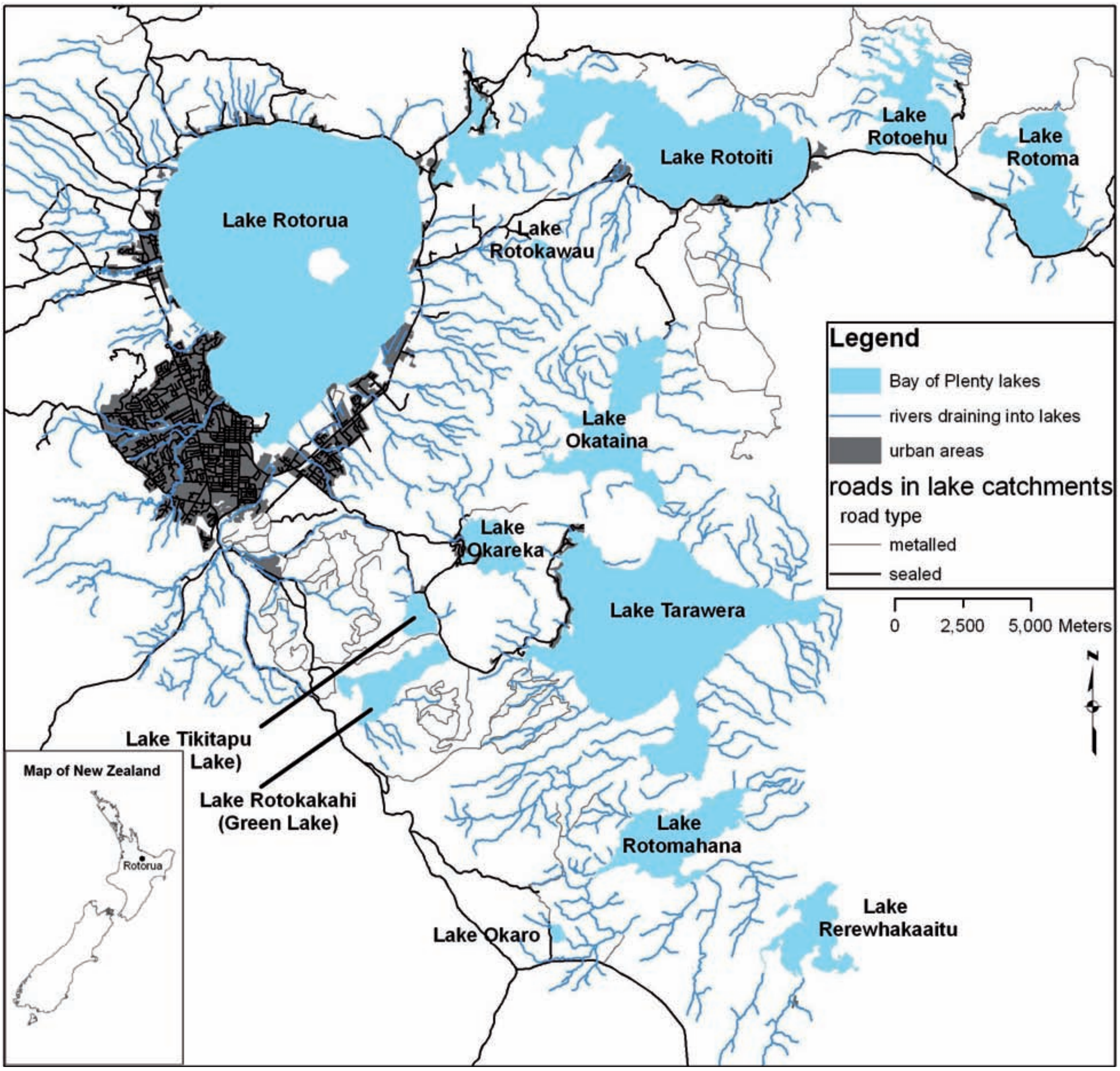

FIGURE 1: The lakes catchments in the Rotorua district.

high nitrogen levels (the highest yearly average ever recorded) and a long algal bloom season.

Environment Bay of Plenty has established a set of regional standards (called Rule 11) to protect lake water quality (EBOP, 2005). Rule 11 specifies nutrient discharge caps for nitrogen and phosphorus on all properties larger than 0.4 ha in the Rotorua lakes catchments. The Rotorua District Council (RDC), EBOP, and Te Arawa Maori Trust Board are working together with farmers to develop a workable land use programme that would remedy the lakes water quality situation without putting these farmers out of business (EDS, 2007).

A major farmer in the area is Ngati Whakaue Tribal Lands Inc. (NWTL), which was formed in 1960 to manage land on behalf of approximately 4500 Maori owners. Thirty-four individual parcels of land were amalgamated into three large farms (Wharenui, Ngongotaha and Tihiotonga) with a total area of 3734.8 ha. All three farms are close to Lake Rotorua, one of the lakes in the district that is being protected under Rule 11. Ngati Whakaue Tribal Lands Inc. are actively working to satisfy their sustainable development plans under the confines of Rule 11, through the determination of appropriate mixes of land uses and management alternatives. Ngati Whakaue Tribal Lands Inc. is also currently undertaking important strategic decisions for their farm properties with a view of growing their net worth to NZ$100 million with an annual profit of NZ$10 million by the year 2010. A range of economic, environmental and social factors affect such decisions. Factors considered included carbon sequestration, water quantity, water quality, profit, wood production, and agricultural production.

Framework for simultaneously optimising for land uses and management alternatives

Framework and accounting system

The central hub of the modelling framework proposed here is a spatially explicit, (i.e. combinatorial), multi-objective optimisation algorithm. A triple bottom line accounting system was used in which the optimal mix of land uses and management alternatives was determined through an amalgamation of management units (in this case, paddocks) with three other inputs: environment, economic and social/cultural.

The mathematical drivers (D) of the model (as in the attributes that give rise to an outcome) were defined by: the availability of information; what the owners' wanted to know; and Rule 11 legislation. The drivers were:

D1: legislation (as in Rule 11, capping on nitrogen and phosphorus outputs from a farm property);

D2: markets (as in profitability reflected in accounting records as discounted cashflows (DCF) and/or earnings before interest rate, and investment strategies); and

D3: cultural values (as in a belief set that plays a major role in decision-making by influencing the nature and outcomes of D1 and D2. For example, burial sites were certain land uses are excluded).

Figure 2 shows the breakdown of the goal of profitability and sustainability into these three drivers, D1 – D3. Each driver is itself a function of three components: (a) ecosystem services (as defined below); (b) economic/financial processes; and (c) a combination of interactions with stakeholders and political processes.

(a) Ecosystems denote the combined physical and biological components that form the environment. Humans modify ecosystems to best suit their lifestyle and by so doing alter "ecosystem processes" that are responsible for the generation of ecosystem services. When ecosystem services are compromised, legislation is traditionally used to curtail human behaviour/lifestyle in ways that will enhance ecosystem processes and with the aim of maintaining or restoring the generation of ecosystem services for the sustained benefit to humans. Note that the contribution of biodiversity (which is the resilience of an ecosystem by virtue of having more species at a location to respond to change and thus "absorb" or reduce its effects) was not included as an ecosystem service (in Figure 2). The generation of both measurable environment services, such as water quality, water quantity, carbon sequestration (CO_2-e), production (e.g. agriculture/wood), and measurable social benefits take account of biodiversity (Brand & McCaughey, 2005).

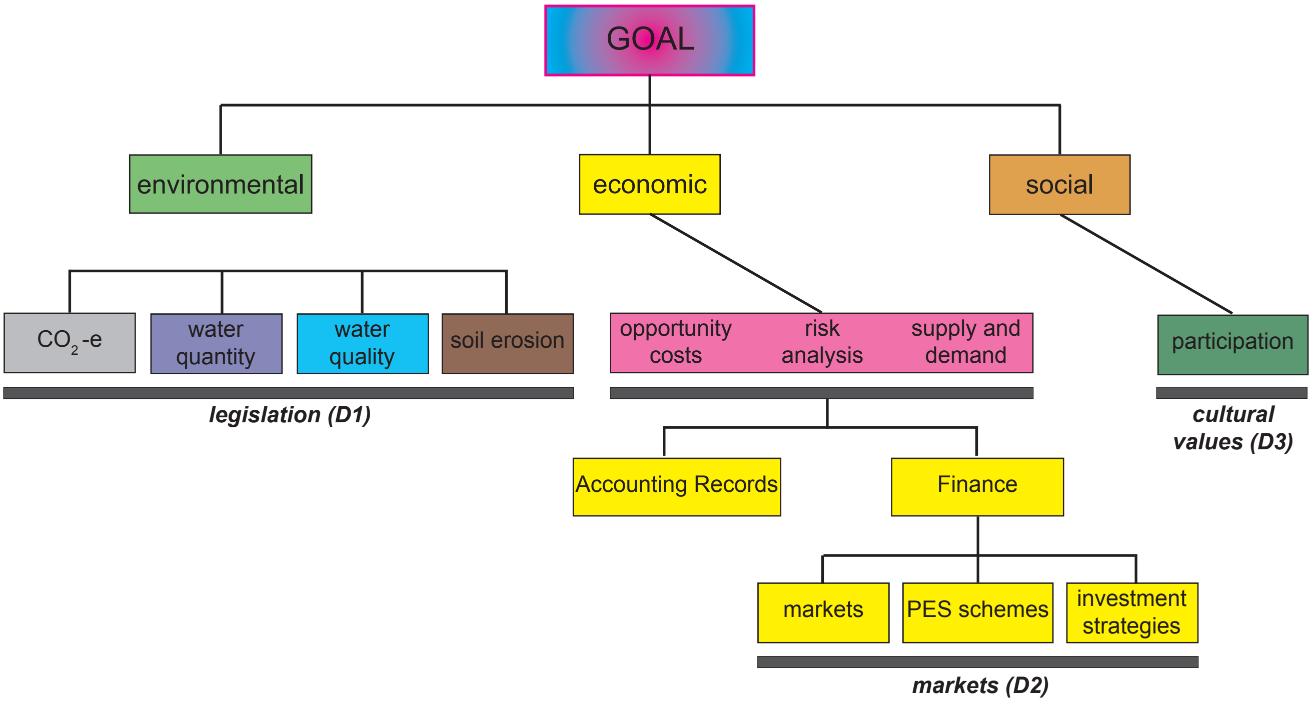

FIGURE 2: Breakdown of the triple bottomline for the three drivers, legislation (D1), markets (D2) and cultural values (D3).

(b) Economics plays a dual role in that it can be used as an instrument to enforce legislation and also used for allocation of ecosystem services, such as water rights. Financial data records and other financial variables (as in Figure 2) are useful in achieving the aforementioned roles. However, it is important to note that this study does not include a complete evaluation of ecosystems and biodiversity, with financial variables that cover other markets through payment for ecosystem services (PES). The trade-offs achieved in our modelling forms a good basis for PES schemes, even in a more sophisticated fashion than what is demonstrated in the piece of software called Integrated Valuation of Ecosystem Services and Tradeoffs (INVEST), which only allows for scenario analysis through simulation with no ability to optimise (The Economist, 2010).

(c) The social component influences both legislation and distribution of both economic wealth and ecosystem services. This was demonstrated through the involvement of those affected i.e. the owners of the land (represented by the NWTL board and chief executive officer, CEO) and the governing bodies EBOP and RDC. It was necessary to amend the plans in order to accommodate the needs of everyone involved in the decision-making process. This was achieved through a consultative process between the NWTL board and the governing bodies, which resulted in agreed compromises or trade-offs that did not jeopardise the fundamentals of NWTL cultural beliefs. Although there were no numerical models for the social component, the cultural values were reflected in the data used for the optimisation modelling and determination of the multiple objectives, thereby influencing D1 and D2, and ultimately the outcomes.

Locational issues (e.g. aesthetics, closeness to a stream/lake, slope of land) may also affect the application of particular land uses and management alternatives to particular paddocks. These were also included in the optimisation framework, as spatial constraints.

Multiple objectives and spatial constraints

Multiple objectives

Further expansion of the three drivers into ecosystem goods and services (i.e. services with market values), and economic wealth are shown in Figure 3. These include carbon sequestration, water quantity, water quality, profit, wood production, and agricultural production. The aim of the model was to increase all of these (as shown with upward arrows on the right hand side of each box in Figure 3). The desired levels were influenced not only by governing bodies (EBOP and RDC) that had an emphasis on management of ecosystem services for public good but also by the landowner (NWTL) who had an emphasis on management of both economic wealth and cultural wellbeing. There was no direct specification of agricultural produce (such as wool or milk solids) in this study because the information was not available, with the exception of costs and revenue. The information for forestry products, i.e. sawlogs and pulpwood were available for both produce, and costs and revenue. The quantities of agricultural produce would have provided refinement and flexibility for finding trade-offs by including them as separate objectives (just like sawlog or pulpwood) in the multi-objective model. Environmental information was however, available for both forestry and agriculture.

The mathematical drivers were mapped into 11 measurable objectives: carbon sequestration and storage; water quantity; phosphorus loss; nitrogen leaching; sedimentation; revenue; costs; earnings before interest and taxes (EBIT); earnings before interest, taxes and depreciation (EBITD); sawlogs and pulpwood. The level of each of these objectives was reflected in the weightings (w_j) that determine the trade-offs. The weightings were formulated as soft constraints in the optimisation model such that minimal violations in trade-offs could be accepted in some years. That acceptance range was set through negotiation by the different decision-makers. It was not obvious, *ab initio*, which weightings to use, especially with so many objectives. We chose a "learn-on-the-analysis" process to find the appropriate suite of weightings. The optimisation model was initially run with all the weightings equal. Analysis of these results gave the decision-makers a feel for determining more appropriate weightings. The model was then re-run with these refined weightings. This interactive feedback process was particularly useful in further defining the social aspect of the triple bottom line accounting. Increased involvement of decision-makers and other stakeholders led not only to different demands on the expected results but also to a capability of generating solutions relevant to the decision-makers (Stewart et al., 2004).

Spatial constraints

In addition to the 11 objectives defined above, spatial constraints were entered into the calculation as three additional objectives, block, spatial, and ranking components:

Block component

The block component controlled the forestry harvested block (an amalgamation of neighbouring forestry paddocks) for its minimum and maximum block size (to lie between 20 and 200 ha for the NWTL problem) with a "greening up" period of two years. The greening

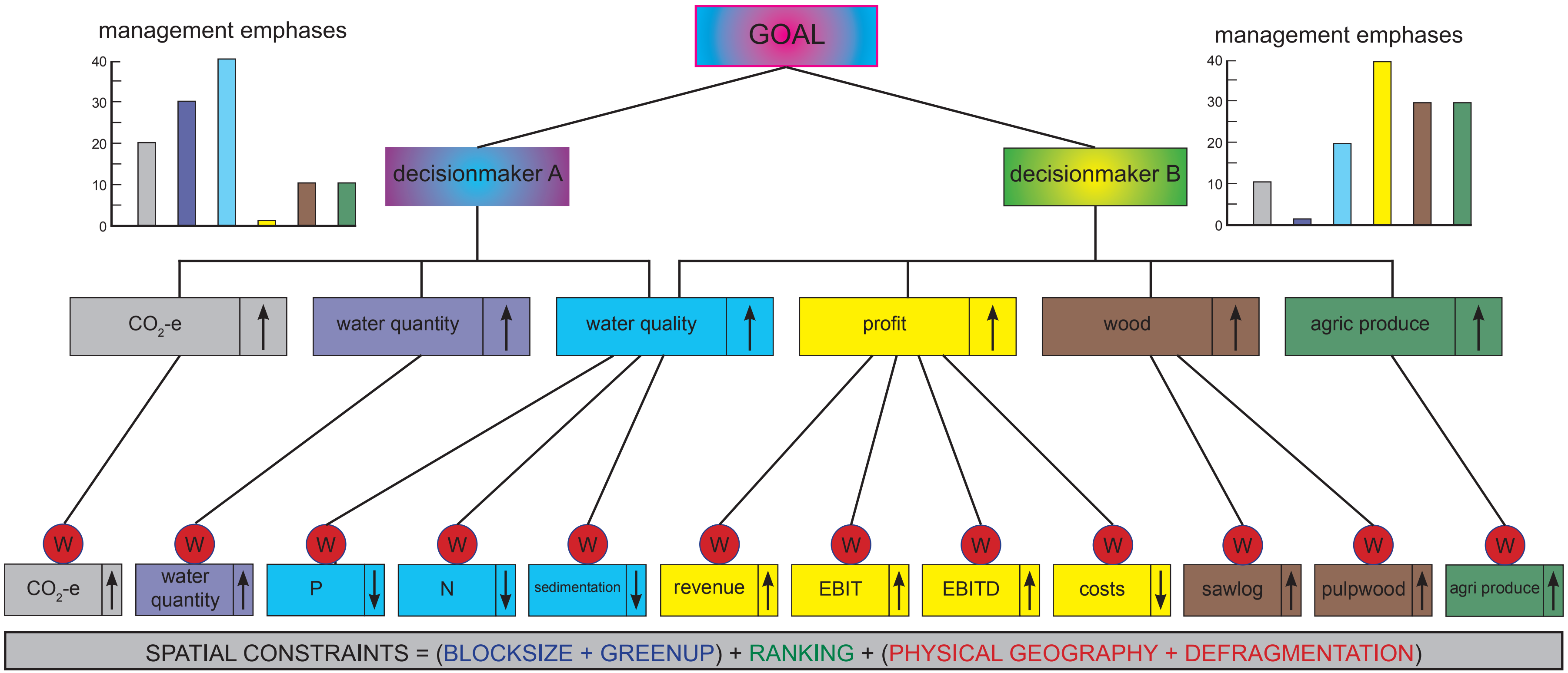

FIGURE 3: Interaction of management emphases from different decision-makers with drivers through multiple of objectives and spatial constraints.

up period ensured that any paddocks adjacent to a harvested block were not available for harvesting for two years after harvesting activities, so that visual impacts and sediment production were kept to a minimum.

Ranking component

The land use assigned to a given paddock influences the land use choice in neighbouring paddocks and therefore this component was used to relatively rank each management alternative under each land use. The management alternatives for land use are shown in Table 1. Land use options with the highest potential income generation were ranked higher than the rest since profitability was a major issue for NWTL. A ranking system using numerical values where, for example, 5 was the highest rank and 1 the lowest, was used in the formulation. This component objective, therefore, helped to bias management alternatives towards profitability. This component conflicted with the spatial component (explained below) where a trade-off had to be found between profitability and spatial layout of the land uses.

Spatial component

The spatial component allowed the control of the spatial arrangement of land use and management alternatives. Land uses and management alternatives were also constrained on the basis of topography, climate, type of soil etc. This information was retrieved from Geographic Information System (GIS) databases of the farms. Each paddock was characterised by physical geography, which meant that some paddocks could not be assigned to a particular land use. For example, dairy faming could not be allocated to sloping terrain.

The areas surrounding the land under study also involved management alternatives and land use restrictions. Use of contiguous land blocks was maximised. For example, if the land area for beef cattle had to be increased, paddocks neighbouring the cattle block were used in preference to isolated paddocks in the forest plantation.

Land uses and management alternatives

The generic framework we developed optimised simultaneously for land uses and management alternatives. Figure 4 shows the generic framework with specific land uses of beef cattle, sheep, dairy cattle, plantation forestry, recreation, conservation, crop farming, and urbanisation. The specific land uses and management alternatives generated for NWTL are shown in Table 1 and do not include any recreation. For each land use, there is one or more management alternative. For example, dairy farming had four alternatives: *status quo*; a feedpad option; a low nitrogen feed supplement option; and a cut-and-carry system. Each of these options has different implications in terms of environmental impacts, operating costs and net profit. The blue arrows (in Figure 4) represent the multiple objectives (see Figure 3) that had to the satisfied. The arrows were stacked to represent a 50-year time sequence.

Project goals and description

Figure 4 shows the central aerial land base in one of the NWTL farms with visible boundaries of the paddocks where the optimisation model and specification of goal statements were applied. The neighbourhood of each paddock was known and was used in the formulation of the optimisation model. When the model was run it produced temporal and spatial results over the 50-year planning period showing the mixes of land uses and management alternatives that satisfied the multi-objective criterion.

A 50-year period (from 2006-2056) was used for the multi-objective optimisation problem. This was deemed to be sufficient for long-term planning with tangible results, subject to review at short-term intervals as NWTL saw fit. The purpose of the short-term reviews is a standard way of validating or refuting, in a feedback loop, what is modelled in planning, based on “implementation” and “effectiveness” monitoring (Tolle & Czaplewski, 1995). Implementation monitoring is about gathering data to answer the question, “Are you doing what you said you would?” It focuses on the standards and guidelines for achieving the objectives. Effectiveness monitoring determines the outcomes from implementing the plan, but does not guarantee that the expected outcomes will be achieved. Rather, it is a means for detecting unexpected consequences of the plan and providing information to update the future plan (Tolle & Czaplewski, 1995).

Each farm was modelled separately but only a description of the model (The Wharenui Land Use Model, WLUM) for Wharenui farm is given here as it is representative of the other two farms. Clearly the optimisation problem was large because of the number of continuous and discrete variables. *A priori* knowledge from the client helped to focus the search for optimal solutions by ranking preferred management alternatives and land uses for each paddock that were most likely to generate maximum return.

There is no single solution for a multi-objective optimisation problem (Srinivas & Deb, 1994). Instead a number of alternative solutions are possible that satisfy Pareto Optimality (i.e. a set of non-dominating solutions where for each solution an improvement in one objective does not lead to a simultaneous degradation in one (or more) of the other objectives) with different levels of the various objectives that maybe defined within specified upper and lower bounds (Osborne & Rubenstein, 1994).

TABLE 1: Management alternatives for the different land uses on the NWTL farms

Landuse	**Management Alternative**	**Description**	**Slope (degrees)**	**Nitrogen Leachate (kg N/ha/y)**	**Phosphorus Loss (kg P/ha/y)**	**2008 EBIT/ha**	**Comments**
Sheep 1	Rolling - Breeding & Finishing	Breeding & Finishing (getting animals in prime condition for meat production) - own replacements, i.e. 10% of stock units are non-producing hoggets[1]; 109% lambing to sale. No capital cost on stock. Six-month interest on operating expenditure.	7-25	16	1.67	149.53	Since animals can only be sold once a year, you have to allow for interest on borrowed operating expenditure before it can all be paid back. Breeding can be run on poor-quality pasture, but finishing requires grazing on high-quality pasture.
Sheep 2	Rolling - Buy replacements	Breeding & Finishing - buying replacements i.e. 112% lambing 25% better gross margin than Sheep 1 land-use. No capital cost on stock, Six month interest on operating expenditure.	0-15	18	1.67	168.69	Same as in Sheep 1.landuse
Sheep 3	Step - Breeding Store lambs	Breeding & Stores - own replacements. Steeper hill country. 107% lambing so 25% worse than Sheep 1 land-use. 10% of stock units as non-producing hoggets. No capital cost on stock. Six-month interest on operating expenditure.	15-35	16	1.67	24.09	Option for 15-35 degree slope, may have breeding cattle part-time.
Beef Cattle 1	*Status quo*	Bull beef – weaners[2] through to rising 2y bulls. No capital cost on stock. Six-month interest on operating expenditure.	7-15	25	1.67	174.11	
Beef Cattle 2	Trading Beef 2 y	Same as Beef Cattle 1 land-use but growing stock to larger size, i.e. Rising 3y bulls. No capital cost on stock. Six-month interest on operating expenditure.	7-15	30	1.67	174.11	Damage to hills from larger stock class.

[1] *young male sheep or maiden ewes having no more than two permanent incisors in wear.*

[2] *calves making the transition from an all-milk diet to grazing.*

TABLE 1: Management alternatives for the different land uses on the NWTL farms, continued

Landuse	**Management Alternative**	**Description**	**Slope (degrees)**	**Nitrogen Leachate (kg N/ha/y)**	**Phosphorus Loss (kg P/ha/y)**	**2008 EBIT/ha**	**Comments**
Dairy Cattle 1	*Status quo*	Base case. 50% sharemilking[3]. 80% Winter Off. Milk solids price = \$4.10-(10% share price x 2) = \$2.78	0-7	40	1.67	433.92	
Dairy Cattle 2	Feed Pad	100% Winter off. 60% less nitrogen leached. Feed pad construction =\$100,000. Feed \$1.85/head/d for 60 d = \$111/cow plus \$30,000 operating costs. No off-farm grazing cost. 5% increase in milk solids.	0-7	16	1.67	241.03	
Dairy Cattle 3	Inhibitor added to nitrogen fertiliser	Inhibitor with all nitrogen fertiliser, extra \$241/t x 50.4 t = \$12,146. 5% production gain. 20% less nitrogen leached,	0-7	32	1.67	433.92	
Dairy Cattle 4	Low-nitrogen feed supplements	Maize Silage autumn and winter = \$75,400. 50% nitrogen fertiliser. 50% less nitrogen leachate and 5% more milk solids than the *status quo*.	0-7	20	1.67	433.92	
Dairy Cattle 5	Cut and Carry system	Shed capital cost \$924,000. Feed 17 cents/kg dry mass =\$1.70/head/d =\$620/head/y. 25% more milk solids. No off-farm grazing costs. 70% fertiliser costs. 50% repair and maintenance costs. Nitrogen leached is 40% of Dairy 2 landuse.	0-7	6.4	1.67	-596.88	

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[3] *a sharemilker carries out dairy farming work as an independent contractor in return for a share of the income from selling milk and other produce.*

TABLE 1: Management alternatives for the different land uses on the NWTL farms, continued

Landuse	**Management Alternative**	**Description**	**Slope (degrees)**	**Nitrogen Leachate (kg N/ha/y)**	**Phosphorus Loss (kg P/ha/y)**	**2008 EBIT/ha**	**Comments**
Plantation Forestry 1[4]	Radiata Pine Clearwood 1	Silvicultural strategy with an initial stocking density of 850 stems/ha, pruning at ages 4, 6 and 8 years for 470, 410 and 350 stems/ha respectively. Non-commercial thinning at age 7 and clearfelling from any age range 25-35 years.	15-35	4	0.095		
Plantation Forestry 2[4]	Radiata Pine Clearwood 2	Silvicultural strategy with an initial stocking density of 850 stems/ha, pruning at ages 4, 5 and 6 years for 470, 410 and 350 stems/ha respectively. Non-commercial thinning at age 7 and clearfelling from any age range 25-35 years.	15-35	>4	0.095		The growth yield here is slightly higher than Clearwood 1, because it land that has just been converted to forestry, which high N and P nutrients in the soil.
Plantation Forestry 3[4]	Radiata Pine Framing	This involves a silvicultural strategy that restricts the knot size diameter to under 30 mm, current stands grown without thinning waste at age 8 years, to 450 stems/ha from an initial stocking density of 850 stems/ha. Clearfelling carried out from 25-35 years.	15-35	4	0.095		
Plantation Forestry 4[4]	Douglas-fir and larch	A total of 12 paddocks of Douglas-fir (*Psuedotsuga menzisii*)and one paddock of larch (*Larix kaempferi*). These stands have commercial value and harvestable between 35 – 60 years for larch and 45 – 60 years for Douglas fir.	15-36	4	0.095		
Plantation Forestry 5[4]	Cypress species	This is a mix of *Cupressus lusitanica* and macrocarpa. To be harvested for timber at age 60 years.	15-38	4	0.095		

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[4] *EBIT and EBITD vary with age and, therefore, are not specified here and for all other forestry regimes/management alternatives.*

TABLE 1: Management alternatives for the different land uses on the NWTL farms, continued

Landuse	**Management Alternative**	**Description**	**Slope (degrees)**	**Nitrogen Leachate (kg N/ha/y)**	**Phosphorus Loss (kg P/ha/y)**	**2008 EBIT/ha**	**Comments**
Plantation Forestry 6[4]	Other	This is a group of small paddocks (between 0.3 – 1.5 ha) with eucalyptus species.	15-37	4	0.095		No commercial value although they still generate environmental benefits.
Native Forest	Non-commercial mixed species forest	This is a reserve of total of 171 ha and will not be considered for other land use even in the future.	15-37	4	0.095		No commercial value, but invaluable environmental benefits. Biodiversity could not be quantifiable because the only information available was coarse meant for national scale strategic planning.
Urbanisation 1	Intensive settlement	Chosen paddocks limited to elevated areas. Flat ground only (as on tops of ridges). Five ha lots. Expansion limited to five ha/y. Yield $360,000/ha net. EBIT = interest on dividends invested off-farm.	7-25	6	0.1	43,200	The paddocks for urbanisation potential were meant to be specified by NWTL board, and therefore not modelled.
Urbanisation 2	Extensive settlement	Elevated areas of farm, limited to areas with view. limited to one-hectare sites. 125-year lease. Also limited to one site per 50 ha. Yield $300,000/ha net, EBIT = interest on dividends invested off-farm.	15-35	6	0.1	31,200	Same as for Urbanisation 1 land-use.

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[4] *EBIT and EBITD vary with age and, therefore, are not specified here and for all other forestry regimes/management alternatives.*

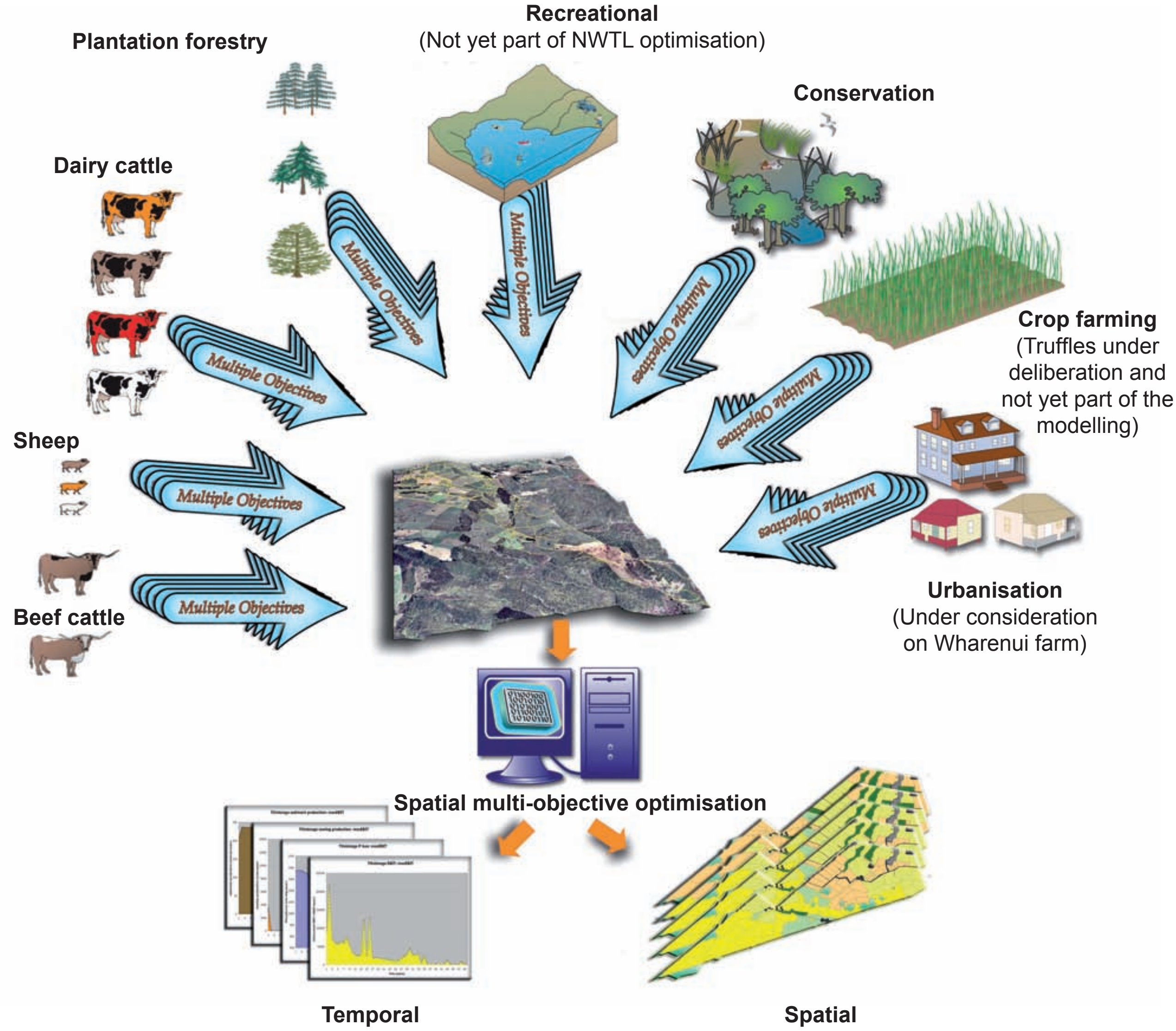

FIGURE 4: Land uses and management alternatives for a multiple objective optimisation model for NWTL.

There are various fully integrated methods for characterising Pareto optimal solutions to multi-objective problems, such as the hyperplane methods (Yano & Sakawa, 1989). In this study, identifying a “Pareto frontier” may not necessarily add value to decision-making given the 14 objective functions included in the WLUM. Instead it may lead to confusion and a delay in decision-making. Suitable solutions to problems involving multiple conflicting and non-commensurable objectives should offer acceptable performance in all objective dimensions, even though these maybe sub-optimal in the single-objective sense. The acceptance of any particular solution is problem-dependent and ultimately a subjective concept (Chikumbo et al., 2000). included in the WLUM. Instead it may lead to confusion and a delay in decision-making. Suitable solutions to problems involving multiple conflicting and non-commensurable objectives should offer acceptable performance in all objective dimensions, even though these maybe sub-optimal in the single-objective sense. The acceptance of any particular solution is problem-dependent and ultimately a subjective concept (Chikumbo et al., 2000).

Optimisation formulation

Using the MA optimisation formulation provided a method of evolving a ‘trajectory’ so that all possible ‘configurations’ in the state space are visited in such a way as to reflect their statistical importance (Press et al., 1992). A configuration defines a unique point in the state space while the trajectory is a set of configurations/points that define a path in the state space. The MA deals with systems that are ergodic. This means that, for a system in statistical equilibrium, all the accessible states have an equal probability of realisation. The process of sampling the configurations, called importance sampling, is achieved using the Boltzmann probability distribution function to assign a weight to all possible configurations, and selecting the next configuration in the trajectory on the basis of a scheme (Press et al., 1992). The statistical process is based on the theory of energetics within a system. The MA algorithm samples the system space and chooses those states that are statistically important (those with lowest energy) and much of the space is high energy and not required for sampling (Chandler, 1987). Energy transformation in the system is expressed with the following formula:

$$\Delta E_{v,v'} = E_{v'} - E_v \qquad [1]$$

where:

E = energy of system;
v = old configuration; and
v' = new configuration.

This energy difference, $\Delta E_{v,v'}$, governs the relative probability of configurations. The Boltzmann distribution, β, is built into the Monte Carlo trajectory by the MA for accepting or rejecting moves to new configurations. If the energy change is negative, the model accepts the move. However, if the change is positive, a random number between zero and one, x, is drawn and a configuration is accepted only if $exp\,(-\beta\,\Delta E_{v,v'}) \geq x$ (Chandler, 1987). Therefore, the MA provides a means of generating a new configuration *B* from a previous configuration *A* such that the transition probability is satisfied for all ergodic systems. Note that the MA only serves the purpose of accepting the proposed change in the system with a certain probability that depends on the change in the system energy.

To generalise the application of the MA so as to apply it beyond thermodynamic systems, the following characteristics are featured (Press et al., 1992):

(a) a description of possible system states;

(b) a generator of random changes in the state – these changes are “options” presented to the system;

(c) an objective function *E* (analogue of energy) whose minimisation is the goal of the procedure; and

(d) a control parameter *T* (analogue of temperature) and an “annealing schedule” that determines the trend of lowering *T*. For example, after how many random changes in the state is each downward step in *T* taken and how large is the step. The assignment of initial *T* and the annealing schedule may require insight into the problem, trial-and-error, and experience.

The major difficulty in implementation of the above algorithm is that there is no obvious analogy for the temperature with respect to a free parameter in the land use combinatorial optimisation problem we are dealing with. However, Simulated Annealing (Lockwood & Moore, 1993), another heuristic search algorithm closely related to the MA, meets all the characteristics (a) – (d), with a temperature schedule that controls convergence. This MA algorithm does not attempt to converge on a single best solution by slowly lowering a temperature parameter, but rather, the individual component weights are adjusted for finer control of convergence. The concept of the weights is elaborated following Equation [2].

The multi-objective optimisation problem was formulated using Habplan (NCASI Forestry, 2000). Habplan is a landscape management and forest harvest-scheduling program written in Java. Habplan uses a simulation approach based on MA with objective function weights, based on user-defined goals that are adaptively determined at each iteration.

The multi-objective functions for each of the three farm properties were formulated as a sum of 14 objective components. The mathematical formulation was based on the MA simulation and was as follows:

$$E(X^r) = \sum w_j^{r-1} C_j(X^r) \qquad [2]$$

where:

E = energy of system;
X^r = land use and management option schedule at iteration r;
w_j^r = the j th weight based on the iteration r schedule; and
$C_j(X^r)$ = the j th multi-objective function component whose value is evaluated at the r th schedule.

A management schedule involves assigning a specific land use and appropriate management alternative to each of the n management units and therefore the vector, X^r, contains all the possible land uses and management alternatives assigned to n management units (paddocks), $x_1^r,...,x_n^r \in X^r$. The weights, evaluated at each iteration, are based on the user-defined goals g_j, for each objective component. These weights were adjusted between the upper and lower limits defined for each goal component. Therefore, they

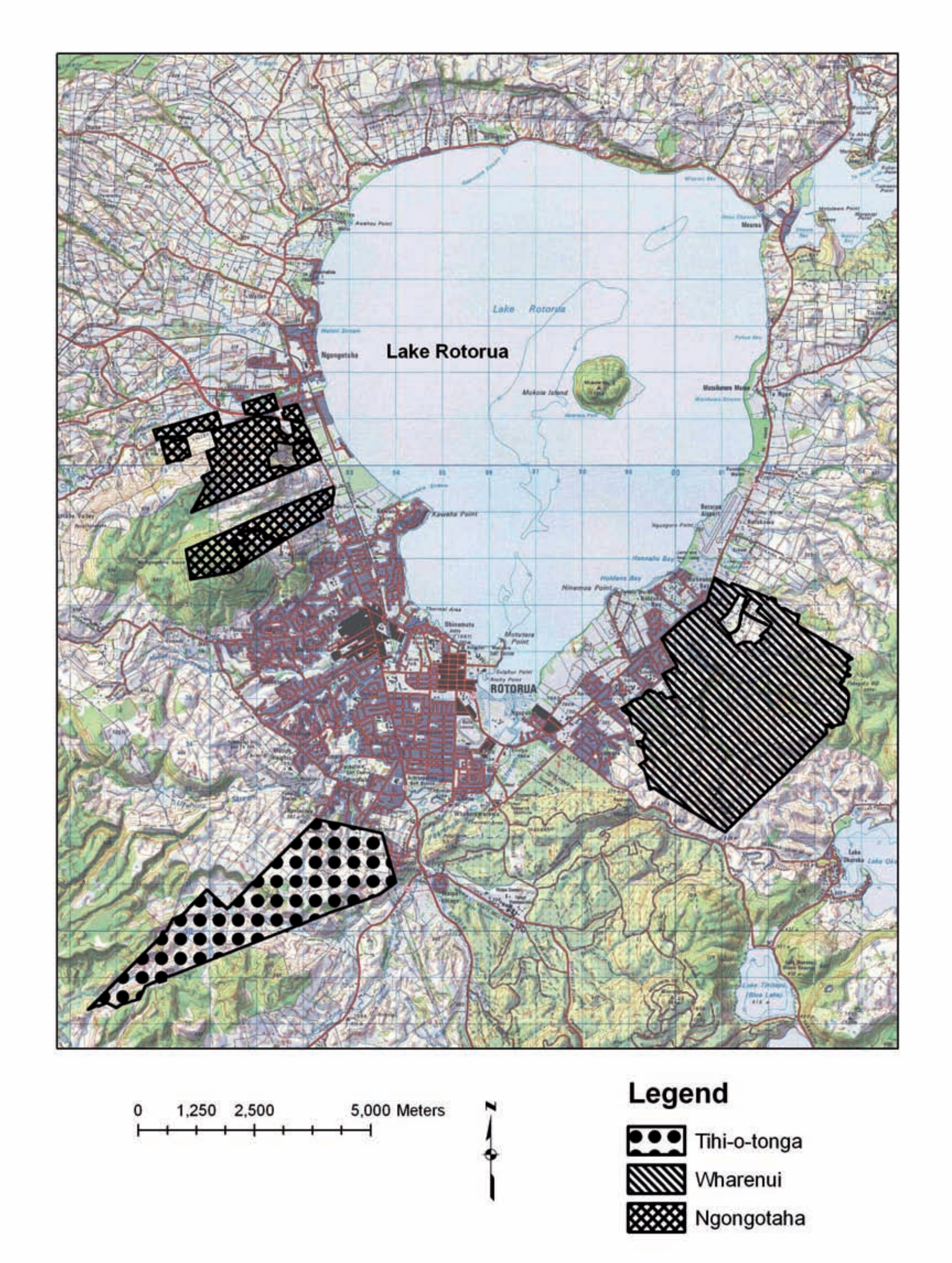

FIGURE 5: Location map of the three NWTL farms, Ngongotaha, Tihiotonga, and Wharenui.

were decreased if the goal, $g_j(X^r)$, is exceeded, or increased if a key goal was not attained (Van Deusen, 1999). Convergence was achieved once a certain level of the weights was attained such that no more changes between the upper and lower limits occurred (Van Deusen, 1999).

This multi-objective function [2] was evaluated at each iteration. The Monte Carlo method estimates the final schedule and then improves on this initial estimate by an unbiased efficient, statistical sample of the vector, X^r. The schedule is represented as a parameter of a hypothetical population and using a random sequence of numbers to construct a sample of the population from which statistical estimates of the parameter can be obtained.

TABLE 2: Composition of NWTL plantation forests.

Species	Age (years)	No. of Paddocks	Area (ha)	Harvestable age (years)
Radiata pine	3	3	24.5	25-35
	4	2	23.9	25-35
	5	2	13.0	25-35
	6	2	19.5	25-35
	7	2	16.6	25-35
	10	1	5.8	25-35
	12	19	108.9	25-35
	16	1	7.6	25-35
	19	1	14.0	25-35
	20	6	56.6	25-35
	21	3	6.8	25-35
	24	1	7.4	25-35
	25	1	0.1	25-35
	26	1	1.1	26-35
	27	3	5.0	27-35
Douglas-fir	20	4	2.1	45-60
	25	1	0.6	45-60
	26	2	1.5	45-60
	31	5	2.3	45-60
Cupressus spp.	17	4	5.9	60
	20	3	7.5	60
	21	3	2.5	60
	23	1	3.4	60
Larch	20	3	14.6	35-60
	21	1	0.8	35-60
Eucalyptus spp.	20	3	1.5	Non-commercial
	21	2	0.7	Non-commercial
	31	1	0.3	Non-commercial

Simulation models and data records

A map of the three NWTL farms is shown in Figure 5. In order to formulate an optimisation problem for each farm using the 14 objectives, data matrices were required that represented a myriad of possible solutions, each of which comprised of mixes of land uses and management alternatives for all paddocks. Each paddock was assigned a number of data matrices. Each matrix was comprised of a series of linked economic and biophysical trends associated with a unique management alternative for a given land use covering the 50-year planning horizon. They were each generated from either specific simulation models (i.e. mathematical functions that are analytically solved to predict the behaviour of a system from a set of parameters and initial conditions) or extrapolated from existing data records.

Development of data matrices

The design of data matrices formed a large part of the formulation of the optimisation model as this equates to creating the space that a heuristic algorithm searches through for optimal solutions. A unique combination of these data matrices for all the management units of a farm defines a potential solution. Those spatial constraints that may not be violated (e.g. the area of each management unit) are hardwired in the data structures. A data matrix for a management unit may have outputs from a single land use or outputs from a variety of different land uses sequenced at different

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times over the planning horizon. The other part of the formulation involves defining the objectives and those spatial constraints that may be relaxed (e.g. an amalgamation of management units to satisfy a threshold area for a unique land use assignment).

Plantation Forest data

Ngati Whakaue Tribal Lands Inc. have 364.5 ha of plantation forests, the majority (320.6 ha) of which is radiata pine. For existing forests, growth and yield tables (i.e. wood volumes by log grade), and related environmental services for commercial species were modelled and collated for radiata pine (*Pinus radiata*), Douglas-fir (*Pseudotsuga menziesii*), two cypress species (*Cupressus lusitanica* and *C. macrocarpa*), larch (*Larix kaempferi*) and eucalyptus species (*Eucalyptus regnans* and other unidentified ones). The existing forest is shown in Table 2 along with possible harvesting alternatives. Projections of growth and yield were modelled only for areas that potentially could be switched to forestry.

For the radiata pine resource, growth and yield tables were derived from simulation modelling, using a combination of data from a large series of experimental plots in the Rotorua basin and inventory plots supplied by Fortus (Forestry Consultants to NWTL) for the current stands. The Scion forest stand simulation model for radiata pine, STANDPAK (Whitehead, 1990), was used to simulate the growth and yield of stands of this species initialised by the inventory information of the current stands. An add-on module to STANDPAK, C-change (Beets et al., 1999), was used to model carbon sequestered and water quantity. A range of alternative forest management regimes was determined through this simulation modelling. The alternatives were simple as they did not involve commercial thinning and just altered the clearfelling age, which was reflected in the size and quality of the products and subsequently the financials.

Another stand simulator, called Calculator, was used for simulating the growth and yield for Douglas-fir (Bateson, 2005). Growth and yield tables for larch were based on empirical data obtained from the farms. The environmental services for all plantation forests included water quantity, water quality (based on nitrogen leaching, phosphorus loss and sedimentation), and carbon sequestered. The sediment regime models used for this analysis were originally developed for the Purukohukohu suite of catchments situated midway between the cities, Rotorua and Taupo on the central North Island volcanic plateau (Dons, 1987). These catchments are predominantly comprised of highly permeable pumice soils that are archetypical of the NWTL properties so this model was applicable to the current situation. A combination of literature review and professional judgement was used to collate environmental services trends that could not be modelled because of lack of appropriate models and/or adequate data.

Indigenous forest data

Indigenous forests cover a total area of 171 ha of the farms and are protected. Consequently, their contribution to the farm capital was predominantly in the form of environmental services. Models for environmental services are scarce and so assumptions were drawn from plantation forests with full site occupancy.

Agricultural data

Agricultural land uses for NWTL included 530 ha in beef, 280 ha in dairy, 815 ha in lamb finishing, and 515 ha in store lamb systems. New management alternatives (as shown in Table 1) were developed with the help of NWTL, based on current research and development by AgResearch (a New Zealand government research agency). Consideration was given to practical issues such as minimum unit size, shed capacity, land slope class, and access. The professional judgement of the CEO and farm manager was relied on heavily here as dynamic models for the environmental impacts of farm land uses and management alternatives were scarce. Consequently, static average values were used (Menner et al., 2004). Water quantity and sedimentation data for pastureland were based on research work done on the North Island of New Zealand (Dons, 1987).

Economic data

Different economic instruments were used to assess investment opportunities in terms of profit, in agriculture and forestry. For agriculture, it is normal to use the farm's gross margin, which is representative of the level of profit that could be expected on an average farm under "normal" conditions. For forestry, net present value (a standard method for the financial appraisal of long-term projects) is predominantly used. A common economic instrument was needed to measure both profitability and feasibility since the NWTL farms operated a mixture of agriculture and forestry. Farm gross margins were suitable for short-term projects such as annual crops or leasing land on a yearly basis. In contrast, net present value is a single number that summarises the difference between the costs and revenue over a whole rotation. Once calculated, however, it is easy to convert to an annual basis called annual equivalent (AE) as follows (Hubbard et al., 1988) so that each year (over the rotation length) is assigned a value:

$$AE = NPV\,[i(1 + i)n] / [(1 + i\,)n - 1] \qquad [3]$$

where

NPV = Net Present Value;
n = final time in years; and
i = 0 to $n-1$ years.

Feasibility is still difficult to identify even when AEs are used for an analysis, because the AE is a constant over the rotation length. The best solution is to use a combination of explicit discounted costs and discounted benefits specified at the time when they are expected to occur. This is preferable to using a single econometric parameter such as NPV that hides the information of when and how much a return/cost occurs during a rotation and ultimately a planning period. Annual equivalents were used initially for the analysis, although the financial constraints (such as a capping on the costs per year that NWTL were willing pay) did not seem to have much effect. Switching to discounted cash flows, caused the model to become sensitive to financial constraints, making it possible to assess feasibility on the basis of both available revenue and profitability. The discounted cash flows were used for calculating EBIT and EBITD for both forestry and agricultural activities.

The discount rate used for calculating the impact of time or interest charged for capital invested was varied for the different land use options on the basis of the perceived risk associated with the investment and the current bank rate likely to be received for term deposit. Costs of purchasing livestock or dairy shares as part of operating costs.

Depreciation on capital items such as sheds, fences, and water was calculated by dividing the cost with its life expectancy. The life expectancy of each item was determined and it was assumed that the capital item had zero value at the end of that period.

For commercial forestry applications, average costs per hectare for establishment and tending operations were obtained from existing forestry companies in the Bay of Plenty. These costs were compared with some costs previously incurred by NWTL and found to be closely aligned so were used without modification. Specific costs for a particular stand may vary because of ground slope, weeds, and access, but this was not included in this analysis. Log prices were taken as market averages as at June 2005 and logging costs were derived from industry averages and adjusted for piece size using a simple model (MAF, 2009).

The annual farm accounts were used to build databases for productivity, costs, and prices scenarios for beef, dairy, lamb finishing and store lamb systems. The farm accounts were updated using the 2006/07 budget forecast as at September 2006.

The detailed costs and revenues used to calculate the agricultural EBIT and EBITD have not been disclosed here for the sake of confidentiality.

Results

The two results presented here for WLUM are non-dominating and may add value to decision-making for the Wharenui property. A single possible solution is presented for each of the other two properties, Ngongotaha and Tihiotonga.

Wharenui farm

Two possible scenarios are described which were run at the request of NWTL board. Scenario 1 involved retaining dairy farming while scenario 2 did not. The description of scenarios 1 and 2 relate to the temporal graphical plots and spatial results shown in Appendices A and B respectively.

Scenario 1

Under this scenario, the model chose to retain the dairy operation but switched it to an alternative with the nitrification inhibitor technology. This alternative had the highest annual EBIT of NZ$159/ha of all dairy alternatives and was only second to beef cattle, which had an annual EBIT of NZ$167/ha. The expectation was that the beef cattle option would be chosen over any dairy options in order to maximise EBIT. However, the best performing option/strategy (for any criterion) at a paddock level is not necessarily the best at a farm level because of complex interactions with other variables in the search space.

The dairy nitrification inhibitor option involved an estimated 32 kg/ha/y of nitrogen leaching as opposed to 55 kg/ha/y for the dairy *status quo* option. Maximising the EBIT for Wharenui also resolved the nitrogen leaching problem by reducing nitrogen from 32 601 kg in year 1 to 22 682 kg in the 11th and subsequent years (a 30.4% reduction). Not only was there a 42% reduction in nitrogen leaching/ha but there were also reductions in phosphorus (16%) and sediment losses (average 9%) during that same period.

A 62% increase in pine plantation area (from 286 ha to 463.5 ha) contributed significantly to the reduction in nitrogen leaching, phosphorus and sediment losses. Water quantity was never an issue but it was important to include it in the balance sheet for sustainability to ensure that satisfying the other objectives would not be done at the expense of water quantity. There was no appreciable drop or increase in the water quantity other than close to cyclical small peaks and troughs of the quantity of surface water flow over the planning horizon.

The spatial constraints were satisfied up to 96% for 80% of the goal target that was specified in the model. Because not all spatial constraints were satisfied, isolated paddocks (in terms of land use) would have to

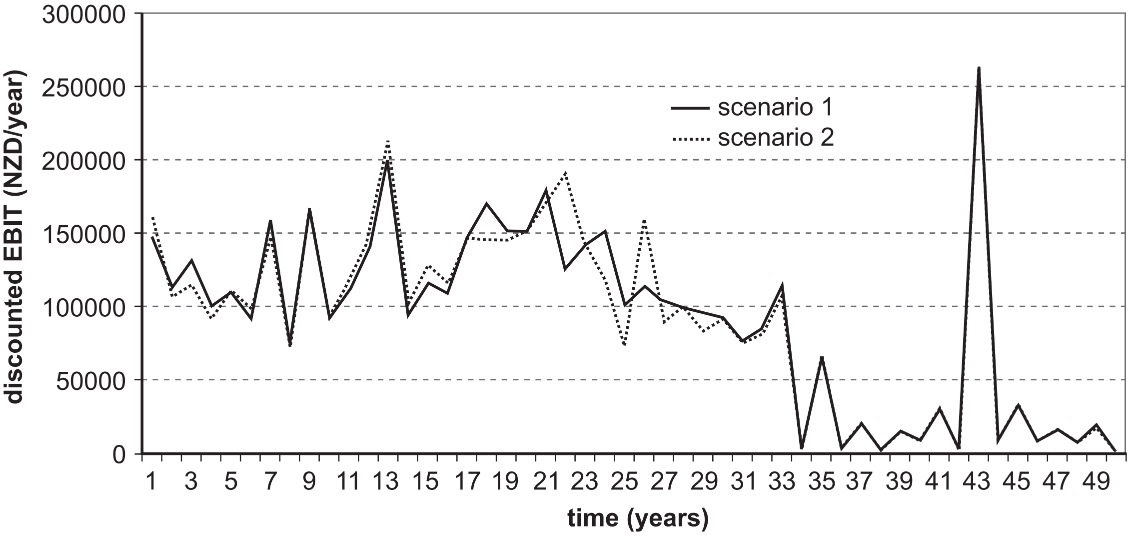

FIGURE 6: A comparison of the discounted EBIT for scenarios 1 and 2, for Wharenui farm.

be merged with neighbouring large contiguous block of paddocks. This allowed a common management option to be assigned (for implementation purposes) in order to maximise economies of scale. At year 50, the land area distribution remained at 163.6 ha for beef cattle, but with dairy cattle scaled down by 22.3% (from 299.2 to 232.5 ha including the nitrification inhibitor option and sheep were reduced by 2.4% (from 533.4 to 520.5 ha). There was no change in the area under forestry.

Scenario 2

In this scenario, the paddocks currently under dairy were given the option to go either to beef cattle or plantation forestry. There were no significant differences in results between Scenario 1 and Scenario 2 outputs, especially the financials (see Figure 6 with the comparisons of the discounted EBIT). At year 50, land area distributions had increased for beef cattle (134%; from 163.6 to 382.4 ha), radiata pine plantation (59.7%; from 286 – 456.7 ha) and sheep (1.4%; from 533.4 – 541.1 ha).

Ngongotaha farm

The temporal results in the form of graphical plots and spatial results are shown in Appendix C. The area of beef cattle increase by 120% (from 136.5 to 301.2 ha), while the radiata pine plantation area increased by 18.0% (from 72.3 to 85.4 ha). Up to 94.8 % of the area originally used for lamb finishing (with an annual EBIT of NZ$142.46/ha) was converted to a use with a higher EBIT. The new use was beef cattle which had the highest annual EBIT of NZ$167.00/ha for all the land uses considered. Sheep breeding land also had a low annual EBIT (NZ$123.35/ha) so this was all converted to beef cattle.

The beef cattle option was the preferred land use choice for maximising EBIT. Unfortunately, maximising the EBIT resulted in a 17.6% increase in nitrogen leaching (average of 7773 kg up to year 11 but 9146 kg in year 12 onwards). This is because beef cattle cause higher nitrogen leaching than either lamb finishing or sheep breeding (25 kg/ha/y cf 16 and 18 kg/ha/y, respectively). If this level of increase in nitrogen leaching was unacceptable, a constraint may have been specified on the nitrogen leaching. This would result in a mix of beef cattle and lamb finishing that would simultaneously maximise EBIT and minimise nitrogen leaching.

An increased area in pine plantation (from 72.3 ha to 85.4 ha) contributed to a reduction in phosphorus and sediment losses (7.7% and 48.9% respectively). Water quantity was not a problem at this farm but it was modelled was to ensure that it was not compromised by any solution adopted for sustainable development. This was indeed the case.

Spatial constraints were included in the model which allowed each paddock to recognise its neighbours. This meant that that chosen land use for each paddock affected the choice of land uses in neighbouring paddocks. Not all spatial constraints were satisfied for 80% of the goal that was specified in the model. As with Wharenui, this resulted in isolated paddocks (in terms of land use) being merged with neighbouring large contiguous blocks of paddocks. A common management option was then assigned (for implementation purposes) in order to maximise economies of scale. At year-50, the land use area distribution was as follows: 301.2 ha for beef cattle; 0.02 ha for lamb finishing; none for sheep breeding; 85.4 ha for radiata pine; and unchanged for the rest of the other land uses.

Tihiotonga farm

Beef cattle experienced a massive 230.6% increase in area (from 152.8 to 505.2 ha), although it was superseded by an even larger (273.5%) increase in radiata pine plantation area (from 20.8 to 77.7 ha). All the area originally under lamb finishing was converted and the area for sheep breeding was reduced by 65.8% (from 303.9 to 107.2 ha). The converted area mainly went into beef cattle with the remainder going into radiata pine. Appendix D shows the temporal results as graphs and maps.

As with the Ngongotaha farm, the expectation for the Tihiotonga farm was that the high annual EBIT for beef cattle would make it the preferred predominant land use of choice to maximising EBIT across the farm. Unfortunately, maximising the EBIT resulted in a 25.7% increase in nitrogen leaching (average of 12 000 kg up to year 11 but 15 085 kg in year 12 onwards). This was again because beef cattle cause higher nitrogen leaching than either lamb finishing or sheep breeding. If this level of increase in nitrogen leaching was unacceptable, a constraint may have been specified on the nitrogen leaching. This would result in a mix of beef cattle and lamb finishing that would simultaneously maximise EBIT and minimise nitrogen leaching.

An increase in area to pine plantation (from 20.8 to 77.7 ha) contributed to a reduction in phosphorus and sediment losses (7.7% and 54.5% respectively).

Unlike the Ngongotaha farm, the spatial constraints for the Tihiotonga farm were satisfied for 80% of the goal target that was specified in the model. At year 50 the land area distribution was as follows: 505.2 ha for beef cattle; 0.3 ha for lamb finishing; 107.2 ha for sheep breeding; 77.7 ha for radiata pine; and unchanged for the rest of the other land uses.

Discussion

Ngati Whakaue Tribal Lands Inc. is currently undertaking important strategic decisions for their farm properties with a view of growing their net worth to NZ$100 million with an annual profit of NZ$10 million by the year 2010. A realisation of this vision would also provide a boost to the local economy of the Rotorua District. NWTL are also actively working to satisfy their sustainable development plans under the confines of Rule 11, through the determination of appropriate mixes of land uses and management alternatives. The definition of these issues was a dynamic process that evolved through time, determined by the clients' needs and expectations. The availability/unavailability of data influenced the definition of the problem, which flowed through into the formulation of the optimisation problem. Despite these limitations, 50-year management plans were determined for the three farm properties using the best available information in a multi-objective optimisation framework. Profitability was a major issue for NWTL and so EBIT was maximised. This was generally achieved by increasing the land area under beef cattle and forestry at the expense of sheep operations.

Uncertainties are pervasive in decision-making and if not taken into account can result in less than stellar decision-making. Most models we use predict trends, based on the bell-curve, and therefore ignores large deviations. This is a sure way of underestimating risk because prediction is degraded as the projected period lengthens, and the random nature of the variable being projected matters (Taleb, 2007). Since the biophysical trends and prices of commodities we used for the optimisation were model projections and values kept constant over time (especially prices for commodities), the optimisation solutions underestimated risk and were, therefore, less robust. Savage (2002) summarised the underestimation of risk by assuming average conditions (which is similar to bell-curve assumptions) as the Flaw of Averages. The Flaw of Averages states that plans based on the assumption that average conditions will occur are usually wrong (Savage, 2002).

The agricultural/forestry revenue data we used were based on current commodity pricing that was kept constant over the 50-year planning period. The biophysical data were also based on data generated from simulation models based on the bell-curve. Our use of these data meant that our formulation of the optimisation problem was subject to the Flaw of Averages and this is a weakness in the analysis. Unfortunately we are unable to quantify the difference in decision-making that would be made from adopting techniques in the analysis which would neutralise the Flaw of Averages. Bell-curve assumptions remove data variability and so many risks may be masked and the magnitude of economic return opportunities may remain unknown and untapped.

Although the framework used here lacked stochastic treatment to avoid Flaw of Averages, this work demonstrates that a capability for addressing sustainability issues that span environmental, social and economic aspects exists in New Zealand. Subjecting both biophysical and market/commodity data to Monte Carlo simulations may produce more realistic simulations and subsequently a more risk-robust optimisation outcome. Future research work will focus on development of a framework for regional/national level as was demonstrated for ecologically sustainable forest management in Australia (Chikumbo et al., 2000; Turner et al., 2002).

Conclusions

The evaluation undertaken here has produced a detailed balance sheet that contains not only all financial information but also an account of both environmental impacts and implicit social and cultural concerns for three farms (Warner, 2003). A key outcome of the evaluation was to recommend major changes in land use at these farms.

Adopting scenarios in full across the time span modelled will largely depend on the client's ability to manage risk in the short term and long term. Minimising risk requires having the best possible estimates of the optimum mix of land uses needed to produce a profitable portfolio. Papers, such as Makdissi and Wodon (2009), have shown that weather and finance are the biggest short-term risks farmers face. Such risks may be mitigated using instruments such as insurance and alternative agricultural options. Ngati Whakaue Tribal Lands Inc. will need to consider the financial implications of managing these risks. There is also a risk in adopting any new technology/options that have not yet been demonstrated at a farm level except under controlled conditions. There is also a systemic risk involving a number of interlinked factors. A problem with any one of these may lead to a cascading failure that causes the entire system to collapse. In order to minimise all these risks, we recommend that NWTL maintains diversification, but increase the land area under beef cattle and forestry at the expense of sheep operations.

Our results recommended that the current dairy farming operations at Wharenui be replaced either with a new dairy operation incorporating nitrification inhibitor technology or by beef cattle and plantation forestry. Ngati Whakaue Tribal Lands Inc. are now in the process of implementing these research findings by stopping dairy farming at Wharenui. The new alternatives land uses will reduce both nitrogen leaching and phosphorus loss (Taylor, 2007). The Rotorua District Council is also helping NWTL with additional measures that will bring economic, environmental, social and cultural benefits (Short, 2007).

Further development and improvement of this systems approach should involve incorporating predicted stochastic prices for forest and agricultural products. This will capture underlying statistical relationships that will help find optimal risk-based trade-offs between different objectives.

Similar modeling systems should also be applied to other complex land use and planning problems elsewhere in New Zealand and overseas.

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References

APR Consultants. (2005). Rotorua Economic Profile. Prepared for Destination Rotorua Economic Development. Updated January 2005. Retrieved June 2006 from http://www.e-c.co.nz/rdc/myfiles/Rotorua_Economic_Profile_-_update_Dec_04.pdf

Bateson, J. (August 2005). The calculator revisited - every farm forester should have one. *New Zealand Tree Grower, 26*(3), 16.

Beets, P. N., Robertson, K. A., Ford-Robertson, J. B., Gordon, J., & Maclaren, J. P. (1999). Description and validation of C change: a model for simulating carbon content in managed *Pinus radiata* stands. *New Zealand Journal of Forestry Science, 29*(3), 409-427.

Bellman, R. E. (1957). *Dynamic programming*. Princeton, NJ, USA: Princeton University Press.

Brand, D., & McCaughey, H. (October 2005). Looking beyond carbon. *Environmental Finance*. ADD PAGE NUMBERS.

Chandler, D., (1987). *Introduction to modern statistical mechanics*. New York, NY, USA: Oxford University Press.

Chikumbo, O., Bradbury, R. H., & Davey, S., (2000).

Large-scale ecosystem management as a complex systems problem: Multi-objective optimisation with spatial constraints. In S. Halloy and T. Williams (Eds.) *Applied Complexity - From Neural Nets to Managed Landscapes* (pp. 124-155). Christchurch, New Zealand: New Zealand, Institute for Crop & Food Research Ltd.

Csete, M. E., & Doyle, J. C. (2002). Reverse engineering of biological complexity. *Science, 295*, 1664-1669.

De Jong, K. A., & Spears, W. M. (1989). Using Genetic Algorithms to Solve NP-Complete Problems. In J. D. Schaffer (Ed.), *Proceedings of the Third International Conference on Genetic Algorithms, George Mason University, Fairfax, VA, USA* (pp. 124-132). San Francisco, CA, USA: Morgan Kaufmann Publishers Inc.

Dons, A. (1987). Hydrology and sediment regime of a pasture, native forest, and pine forest catchment in the Central North Island, New Zealand. *New Zealand Journal of Forestry Science, 17*(2/3), 161-78.

Environment Bay of Pleanty (EBOP). (2000). *Strategy for the lakes of the Rotorua district*. Rotorua, New Zealand: Environment Bay of Plenty, Te Arawa Māori Trust Board and Rotorua District Council.

Environment Bay of Pleanty (EBOP). (2005). *What is Rule 11?* Retrieved Jan 2006 from http://www.ebop.govt.nz/water/media/pdf/Lakes_Rule11_221105.pdf

Environmental Defence Society. (2007). *Rotorua's dying lakes - the need for action*. Retrieved Jan 2008 from http://www.eds.org.nz/campaigns/water/actions.cfm

Fonseca, C. M., & Fleming, P. J. (1993). Genetic Algorithms for multi-objective optimisation: Formulation, discussion and generalisation, In S. Forrest, (Ed.). *Genetic Algorithms: Proceedings of the Fifth International Conference, Urbana-Champaign, IL USA* (pp. 416-423). San Francisco, CA, USA: Morgan Kaufmann.

Glover, F. (1994). *Tabu search fundamentals and uses*. Technical Paper, Graduate School of Business. Boulder, CO, USA: University of Colorado at Boulder.

Goldberg D. E. (1989). *Genetic algorithms in search, optimization, and machine learning*. Reading, MA, USA: Addison-Wesley.

Hubbard, W. G., Abt, R. C., & Duryea, M. L. (1988). *Estimating the profitability of your forest enterprise*. (Circular 836). Gainesville, FL,USA: University of Florida, Cooperative Extension Service, Institute of Food and Agricultural Sciences.

Kirkpatrick S., Gelatt, C. D., & Vecchi, M. P. (1983). *Optimisation by simulated annealing. Science, 220*, 671-680.

Lin, S., & Kernighan, B. (1973). *An efficient heuristic procedure for the travelling salesman problem. Operations Research, 21*, 498-516.

Lee, J. (2004). *A First Course in Combinatorial Optimization*. Cambridge, UK: Cambridge University Press.

Lockwood, C., & Moore, T. (1993). Harvest scheduling with spatial constraints: a simulated annealing approach. *Canadian Journal of Forest Research, 23*, 468-478.

Makdissi, P., & Wodon,Q. (2009). *Can risk adverse competitive input providers serve farmers efficiently in developing countries?* (Policy Research Working Paper 4922). Washington DC, USA: The World Bank, Human Development Network.

Ministry of Agriculture and Forestry (MAF), (2009). *Indicative New Zealand Radiata Pine Log Prices*. Retrieved Jan 2009 from http://www.maf.govt.nz/forestry/statistics/logprices

Menneer, J. C. Ledgard, S. F, & Gillingham A. G. (2004). *Land use impacts on nitrogen and phosphorus loss and management options for intervention*. (Client Report for Environment Bay of Plenty). Hamilton, New Zealand: AgResearch.

Morgenstern, U., Reeves, R., Daughney, C., & Camron, S. (2004). *Groundwater age, time trends in water chemistry and future nutrient load in the Lakes Rotorua and Okareka Area*. (Client Report prepared for Environment Bay of Plenty, Project Number: 520W2008). Wellington, New Zealand: Institute of Geological and Nuclear Sciences.

NCASI-Forestry. (2000). *Habplan: Software for Forest Harvest Scheduling - Documentation*. Research Triangle Park, NC, USA: National Council for Air Stream Improvement Inc.

Osborne, M. J., & Rubenstein, A. (1994). *A course in game theory* (p.7). Cambridge, MA, USA: MIT Press.

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. (1992). *Numerical recipes in C: The Art of Scientific Computing*. New York, NY, USA: Cambridge University Press.

Rana, S. (1999). *Examining the role of local optima and schema processing in genetic search*. Fort Collins, CO, USA: Colorado State University, Department of Computer Science.

Richardson, P., & Botherway, K. (2006). *Restoring the Rotorua Lakes: the ultimate endurance challenge*. Parliamentary Commissioner for the Environment, Wellington, NZ. Retrieved Jan 2007 from http://www.pce.parliament.

nz/__data/assets/pdf_file/0011/1226/rotorua.pdf.

Rolland, E., & Gupta, R. (1996). *New linkages between GIS and combinatorial optimisation*. Americas Conference on Information Systems, Retrieved from: http://hsb.baylor.edu/ramsower/ais.ac.96/papers/rolland.htm.

Quagliarelli, D., Periaux, J., Poloni, C., & Winter, G. (Eds), (1997). *Genetic Algorithms in Engineering and Computer Science*. Chichester, UK: John Wiley & Sons Ltd.

Savage, S. L. (2002, November). The Flaw of Averages. *Harvard Business Review*.

Short, M. (2007, July 19). Council and Ngati Whakaue together. *The Daily Post*. Rotorua, New Zealand: APN News & Media Ltd

Srinivas, N., & Deb, K. (1994). Multi-objective optimisation using non-dominated sorting in genetic algorithms. *Journal of Evolutionary Computation, 2*(3), 221-248.

Stewart, T. J., Janssen, R., & van Herwijnen, M. (2004). A genetic algorithm to multi-objective land use planning. *Computers and Operations Research, 31*, 2293-2313.

Taleb, N. N. (2007). *The Black Swan: The Impact of the Highly Improbable*. London, UK: Penguin Books.

Taylor, C. (2007, June 6). Mini City plans for Eastside. *The Daily Post*. Rotorua, New Zealand: APN News & Media Ltd

Money can grow on trees - A Special Report on Forests. (2010, September 23). *The Economist*.

Tolle, T., & Czaplewski, R. L. (1995). An interagency monitoring design for the Pacific Northwest forest ecosystem plan. In J. E. Thompson (Compiler), *Analysis in Support of Ecosystem Management. Analysis Workshop III* (pp. 293-307). Fort Collins, CO, USA: United States Department of Agriculture.

Turner, B. J., Chikumbo, O., & Davey, S. M. (2002). Optimisation modelling of sustainable forest management at the regional level: an Australian example. *Ecological Modelling, 153*(1-2), 157-179.

Van Deusen, P. C. (1999). Multiple solution harvest scheduling. *Silva Fennica, 33*(3), 207-216.

Warner, M. (2003). Putting the Sustainable 'Development' Performance of Companies on the Balance Sheet. London UK: Overseas Development Institute.

Whitehead, I. D. (1990). STANDPAK stand modelling system for radiata pine. In R. N. James & G. L. Tarlton (Eds.), *New approaches to spacing and thinning in plantation forestry*. (FRI Bulletin No 151). Wellington, New Zealand: Ministry of Forestry.

Yano, H., & Sakawa, M. (1989). A unified approach for characterizing Pareto optimal solutions of multiobjective optimization problems: The hyperplane method. *European Journal of Operational Research 39*(1), 61-70.

APPENDIX A: Multi-objective optimisation results for Wharenui farm under Scenario 1. Results over a 50-year planning period are described in A1 through A11. Land use change results in years 1, 2, 5, 10 and 50 are described in A12 through A16, respectively.

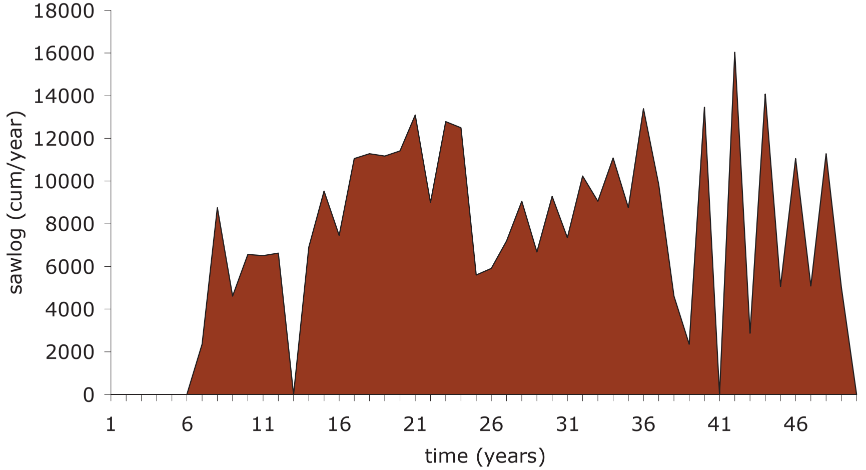

Figure A1. Wharenui farm Scenario 1: Sawlog harvest (m^3/y)

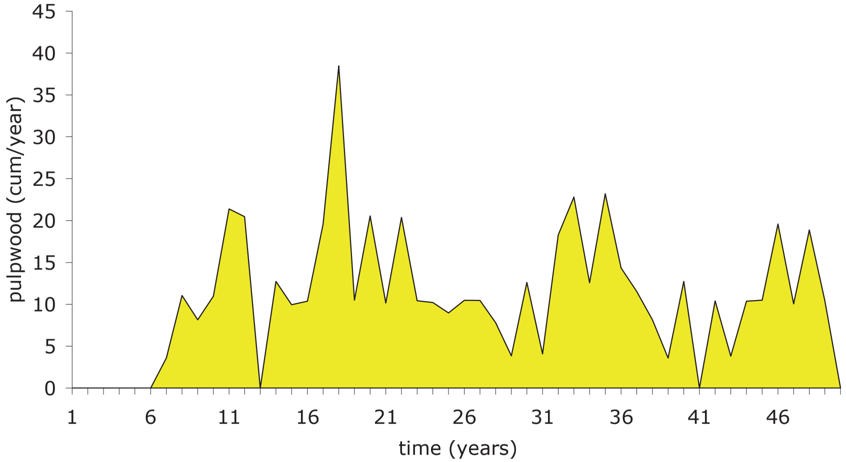

Figure A2. Wharenui farm Scenario 1: Pulpwood harvest (m^3/y)

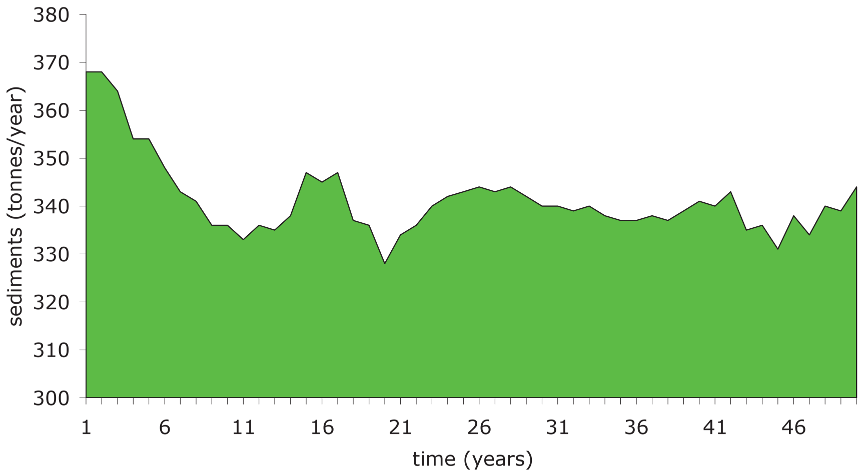

Figure A3. Wharenui farm Scenario 1: Sediment production (tonnes/y)

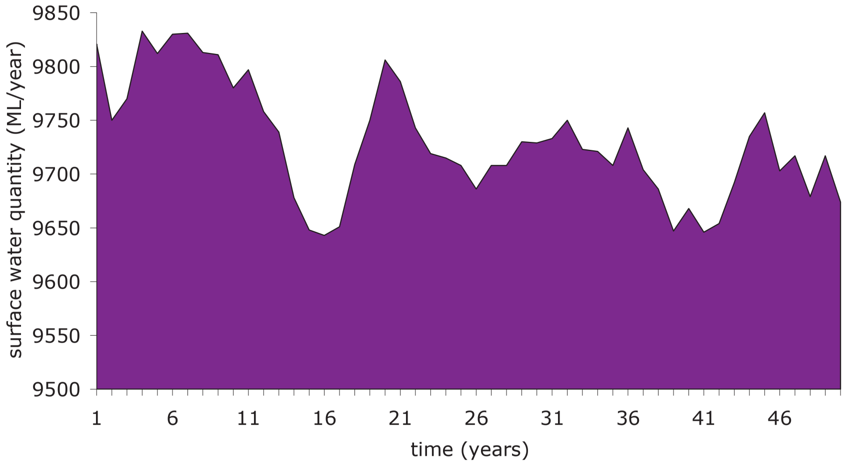

Figure A4. Wharenui farm Scenario 1: Surface water flow (ML/y)

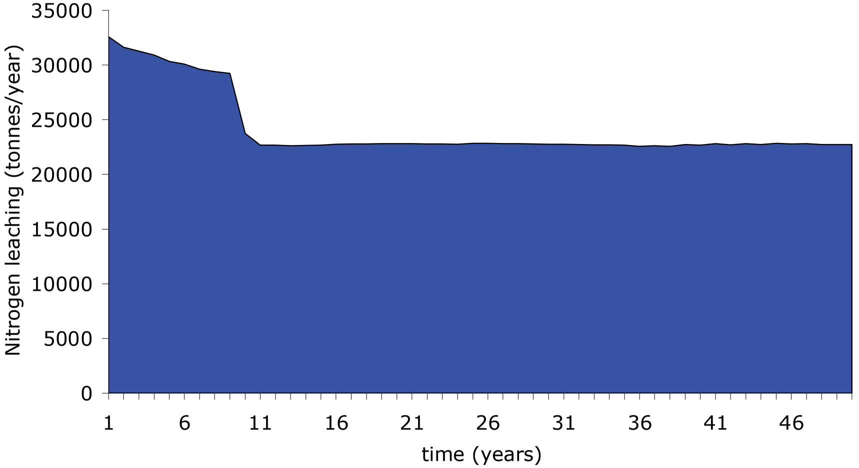

Figure A5. Wharenui farm Scenario 1: Nitrogen leaching (kg/y)

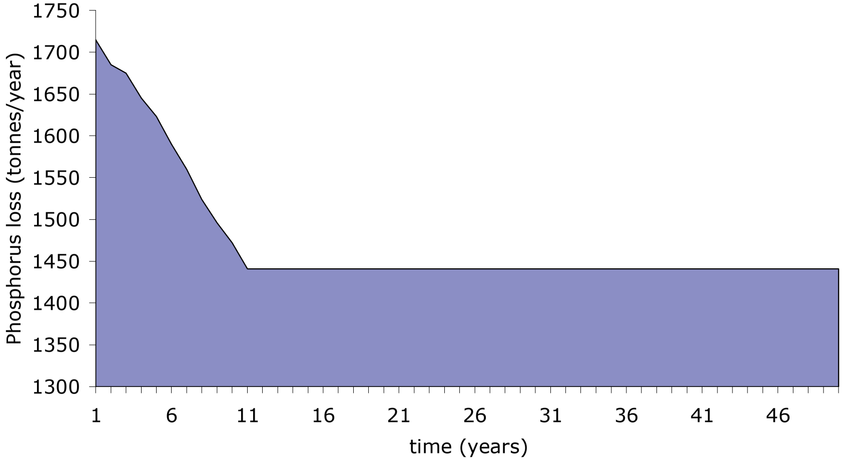

Figure A6. Wharenui farm Scenario 1: Phosphorus loss (kg/y)

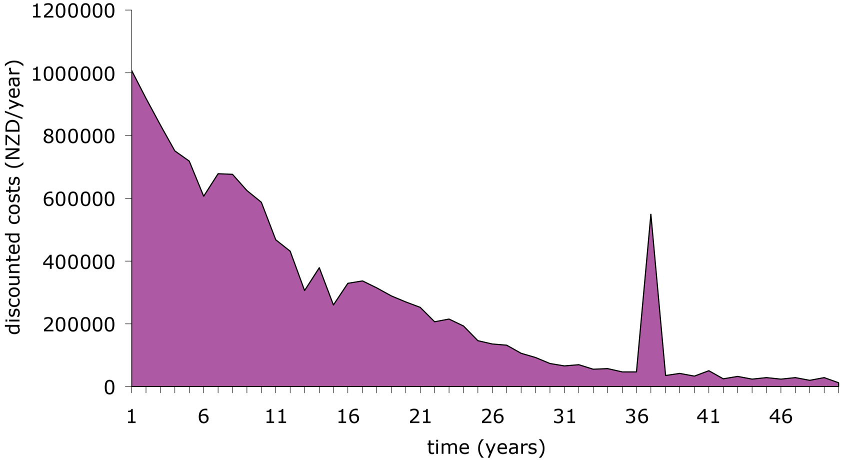

Figure A7. Wharenui farm Scenario 1: Discounted costs (NZD/y)

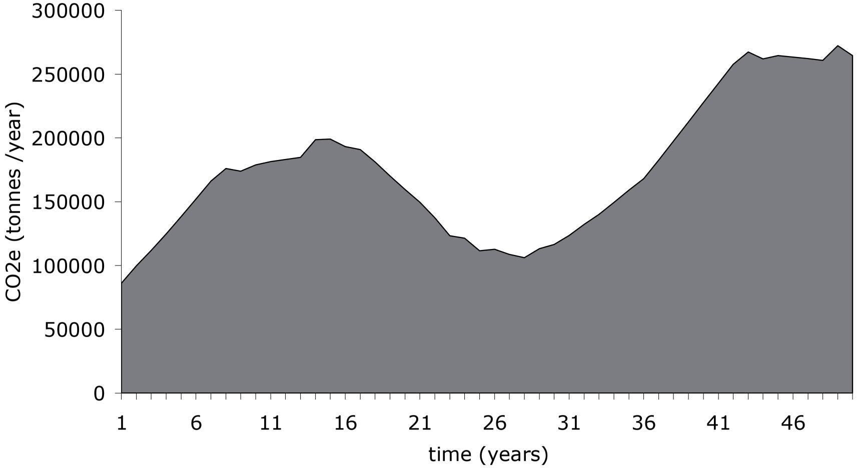

Figure A8. Wharenui farm Scenario 1: Carbon sequestrated (tonnes/y)

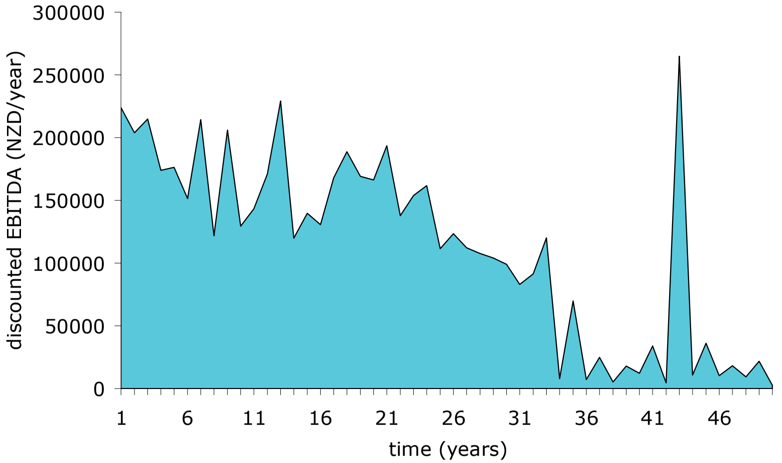

Figure A9. Wharenui farm Scenario 1: Discounted EBITDA (NZD/y)

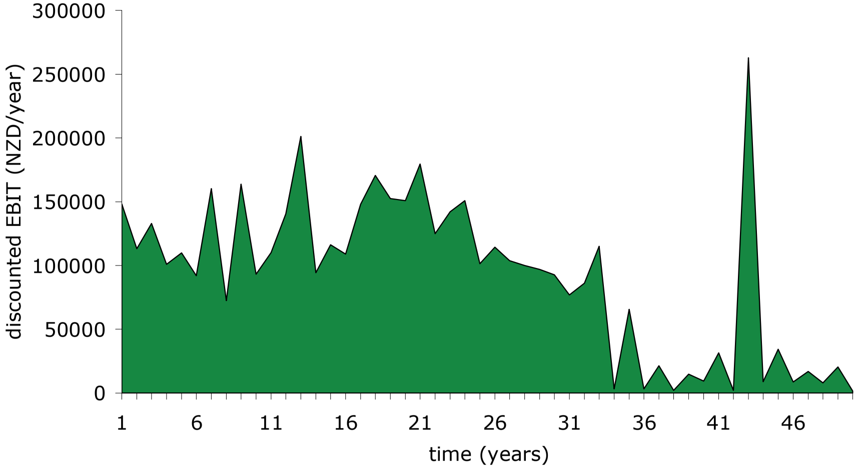

Figure A10. Wharenui farm Scenario 1: Discounted EBIT (NZD/y)

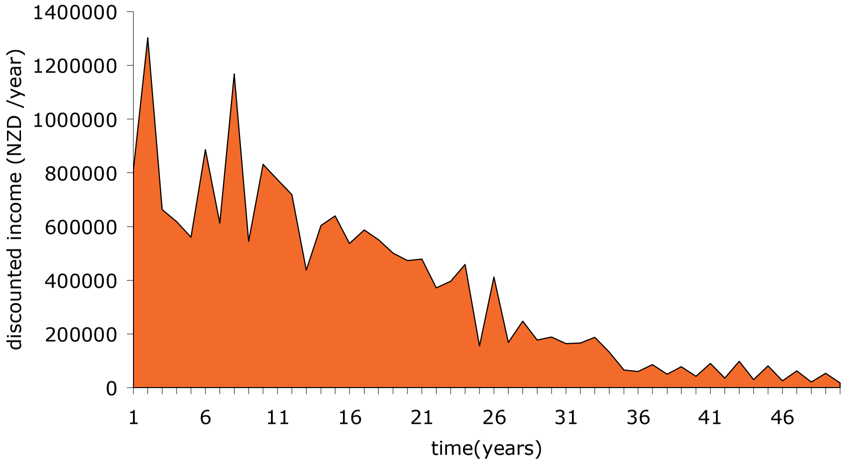

Figure A11. Wharenui farm Scenario 1: Discounted income (NZD/y)

Legend

🟧 Income
▨ EBITDA
▨ Carbon sequestrated
🟪 Costs
🟩 EBIT
▨ Phosphorus
🟦 Nitrogen
▨ Water Quality
🟩 Sediments
🟫 Sawlog
🟨 Pulpwood

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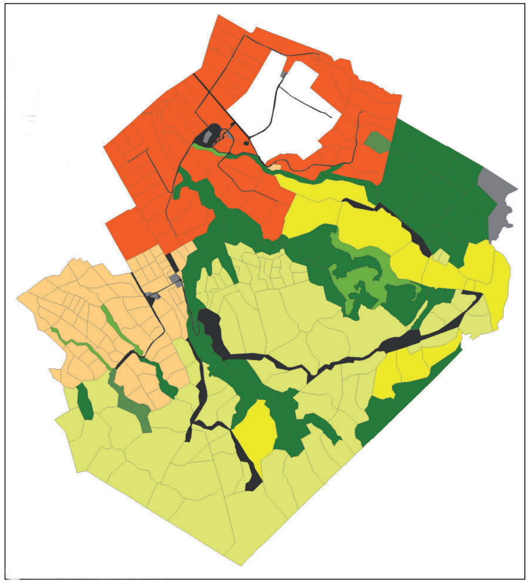

Figure A12. Wharenui farm Scenario 1: Land use change year 1

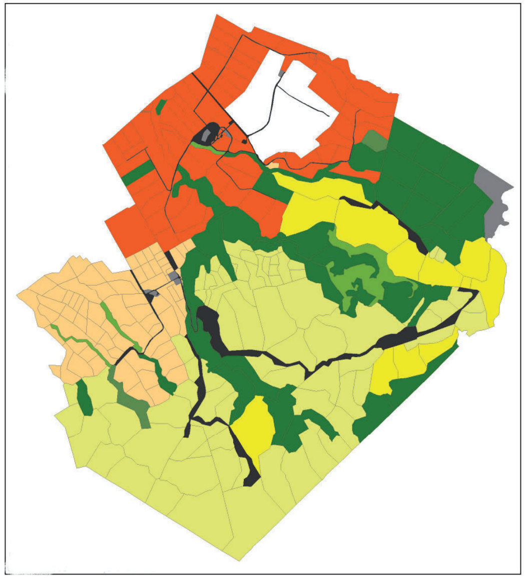

Figure A13. Wharenui farm Scenario 1: Land use change year 2

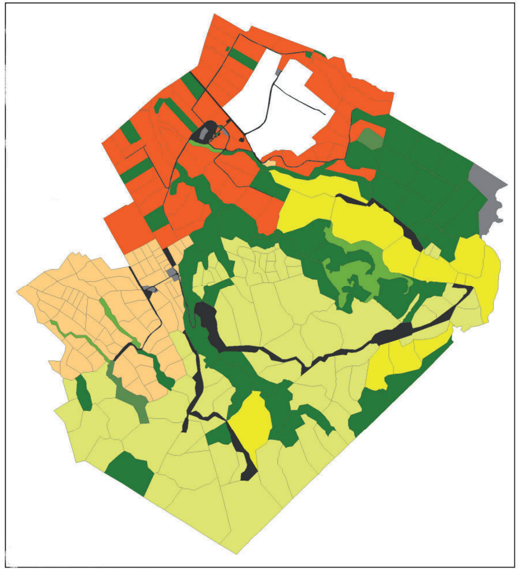

Figure A14. Wharenui farm Scenario 1: Land use change year 5

Figure A15. Wharenui farm Scenario 1: Land use change year 10

Figure A16. Wharenui farm Scenario 1: Land use change year 50

Legend

🟧 beef cattle
🟩 sheep breeding and finishing
🟨 breeding store lambs
🟥 dairy
🟩 radiata pine
🟩 cypress pine
🟩 mixed non-commercial forest
⬛ building infrastructure
⬛ road
🟪 dairy option with nitrification inhibitor

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APPENDIX B: Multi-objective optimisation results for Wharenui farm under Scenario 2. Results over a 50-year planning period are described in B1 through B11. Land use change results in years 1, 2, 5, 10 and 50 are described in B12 through B16, respectively.

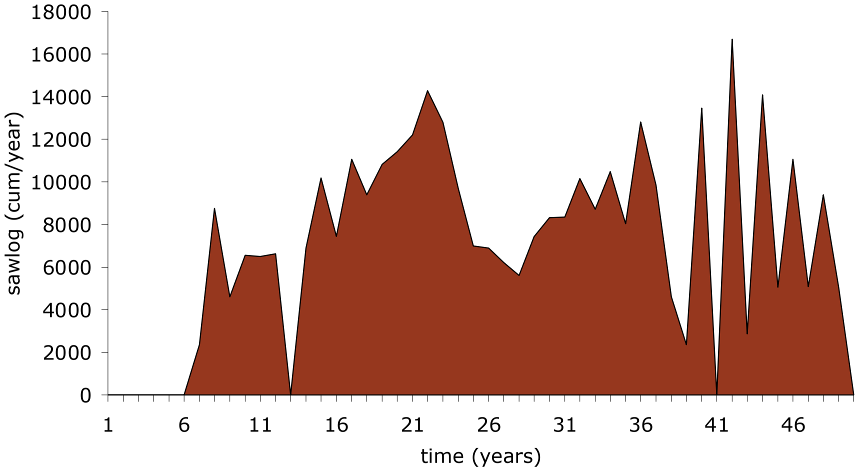

Figure B1. Wharenui farm Scenario 2: Sawlog harvest (m^3/y)

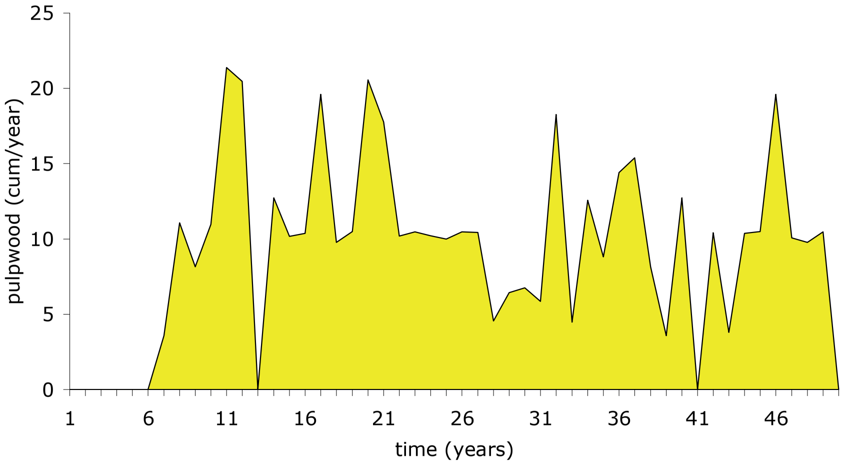

Figure B2. Wharenui farm Scenario 2: Pulpwood harvest (m^3/y)

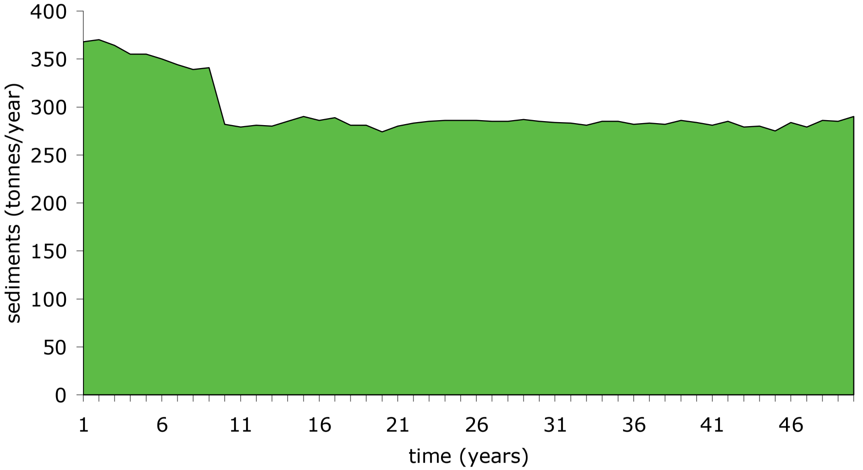

Figure B3. Wharenui farm Scenario 2: Sediment production (tonnes/y)

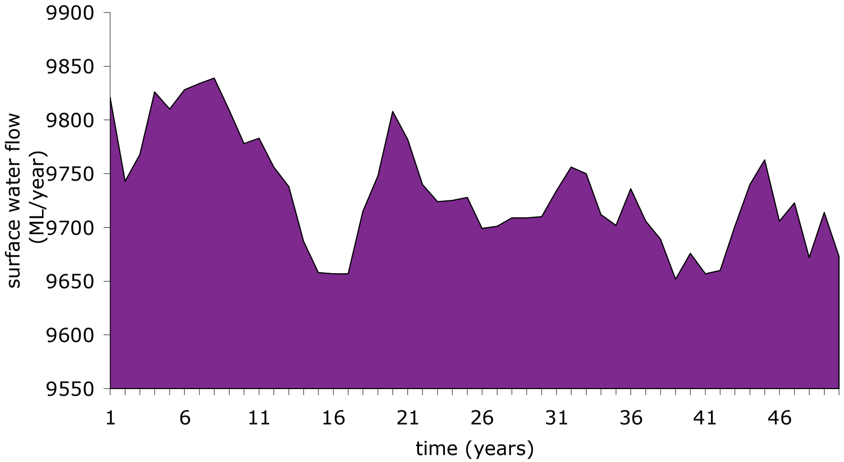

Figure B4. Wharenui farm Scenario 2: Surface water flow (ML/y)

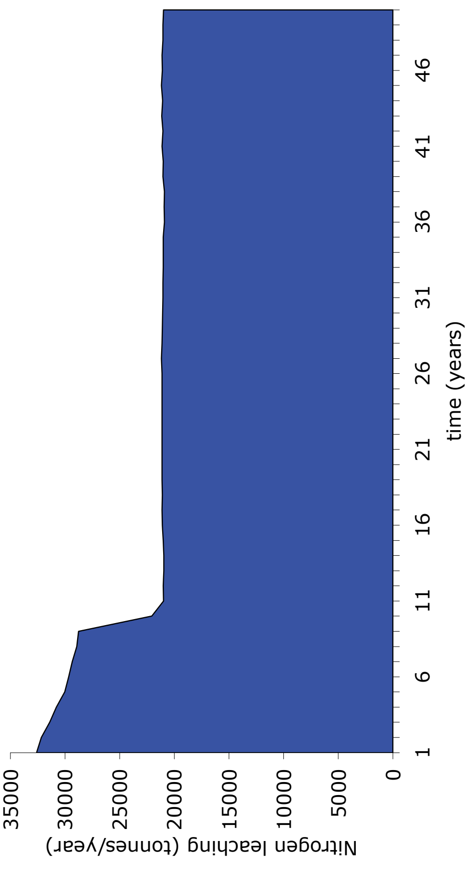

Figure B5. Wharenui farm Scenario 2: Nitrogen leaching (kg/y)

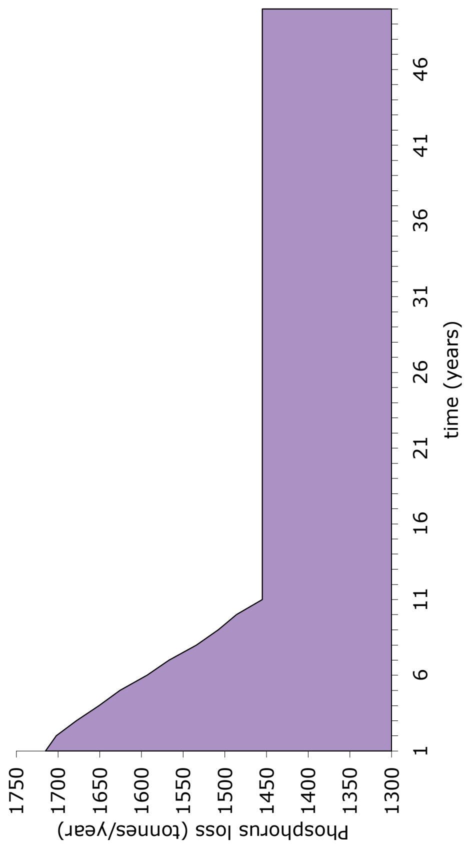

Figure B6. Wharenui farm Scenario 2: Phosphorus loss (kg/y)

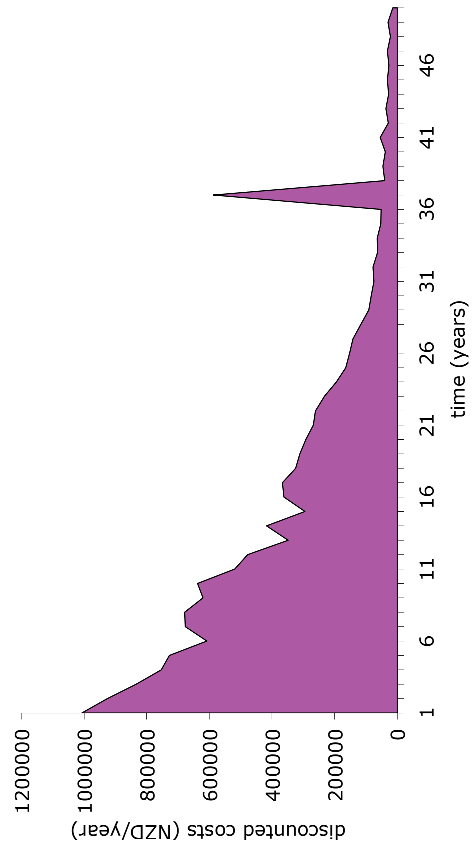

Figure B7. Wharenui farm Scenario 2: Discounted costs (NZD/y)

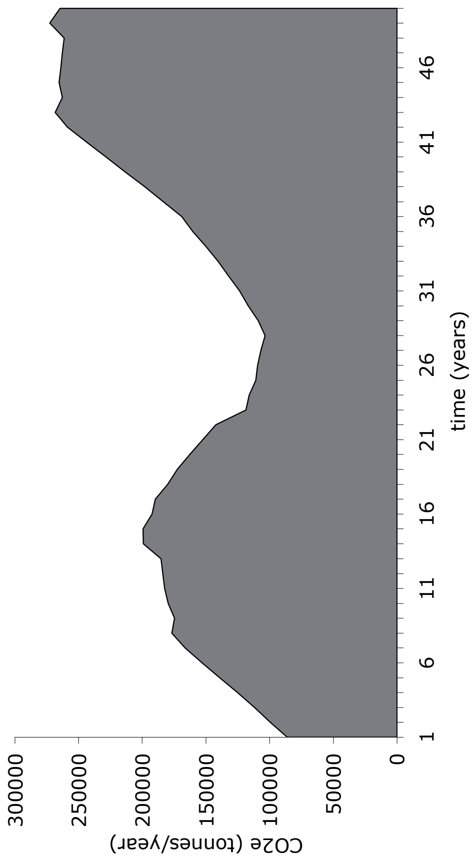

Figure B8. Wharenui farm Scenario 2: Carbon sequestrated (tonnes/y)

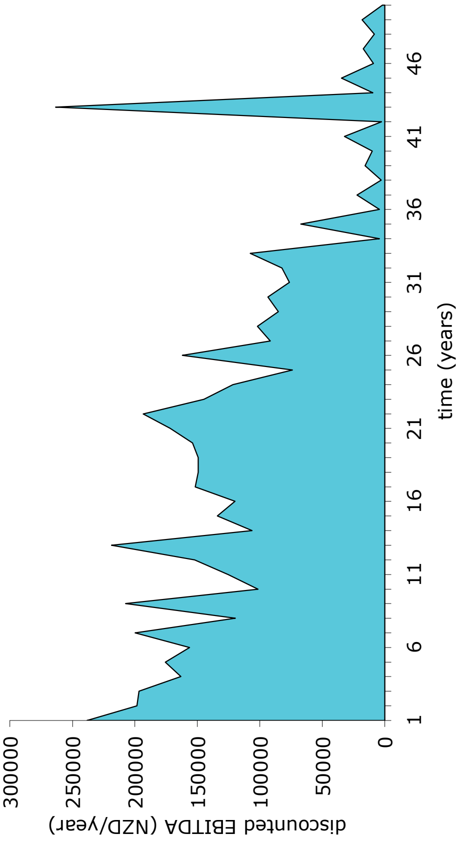

Figure B9. Wharenui farm Scenario 2: Discounted EBITDA (NZD/y)

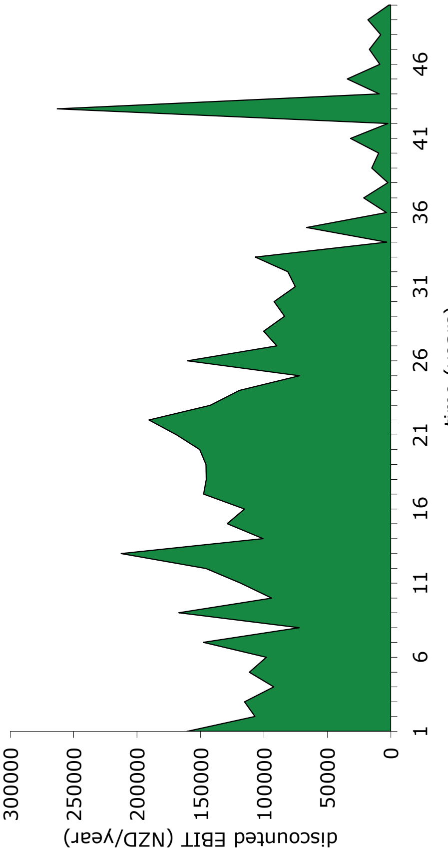

Figure B10. Wharenui farm Scenario 2: Discounted EBIT (NZD/y)

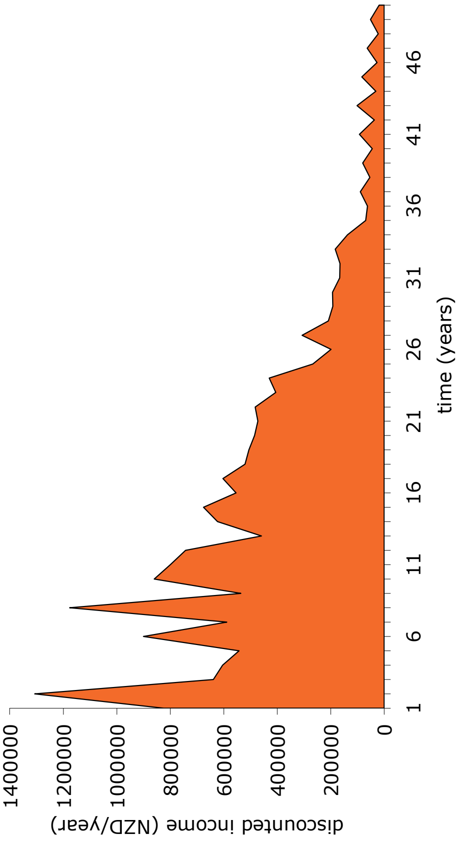

Figure B11. Wharenui farm Scenario 2: Discounted income (NZD/y)

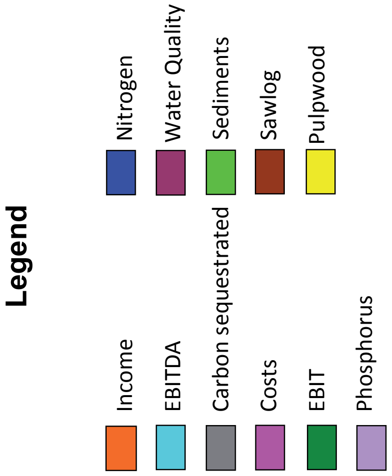

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Figure B12. Wharenui farm Scenario 2: Land use change year 1

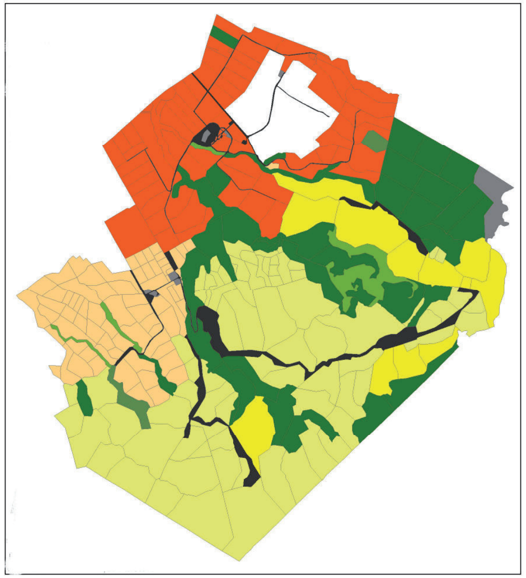

Figure B13. Wharenui farm Scenario 2: Land use change year 2

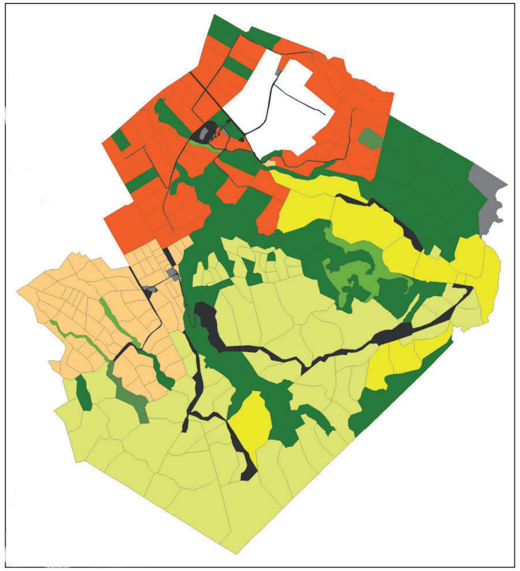

Figure B14. Wharenui farm Scenario 2: Land use change year 5

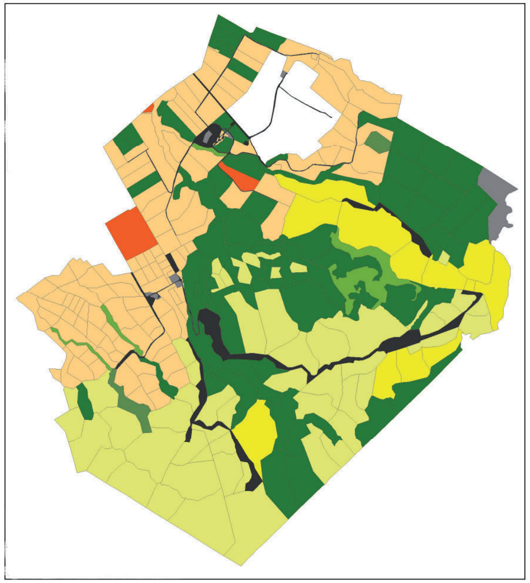

Figure B15. Wharenui farm Scenario 2: Land use change year 10

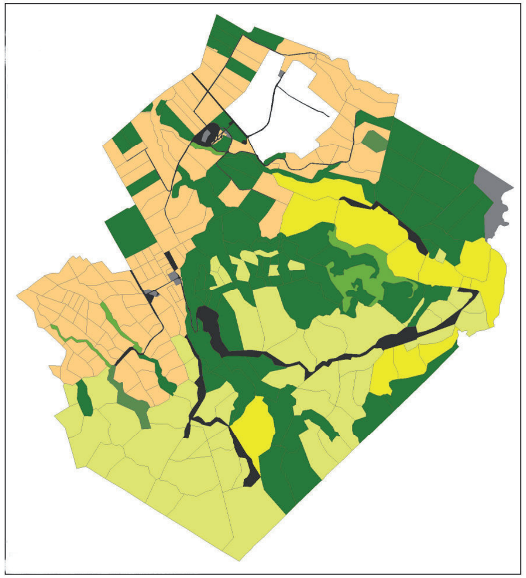

Figure B16. Wharenui farm Scenario 2: Land use change year 50

Legend

🟧 beef cattle
🟨 sheep breeding and finishing
🟨 breeding store lambs
🟥 dairy
🟩 radiata pine
🟩 cypress pine
🟩 mixed non-commercial forest
⬜ building infrastructure
⬛ road

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APPENDIX C: Multi-objective optimisation results for Ngongotaha farm. Results over the 50 year planning period are described in C1 through C11. Land use change results in years 1, 2, 5, 10 and 50 are described in C12 through C16, respectively.

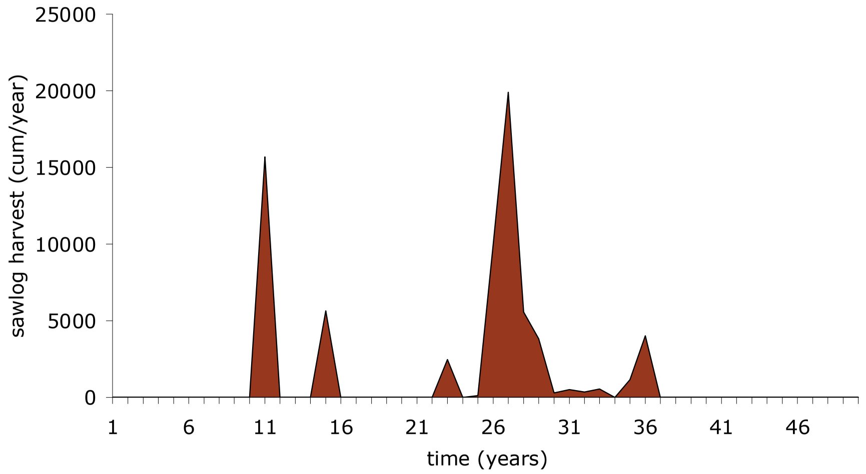


Figure C1. Ngongotaha farm: Sawlog harvest (m^3/y)

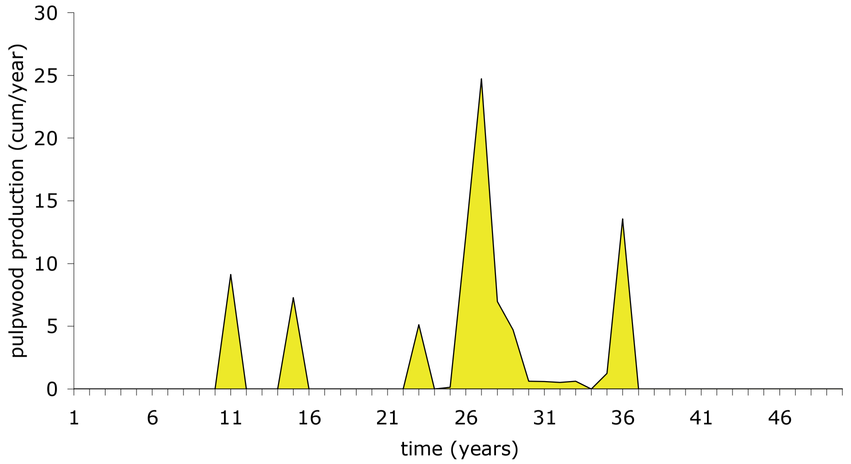


Figure C2. Ngongotaha farm: Pulpwood harvest (m^3/y)

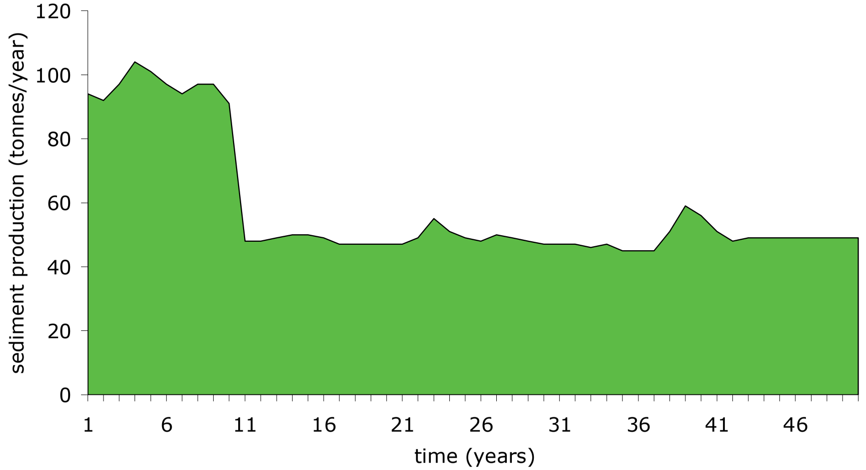


Figure C3. Ngongotaha farm: Sediment production (tonnes/y)

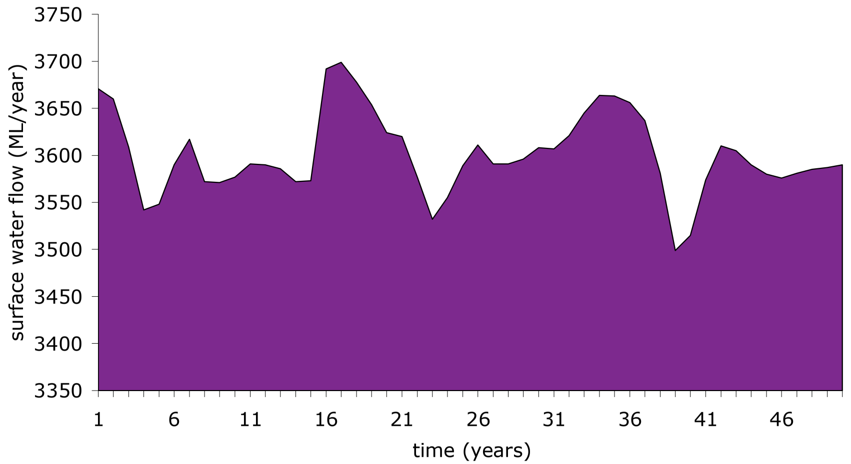


Figure C4. Ngongotaha farm: Surface water flow (ML/y)

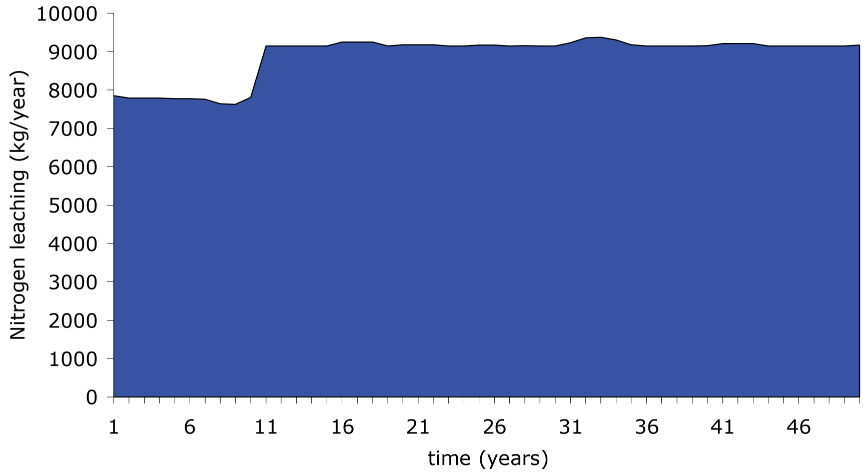


Figure C5. Ngongotaha farm: Nitrogen leaching (kg/y)

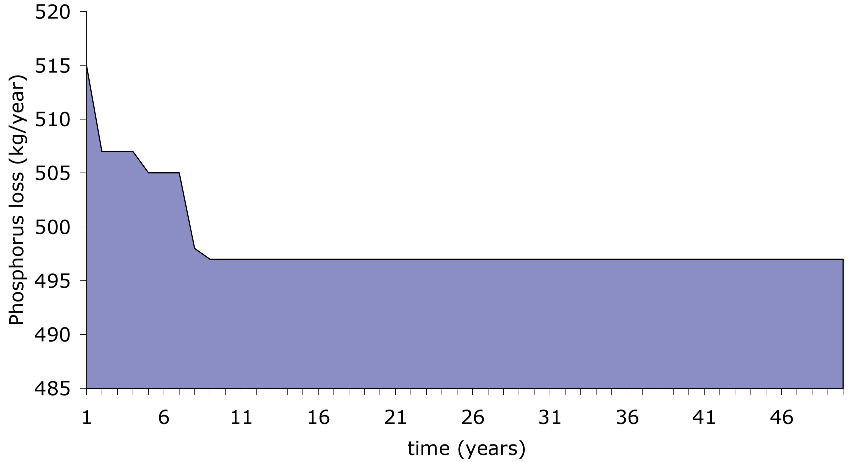


Figure C6. Ngongotaha farm: Phosphorus loss (kg/y)

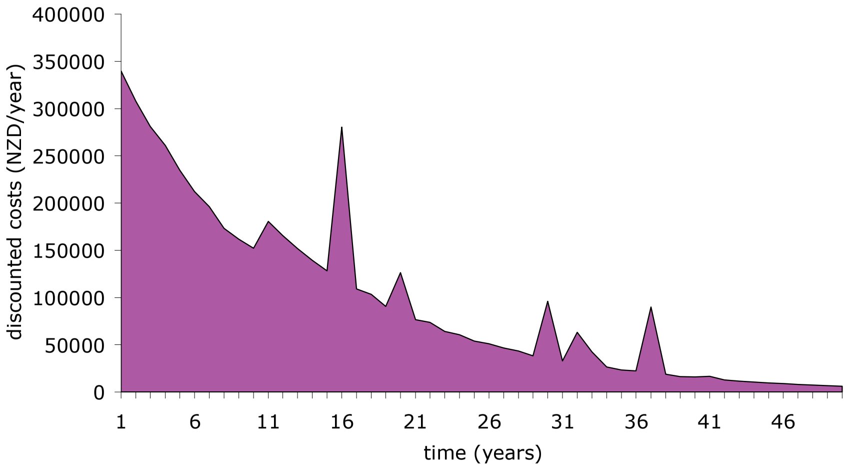


Figure C7. Ngongotaha farm: Discounted costs (NZD/y)

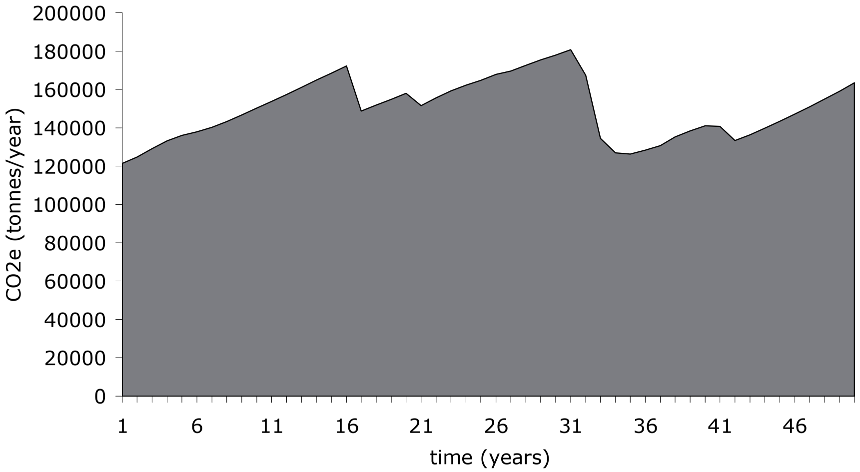


Figure C8. Ngongotaha farm: Carbon sequestrated (tonnes/y)

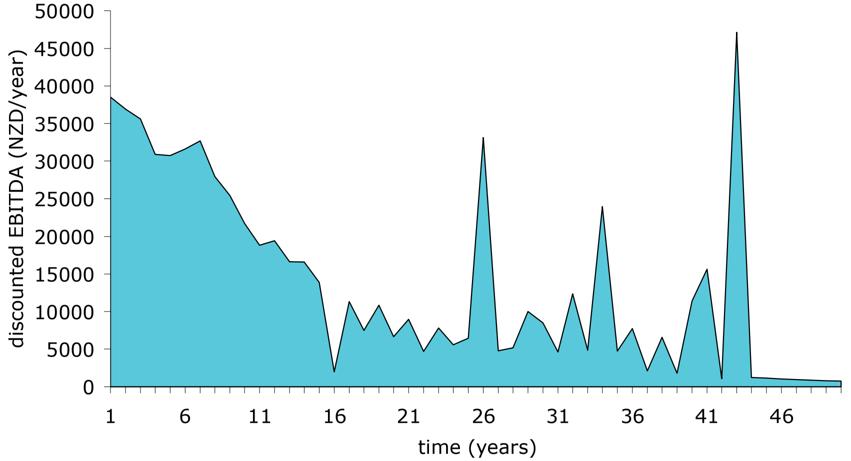


Figure C9. Ngongotaha farm: Discounted EBITDA (NZD/y)

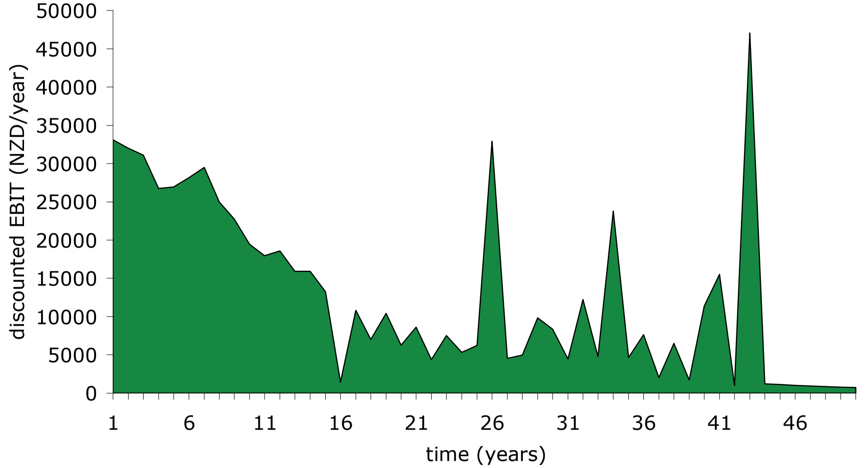


Figure C10. Ngongotaha farm: Discounted EBIT (NZD/y)

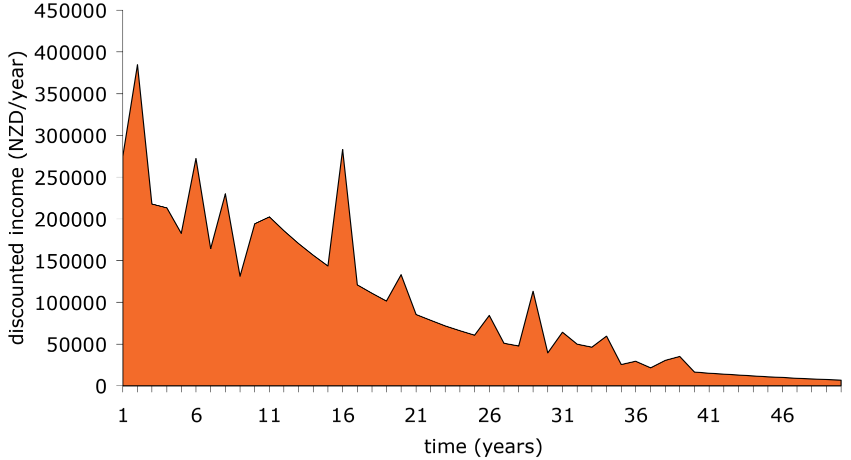


Figure C11. Ngongotaha farm Scenario 2: Discounted income (NZD/y)

Legend

- 🟧 Income
- 🟦 EBITDA
- ⬛ Carbon sequestrated
- 🟪 Costs
- 🟩 EBIT
- 🟪 Phosphorus
- 🟦 Nitrogen
- 🟥 Water Quality
- 🟩 Sediments
- 🟫 Sawlog
- 🟨 Pulpwood

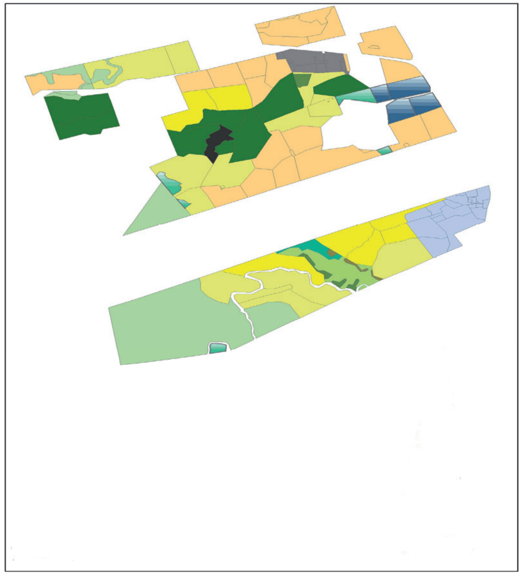


Figure C12. Ngongotaha farm: Land use change year 1

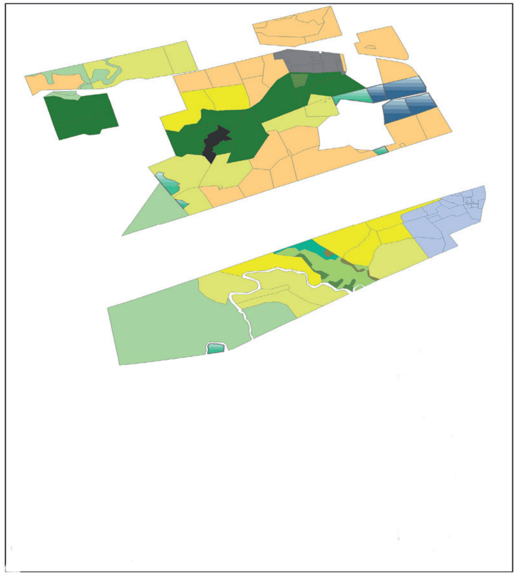


Figure C13. Ngongotaha farm: Land use change year 2

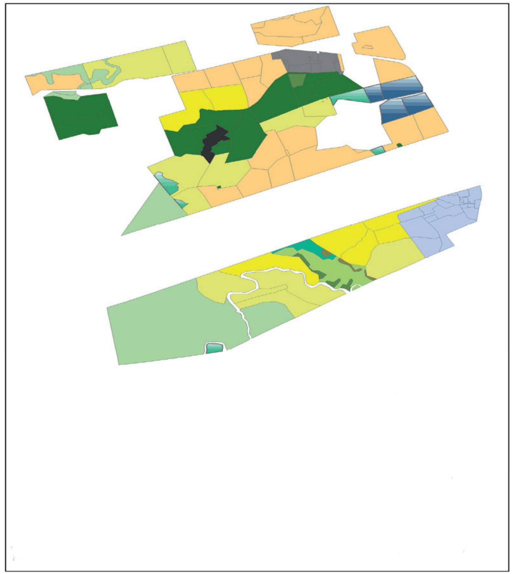


Figure C14. Ngongotaha farm: Land use change year 5

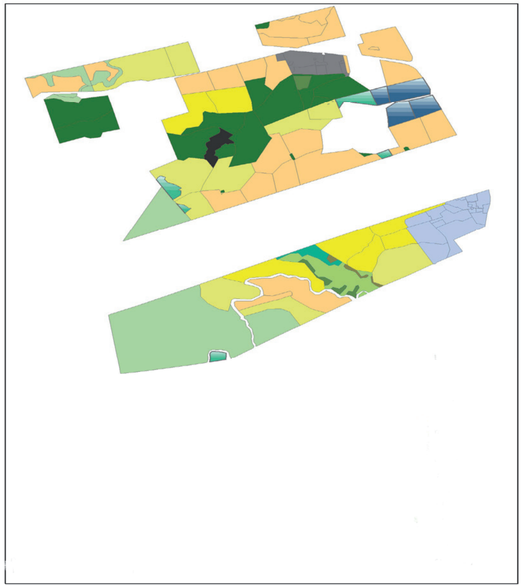


Figure C15. Ngongotaha farm: Land use change year 10

Figure C16. Ngongotaha farm: Land use change year 50

Legend

- 🟧 beef cattle
- 🟨 sheep breeding and finishing
- 🟨 sheep (buy replacements)
- 🟩 radiata pine
- 🟩 Douglas fir plantations
- 🟫 eucalypt plantations
- 🟩 larch
- 🟩 cypress (macrocarpa)
- ⬛ building infrastructure
- 🟩 conservation
- 🟦 recreation
- 🟩 bush
- 🟦 cemetary

APPENDIX D: Multi-objective optimisation results for Tihiotonga farm. Results over the 50-year planning period are described in D1 through D11. Land use change results in years 1, 2, 5, 10 and 50 are described in D12 through D16, respectively.

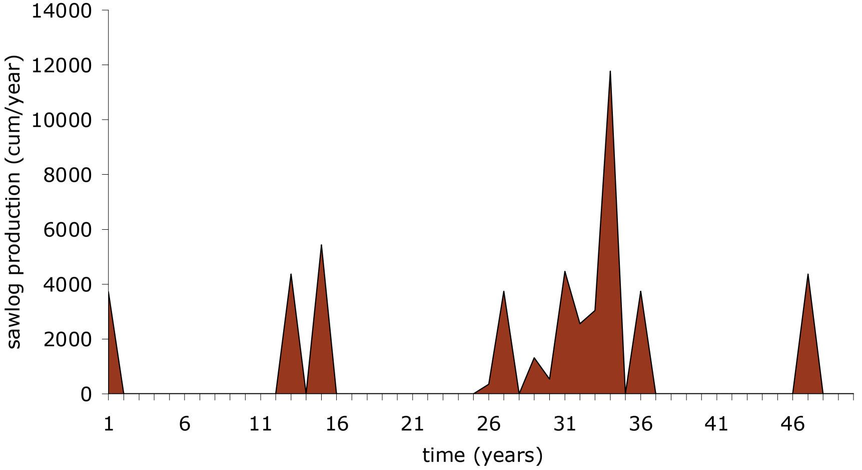


Figure D1. Tihiotonga farm: Sawlog harvest (m^3/y)

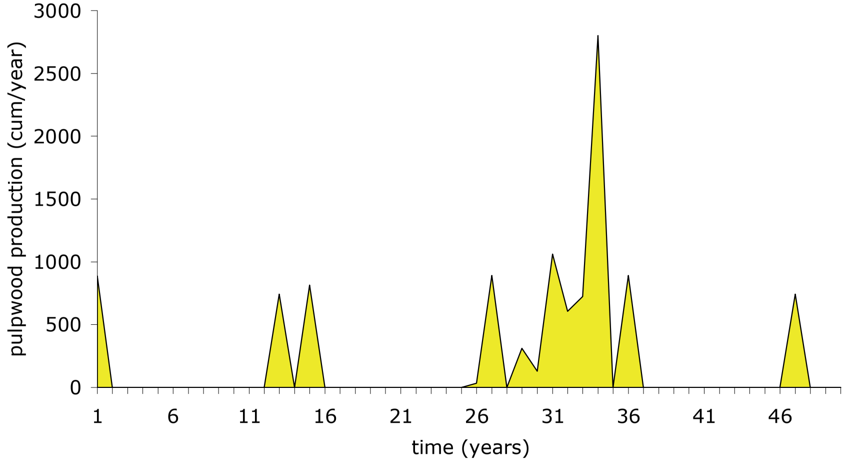


Figure D2. Tihiotonga farm: Pulpwood harvest (m^3/y)

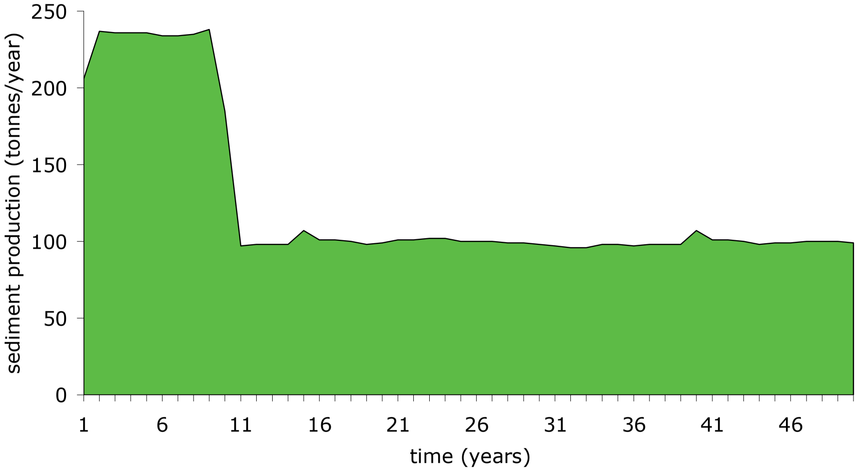


Figure D3. Tihiotonga farm: Sediment production (tonnes/y)

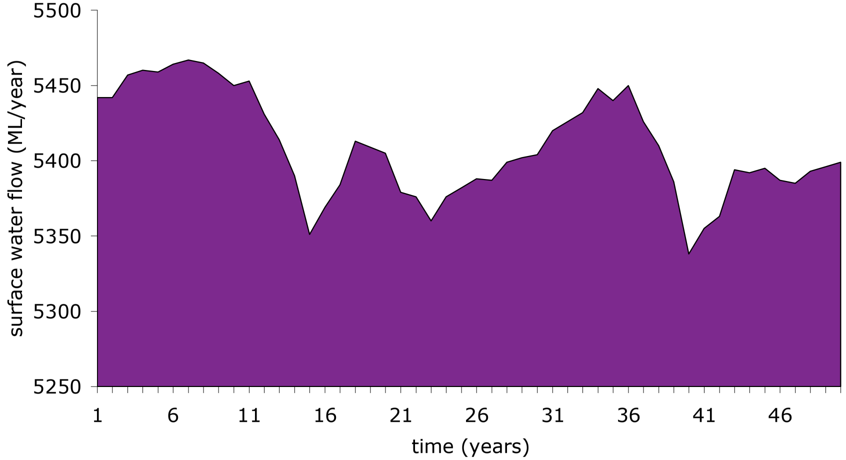


Figure D4. Tihiotonga farm: Surface water flow (ML/y)

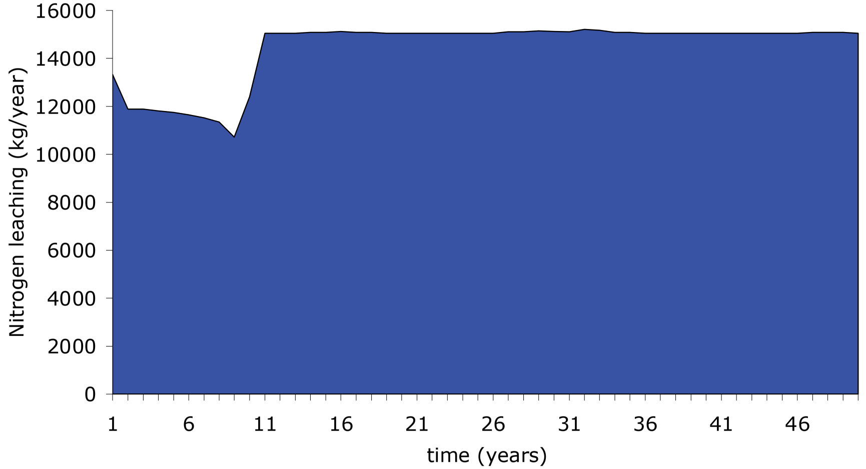


Figure D5. Tihiotonga farm: Nitrogen leaching (kg/y)

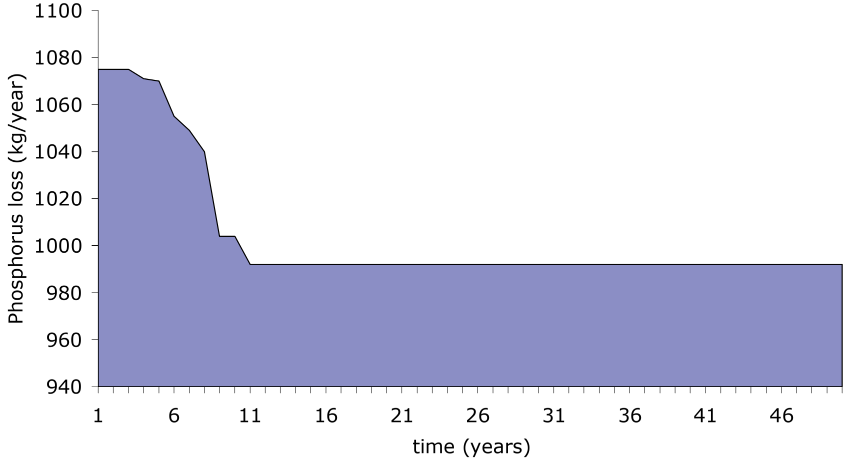


Figure D6. Tihiotonga farm: Phosphorus loss (kg/y)

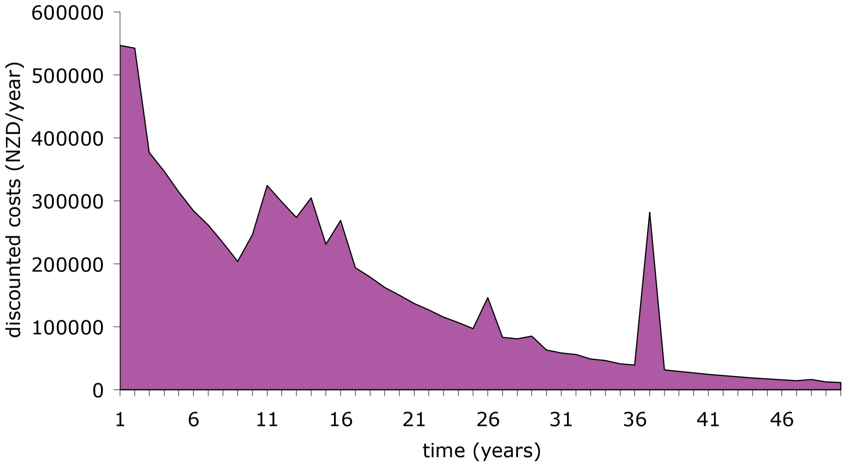


Figure D7. Tihiotonga farm: Discounted costs (NZD/y)

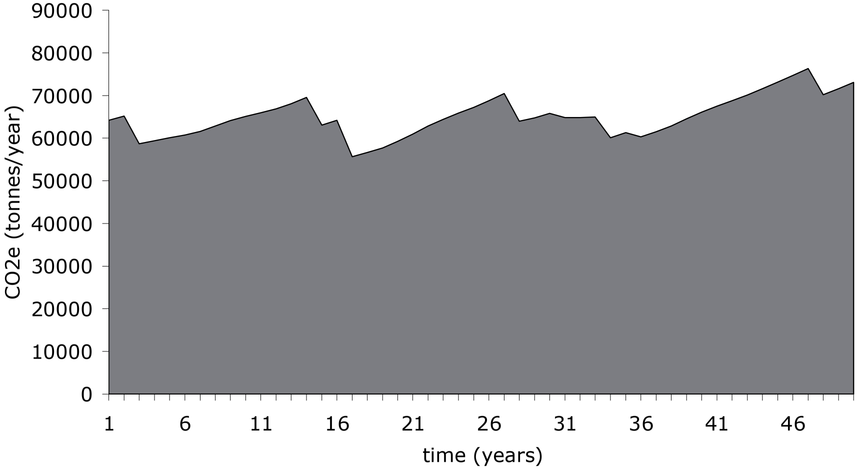


Figure D8. Tihiotonga farm: Carbon sequestrated (tonnes/y)

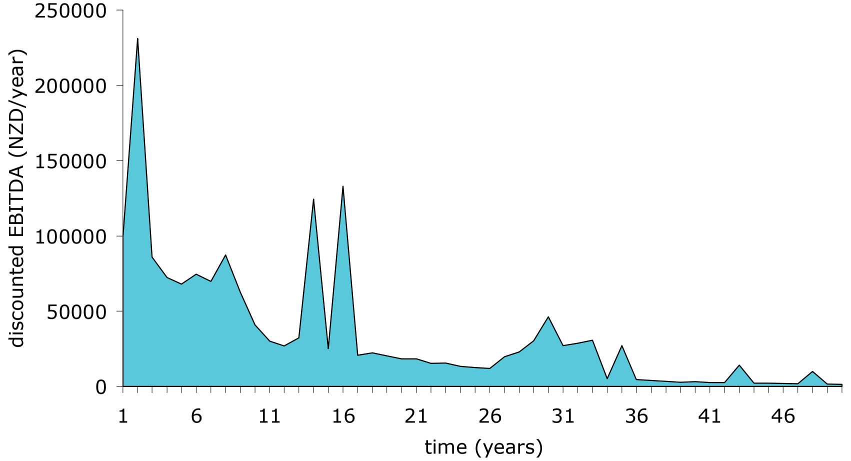


Figure D9. Tihiotonga farm: Discounted EBITDA (NZD/y)

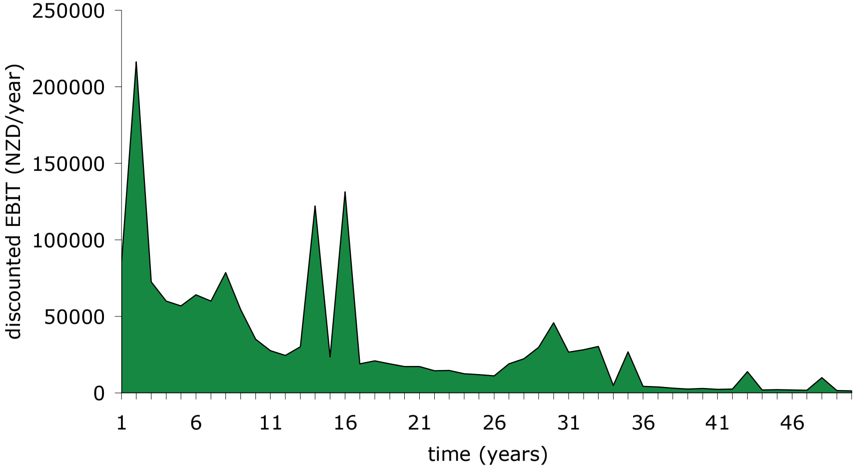


Figure D10. Tihiotonga farm: Discounted EBIT (NZD/y)

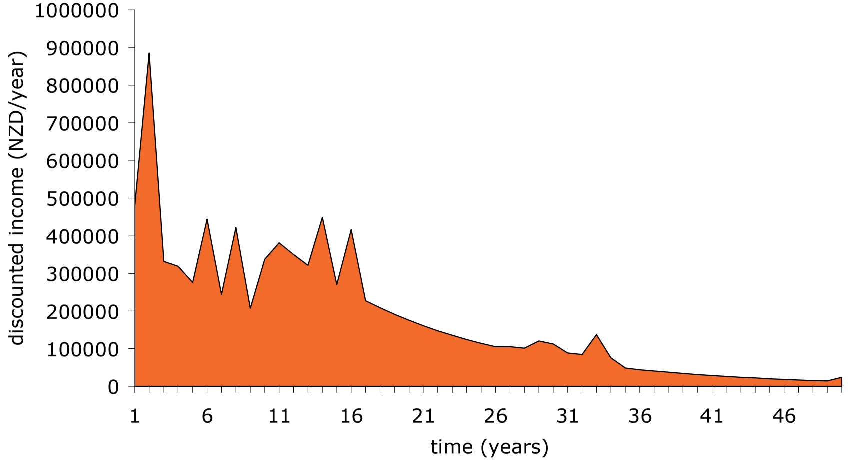
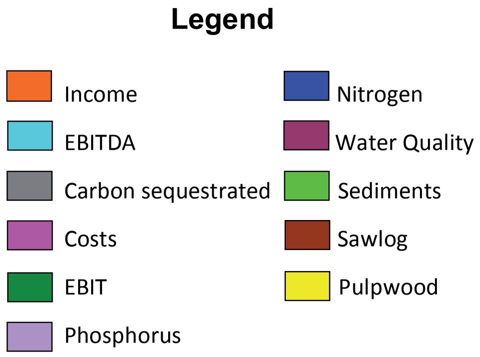


Figure D11. Tihiotonga farm Scenario 2: Discounted income (NZD/y)



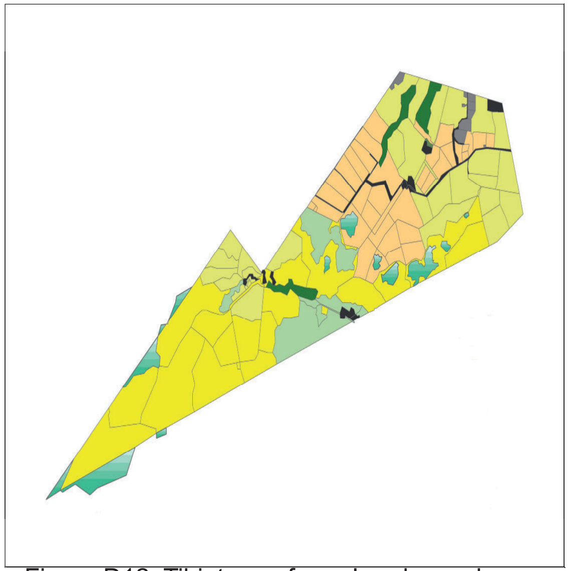


Figure D12. Tihiotonga farm: Land use change year 1

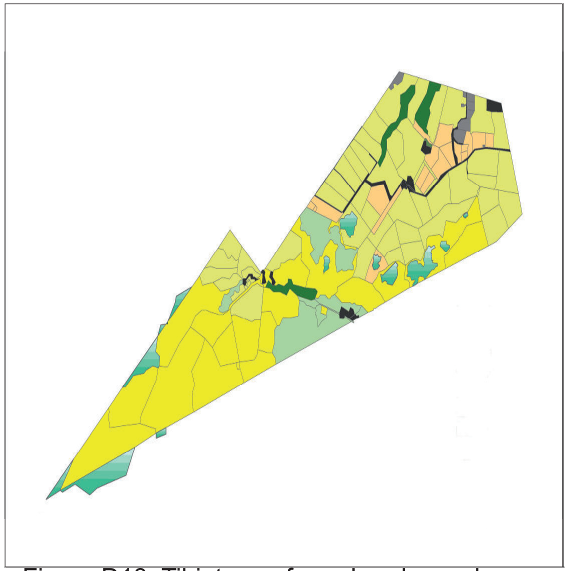


Figure D13. Tihiotonga farm: Land use change year 2

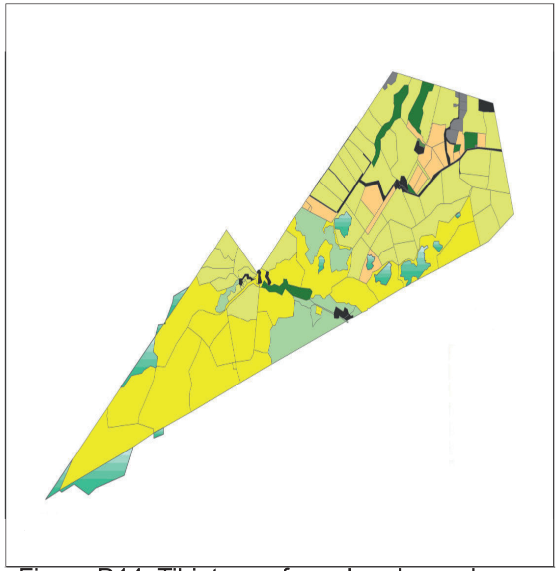


Figure D14. Tihiotonga farm: Land use change year 5

Legend

- 🟧 beef cattle
- 🟨 sheep breeding and finishing
- 🟨 sheep (buy replacements)
- 🟩 radiata pine
- 🟩 Douglas fir plantations
- ■ building infrastructure
- ■ road
- 🟩 conservation
- 🟩 bush
- ■ unknown area

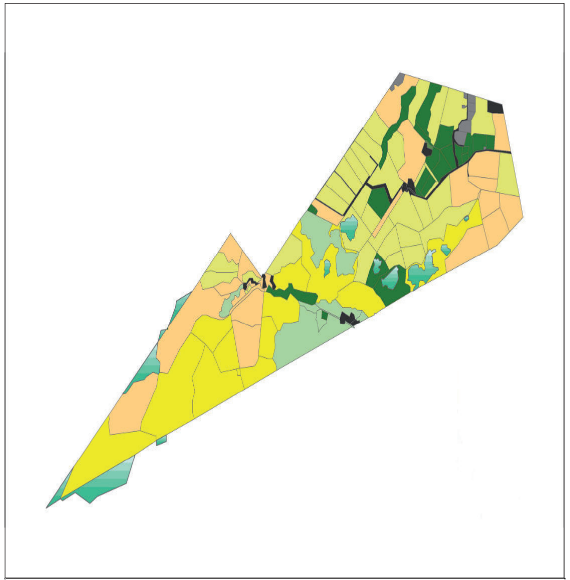


Figure D15. Tihiotonga farm: Land use change year 10

Figure D16. Tihiotonga farm: Land use change year 50