



Jul 1st, 12:00 AM

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Optimising Land Use for Multiple Ecosystem Services Objectives: A Case Study in the Waitaki Catchment, New Zealand

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Abstract: In New Zealand there has been rapid land-use change over the last 170 years, from all natural ecosystems to a mix of natural ecosystems (alpine ecosystems, indigenous forests, and tussock grasslands) and managed ecosystems (primarily pastoral farming and forestry). Tools are required to assess the balance between natural and managed ecosystems, and to ensure the sustainability of human development and equity in resource use. We use the ecosystem services approach to help resource managers achieve that balance. In this paper we combine several critical ecosystem services (provision of food and fibre, provision of clean water, regulation of water-flow, provision of natural habitat) into a framework for land-use optimisation, LUMASS. We developed spatial explicit models of these services based on process-based models upscaled to national level using look-up tables. Quantification depends on land use, climate, and soil, and can be used to analyse trade-offs and the optimal configuration of the landscape that would maximise the benefits for humans. The Waitaki catchment is subject to such trade-offs with the conversion of natural areas (mainly tussock grasslands) into dairy farming, which, while increasing the provisioning of food, will impact on water quality and quantity, and reduce habitat provision. We applied the LUMASS optimisation algorithm with an objective function designed to maximise regulating services (clean water provision, water-flow regulation) while still maintaining provisioning services (food). The land-use options are managed agro-ecosystems (dairy, sheep, and beef) and natural ecosystems (conservation land). We explain differences between the current land-use pattern and the optimal land-use pattern.

Keywords: land-use change, spatial optimisation, ecosystem services, landscape modelling, trade-offs.

1 INTRODUCTION

The Millennium Ecosystem Assessment [MEA 2003] has highlighted the dependence of human well-being on ecosystem services (ES). The MEA classifies ecosystem services into provisioning (e.g. provision of food and fibre), regulating (e.g. regulation of climate through carbon storage), cultural (e.g. recreation values), and supporting services (e.g. nutrient cycling and soil formation). The MEA assessment showed net gains in human well-being and economic development over the last 50 years, but these have come at a cost in the form of “degradation of many ecosystem services, increased risks of nonlinear changes, and exacerbation of poverty for some groups of people” [MEA 2003].

Recently, recognition of the need to preserve and enhance multiple ecosystem services has yielded attempts to identify “hotspots”, where high levels of various

ecosystem services converge [Naidoo et al. 2008, Crossman et al. 2009, Egoh et al. 2009]. Some studies have used monetary valuation to assess ecosystem services and be able to compare them [Turner et al. 2007, Dymond et al. 2012]. Other studies consider the spatial correlation of biophysical indicators [Egoh et al. 2009, Raudsepp-Hearne et al. 2010]. These studies are based on static, spatial congruence of ecosystem services.

In New Zealand, agriculture forms the backbone of the economy, so minimising environmental impacts of agriculture while maintaining (or increasing) economic returns is a major national concern. While agricultural production underpins human society, it is known to be associated with multiple environmental impacts that lead to depletion of natural capital stocks. Impacts of agricultural production include degradation of water quality, increased erosion, greenhouse gas emissions, and loss of biodiversity. In contrast, natural areas provide support for biodiversity. However, native forests and scrubs are decreasing water yield compared to grasslands, which can be an issue in drier parts of the country where water demand is high. Tools are thus required to understand trade-offs between these ecosystem services.

In this paper, we used models to quantify ecosystem services as a function of land use, climate, and soil. The services were then optimised using LUMASS, a software tool for spatial optimisation [Herzig 2008]. The objective is to maintain production of food, while maximising regulating services such as water regulation, habitat provision and clean water provision. We focused on the Waitaki catchment, which has major environmental impacts associated with land-use changes driven by economic development.

1 METHODS

1.1 Study area

The study area, the Waitaki catchment, is located in the South Island of New Zealand. The catchment is 12,000 square kilometres, ranging from the South Canterbury coast to Mount Cook at 3754m (the highest peak in New Zealand). There are three major hydropower lakes (Ohau, Pukaki and Tekapo). The climate is very diverse, with rainfall varying from 8,000 mm on the mountains, to just over 500 mm in the drier parts of the catchment. The land use mainly comprises sheep and beef (60%), conservation land (32%), dairy in the lowlands (3%), and other minor land uses such as cropping and viticulture (Figure 1). The land cover comprises 35% tussock grasslands, mainly corresponding to sheep and beef farming, 30% pasture and cropping, 35% indigenous forest, alpine rocks and scrub.

The catchment is important for its natural, recreational, community and fishery values. However, many parts of the catchment are experiencing intensification of agriculture, which could compromise some of these values. Many of the high country farms are undergoing tenure review where the high country part of farms are returned to conservation management and the lower parts are sold to farmers who are able to intensify if they wish – this is the normal consequence if farmers wish to maintain the same level of agricultural output. Irrigation is being used more commonly on the intermontane plains of the McKenzie basin to introduce dairy land use to the normally dry soils. Possible impacts of this intensification are increased nitrate leaching into the ground water and subsequent reduction of water quality of the normally pristine Waitaki River.

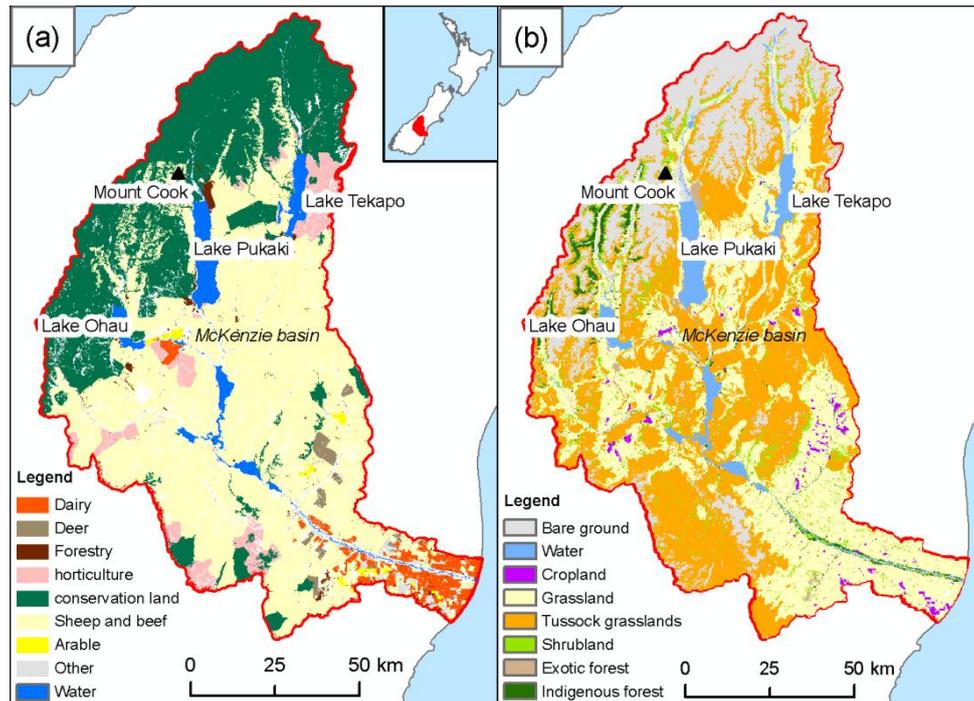


Figure 1. Land use (a) and land cover (b) of the Waitaki catchment, New Zealand.

1.2 Ecosystem services considered

The quantification of ecosystem services followed models developed by Ausseil et al. [submitted]. For the Waitaki catchment, four services were evaluated:

- Clean water provision
- Natural habitat provision
- Water regulation
- Provision of food

1.2.1 Clean water provision

We estimated nitrogen leaching using OVERSEER[®] [Ministry of Agriculture and Forestry et al. 2011], a nutrient budget tool that takes farm management, soil and climate variables as inputs, and produces annual nutrient budgets including nitrogen leaching. We ran OVERSEER[®] for 100 combinations of soils and climate from level II of LENZ [Leathwick et al. 2003], assuming stocking rate was at the stock carrying capacity of the land according to the New Zealand Land Resource Inventory [Landcare Research Ltd 2011], and calculated the annual leaching rate per stock unit. The nitrogen leaching rates per stock unit were then combined with a map of animal numbers to produce a map of nitrogen leaching amount per hectare (Nleach). The clean water provision was then assumed to be $(-Nleach)$, which means that a zero value (no leaching) is the maximum attainable value.

1.2.2 Natural habitat provision

A simple benefit function was used to assess the impact on natural habitat of conversion from pasture to forested land [Ausseil et al. 2011]. We used an indicator that calculates the proportion of natural (pre-human) area remaining in a land environment [Leathwick et al. 2003], weighted by a condition index. Indigenous forest, subalpine shrublands, and alpine habitats are all assumed to have a condition of 1.0. Tussock grasslands and indigenous shrublands are not climax ecosystems so are assigned grassland conditions less than unity, at 0.8 and 0.5 respectively, thought to represent their contribution to biodiversity relative to the climax state. All other land covers are assumed a condition of 0.

1.2.3 Provision of food

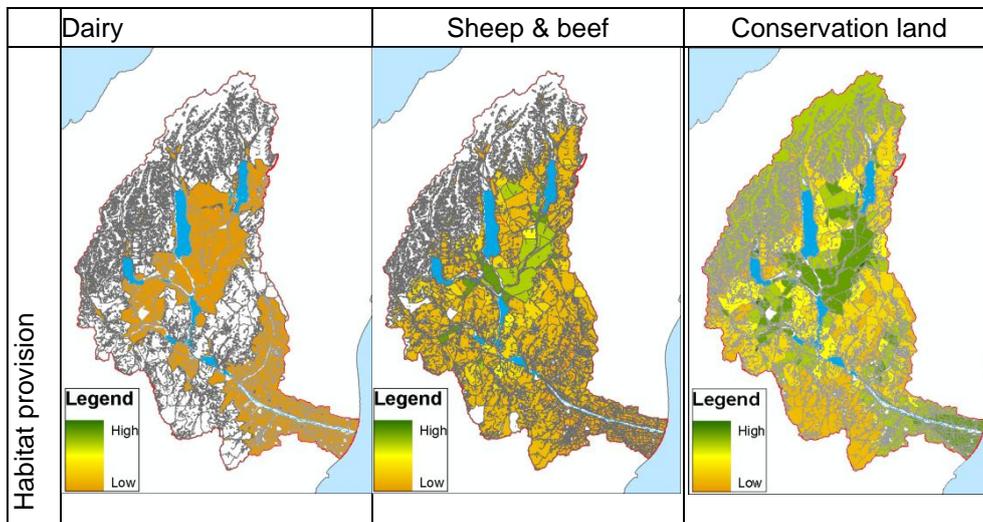
The livestock products represent the greatest proportion of food provision in the Waitaki catchment. We used the animal distribution map previously created and retrieved statistics at the district level [Statistics New Zealand 2007]. We then created maps of food production flow for average milk solids per cow (in kg of milk solids/ha/year), average meat in terms of sheep, lamb and cattle (in kg meat/ha/year). We converted food production into gross outcome, assuming \$7/kg of milk solids, and \$7.5/kg of meat.

1.2.4 Water-flow regulation

Changes in forest cover can reduce the amount of water received by rivers and aquifers, and could potentially restrict the availability of freshwater for other purposes. We used a model (WATYIELD) to predict the hydrological effects of land cover change [Fahey et al. 2004]. The model was calibrated to New Zealand conditions. It requires data on land covers, soil types and physical properties, and daily evaporation and rainfall. The model was run for a 10-year time period and the average reduction in water yield found for four land covers: forest, scrub, tussock, and grass.

For each land use (dairy, sheep & beef and conservation land) we calculated the potential maps for each ecosystem service (figure 2). We assumed several hypotheses:

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



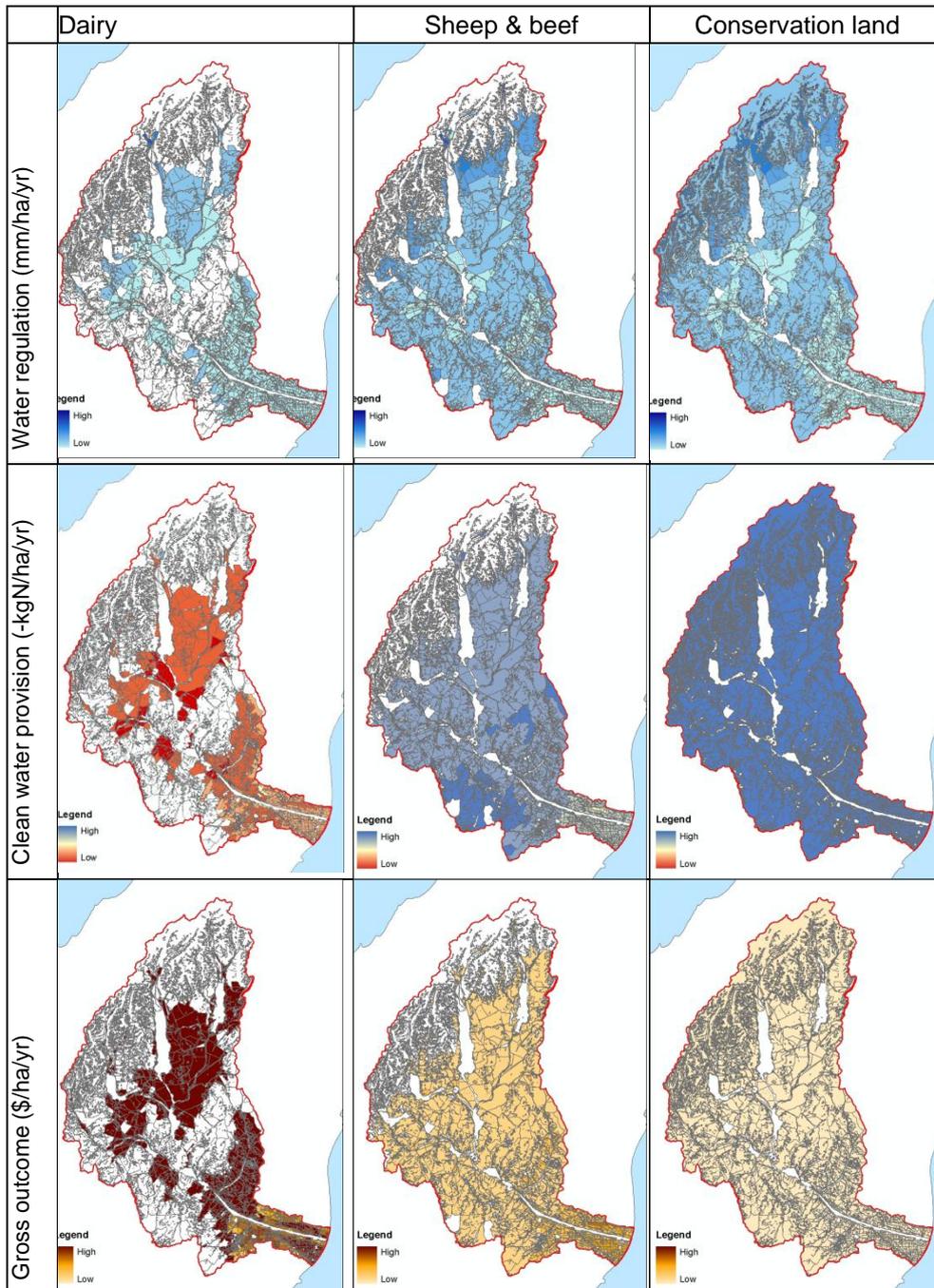


Figure 2. Potential ES maps for dairy, sheep & beef and conservation land. White areas are unsuitable.

1.3 Land use optimisation (LUMASS)

The Land-Use Management Support System (LUMASS) is a free and open-source software tailored to land-use modelling and optimisation. It is built on open source software libraries for geospatial raster-based processing, visualisation, and optimisation: (i) the Orfeo Toolbox [CNES 2012], (ii) the Visualisation Toolkit (VTK) [Kitware Inc. 2012], the Mixed Integer Linear Programming System Ip_solve [Berkelaar et al. 2005], and the cross-platform application and user interface framework Qt [Nokia 2012].

LUMASS determines the allocation of a set of land-uses to a set of spatial units (e.g. polygons) in order to optimise an objective and subject to a set of constraints. However, some land uses can be unsuitable for the unit. For example, the dairy

industry will not implement on the mountainous part of the catchment. We introduced spatial constraints to limit dairy farming on land no steeper than 15 degrees. Sheep farming was constraint to areas were carrying capacity was non-zero.

1.4 Scenario testing

We tested three scenarios of optimisation (table 1). Each scenario optimised one ecosystem service while maintaining total gross outcome from dairy and from sheep & beef (as separate criteria). We optimised clean water provision in scenario 1 to determine whether the current agricultural land uses could have been configured better for minimising impact on water quality. We optimised habitat provision in scenario 2 to determine whether and where biodiversity values could be restored while maintaining agricultural productivity. We optimised water regulation in scenario 3 to determine how much water could be gained for hydroelectricity by land use reconfiguration.

Table 1. Scenarios for land use optimisation in the Waitaki catchment.

	Scenario 1	Scenario 2	Scenario 3
Land use options	Dairy, sheep & beef, conservation land		
Objective	Maximise clean water provision	Maximise habitat provision	Maximise water regulation
Criteria constraint	Maintain gross outcome for dairy and for sheep & beef		
Spatial constraint	Dairy and sheep & beef in suitable areas		

2 RESULTS

The resulting optimal land use configurations are shown in Figure 3.

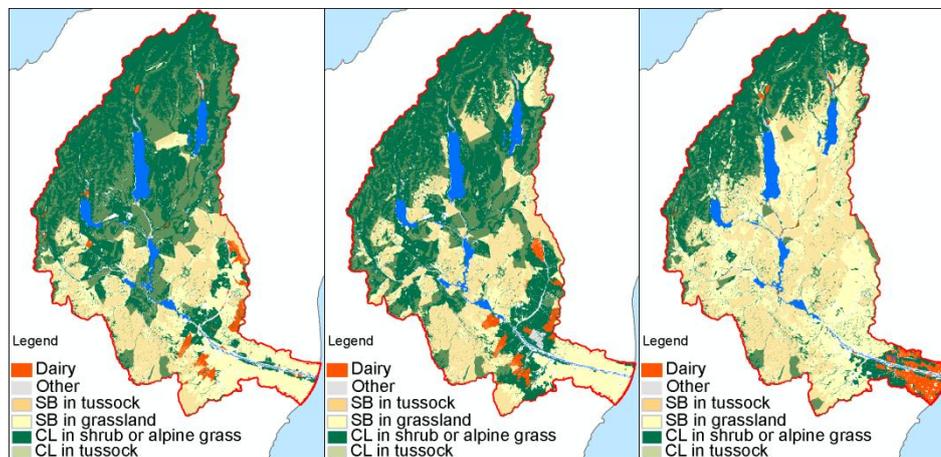


Figure 3. Results of land-use optimisation for scenarios 1, 2, 3 from left to right (SB = Sheep and beef, CL = conservation land).

In scenario 1 clean water provision was improved by 51%. Habitat provision was reduced by 3% and water yield was reduced by 18%. The optimal configuration achieved this by increasing the area of conservation by 31%, and reducing the area of dairy and sheep & beef by 19% and 37% respectively. Dairy land use was displaced from the coastal area due to lower nitrate leaching rates in the optimal areas. The maximum gain in clean water provision was achieved by selecting conservation areas in the upper part of the catchment next to current conservation land. These areas were chosen due to their higher sensitivity to nitrate leaching.

In scenario 2 habitat provision was improved by 47%. Clean water provision was improved by 37% and water yield was reduced by 2%. The optimal land use

configuration has a similar spatial pattern to scenario 1, showing some spatial congruence between clean water provision and habitat provision. There was a large addition of conservation land in the catchment (+85%), including some additional mid-catchment areas as compared to scenario 1.

In scenario 3 the water regulation improved by 6%. Clean water provision was improved by 7% and habitat provision was improved by 6%. The optimal configuration achieved this by increasing the area of sheep & beef (+17%) and reducing the area of conservation (-5%). The optimisation privileged the prominence of tussock grasslands which have high water yield. The spatial pattern looks similar to the current land use, suggesting that the current use of land with extensive sheep and beef in tussock grasslands should not change to maintain water flow in the Waitaki River.

3 DISCUSSION

The results show that for three different scenarios, the optimal land-use configuration kept dairy off the intermontane plains of the McKenzie basin, where there are shallow soils susceptible to nitrate leaching. 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 (dairy) to keep agricultural output up. The results are based on the hypothesis that sheep & beef farming on the tussock grasslands would remain at a low stocking rate and that it would not change tussock into exotic grasslands. High levels of sheep and beef, however, would increase bare ground and degrade soil, introduce weeds, and lower biodiversity condition. If dairy intensification occurs in the upper part of the catchment, it would come at the cost of reduced habitat provision and clean water provision.

The optimal configurations act as a communication tool to show that the current land-use pattern should not differ too much if we want to preserve ecosystem services. However, the results are to be taken with caution. While the optimisation algorithm relies on the ability of the models to describe ecosystem services in a robust manner, quantifying ecosystem services is a difficult task and using the simple models may overshadow some aspects that may have a major influence on the outcome. For instance, water yield is currently calculated on the basis of soil, climate, and vegetation, but the impact of irrigation and groundwater are not taken into account. Another limitation to the approach is that the ES optimisation did not consider the full range of ES. For instance, cultural ES, such as recreation, tourism, and aesthetic value, all very important in the Waitaki catchment, are not considered because it is difficult to spatially quantify these ES.

The combination of quantification of ES with LUMASS permits exploration of land use patterns that would maximise regulating services, whilst maintaining provisioning services. The congruencies, or differences, between the current land-use pattern and the optimal land-use pattern help us understand to what extent human activities are optimal and therefore more sustainable. We used an objective with a single criterion to understand the implications of each ecosystem service optimisation. The next step will be to explore the convergence of clean water provision, habitat provision, and water regulation with a multi-objective optimisation.

ACKNOWLEDGMENTS

This work was funded under the “Reducing Greenhouse Gas Emissions from the Terrestrial Biosphere” and the “Ecosystem Services for Multiple Outcomes” programs (contract number C09X0701 and C09X0912 of the Foundation of Research, Science and Technology of New Zealand).

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