SPATIAL OPTIMISATION OF ECOSYSTEM SERVICES

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ABSTRACT: Human well-being depends on the ecosystem services provided by the landscape. The nature and magnitude of these services depend on the interaction of a land use with its local and catchment environment, and consequently also on land management practices. In a landscape of spatially varying climate, soils, slope, and susceptibility to processes such as erosion, these services depend crucially on the location of the land use within the landscape. A land use may be detrimental or benign, depending on where it occurs in the landscape mosaic. Consequently, there is increasing interest in providing advice on precisely how land-use mosaics can be spatially configured to optimise ecosystem services. These complex spatial planning problems involving competing land uses and contradicting objectives can be tackled using an emerging set of tools for spatial optimisation. In this chapter we demonstrate how to optimise land-use configuration in order to maximise ecosystem services and land-use performance. First, we illustrate the impact of the spatial configuration of land use on ecosystem services. Then, we introduce the method of multi-objective spatial optimisation and its implementation in the Land-Use Management Support System (LUMASS). LUMASS allows for optimising a land-use configuration subject to multiple and possibly conflicting objectives and constraints.

Using LUMASS in two different case study areas in New Zealand, we demonstrate how to reconfigure the land-use pattern to improve ecosystem services while maintaining agricultural production. In the first case study in the Waitaki catchment in the South Island, we used LUMASS in three different scenarios to maximise clean water provision, habitat provision, and water regulation. Dairying was not allocated to the shallow soils of the intermontane plains in the Mackenzie Basin in any of these scenarios. Optimising for water flow regulation produced a land-use pattern similar to the current land use. This suggested extensive sheep and beef farming should be kept on tussock grasslands to maintain the Waitaki River flow. The second case study, in the central North Island, involved plantation forest, dairying, and sheep and beef farming. We optimised the land-use pattern to minimise nitrate leaching, soil erosion, and nitrate leaching and soil erosion concurrently. The results show that the current landscape configuration is suboptimal and point to a possible shift between dairying and forestry if we were to prioritise these criteria. The case studies demonstrate that spatial optimisation can be used to maximise the potential of the landscape in terms of its land use and ecosystem services performance. By testing different objectives and constraints to represent different stakeholder preferences, decision-makers can gain insight into the full spectrum of feasible solutions. They can explore the opportunities that lie within the landscape, and critically assess the limits within which compromises need to be found.

Key words: clean water provision, erosion control, habitat provision, land-use pattern, locational impact, LUMASS, multiple objectives, nitrate leaching, spatial optimisation, trade-off, water yield.

INTRODUCTION

A landscape is a mosaic of ecosystems, each of which provides benefits or 'disbenefits' for the others. To the extent that an ecosystem such as an area of native bush, or even a human-dominated ecosystem such as a rural settlement, provides ecological benefits to others, we say it provides ecosystem services. These benefits may be absolute, such as provision of habitat for native species, or relative, such as when one ecosystem, perhaps an area of scrubland, is less susceptible to erosion than an alternative, perhaps pasture. In all cases, the environmental performance of the ecosystem determines the level of ecosystem services that are provided. The ecosystem services our landscapes provide depend on the way we use and manage our land. For large areas of New Zealand, conversion of native bush into pasture has had a huge impact on biodiversity, erosion rates, stream flows, and water quality (Ausseil et al. 2013). Water quality is affected by nitrate leaching from the soil into water bodies, which occurs at different rates under dairying, sheep, and beef farming land uses (Dymond et al. 2013). The magnitude of nitrate leaching depends on the number and type of livestock, and fertiliser application rates (Beukes et al. 2012). It also depends on soil characteristics since, for example, a shallow stony soil is more likely to leach nitrate than a deep loamy soil. Similarly, soil erosion and stream flows depend on soil characteristics, rainfall, and other factors that vary spatially. Thus, the quality and quantity of ecosystem services provided by our landscapes depend not only on the aggregate area of each land use, but also on how these land uses (or land-use variants) are distributed spatially, and how they are managed. This in turn raises the question as to whether, from the perspective of ecosystem services, land uses in New Zealand are distributed and managed optimally – that is, in a way that maximises ecosystem services while maintaining, or perhaps increasing, levels of primary production.

Currently, as a means of reducing damaging effects of land-use change, or intensifying land use, land managers in New Zealand are encouraged to adopt management systems that minimise environmental or health effects. Thus, for example, managers of erosion-prone land routinely take advantage of incentives for soil conservation measures such as tree planting to minimise soil erosion (Mitchell and Cooper 2011). However, some of the more recent management innovations, such as the use of nitrogen inhibitors such as dicyandiamide (DCD) to reduce nitrate leaching and nitrous oxide emissions (Di and Cameron 2005), may yet prove to be unsustainable, depending on the tolerance of consumers for even low levels of DCD contamination in food products. Maintaining overall environmental performance through greater attention to the spatial pattern of land use may well prove to be a more sustainable approach. The challenge is increasing as population-driven demands for greater agricultural output from the same natural resources puts more pressure on natural capital and ecosystem services, and the effects of climate change become more apparent (Fischlin et al. 2007).

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In New Zealand, land managers tend to rely on generalised rules and guidelines to determine whether to approve an application for a change in land use, or abstraction of water resources. These rules and guidelines may be relatively ineffectual as a means for delivering an optimal land-use configuration, with the result that waterways are needlessly polluted, stream flows needlessly reduced, and so on. In principle, at least, there is an opportunity to improve on the case-by-case, or 'first come, first served', basis, on which applications are currently processed. Applications could potentially be dealt with more efficiently, and to greater benefit to ecosystems and the wider community, by taking into account the extent that the application takes the regional land-use pattern further away or closer to the optimal pattern, which might be presented explicitly as part of a regional plan.

Consequently, as we seek to deliver *kaitiakitanga* (Māori: guardianship of the sky, sea, and land) and achieve sustainable land management, we need to ensure we take advantage of our capacities for both on-site management system innovations and, through spatial land-use optimisation, smart use of our natural capital and ecosystem services. Accordingly, it would seem that, as a country, we should not only continue to make generic improvements in management systems, but also build competencies in spatial land-use optimisation. This chapter is an initial attempt at the latter.

The structure of this chapter is as follows. First we illustrate the impact of land-use configuration on ecosystem services and landscape performance. Then we examine the procedures and modelling technologies available to support spatial land-use optimisation, and present two New Zealand case studies in their application. We then appraise the approach, and conclude with recommendations for future research.

IMPORTANCE OF LAND-USE CONFIGURATION

Can New Zealand's current land-use pattern be improved? Despite much work on spatial land-use suitability and capability, it is not straightforward to identify areas where land uses could be altered to maximise ecosystem services and measures of aggregate environmental and economic performance. Some ecosystem services have been modelled at a national scale using a set of indicators (Ausseil et al. 2013). These models are spatially explicit and allow the impact of land use on ecosystem services to be analysed. The models assess the performance of a particular land use on a particular piece of land with regard to a particular criterion, such as carbon sequestration, soil erosion, or agricultural production. The application of these models to a landscape, a catchment, or the whole country yields performance maps showing the spatially varying effect of a particular land use on the environment (Figure 1).

For example, Figure 1 (left) shows the potential for nitrate leaching per cow and year for a region in the central North Island of New Zealand. The potential for nitrate leaching in the northwest is higher than in the south. Since the land use is uniform over the region, the differences represent the effects of factors intrinsic to the physical environment. In this case the variation is mainly attributable to spatially varying soil properties, such as water holding capacity, which govern nitrate leaching. When we compare the map of potential nitrate leaching (Figure 1) with the actual land-use distribution as at 2008 (Figure 2), we can see that the 'spatial match' is not as good as it could be. Many parcels with a high potential for nitrate leaching are still used, non-optimally, for dairying. But what does it mean in terms of land use and ecosystem services performance? How might this non-optimal situation be rectified?

In the real world, land-use decisions take into account many

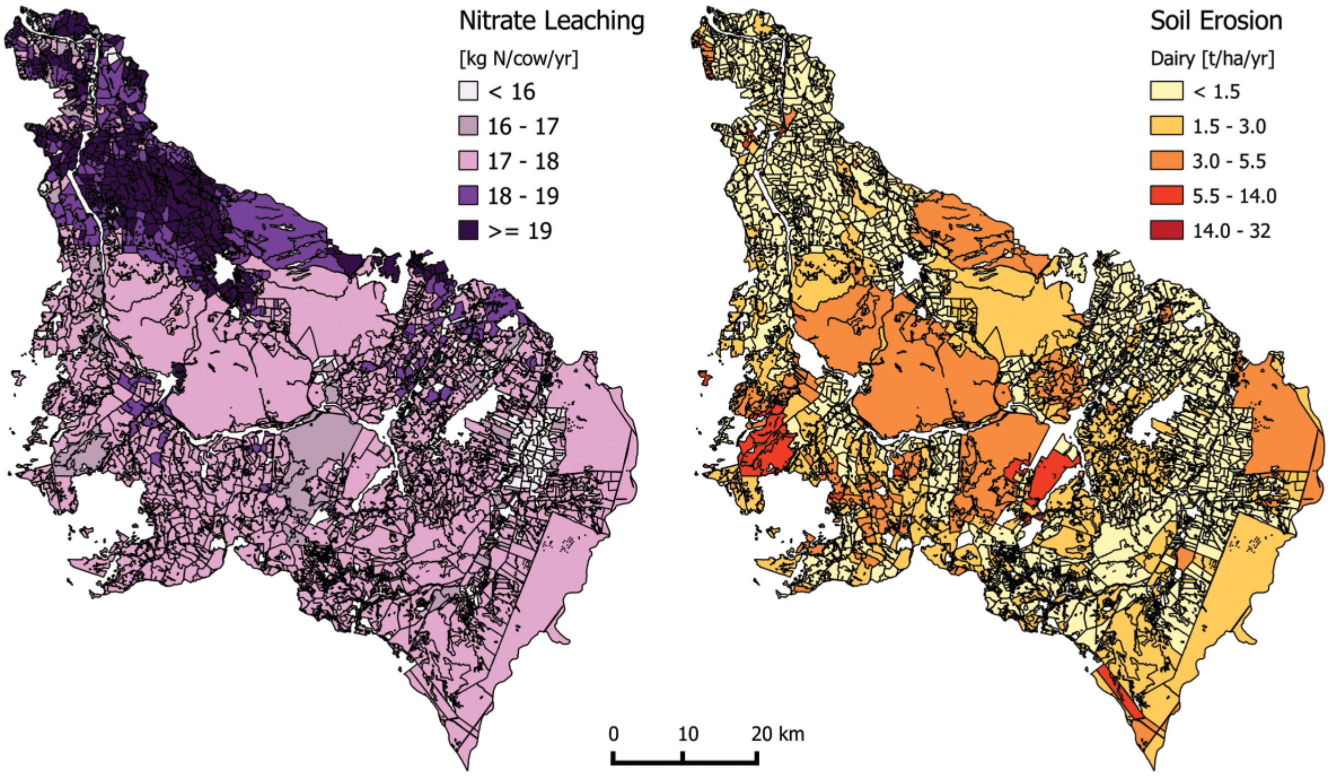


FIGURE 1 Spatial variability of land-use (dairy) performance with regard to nitrate leaching (left) and soil erosion (right).

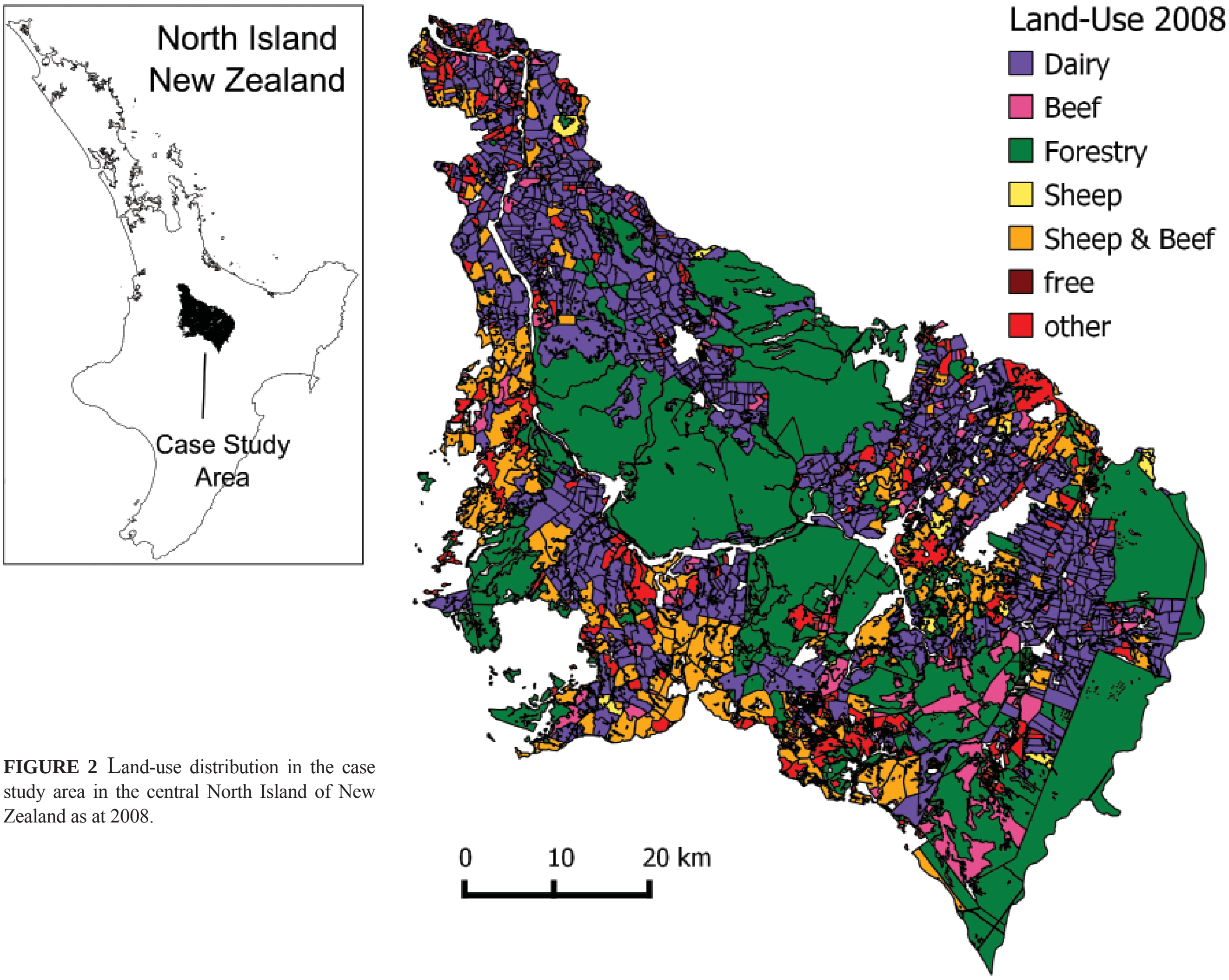


FIGURE 2 Land-use distribution in the case study area in the central North Island of New Zealand as at 2008.

environmental, economic, social and cultural factors. The more factors that need to be considered, the more complex this decision-making becomes, and the less obvious it is how to distribute land uses and activities throughout the landscape. To illustrate this, we consider the hypothetical case of optimally allocating just two land uses, dairying and forestry, in the region of Figure 1, noting that forest cover in general reduces soil erosion by approximately an order of magnitude (Dymond et al. 2010). Figure 1 (right) shows the performance of dairying (and likewise all pastoral land uses) in terms of soil erosion for the same region and land parcels as in Figure 1 (left). Using these maps, we are presented with two views of where we might prefer to retain dairying rather than plant trees – either in the areas of low nitrate leaching, or the areas of low erosion rate under dairying. The areas are not the same. Effectively we have four categories of land: land where nitrate leaching and erosion rates under dairying are both high, land where they are both low, and areas where one of these is high and the other low. We can agree that where they are both high, the land use should be forestry. Likewise, where they are both low, it may be safe to have dairying. Where nitrate leaching is high and erosion rate is low, and vice versa, we cannot choose a land use that minimises both, and we need to prioritise. There may need to be a trade-off between minimising nitrate leaching and minimising soil erosion. The situation becomes considerably more complex if we allow more than two land uses, and more than two environmental factors, or criteria. In the following we describe a methodology for allocating land use optimally, when we have multiple competing land uses and multiple, often conflicting planning objectives.

SPATIAL MULTI-OBJECTIVE DECISON-MAKING

Spatial multi-objective optimisation is one method of multi-criteria decision-making (MCDM) (Steuer 1986). MCDM is a general class of methods for facilitating decision-making involving multiple and conflicting criteria. Depending on the characteristics of the decision problem and the methods used to solve the problem, MCDM can be further subdivided into multi-attribute decision-making (MADM) and multi-objective decision-making (MODM) (cf. Jankowski 1995, Malczewski 1999, Eastman 2003). Spatial MADM is suitable for identifying areas of land that exhibit optimal characteristics, or that, on the basis of a number of criteria, are most suitable for a particular activity. It is widely used for spatial analysis and decision-making, especially because it can easily be implemented using common GIS tools (Malczewski 1999; Eastman 2003). A set of spatial layers, representing the criteria, is processed by means of GIS map algebra and overlay procedures to calculate a map of overall performance scores. This map represents the spatially varying degree of achievement with regard to a particular objective. For example, it has been used for identifying optimal locations for housing, taking into account criteria such as air quality and land accessibility (Joerin and Musy 2000). Robinson et al. (2002) used spatial MADM to identify regions for effectively fighting narcolepsy (sleeping sickness) considering stocking rates, population density, and land-use intensity. In our example problem discussed above, MADM would be able to identify optimal locations for (say) dairying, considering multiple criteria, such as nitrate leaching and soil erosion. However, the method cannot be used to find a trade-off between competing land uses (e.g.

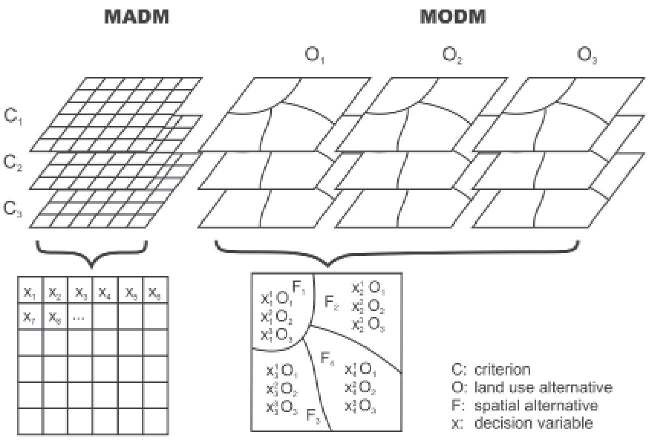


FIGURE 3 Spatial multi-attribute decision-making (MADM) vs spatial multi-objective decision-making (MODM).

dairying and forestry). These more-complex-decision problems can be addressed by MODM (Figure 3). It has been applied to many different types of problems, including resource allocation (Janssen and Rietveld 1990; Grabaum et al. 1999; Herzig 2008b), route optimisation (Lee 2004), and the optimisation of geometric properties of spatial units (e.g. shape of land parcels, or ski routes) taking into account neighbouring units (Aerts and Heuvelink 2002; Tourino et al. 2003).

In the following, we describe the application of multi-objective linear programming (MOLP) to implement MODM for optimising spatial resource allocation. Linear programming is a widely used technique in optimisation studies. Typically it is used to identify optimum amounts of resources to be used to satisfy an objective, subject to some constraints. Whereas in a non-spatial problem we may simply be concerned only with the total amount of resources being used in an entire region, in spatial problems we are interested in the use of each individual resource on every single land parcel in the whole region. In contrast to MADM, this allows the decision-maker to not only identify locations where to make best use of a particular resource (Figure 1), but to identify trade-offs between multiple resources and multiple possible locations at the same time. This conceptual difference is reflected by the different meaning of the decision variables ($x_1, x_2, ..., x_u$) in MADM and MODM respectively (Figure 3). In MADM the decision variables represent performance scores of the *n* criteria considered in the decision-making process. As a result, MADM yields a map of aggregated performance scores, denoting the degree of achievement of the underlying objective. In MOLP, the decision variables are unknown and represent the quantities of resources, which have to be allocated to the individual spatial units (e.g. land parcels) such that the objectives of the decision-making problem are optimally achieved.

Mathematically, the optimisation problem can be stated as follows. Let $\boldsymbol{x}$ be the vector of decision variables ($x_1, x_2, \ldots, x_u$), where *u* is equal to the number of available resources (e.g. land-use options) multiplied by the number of available spatial units (e.g. land parcels). There are multiple objectives, expressed in terms of *n* objective functions. Each objective is represented by the linear combination of the vector of decision variables $\boldsymbol{x}$ and a vector $\boldsymbol{c}_j$ holding the performance scores of the available resources for each of the available spatial units with regard to criterion *j*. In the standard form of MOLP (Steuer 1986)

$$max\ \boldsymbol{c}_j \boldsymbol{x} = z_j$$
$$\text{with } \boldsymbol{x} \in B, \text{where } B = \{\boldsymbol{x} \in \mathbb{R}^u : \boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{b}, \boldsymbol{x} \geq 0, \boldsymbol{b} \in \mathbb{R}^q\} \quad (1)$$

$\boldsymbol{c}_j$ represents a benefit criterion such as economic profit, i.e. the higher the score the greater the represented benefit. The goal of the optimisation is then to maximise the objective function result z_j of each objective function, such that the vector of objective function results **z,** i.e. the overall benefit, is maximised. However, when $\boldsymbol{c}_j$ represents a cost criterion, such as nitrate leaching, the goal of the optimisation is to minimise the objective function. A minimisation problem can be transformed into a maximisation problem by multiplication with minus one, hence cost and benefit criteria can both be considered in the same MOLP.

The set of feasible solutions *B* is restricted by the set of *q* constraints, $\boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{b}$, where $\boldsymbol{A}$ denotes a *u* x *q* matrix of performance coefficients. The multiplication of $\boldsymbol{A}$ with the allocated quantity of resources $\boldsymbol{x}$ expresses how particular items (attributes) are affected by the allocation of the given resources. The vector $\boldsymbol{b}$ represents the thresholds or limits with regard to the desired or tolerable impact of the allocated resources on the particular items.

In decision-making problems involving multiple objectives, often objectives oppose each other, for example profit maximisation and resource minimisation. Hence, in multi-objective optimisation problems, there is rarely an $\boldsymbol{x}$ such that each individual objective function value z_j is maximal. Instead, an efficient (pareto-optimal) solution is sought, such that there is no other point, which improves at least one objective without worsening any of the other objectives (Steuer 1986; Ehrgott 2005).

In general, an optimisation problem with multiple objectives is often solved by turning it into a single-objective optimisation problem, which can then be addressed by efficient algorithms (cf. Steuer 1986; Benker 2003; Collete and Siarry 2003; Ehrgott 2005). This 'scalarisation' can be achieved using different methods. The commonly used 'weighted-sum' approach weighs the individual *n* objective functions and sums them up and then maximises the obtained single objective function (cf. Steuer 1986; Benker 2003; Collete and Siarry 2003; Ehrgott 2005):

$$max \sum_j \lambda_j z_j$$
$$\text{with } \boldsymbol{x} \in B, \lambda_j \in \mathbb{R}^n, \lambda_j > 0, \sum_j \lambda_j = 1 \quad (2)$$

Here, the weights may be chosen so as to be consistent with stakeholder preferences. The performance scores $\boldsymbol{c}_j$ need first to be normalised to remove any bias in the optimisation result, and each of the individual objective functions must be independent of the others (Steuer 1986). An alternative approach to scalarisation is the 'ε-constraint' approach. It converts *n–1* objective functions into constraints ($z_v \leq \varepsilon_v$) and solves the remaining single-objective optimisation problem (cf. Steuer 1986; Ehrgott 2005):

$$max\ z_j$$
$$\text{with } \boldsymbol{x} \in B \cap \{\boldsymbol{x} \in \mathbb{R}^u : z_v \leq \varepsilon_v, v \neq j, \varepsilon \in \mathbb{R}^n\} \quad (3)$$

Differences in the significance stakeholders may attach to each objective are taken into account in the iterative solution process. The optimisation problem for the highest priority objective is solved first. The objective function result z_1 then becomes a constraint to the optimisation problem for the next highest priority (Collette and Siarry 2003). Finding a feasible solution that satisfies all the given objectives often requires successive relaxation of the given objective function constraints in an iterative process.

OPTIMISING THE LAND-USE PATTERN USING LUMASS

The Land-Use Management Support System (LUMASS) (Herzig 2008a; Herzig 2013) incorporates dynamic and spatially explicit modelling of ecosystem processes as well as spatial optimisation. Dynamic process modelling provides insight into how the system works, including the effects of land management practices and land-use decisions (Jorgensen and Salomonsen 1994; Leser and Mosimann 1997), while spatial optimisation helps the user to align land use to the available natural resources and ecosystem services.

LUMASS is open-source software and built upon a range of powerful cross-platform open-source libraries for geospatial data processing and visualisation (Herzig 2013). To solve spatial multi-objective optimisation problems, LUMASS uses the mixed integer linear programming system lp_solve (Berkelaar et al. 2005). LUMASS also incorporates a graphical user interface to facilitate model development and optimisation as well as the evaluation of results.

A set of land uses L is allocated across a landscape represented by a set of polygons (i.e. land parcels) F. In this context, a land use can either be a land cover, such as indigenous forest, or it can be a land-use variant, as differences may simply reflect different management practices, such as conventional or minimal tillage. The optimisation (allocation) process is subject to one or more objectives expressed in terms of criteria. They define the overall goal to be achieved by the optimisation process, such as minimising nitrate leaching, or maximising agricultural output. Objectives are specified using the objective function (equation (1)), which is a function of the relevant performance scores. The value z_j (equation (1)) represents the optimised total performance score with regard to criterion j as a result of the optimisation process. For example, for the single-objective optimisation problem ‘minimise soil erosion’, $z_{erosion}$ would represent the minimum amount of sediment (e.g. t year^{-1}) eroded from the landscape as a result of the particular land-use pattern emerging from the optimisation process, subject to the given constraints. No other land-use pattern would be able to achieve less soil erosion unless the constraints changed. Obviously, we would get the least soil erosion when we had forest cover everywhere. But this, of course, leaves no space for other uses society depends on, such as agriculture. To balance different demands and specify expected returns from the landscape, we constrain the optimisation problem, using two types of constraints.

Allocation constraints

To avoid monocultures, LUMASS allows the user to specify how much of a particular land use may occur in the landscape and where it may occur. Area thresholds b_{lD} can be directly specified for a particular land use l and a particular sub-region D of the landscape F:

$$\sum_{d\in D} x_{dl} \le b_{lD} \quad \text{with } x_{dl} \in \mathbb{R}, b_{lD} \in \mathbb{R}, b_{lD} \ge 0, l \in L, D \subseteq F \tag{4}$$

where x_{dl} denotes the area share of land use l allocated to parcel d. Allocation constraints are useful for handling areas where certain land uses must not occur, such as buffer zones around water bodies. They can also be used to lock in a land use, such as conservation land. The performance (e.g. biodiversity benefit) of these land uses can still contribute to the overall landscape performance. Additionally, LUMASS automatically constrains the sum of area shares of land uses allocated to an individual parcel, so as not to exceed the parcel’s total area.

Performance constraints

Another way to shape the outcome of the optimisation process and therefore the allocated area of land uses is to specify performance constraints. These allow the user to express expectations with regard to the performance b_{UDj} of a set of land uses U in terms of a certain criterion j in a particular sub-region D of the landscape F. For example, this could be the total production derived from the horticultural sector in a particular region of the landscape.

$$\sum_{d\in D}\sum_{u\in U} s_{duj} x_{du} \le b_{UDj} \text{ with } x_{du} \in \mathbb{R}, s_{duj} \in \mathbb{R}, b_{UDj} \in \mathbb{R}, b_{UDj} \ge 0, U \subseteq L, D \subseteq F \tag{5}$$

where s_{duj} is the performance of land use u on parcel d in terms of criterion j, and depends on the area share x_{du} of land use u allocated to parcel d. This could, for example, be the annual meat production (kg year^{-1}) from sheep farming on a particular parcel and b_{UDj} could represent the total annual meat production (kg year^{-1}) from sheep and beef farming for the whole landscape. Analogously, performance constraints can be used to ensure the performance of ecosystem services. For example, the user can specify the maximum tolerable nitrate leached from particular land uses in particular areas.

OPTIMISING ECOSYSTEM SERVICES

Sheep and beef farming, dairying and forestry are all important production land uses in New Zealand. Not only do they significantly contribute to the country’s economy, but they also shape large parts of the country’s landscape and environment (Table 1). Additionally, about a third of New Zealand’s area is legally protected conservation land (Ministry for the Environment 2010). In total, livestock farming and conservation land have covered approximately 80% of New Zealand’s land area in recent years (Statistics New Zealand 2007).

The land uses given in Table 1 impact on a range of ecosystem services of importance for New Zealand. Many of the impacts of these land uses are negative – for example the contribution of non-forested land uses to soil erosion and hence their negative effects on the erosion control service. But the impact can also be positive, such as the effect of non-forested land uses on stream flows (and hence on water regulation services) or the contribution of conservation land to New Zealand’s biodiversity and other services (Ministry for the Environment 2010). Increases, decreases or intensification of these land uses therefore have an effect on landscape ecosystem services. We investigate the complex interplay of positive and negative impacts of significant

TABLE 1 Important New Zealand land uses

Land use	Total area (million hectares)	Area share (percent of total land area)	Value of exports (billion NZ$)
Sheep and beef	1[1]	38	5.1[2]
Forestry	1.8[1]	7	4.5[2]
Dairying	1.9[1]	6	12[2]
Conservation land	8.7[3]	33	-

[1] Statistics New Zealand, Agricultural Census (2007), [2] Beef and Lamb (2012), [3] Ministry for the Environment (2010).

New Zealand land uses on a range of ecosystem services in the two case studies. We especially focus on the effect of the spatial configuration of land use on ecosystem services, and explore how the spatial configuration of land uses might be improved to maximise ecosystem services. These case studies serve to illustrate the general applicability and flexibility of spatial optimisation and its potential as a further tool to help land managers achieve more sustainable outcomes.

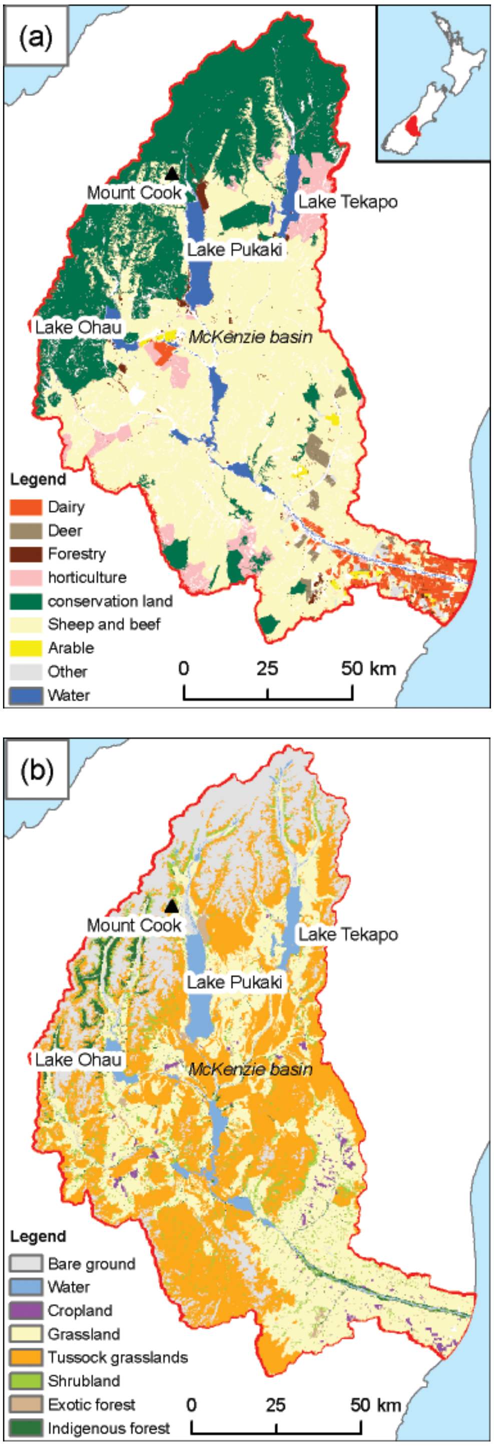


FIGURE 4 Land use (a) and land cover (b) of the Waitaki catchment, New Zealand (adapted from Ausseil et al. 2012).

TABLE 2 Land-use optimisation scenarios for the Waitaki catchment, New Zealand (redrawn from Ausseil et al. 2012).

	Scenario 1	Scenario 2	Scenario 3
Land-use options	Dairy, sheep and beef, conservation land	Dairy, sheep and beef, conservation land	Dairy, sheep and beef, conservation land
Objectives	Maximise clean water provision	Maximise habitat provision	Maximise water regulation
Performance constraints	Maintain gross outcome for dairying and for sheep and beef farming	Maintain gross outcome for dairying and for sheep and beef farming	Maintain gross outcome for dairying and for sheep and beef farming
Allocation constraints	Dairying and sheep and beef farming to be allocated to suitable parcels only	Dairying and sheep and beef farming to be allocated to suitable parcels only	Dairying and sheep and beef farming to be allocated to suitable parcels only

Case study 1: Waitaki catchment

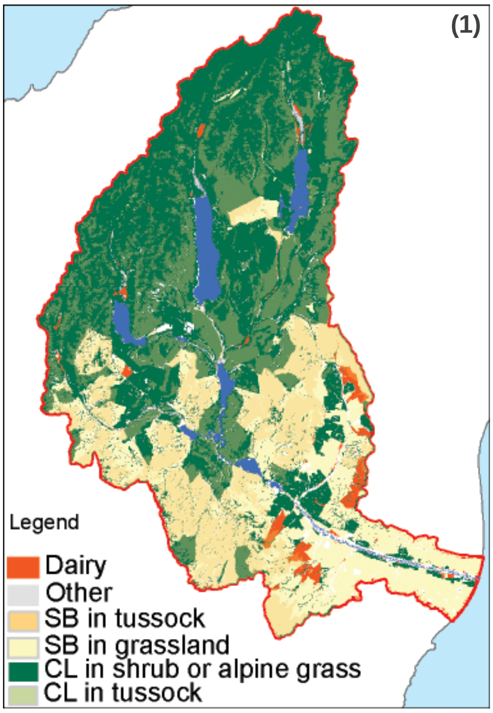
The Waitaki catchment (12 000 km^2) in New Zealand's South Island extends from the South Canterbury coast to Mount Cook at 3754 metres elevation. It contains three major hydropower lakes (Ohau, Pukaki and Tekapo). The climate is highly variable, with 8000 millimetres precipitation annually in the mountain areas, and not much more than 500 millimetres per year in the drier parts of the catchment. The land use comprises sheep and beef farming (60%), conservation land (32%), dairying in the lowlands (3%), and other minor land uses such as cropping and viticulture (Figure 4). The land cover comprises 35% tussock grasslands, most of which is used for sheep and beef farming, 30% exotic grasslands and arable crops, 35% indigenous forest, and lesser areas of alpine rocks and scrub.

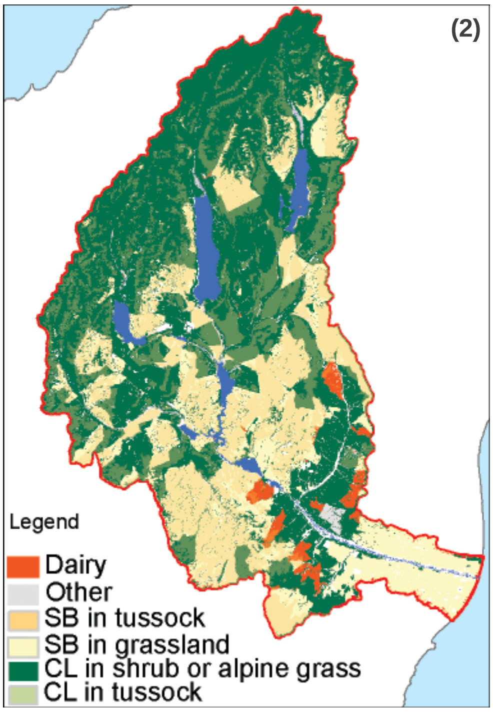
The catchment is important for its natural, recreational, community, and fishery values. However, ongoing intensification of agricultural land use threatens to compromise some of these values. Many of the high country farms are undergoing tenure review. This commonly results in the high country part of farms being returned to conservation management and the lower parts being sold to farmers who may intensify land use to maintain the same overall level of agricultural output. Irrigation is becoming more common on the intermontane plains of the Mackenzie Basin, as a means to introduce dairying to the otherwise dry soils. Likely impacts of this intensification are increased nitrate leaching into the groundwater and subsequent reduction of water quality of the pristine Waitaki River.

We applied LUMASS to determine land-use patterns optimised for maximising clean water provision (Scenario 1), habitat provision (Scenario 2), and water regulation (Scenario 3), while maintaining food production (Table 2) (Ausseil et al. 2012). We modelled the impact of these scenarios on ecosystem services in terms of indicators developed at national scale (Ausseil et al. 2013). The modelling was based on the following assumptions:

- Sheep and beef farming on tussock grasslands would not change the land cover, but other land covers would be converted to grasslands under sheep and beef farming.
- Conservation land on grassland would revert into shrubland, but natural tussock would be maintained.
- Dairy farming would always involve conversion to exotic grassland.

Furthermore, for each of the optimisation scenarios, we specified, as constraints, that total gross output from dairying and sheep and beef farming should remain constant (Table 2). In Scenario 1 we investigated the impact of the configuration of the existing agricultural land uses on water quality. For Scenario 2, the main objective was the restoration of biodiversity values while maintaining the current agricultural production. In Scenario 3, we maximised water yield to assess how much water could be gained for hydroelectricity by the spatial reconfiguration of land use. While each scenario involved a single-objective optimisation problem, a further investigation could explore the joint





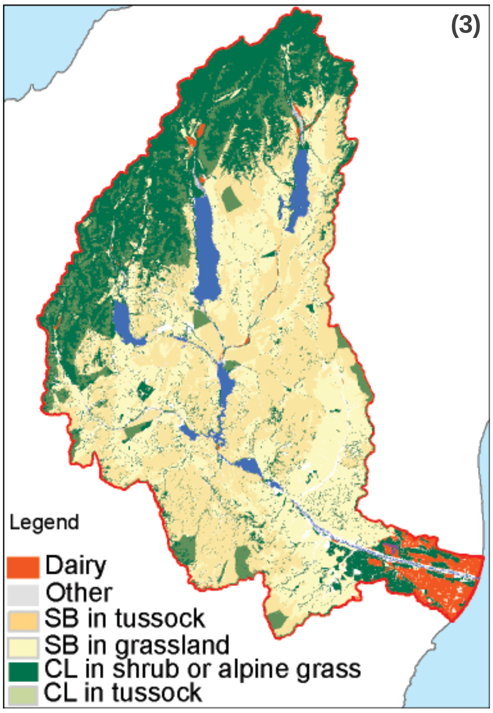


FIGURE 5 Case study 'Waitaki Catchment': Optimised land-use pattern for Scenario 1 (maximise clean water provision), Scenario 2 (maximise habitat provision), and Scenario 3 (maximise water yield) respectively (SB = Sheep and beef, CL = conservation land) (adapted from Ausseil et al. 2012).

maximisation of clean water provision, habitat provision, and water regulation as a multi-objective optimisation problem. The resulting optimal land-use configurations are shown in Figure 5 with percent changes in Figure 6.

In Scenario 1, clean water provision was improved by 51% (Figure 6). However, habitat provision was reduced by 3%, because conservation land was not the targeted area, and water yield was reduced by 18%. Dairying was displaced from the coastal area due to lower nitrate leaching rates in the optimal areas (Figure 5). Greatest benefit for clean water provision was obtained by expanding conservation areas in the upper part of the catchment. These areas were selected because of their greater propensity to leach nitrate.

In Scenario 2, habitat provision was improved by 47% (Figure 6). But in this case we have a co-benefit with clean water provision, which was improved by 37%. Water yield reduced by 2%. The optimal land-use configuration is similar to that for Scenario 1, showing some spatial congruence between clean water provision and habitat provision. Compared to the outcome for Scenario 1, there was a large increase in conservation land in the catchment (+85%), including significant new areas in the mid-catchment (Figure 5).

In Scenario 3, water regulation improved by 6% (Figure 6). We also achieved co-benefits for both clean water provision and habitat provision with improvements of 7% and 6%, respectively. This was a result of the 17% increase in total sheep and beef area, as well as the 5% reduction in conservation area in the optimised land-use configuration (Figure 5). The optimisation procedure privileged the prominence of tussock grasslands, which show high water yield. The spatial pattern resembles the current land use (Figure 4). It suggests that extensive sheep and beef farming

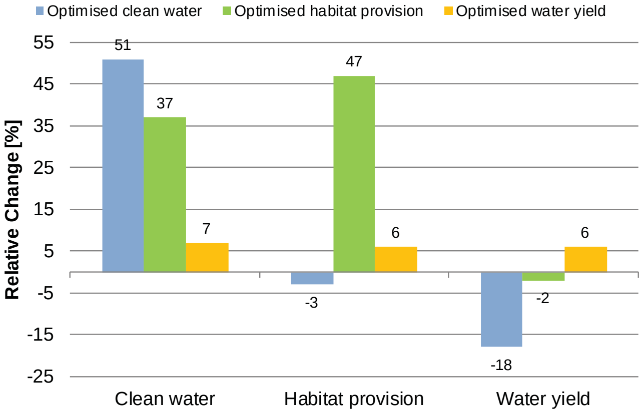


FIGURE 6 Case study 'Waitaki Catchment': Relative change in performance (%) from the actual land-use configuration to the optimised land-use patterns of Scenarios 1 to 3 in terms of clean water provision, habitat provision, and water yield respectively.

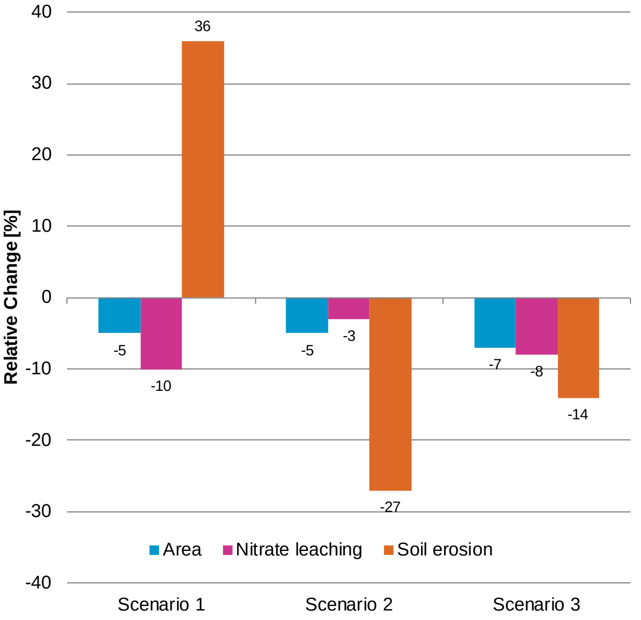


FIGURE 7 Case study 'Central North Island': Relative change in performance (%) from the land-use configuration as at 2008 to the optimised land-use patterns of Scenarios 1 to 3 in terms of occupied area, nitrate leaching, and soil erosion.

should be kept in tussock grasslands to maintain the water flow in the Waitaki River.

In summary, in each of the three scenarios described above, spatial optimisation kept dairying off the intermontane plains of the Mackenzie Basin, whose shallow soils are prone to nitrate leaching. The results suggested tussock grasslands should be maintained through low levels of sheep and beef farming to maximise water for hydro lakes and for irrigation of the lower coastal areas (dairying) to keep agricultural output up. We assumed that sheep and beef farming on the tussock grasslands would remain at a low stocking rate and that no areas in tussock would be converted to exotic grasslands. More intensive sheep and beef farming, however, would increase bare ground, degrade soils, introduce weeds, and reduce biodiversity. If intensification in dairying occurs in the upper part of the catchment, this would come at the cost of reduced habitat and clean water. We assumed that conservation land under grassland cover would

TABLE 3 Land-use optimisation scenarios for the case study area in the central North Island, New Zealand.

	Scenario 1	Scenario 2	Scenario 3
Land-use options	Dairying, forestry, sheep and beef, beef farming, sheep farming		
Objectives	Minimise nitrate leaching	Minimise soil erosion	Minimise nitrate leaching and soil erosion
Performance constraints	Maintenance of agricultural output (milk solids, wood, meat, wool) of each of the individual land uses as at 2008		
Allocation constraints	Land-use change may occur only on parcels occupied by one of the land uses in focus (the 5 land-use options above); 'other' land-uses to be kept constant		

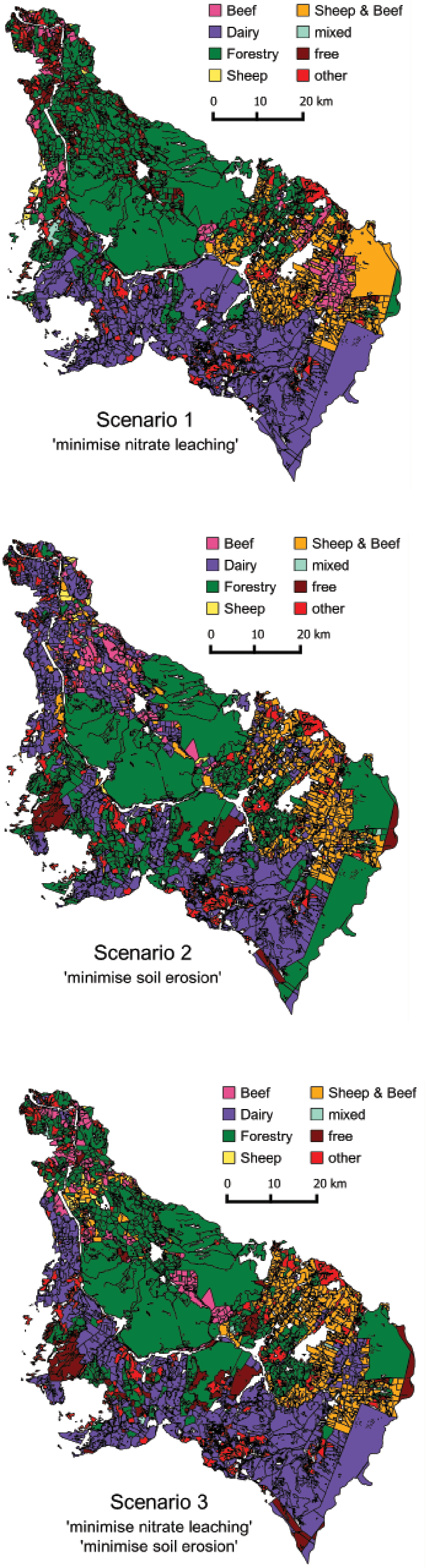


FIGURE 8 Case study 'Central North Island': Optimised land-use pattern for Scenario 1 (minimise nitrate leaching), Scenario 2 (minimise soil erosion), and Scenario 3 (minimise nitrate leaching and soil erosion).

revert to shrubland, and that natural tussock would be maintained. The validity of this assumption depends on active management of weeds (e.g. wilding pines, *Hieracium* invasion). The impact of weeds has not been taken into account yet has an effect on ecosystem services.

Case study 2: Central North Island

The second case-study area is located in the central North Island of New Zealand, between Cambridge in the north-west, Rotorua in the north-east, and Taupo in the south (Figure 2). It occurs within the ‘Central Hill Country and Volcanic Plateau’ land environment (Level I environment F); the northern part of the area belongs to Level II environment F6, and the southern part of the area belongs to Level II environment F7 (Leathwick et al. 2003). In 2008, the land use was mostly pastoral farming and forestry, with 43% plantation forests, 31% dairy, 12% sheep and beef, 5% beef, and 1% sheep farming. Eight percent of the area was occupied by other land uses. We investigated the impact of these land uses on clean water provision and erosion control. Especially in the light of dairy expansion and intensification (Mulet-Marquis and Fairweather 2008; DairyNZ 2011; Statistics New Zealand 2013), clean water provision (i.e. water quality) is currently a topic of debate in New Zealand (Mackay et al. 2011). In the case study area, dairy farming increased in area by 12% from 2003 to 2008, whereas the area of plantation forest decreased by approximately the same amount. Also, soil erosion (i.e. erosion control) represents an important issue for New Zealand’s landscape and is closely linked with pastoral farming systems (Dymond et al. 2010; Herzig et al. 2011; Marden et al. 2011).

In this case study, we assess the effect of the land-use configuration on clean water provision and erosion control. We use total annual nitrate leaching (kg year^{-1}) from soils as an (inverse) indicator for the provision of clean water, and we use the total annual amount of eroded sediment (t year^{-1}) as an (inverse) indicator for the performance of the erosion control service. We ran three land-use optimisation scenarios with different objectives but identical constraints (Table 3). All scenarios were based on the 2008 land-use configuration (Figure 2). The results are expressed as relative change in performance (%) from the land-use pattern as at 2008 to the optimised land-use patterns (Figure 7), as well as maps showing the optimised land use as a result of the individual optimisation scenarios (Figure 8).

We optimised the land-use pattern to minimise nitrate leaching (Scenario 1) and soil erosion (Scenario 2). In Scenario 3, we combined both objectives to minimise both nitrate leaching and soil erosion. To achieve that, we employed the ‘ε-constraint’ approach described earlier and used the objective function result of Scenario 1 (‘minimise nitrate leaching’) as an objective constraint for the single optimisation problem ‘minimise soil erosion’. We relaxed the objective constraint in an iterative process, until we found a solution for the problem. In all three scenarios, we restricted land-use change (i.e. reallocation) to those parcels that were already occupied by one of the land uses under consideration (Table 3) in 2008. All ‘other’ land uses were constrained to be unaffected by the optimisation procedure. To avoid monocultures, we constrained the optimisation procedure to produce the same agricultural output as in 2008.

Scenario 1 showed that optimising the land-use pattern to minimise nitrate leaching reduced the nitrate leaching for the whole case study area by 10% (Figure 7). At the same time, total annual soil erosion increased by 36%. The total agricultural output of the area could be maintained or increased for each individual land use. Additionally, the total overall area occupied by the considered land-use options could be reduced by 5% compared to 2008.

Overachievements, as represented by the relative changes in wool production and total occupied area, are a result of the spatial constraints LUMASS automatically sets for each individual parcel. Each parcel has to be either completely occupied by the different land-use options, or left completely unoccupied. This leads to a degree of ‘discreteness’ in the model in the sense that parcels have to be either completely allocated with the available land-use options, or left completely unoccupied. In the case of wool production and total occupied area, the practical result is that there is no other allocation possible that would not either worsen the objective function result (cause higher nitrate leaching) or violate some of the given constraints (allocation constraints, performance constraints, and the ‘complete-parcel-constraint’). Using continuous decision variables (equation (1)) in principle allows for the occurrence of parcels with mixed land uses (Figure 8), and therefore some spatial fuzziness in the model result. However, allowing mixed land-use parcels significantly reduces computational costs by essentially turning a combinatorial optimisation problem into a mixed-integer linear program, which can be solved much easier and faster. In fact, only a few mixed land-use parcels result from the land-use optimisation as implemented in LUMASS. Also, the area share of each individual land use is reported by LUMASS and accounted for in the evaluation of ecosystem services and land-use performance. From a practical point of view, a mixed land use indicates that the given area shares of the land uses allocated to the particular parcel can be arbitrarily distributed within the parcel, without compromising the result of the optimisation procedure.

The optimised land-use configuration for Scenario 1 shows pastoral farming was shifted to the south of the case study area, and forestry was mostly shifted to the north. This reflects the general spatial pattern of nitrate leaching potentials as given in Figure 1 (left). Pastoral farming was shifted to areas with lower nitrate leaching potentials and forestry was shifted to areas with higher nitrate leaching potentials. This pattern is maintained for the particular pastoral farming land uses. Sheep and beef farming, less prone to nitrate leaching than dairy farming, was shifted to areas with a higher nitrate leaching potential, whereas dairying was allocated to areas with a lower nitrate leaching potential. Overall, we find the general trend towards land uses less prone to nitrate leaching being allocated preferentially to the northern part of the case study region, and those more prone to nitrate leaching being allocated to the southern part of the case study region. The boundary between those areas coincides more or less with the boundary between Levels II F6 and F7 land environments. In the model, these environments are represented by different climates and soil types (Dymond et al. 2013).

In Scenario 2, optimising the land-use pattern to minimise soil erosion (Figure 8) reduced total soil erosion for the whole area by 27% (Figure 7). Nitrate leaching was reduced by 3%. Agricultural output stayed the same as for 2008. Also, the total overall area devoted to the considered land uses was 5% less. Similar to Scenario 1, the spatial allocation pattern reflects the spatial pattern of soil erosion potential as shown in Figure 1 (right). Differences in soil erosion potential are dictated mainly by the presence or absence of forest cover. Since pastoral farming significantly increases the potential for soil erosion as compared to land uses with forest cover, dairying and sheep and beef farming are allocated to parcels with relatively low soil erosion potential, and forestry is allocated to parcels with relatively high soil erosion potential. Parcels with potential soil erosion rates equal to or above 5.6 t ha^{-1} year^{-1} remain unallocated. Overall, the pattern is remarkably different from the pattern for Scenario 1, especially for dairy farming, which is allocated to parcels with relatively high nitrate leaching potentials, which were not occupied by dairying in Scenario 1.

In Scenario 3, the combined objectives of minimising nitrate leaching and soil erosion resulted in an optimised land-use pattern that reduced total nitrate leaching for the whole case study area by 8%, and soil erosion by 14%. The land-use configuration more closely resembles that for Scenario 1 than that for Scenario 2. This reflects the higher priority attached to minimising nitrate leaching compared with minimising soil erosion. Overall, pastoral farming is mostly allocated to the southern part of the case study area, whereas forestry is mostly allocated to the northern part. Parcels in the northern part of the area allocated to sheep and beef farming reflect a trade-off being made by the algorithm to minimise the objective function and fulfil all given constraints.

These results appear sensible and demonstrate the potential for using spatial optimisation to help maximise ecosystem services. The result for Scenario 3 reaffirms that the land-use configuration has a marked effect on the performance of ecosystem services. It also shows that dairying might be increased to the equivalent of 8% nitrate leaching, without negatively impacting system-wide measures of clean water (water quality) in the region. At the same time, soil erosion can be reduced 14%, and 7% of the area can be reallocated to non-pastoral land uses (conservation land or forestry) thus increasing biodiversity or wood production.

DISCUSSION

This work shows how land-use configuration can in principle be manipulated to improve aggregate measures of land use and ecosystem services performance, for large areas. The magnitude of the impact depends on the actual land-use pattern, the overall goals of land management (represented by the objective functions), and the societal demands with regard to the expected return from the landscape (represented by the constraints). The existence of this potential for improvement might be seen as revealing the unused potential of a landscape. In practice this unused potential can be realised through sensible consideration of the spatial variability of landscape attributes, land-use suitability, and appropriate management practices. Spatial optimisation offers promise as an appropriate tool to maximise the potential of the landscape in terms of its land use and ecosystem services performance.

The work also shows that the spatial optimisation tools we now have available can be used successfully to address complex spatial planning problems involving competing land uses and contradictory objectives (see also Seppelt and Voinov 2002; Groot et al. 2008; Meyer and Grabaum 2008; Polsaky et al. 2008; Lautenbach et al. 2012). The ability of multi-objective spatial optimisation (MOSO) to help a land manager to identify and quantify the unused potential of a landscape represents an advantage over other methods such as spatial multi-attribute decision making (MADM) (e.g. Joerin and Musy 2000; Robinson et al. 2002; Jackson et al. 2013) or spatial prioritisation (see Moilanen et al. 2009a). Whereas MADM allows a user to identify and rank suitable locations for a particular land use or activity with regard to a given objective and possible constraints, MOSO and spatial prioritisation can be used to compare different land uses or activities with one another at the same time (cf. Scenario 3, Case study 2: Central North Island). However, in contrast to spatial prioritisation (e.g. Moilanen et al. 2005, 2011), MOSO also considers different spatial land-use configurations in the optimisation procedure. This is achieved by using indicators for performance potentials as input criteria (Figure 1), rather than measurements or estimates of the actual state of an indicator based on the actual land use or land cover. In a biodiversity context, for example, this could be used to include, within the optimisation procedure, the search for suitable potential sites for biodiversity offsetting or conservation (cf. Holzkamper and Seppelt 2007b). Biodiversity offsetting could be represented as a land use or land-cover option associated with specific management practices. Indicators for biodiversity performance as well as development or maintenance costs for potential sites could be brought into the spatial planning problem as criteria.

The modelling approach has a further significant benefit. Using computer tools that systematically consider a range of scenarios, objectives, constraints, and stakeholder or societal preferences helps decision-makers gain insight into the full spectrum of feasible solutions. It allows them to creatively explore opportunities in relation to the imposed limits. Hence, MOSO is a useful tool to help develop goals or a ‘Leitbild’ (Mosimann 2000; Meyer and Grabaum 2008; Potschin et al. 2010) for landscape development in a particular region. The next question is then how the goals can be achieved, taking into account factors such as transition costs and property rights. The former can be included as a criterion in the optimisation procedure, depicting the costs involved to switch from one land-use option to another. Depending on the question and preferences, transition costs can be modelled either as an objective (i.e. ‘minimise transition costs’) or as a set of constraints specifying maximum tolerable costs. Property rights, however, can be accommodated in the optimisation process only indirectly. For example, spatial allocation constraints can be used to restrict land-use change to a particular set of parcels in the study area. In general, land use or management changes on private land can only be achieved by regulatory mechanisms (cf. Pannell 2008) where the private benefit is insufficient to encourage ‘endogenous’ land-use change. This highlights the challenge involved in operationalising theoretical landscape development goals from a policy perspective.

A practical challenge, from a planner’s point of view, is how they themselves might apply the procedures to derive a spatially-explicit optimal land-use pattern. Since multi-objective spatial optimisation is not part of the common GIS (Geographical Information System) toolkit, other software tools have to be used. Moilanen et al. (2009a) discuss quantitative methods and computational tools for spatial conservation prioritisation. Mathematical optimisation techniques are used for site prioritisation and selection, as well as the allocation of conservation actions with the objective to maximise the conservation value (Moilanen et al. 2009b). Some of the discussed software packages (Ball et al. 2009; Moilanen et al. 2009c; Pressey et al. 2009; Sarkar et al. 2009) allow for detailed non-linear process descriptions and/or account for sophisticated spatial neighbourhood relationships. However, they are predominantly focused on conservation biology and hence only offer limited flexibility to configure the number and type (i.e. minimisation or maximisation) of objective functions as well as the specification of constraints. Therefore, it would appear they are less applicable to general land-use pattern optimisation for maximising ecosystem services. On the other hand, only a few ready-to-use MOSO software packages for land-use pattern optimisation have been documented in the literature. They are either implemented as a library and require programming skills to be utilised and adopted to specific projects (e.g. Holzkamper and Seppelt 2007a), or they are not publicly available (e.g. Meyer and Grabaum 2008), or they are packaged for a specific project (e.g. Roetter et al. 2005) and cannot easily be reused for other applications.

In this project we have used the open-source LUMASS (Land-Use Management Support System; Herzig 2005, 2013). It includes a generic module for optimising spatial resource allocation to fixed spatial units and offers great flexibility in specifying the number and type of objective functions as well as allocation and performance constraints. This allows LUMASS to be used not only for land-use pattern and ecosystem services optimisation, but also for optimising the spatial allocation of water, fertiliser, pesticides or other resources. LUMASS represents spatial optimisation problems in terms of the techniques of multi-objective linear programming, which means objective functions and constraints (equations (1) and (2)) must be linear. This means we use performance indicators (e.g. soil erosion per hectare) that are normalised to the unit of the decision variables (e.g. hectares of a particular land use). This way, the models used to estimate performance scores can still employ non-linear relationships, e.g. soil erosion (Dymond et al. 2010) and habitat provision (Ausseil et al. 2011), as long as the calculation of the performance scores is independent from the decision variables. Where the decision variables are part of a non-linear term to calculate performance scores (e.g. Aerts and Heuvelink 2002; Tourino et al. 2003; Holzkamper and Seppelt 2007), the optimisation problem is also non-linear. Such problems are in general much harder to solve and are often addressed by search heuristics, such as simulated annealing (SA) (e.g. Aerts and Heuvelink 2002; Tourino et al. 2003), or genetic algorithms (GA) (e.g. Holzkamper and Seppelt 2007; Lautenbach et al. 2012).

The same applies to combinatorial optimisation (CO) problems, which involve binary decision variables (e.g. Ball et al. 2009). Unlike algorithms for solving linear optimisation problems, for example the generalised simplex method by Dantzig et al. (1955), search heuristics are not guaranteed to find the global optimum of a non-linear optimisation problem (Osman and Kelly 1996). The modeller has to trade off the greater performance of solving mathematically simpler multi-objective linear programs with the higher computational costs but more realistic representation of the optimisation problem by multi-objective non-linear programs. For a more in-depth discussion, with particular focus on reserve selection, see for example Vanderkam et al. (2007) and Moilanen (2008). In our case studies, only small trade-offs had to be made to significantly enhance the chances of finding a global solution and to decrease computational costs. Land-use pattern optimisation in LUMASS can be modelled with binary or continuous decision variables. Whereas binary decision variables yield an exact allocation of one land use to any one parcel, continuous decision variables introduce a certain degree of fuzziness, because they allow more than one land use to be allocated to an individual parcel. However, as indicated by Figures 5 and 8, very few polygons were allocated with more than one land-use option (i.e. category 'mixed' in the maps) as a result of using continuous decision variables. On the benefit side, using continuous decision variables often makes a particular problem solvable and also significantly reduces the runtime of the optimisation procedure. Computational performance and exactness of the process description, while important, are not the only aspects considered for selecting an optimisation algorithm. For example Ball et al. (2009) point out that, especially in light of often imprecise input data, a single global solution, as produced by linear programming algorithms, is not very useful in conservation planning. In contrast, GA and SA produce a set of near-optimal solutions while searching for the optimum result. Hence, stakeholders are provided with a number of near-optimal solutions to assist decision-making. Using linear programming, multiple optimisation runs with varied constraints have to be conducted to produce a set of quasi optimal solutions.

The accuracy of the result of a spatial optimisation project depends critically on the quality of the input data. Performance scores used as input data for the LUMASS optimisation module can be derived in many ways. They can be derived from quantitative process-based landscape models, or from expert empirical knowledge. The effects of input data provenance or uncertainty have been considered in only a few applied studies. For example, Aerts et al. (2003) discuss the spatial impact of uncertain elevation data on piste planning using SA. Moilanen et al. (2007) use information-gap decision theory for uncertainty analysis in reserve selection. In the area of land-use optimisation, no study is known to the authors that analyses the impact of uncertain input data in terms of performance scores and constraints on the produced land-use pattern. Of special relevance to planners is the sensitivity of the spatial pattern to the input data uncertainties. A relatively stable pattern indicates a larger degree of freedom in terms of planning alternatives, whereas a relatively unstable pattern indicates that there is little room for trade-offs without significantly changing the expectations (i.e. constraints).

CONCLUDING REMARKS

In our future work we want to investigate the sensitivity of the spatial land-use pattern to uncertainty in the input data (performance scores and constraints). We also want to improve the representation of neighbourhood constraints in the optimisation procedure. In particular, we want to implement spatial neighbourhood relationships between different land-use options – for example the minimum or maximum distance between land uses or the minimum or maximum size of a cluster of land-use options – with the aim to better represent habitat requirements. Currently, LUMASS only allows for proximity neighbourhood relationships with regard to fixed spatial objects, that is, objects which themselves are not part of the optimisation procedure (i.e. land-use options). This is achieved by introducing another criterion (layer) into the optimisation procedure that contains performance scores for the given land-use options depending on the proximity to an object outside the set of parcels available for land-use allocation. Another open question in applied land-use optimisation is how best to transition from the current land use to the optimal land-use pattern. What are the trade-offs to be made to actually reach the optimum state? So far, land-use optimisation studies have mostly focused on the scientific aspects and the performance of the methodology as such. More applied as opposed to purely scientific studies are required to integrate spatial optimisation into actual real-life regional planning to enhance sustainable management of our natural resources and ecosystem services.

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