Manaaki Whenua
Landcare Research

Interoperable Modelling – spatial economic optimisation

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Interoperable Modelling – spatial economic optimisation

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Alexander Herzig, Utkur Djanibekov

Manaaki Whenua – Landcare Research

Steve Wakelin

SCION

Juan Monge

Market Economics

Reviewed by:	*Approved for release by:*
Tarek Soliman Economist Manaaki Whenua – Landcare Research	Sam Carrick Portfolio Leader – Characterising Land Resources Manaaki Whenua – Landcare Research

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Summary

In this report we describe the application of the spatial modelling and optimisation framework LUMASS as a spatial optimisation tool in the Interoperable Modelling Project. We demonstrate the potential use of the optimisation component for exploring ecological, economic, and policy objectives in the Aparima catchment. In the absence of a full dataset of outputs generated by the biophysical and ecological models in the Interoperable Modelling Project, we use a simplified representation of land uses and associated environmental and economic indicators. We considered the dominant land uses in the Aparima catchment, i.e. dairy, sheep and beef, and forestry, and characterised their performance regarding nitrate-N leaching, sediment loss, greenhouse gas (GHG) emissions, milk-solids production, and wool production. We modelled hypothetical scenarios that explore the best possible outcome for the catchment with respect to each of those individual performance indicators without changing the present set of land uses or land-use management practices (i.e. the land-use system) and we explored the economic and environmental effects of introducing incentive payments for reducing environmental impacts.

Our modelling results suggest that the modelled land-use system provides very little headroom to improve the catchment's performance without environmental and/or economic impacts. Furthermore, we could show that payments for nitrate leaching and/or sediment reduction have potential to be effective options to reduce environmental pollutants. However, our modelling results also highlighted the need for detailed land-use and land-use management information as well as spatially discriminate land-use performance assessments. Detailed data that reflect the effects and spatial variability of land-use and land-use management practices on economic and environmental indicators can support farmers' decision-making and policy development.

In addition to the highlighted data requirements, our study also showed that extended modelling capability would be required for more sophisticated economic land-use analyses. This includes the capability to represent non-linear relationships, for example, reflect the effect of factors that are not explicitly modelled, such as knowledge and perceptions of farmers in land-use change and management. Potential effect on prices through modelled changes in demand could be addressed with partial equilibrium modelling. Furthermore, the explicit inclusion of uncertainty and risk in the model would make it possible to understand the uncertain impacts of policies on risk-averse decision-making processes.

1 Introduction

1.1 Interoperable Modelling Project

The Interoperable Modelling Project within the Our Land and Water National Science Challenge aims to develop an interoperable modelling system suitable for the integrated spatial assessment of economic and environmental implications of land use and land-use change at the catchment scale. The anticipated uses of the system include the assessment of water quality contaminant dynamics and production potential of the land.

In this report, we describe the application of the spatial modelling and optimisation framework LUMASS (Herzig et al. 2013a; Herzig & Rutledge 2013) as a spatial optimisation tool in the interoperable modelling project. We use the model to compare the impacts of payments for nitrate leaching and sediment loss reductions on land use and the subsequent economic and environmental outputs with the baseline situation.

1.2 Case study – Aparima Catchment

The optimisation case study area is the Aparima river catchment, the smallest of Southland's four main catchments. The headwaters of the Aparima river in the Takitimu mountains drain alpine, tussock, and native forest land and the river meets the Foveaux Strait at Riverton.

Aparima River Catchment

The rolling hill country in its middle reaches is more agriculturally developed, and much of the lower catchment has been extensively modified over the last century, with the drainage of wetlands and the straightening and shortening of streams to assist in flood management activities.

Major tributaries of the Aparima River include the Hamilton Burn in the upper reaches and the Otautau Stream in the lower reaches. The Otautau Stream has very poor water quality. The main pressures on water quality in the Aparima catchment are due to dairy farm intensification as drain networks in the lower catchment can discharge degraded water to receiving streams. Overland flow and nutrient loss from wintering practices contribute significantly, particularly when soils are saturated. Flood and drainage works also potentially impact water quality in the Aparima catchment.

Environment Southland collects water quality information from five sites in the Aparima catchment. Nuisance algal growths, driven by low flows and high nutrient levels and temperatures, increase further down the catchment. Macroinvertebrate health indices progressively decline at sites down the catchment.

https://www.lawa.org.nz/explore-data/southland-region/river-quality/aparima-river/

1.3 Objective

The main objective of the study was to develop a spatial optimisation component that is compliant with the Basic Model Interface (BMI) interoperability standard and that can be integrated in a BMI composite model to conduct land-use scenario analyses. However, due to time constraints within the interoperable modelling project, we were not able to test the optimisation component as part of the composite model assembly. Thus, in this study, we could not use the output data produced by the bio-physical model components as an input data for our analysis. Therefore, in the absence of a full dataset of outputs generated by the biophysical and ecological models in this project, we use a simplified representation of environmental and economic indicators for land uses within the Aparima catchment and demonstrate the potential use of the optimisation component for exploring the ecological and economic policy objectives.

2 Methods

2.1 LUMASS overview

LUMASS is a Land Use MAnagement Support System (Herzig et al. 2013) designed to provide support for two high level aspects of land management: i) dynamic, and ii) spatial planning of ecosystem processes and optimisation. The former aspect is supported by LUMASS' spatial system dynamics modelling framework; the latter is supported by LUMASS' spatial optimisation component. The flexible optimisation framework provides insight into the system operation like the impacts of land-management practices and land-use choice. Spatial optimisation estimates the optimal land-use allocation subject to the available natural resources, ecosystem services and other constraints.

LUMASS is an open-source modelling software and developed using different cross-platform open source libraries for geospatial data processing and visualisation (Herzig 2013). To solve spatial optimisation problems, LUMASS uses the mixed integer linear programming solver "lp_solve" (Berkelaar et al. 2005). LUMASS also provides a graphical user interface to facilitate model development, optimisation, and results presentation.

In this study, LUMASS is used for optimisation processing and displaying raster data. However, it also provides selected functionalities for displaying (polygon) vector data and 3D point clouds. Spatial optimisation scenarios can also be run on polygon vector layers.

To model the scenarios for this study, we use the spatial optimisation component to allocate land-uses to parcels within the Aparima catchment to minimise or maximise an objective function subject to constraints. Land uses vary spatially in their performance as defined by a set of criteria, e.g. nitrate leaching or sediment loss. These criteria can be used to define the model objectives and constraints.

For example, a model objective may be to maximise total economic return for a catchment subject to a maximum level of total N leaching. Each land use may achieve different levels of economic performance and N leaching that vary spatially across the catchment. These criteria are used to optimise the spatial allocation of land uses across the catchment, such that economic return is maximised within the limits on N leaching specified by the constraints. The outputs of the model include land-use area, as well as commodity (milksolids, wool), economic (profits) and environment (GHG emissions, nitrate leaching, sediment loss) indicators.

Currently, LUMASS provides static optimisation without consideration of temporal aspects. Land-use performance criteria are represented as 'steady state' and land-use transition is not modelled. Also, LUMASS does not account for spatial neighbourhood relationships, i.e. the modelled land-use performance per spatial unit (e.g. polygon) is not affected by surrounding land uses.

2.2 Aparima catchment model

In this study, we consider land uses and their produced commodity, as well as the economic and environmental outputs. The following three land uses were recognised in the model:

DAI	Dairy
FOR	Forestry (production)
SNB	Sheep and Beef

In LUMASS, DAI, FOR, and SNB coding were used for dairy, forestry and sheep and beef, respectively. The model allocates these land uses across space (by parcel) to meet the objective function (maximise/minimise) subject to constraints.

Land retired from production was not explicitly modelled but is implicitly recognised as an option. In more detailed modelling these land uses can be further subdivided (e.g. into farm systems or classes, forestry species and regime combinations, with and without management practices etc).

In the LUMASS model coding, we considered land uses to have the agricultural production, economic and environmental indicators shown in Table 1.

Table 1. Land use production, economic and environmental indicators

Indicators	Abbreviation	Unit
Greenhouse gas emissions	GHG	$tCO_2e/ha/yr$
Nitrate-N leaching	NLeach	kgN/ha/yr
Net revenue (gross margin)	Revenue	NZD/ha/yr
Sediment loss	Sediment	t/ha/yr
Milk solids	MilkSolids	kgMS/ha/yr
Wool output	Wool	kg/ha/yr

Hence, modelled land uses have commodity outputs (milk solids, wool), and economic (net revenue) and environmental (GHG emissions, nitrate leaching, and sediment loss) indicators. We have annualised the economic and environmental indicators for forestry to be comparable with dairy and sheep and beef, but we have not explicitly modelled forestry commodity outputs (e.g. wood production).

2.3 Data sources

We used a reclassified land-use map provided by Environment Southland as our baseline land-use configuration. Dairy production was reflected as annual production of milksolids. Mean production is 786 kg/ha/yr. Sheep and beef farm production was modelled only as production of wool, with mean production 31 kg/ha/yr. Forestry production was not modelled. For scenarios where the intention was to maintain (or improve) baseline production, total area allocated to forestry was used instead.

The data on net revenues for dairy and sheep and beef are as of 2017 and were obtained from Djanibekov et al. (2018), who used data from DairyNZ and Beef+Lamb NZ. A spatially variable value for forestry net revenue (expressed as an annuity) was provided by Scion. Land-use revenues used in this study do not consider carbon sequestration payments or potential emission liabilities under the Emission Trading Scheme (ETS).

Greenhouse gas emissions (GHG) were estimated based on an average stocking rate across dairy systems (2.42) and another one across SNB systems (5.28 sheep, 0.21 beef), together with emission factors per animal type. This means there is no spatial variability – GHG emissions are based entirely on animal numbers, and therefore on total area. Forestry was assumed to be GHG neutral for the purposes of this study.

Nitrate-N leaching also uses average stocking rates for dairy and sheep and beef, but spatially variable leaching factors per animal type based on Dymond et al. (2013).

Overall, the data lack spatial variability in net revenues (for pastoral farming) and selected environmental outputs of land uses, i.e. no spatial variation in the input data for GHG emissions, production, or revenue by land use. The modelled (SedNetNZ, Smith et al. 2019) sediment loss output is spatially variable, but because of its dependence on land-cover, it can only distinguish between pastoral farming and forestry and shows identical performance for dairy and sheep and beef. In addition, the forestry data lack information on commodity production and environmental outputs. The lack of spatial variability limits the capability of the optimisation process to determine where land use change can best occur to meet all objectives. The incorporation of such information can significantly change the land-use pattern and its economic and environmental consequences resulting from the implementation of agri-environmental policies. In this study, therefore, we can only explore hypothetical scenarios to showcase the type of analyses that could be done if appropriate spatially discriminate data produced by spatially explicit bio-physical and ecological models were available. In addition, temporal variability can be more important than spatial variability for commercial forestry (e.g. cashflow, sediment loss), which is masked by temporal averaging.

2.4 Scenarios

2.4.1 Baseline

We have compared modelled scenarios against the baseline. The baseline assumes that there are no agri-environmental policies or other interventions. The baseline scenario reports the performance of the current spatial arrangement of land uses in the catchment, without an optimisation process. Thus, the baseline is not simulated by the model and is presented here to compare the results of other scenarios.

The total baseline land-use area in the Aparima catchment is 80,069 ha, where the main land use is dairy (34,976 ha), followed by sheep and beef (30,948 ha) and forestry (14,145 ha) (Table 2). The highest net revenue source is from dairy followed by sheep and beef (Table 2). Other land uses are not modelled and assumed to be neutral with respect to all attributes. Total net revenues from dairy in the catchment is around $56 million, from sheep and beef is $13 million and from forestry is $1 million.

Dairy is almost four times more profitable than sheep and beef and over 17 times more profitable than forestry. Forestry produces little sediment and no N or GHG, while sheep and beef farms produce more sediment than dairy but much less N and GHG emissions. However, in terms of adverse impact per $1,000 in net revenue, dairy has higher net revenues per unit of sediment and GHG than sheep and beef.

Table 2. Land use area, net revenues, N leaching, sediment and GHG outputs

Land use	Area, ha	Net revenue, $/ha	N leaching, t	Sediment, 1,000 t	GHG emissions, 1,000 tCO_2e
Dairy	34,976	1,614	1,033	36	202
Forestry[1]	14,145	91	0	3	0
Sheep and beef	30,948	421	152	40	66
Total	80,069	70,774,531	1,185	79	267

[1] N leaching for forestry assumed to be at the same background level as for indigenous forest, so set to zero. For this exercise, forestry was assumed to be GHG neutral in the long term.

Dairy occupies most of the land-use area and produces the main commodity (i.e. milk solids) in the catchment (Table 3). Forestry production was not modelled. Instead, for scenarios where the intention was to maintain baseline production, total area allocated to forestry was used instead.

Table 3. Commodity production

Commodities	Production, t
Milk solids	27,491
Wool	959

2.4.2 Optimisation Scenarios – objectives and constraints

There are different ways in which multiple goals can be modelled within an optimisation framework. One option is to use one criterion in the objective function (e.g. maximise revenue) while the other criteria are used within constraints. A goal programming formulation can also be used, such that constraints that set desired levels of various indicators do not have to be strictly met, but deviations from these targets will be penalised as a cost in the objective function. Another option is to include multiple criteria within the objective function. This is simplest if all criteria are expressed in the same units (usually monetary) but if not, weightings can be used. Alternatively, incentives for reducing negative environmental land-use impacts or increasing positive impacts over the baseline can be added to the objective function, so that the objective becomes 'maximisation of revenue including incentives'. An example of this would be the inclusion of revenue for trading NZUs earned through the ETS by qualifying forests.

We have analysed nine optimisation scenarios (Table 4). These different scenarios were selected for demonstrating the use of the LUMASS optimisation framework to explore landscape limits (scenarios 1–6) (Herzig et al. 2018) and represent freshwater management policy initiatives (scenarios 7–9).

Scenarios 1–4 optimise for a single objective (minimising nitrate leaching, sediment, or GHG emissions, or maximising revenue) without consideration of the other criteria. In all cases baseline production of milk solids and wool was required to be maintained, and existing forests were not allowed to be replaced, i.e. exotic forest was only allowed to expand into existing pastoral land-use areas. Based on land-use performance and land-use management data, these scenarios help exploring the landscape's limit to utilise its natural resources to provide ecosystem services through the given land-use system (i.e. land-use types and management as well as land-covers; Herzig et al. 2018):

1 The objective of the minimising nitrate leaching scenario (minNLeach) is to minimise total nitrate-N leached from all land uses within the catchment. The minimisation of nitrate leaching is subject to maintaining or improving baseline production levels. In lieu of forestry production data, we constrained the model to maintain the baseline forestry area. Furthermore, dairy was not allowed to be allocated to land with a slope class greater than 3, i.e. greater than 15°.

2 The minimising sediment loss scenario (minSediment). As above, but minimising sediment.

3 The minimising GHG emissions scenario (minGHG). As above, but minimising livestock emissions.

4 The maximising net revenues scenario (maxRev). As above, but maximising net revenue.

Scenarios 5 and 6 explore the potential impact of achieving environmental targets without policy interventions. These scenarios maximise net revenue within the given environmental limits on nitrate leaching and sediment loss, respectively. In contrast to scenarios 1–4, they do not constrain basic production levels, but retain the spatial constraints, i.e. they restrict dairy to land with slope classes 1 to 3 and maintain the baseline forestry area:

5 The maximising net revenues and reducing N leaching scenario (maxRevRedNleach) has the objective function of maximising net revenues from the catchment. The total N leaching is constrained to not exceed 888,609 kg/yr (a 25% reduction from the baseline).

6 The maximising net revenues and reducing sediment loss scenario (maxRevRedSed) has the objective function of maximising net revenues from the catchment. It includes the constraint to keep sediment loss levels below 59,567 t/yr (a 25% reduction from the baseline). The total nitrate leaching is not constrained.

Scenarios 7–9 introduce rewards for reducing environmental impacts. Scenarios 7 and 8 incentivise reduction of nitrate leaching and sediment, respectively, while scenario 9 rewards reductions in both. Variations of each scenario were run to cover a range of incentive values. In all of those scenarios we applied the spatial constraints from scenarios 1 to 4, i.e. dairy is limited to land with slope classes between 1 and 3, and forestry is maintained in its baseline extent and allowed to expand into pastoral farming areas, i.e. replace either dairy or sheep and beef land uses. However, in contrast to scenarios 1–4, we do not apply a baseline commodity production constraint for individual land uses, instead, we constrain the net revenue realised within individual farm-type areas, i.e. within the respective total dairy, sheep and beef, and forestry areas of the baseline land-use configuration, to achieve their respective baseline net revenue. This is to model the impact of different nitrate leaching and sediment reduction prices on potential land-use changes within the collective areas of the agricultural farming sectors (i.e. DAI, FOR, SNB) represented in the baseline configuration:

7 Maximises net revenues including payments (rewards) for reducing nitrate leaching (maxRevN1–maxRevN10). Here per hectare net revenues consist of the baseline net revenues and additional revenues generated from reducing N leaching. Payments were modelled per kilogramme of reduced N loss including the following variations: \$150/Nkg, \$90/Nkg, \$75/Nkg, \$60/Nkg, \$58.5/Nkg, \$57/Nkg, \$52.5/Nkg, \$48/Nkg, \$46.5/Nkg, \$45/Nkg, and \$30/Nkg. This allowed us to observe the sensitivity of the model to changes in N leaching reduction payments and subsequently to analyse the land-use allocation and its economic and environmental impacts.

8 Maximises net revenues and payments (rewards) for reducing sediment loss (maxRevS1–maxRevS14). This is the equivalent to scenario 7 with the same constraints, but with incentives for reducing sediment rather than nitrate leaching. The model maximises objective function, consisting of land use net revenues and the following payment variations per reduced tonne of sediment loss: \$1,880/t, \$880/t, \$80/t, and \$48/t.

9 Maximises net revenues and payments (rewards) for both nitrate leaching and sediment loss reductions (maxRevNS1–maxRevNS3). In this scenario total net revenues from land uses are maximised subject to the same constraints as above. We modelled the following payment variations for nitrate leaching and sediment loss reductions: \$52.5/Nkg (for nitrate leaching) and \$80/t (for sediment loss), \$48/Nkg and \$80/t, and \$45/Nkg and \$80/t.

Table 4. Summary of scenarios

Scenarios	Constraints	Prices for reducing nitrate leaching and sediment loss
1. Minimising nitrate leaching output (minNLeach)	Production levels = Baseline production levels Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Not applicable
2. Minimising sediment loss (minSediment)	Production levels = Baseline production levels Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Not applicable
3. Minimising GHG emissions (minGHG)	Production levels = Baseline production levels Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Not applicable
4. Maximising net revenues (maxRev)	Production levels = Baseline production levels Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Not applicable
5. Maximising net revenues and reducing nitrate leaching (maxRevRedNleach)	Nitrate leaching ≤ 888,609 kg Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Not applicable
6. Maximising net revenues and reducing sediment loss (maxRevRedSed)	Sediment loss ≤ 59,567 t Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Not applicable
7. Maximising net revenues and having payments for reducing nitrate leaching (maxRevN1–maxRevN11)	Total revenue within individual farm type areas ≥ baseline revenue within same area Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Nitrate leaching reduction prices: \$150/Nkg, \$90/Nkg, \$75/Nkg, \$60/Nkg, \$58.5/Nkg, \$57/Nkg, \$52.5/Nkg, \$48/Nkg, \$46.5/Nkg, \$45/Nkg and \$30/Nkg
8. Maximising net revenues and having payments for reducing sediment loss (maxRevS1–maxRevS14)	Total revenue within individual farm type areas ≥ baseline revenue within same area Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Sediment loss reduction prices: \$1,880/t, \$880/t, \$80/t, \$48/t.
9. Maximising net revenues and having payments for reducing nitrate leaching and sediment loss (maxRevNS1–maxRevNS3)	Total revenue within individual farm type areas ≥ baseline revenue within same area Slope of dairy land < 16° Forestry area ≥ Baseline forestry area	Nitrate leaching and sediment loss reduction prices: \$52.5/Nkg and \$80/t, \$48/Nkg and \$80/t, and \$45/Nkg and \$80/t

We compare the results of the above scenarios with the baseline input data.

3 Results and Discussion

3.1 Scenario 1. Minimising nitrate leaching

The spatial optimisation of land use in the Aparima catchment to minimise nitrate leaching showed only a small achievable nitrate leaching reduction of ~3.42% (Table 5). It resulted in a land-use shift among dairy and sheep and beef farming. High leaching dairy land use was moved on soils that are less susceptible to nitrate leaching and relatively low leaching sheep and beef farming was moved on soils that are more susceptible to nitrate leaching, thus achieving an overall nitrate leaching reduction. Since neither the total dairy nor sheep and beef areas changed, the respective commodity production and GHG emissions did not change. Also, since both dairy and sheep and beef are equally susceptible to soil erosion, the total sediment loss did not change.

Table 5. Relative change in the minNLeach scenario from the baseline

Land use	Net revenue change %	N leaching change %	Sediment change %	GHG emissions change %	Milk solids % change	Wool % change
Dairy	0	–4.66	1.35	0	0	n.a.
Forestry	0	0	0	0	n.a.	n.a.
Sheep and beef	0	4.98	-1.2	0	n.a.	0
Total	0	–3.42	0	0	0	0

3.2 Scenarios 2–4. Minimising sediment loss, minimising GHG emissions, maximising revenue

For these scenarios there was no scope to achieve a better result than the baseline for each objective while still maintaining the same production level, because there was no spatial variation in the relevant input data or difference in land-use specific performance (e.g. pastoral farming and sediment loss). Any random reallocation of land uses that still maintained baseline production would be equally acceptable to the optimiser, which means that nitrate leaching can increase or decrease, depending on where land uses changed. The results are therefore not informative, as they reflect the indifference of the optimisation to nitrate leaching levels (and to each of the other indicators when excluded from each objective function) and the lack of any opportunity to improve indicators beyond the baseline through land use change.

3.3 Scenario 5. Maximising net revenues while reducing nitrate leaching by 25%

This scenario achieved the required 25% reduction in N leaching but at the cost of a 17% reduction in revenue (Table 6). However, there were co-benefits in improved sediment loss (down 3%) and GHG emissions (down 15%). The reduction in nitrate leaching was achieved through conversion of dairy land to sheep and beef, resulting also in a reduction in milk-solid production and increase in wool production. Dairy has high nitrate leaching levels per net revenue (i.e. $/Nkg) and while forestry was assumed to have zero leaching, the lower revenue meant that conversion of dairy to sheep was a more cost-effective way of achieving the target. Additionally, forestry expanded into sheep and beef areas contributing to the overall nitrate leaching reduction and essentially achieving the reduction in sediment loss.

Table 6. Relative change in the maxRevRedNLeach scenario from the baseline

Land use	Area change %	Net revenue change %	N leaching change %	Sediment change %	GHG emissions change %	Milk solids % change	Wool % change
Dairy	–27.53	–27.53	–31.82	–26.69	–27.53	–27.53	n.a.
Forestry	18.10	18.96	0	20.96	0	n.a.	n.a.
Sheep and beef	22.84	22.84	21.36	16.29	22.84	n.a.	22.84
Total	0	–17.41	–25.00	–3.11	–15.15	–27.53	22.84

3.4 Scenario 6. Maximising net revenues while reducing sediment loss by 25%

This scenario achieved the target 25% reduction in sediment loss while also increasing revenue by 31% (Table 7). The sediment loss was reduced by the complete cessation of sheep and beef farming. All sheep and beef area is shifted to dairy, where slopes are suitable, or else to non-productive uses. As a result of such land-use change, aggregated net revenues and milksolid production in the catchment substantially increase, but at the expense of a substantial increase in nitrate leaching and GHG emissions. In addition, about 12% of the land area that was under sheep and beef becomes unused.

Table 7. Relative change in the maxRevRedSed scenario from the baseline

Land use	Area change %	Net revenue change %	N leaching change %	Sediment change %	GHG emissions change %	Milk solids % change	Wool % change
Dairy	61.89	70.31	66.36	64.70	61.89	61.89	n.a.
Forestry	0	0	0	0	0	n.a.	n.a.
Sheep and beef	–100.00	–100.00	–100.00	–100.00	–100.00	n.a.	-100
Total	–11.62	30.95	45.03	–25.00	22.11	61.89	–100

3.5 Scenario 7. Maximising net revenues including payments for reducing nitrate leaching

Introducing payments for reducing N leaching increases net revenues (Table 8). With the lowest simulated N leaching price ($30/Nkg), the net revenues increase only by 0.01%. Further increases in the N leaching price drive land-use change and result in greater reductions. The impact is not proportional with the change in price, because of the model constraints and spatial variability in N leaching outputs.

Figure 1 shows that there is little change with incentives below $40/Nkg, and little further change beyond a price of $80/Nkg. Within that range, sheep and beef replaces dairy, enabled through the increasing payments for N leaching reductions. At the same time, also enabled through N leaching payments, forestry is replacing sheep and beef, albeit to a lesser extent. Beyond a payment of about $52.5 per kilogram of reduced N leaching, there is an almost complete shift from dairy and sheep and beef land uses to forestry, with corresponding reductions in milksolid and wool production, elimination of GHG emissions and N leaching, and sediment reduced by 75%. Revenue from the incentives compensates for the loss of milksolid and wool revenue – at the highest simulated N leaching price ($150/Nkg) the net revenues increase by 162%.

Table 8. Relative change in the maxRevN1-maxRevN11 scenario from the baseline

N leaching reduction price	Net revenue change %	N leaching change %	Sediment change %	GHG emissions change %	Milk solids % change	Wool % change
$30/Nkg	0.01	–0.16	0.00	-–0.06	–0.12	0.13
$45/Nkg	0.72	–13.48	–1.12	–8.10	–15.15	13.54
$46.5/Nkg	1.16	–23.41	–1.94	–14.38	–27.83	26.91
$48/Nkg	1.89	–34.82	2.87	–22.07	–42.42	40.42
$52.5/Nkg	6.01	–74.68	–3.53	–49.46	–98.83	102.09
$57/Nkg	11.73	–76.65	–8.91	–51.89	–99.98	95.73
$58.5/Nkg	13.66	–76.86	–9.36	–52.24	–99.98	94.30
$60/Nkg	15.59	–77.04	–9.82	–52.56	–99.98	93.02
$75/Nkg	36.68	–96.84	–65.11	–92.92	–99.98	–71.27
$90/Nkg	61.63	–99.93	–74.99	–99.66	–99.98	–98.68
$150/Nkg	162.02	–99.95	–75.19	–99.74	–99.98	–99.00

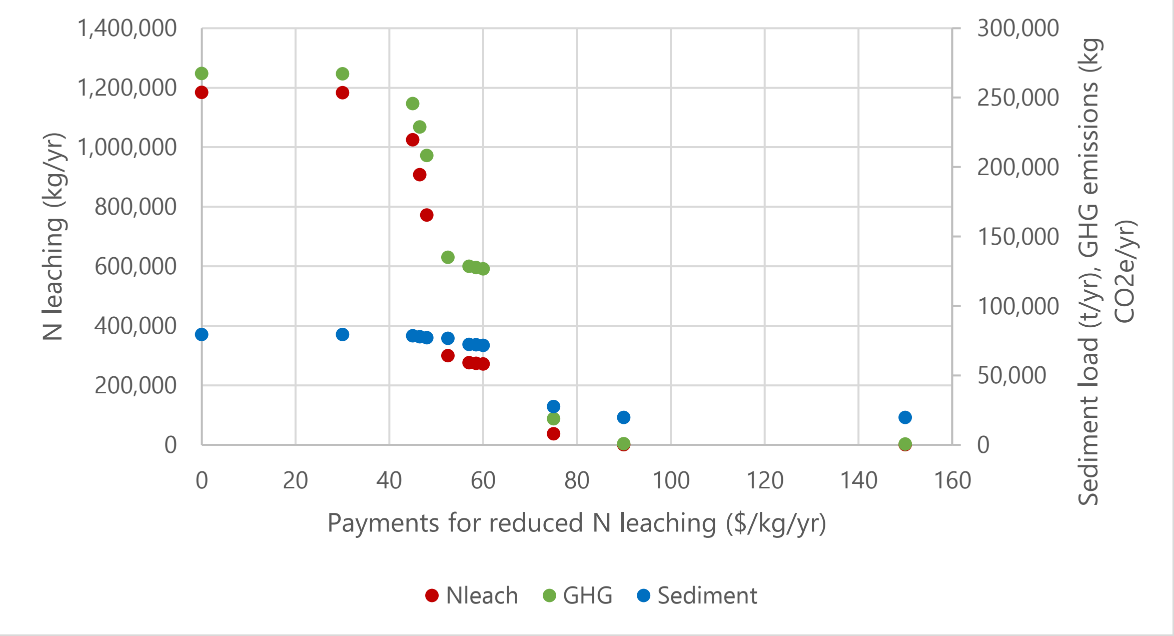

Figure 1. Impact of payments for nitrate leaching reductions on environmental indicators.

Payments incentivise farmers to reduce their environmental impacts, as farmers can generate revenues from reduced N leaching by changing the livestock farming into forestry. This type of N leaching reduction payments can be received through the trade mechanism (e.g. cap-and-trade scheme), where farmers receive payments for decreasing their N leaching levels from those farmers who continue to produce nutrient. However, such payments need to be established through a policy scheme implemented by the government, which might also incur costs for the scheme's introduction and monitoring.

3.6 Scenario 8. Maximising net revenues including payments for reducing sediment loss

Payments of less than about $880 per tonne of reduced sediment loss lead to a substantial increase of dairy area at the expense of decrease in sheep and beef area. This can be attributed to the overall objective of maximising revenue and the high profitability of dairy farming that cannot be offset by incentives below about $880/t for sediment reduction (Table 9). This change is associated with an increase in milk solid production, but also with an increase in GHG emissions and N leaching. However, payments from about $80/t introduce a relatively small land-use change from sheep and beef to forestry that leads to a reduction in sediment loss by about 2.4%. Sheep and beef farming is completely replaced by dairy and forestry at a payment level of about $880/t for sediment reduction. Payments beyond that level become profitable enough to outcompete dairy and lead to shifting dairy into forestry. This change is associated with a corresponding reduction in milk solid production, GHG emissions and N leaching and the increase of sediment reduction from about 2.5% to more than 10%. The highest modelled payment of $1,880/t for sediment reduction shows a net revenue increase of about 74.37% and a sediment loss reduction of about 18.4%. Due to a land-use change from dairy to forestry at this level of financial incentives, N leaching and GHG emissions reduce by 50.87% and 26.10%, respectively.

Table 9. Relative change in the maxRevS1-maxRevS14 scenario from the baseline

Sediment reduction price	Net revenue change %	N leaching change %	Sediment change %	GHG emissions change %	Milk solids % change	Wool % change
$48/t	51.36	68.97	0.00	41.52	87.12	–98.46
$80/t	51.38	68.86	–2.42	41.21	87.12	–99.76
$880/t	56.71	63.03	–10.04	36.85	81.42	–100.00
$1,880/t	74.37	50.87	–18.4	26.10	67.18	–100.00

3.7 Scenario 9. Maximising net revenues including payments for reducing nitrate leaching and sediment loss

This scenario incentivises reductions in both sediment loss and nitrate leaching, giving rise to a compromise in land use not seen when they are incentivised separately. Environmental pollutants are significantly reduced, with a slight increase in net revenues (Table 10). The magnitude of the joint policy's effect on net revenues and nitrate leaching amount is similar to some of the nitrate-N reduction payment levels. For example, with the highest joint payments of $52.5/Nkg and $80/t, the net revenues increase by 7.25% and nitrate leaching reduces by about 80%. In comparison, in the scenario maxRevN1-maxRevN11 with nitrate leaching payment value of $52.5/Nkg the net revenues increase by 6.01% and nitrate leaching reduces by 74.68%; however, in that scenario sediment loss and GHG emission reductions are lower. Overall, the incentives for reducing nitrate leaching and sediment losses lead to land-use changes from dairy to sheep and beef and forestry on land with low susceptibility to soil erosion as well as change from sheep and beef to forestry on land with higher susceptibility to soil erosion to achieve the aspired reductions in nitrate leaching and sediment loss. At the lowest modelled payment levels of $45/Nkg and $80/t, the model shows a small decrease in sheep and beef area and a corresponding reduction of wool production by about 8.41%. From the next highest payment levels, we observe a net increase in sheep and beef as well as forestry land. This comes at the expense of dairy farming, accompanied by a corresponding reduction of milk solid production, GHG emissions and nitrate leaching. The increased replacement of pastoral farming by forestry leads to a reduction of sediment loss of up to 27.32% for the modelled payment levels. The replacement of dairy farming with sheep and beef on the flat land shows an increase in wool production by up to 57.73%.

Table 10. Relative change in the maxRevNS1-maxRevNS3 scenario from the baseline

Sediment reduction price	Net revenue change %	N leaching change %	Sediment change %	GHG emissions change %	Milk solids % change	Wool % change
$45/Nkg and $80/t	1.46	–16.99	–16.79	–13.71	–15.44	–8.41
$48/Nkg and $80/t	2.81	–38.29	–18.73	–27.89	–42.83	17.96
$52.5/Nkg and $80/t	7.25	–80.56	–27.32	–60.37	=–98.84	57.73

4 Conclusions

The study demonstrates the application of the BMI-compliant interoperable LUMASS engine library for conducting land-use scenario analyses based on spatial optimisation. Technical aspects of wrapping the LUMASS engine with the BMI interface and sample code to use the LUMASS engine through BMI are detailed in the main report and are available on the associated github repository. In this report, we focused on demonstrating the capabilities of LUMASS' spatial optimisation framework for exploring landscape limits and freshwater policy scenarios.

The study showed the impacts of nine different scenarios and their variants on the economic and environmental outputs of dairy, sheep and beef, and forestry in the Aparima catchment. Scenarios 1–6 explored the catchment's performance limits to maximise the provision of ecosystem services without policy interventions or changes within the land-use system, e.g. through adoption of specific land-management practices or the introduction of alternative land-uses. The scenario results did not show any significant headroom within the catchment to maximise the provision of ecosystem services. The simplified representation of land uses and their associated largely spatially indiscriminate land-use performance data available did not enable a realistic assessment of the catchment's performance limits. This highlights the potential benefit of an interoperable optimisation library that can be coupled with bio-physical and ecological process models for the analysis of spatially explicit land-use performance data of different land-use types characterised in appropriate detail (e.g. different dairy or sheep and beef systems). In real-world and in modelling analysis, productivity, profitability, and environmental indicators should be considered heterogenous across space and time, and land-use change takes place at the margins. The use of average values masks this heterogeneity and limits the ability of analysis tools to provide meaningful insights. In our study, dairy and sheep and beef do not differ by systems, and different management practices are not represented. More detailed and spatially explicit land-use data would lead to different results from the ones presented in this report.

Scenarios 7–9 showed that payments for N leaching and/or sediment reduction have the potential to be effective options to reduce environmental pollutants. Such payments increase farmers' net revenues but reduce production of milk solids and wool. However, an increase in net revenues can be implemented through the trade mechanism (e.g. cap-and-trade scheme), where farmers receive payments for decreasing their nitrate leaching and/or sediment levels from the farmers who continue to have nitrate leaching and sediment loss. However, such payments need to be established through a policy scheme implemented by the government, which might incur costs for its introduction and monitoring, which, in turn, can affect net revenues of land uses and government expenditures. In this study, the modelled variation in incentive payments were used to drive land-use change between land-use types. With the availability of more detailed land-use management information and their impact on the considered economic, production, and environmental criteria, incentives payments could be used to drive land-use management change, and thus potential policy relevance.

Our study also highlighted current limitations of the LUMASS optimisation framework, especially regarding more sophisticated economic analyses. For example, substantial changes in indicators were observed with the increase in payments for reducing nitrate leaching and sediment loss. Within the LUMASS optimisation framework, this could only be mitigated by adding specific linear constraints to the optimisation model. Including non-linear functions in the optimisation model could smooth drastic land-use changes and reflect the effect of non-modelled factors (i.e. impact of knowledge, perceptions towards land use change).

The simulated scenarios impact agricultural production and consequently can affect their prices. The model itself assumes that revenue is not affected by the quantity supplied. A decrease in milk solid and wool production, while not reducing the demand for these products, might in practice increase their prices. This change would increase net revenues on per hectare level of agricultural producers but increase purchase expenses of consumers. To address such changes a partial equilibrium model is needed. Such a model derives endogenously commodity prices in agricultural and forestry sectors. Also, changes in agricultural and forestry production would have economy-wide impacts (e.g. industry, services). The computable general equilibrium model can be useful to address such economy-wide impacts.

The impacts of policy scenarios have uncertain outcomes. When risk and uncertainty are taken into account, the optimal portfolio of land uses may change. Uncertainty can be introduced through the Monte Carlo or Latin Hypercube simulations by generating distributions of uncertain parameters and then analysing the range of impacts. Alternatively, stochastic processes can be used to address uncertainty in future parameters such as net revenues. To assess the impact of uncertain input data or stakeholder assumptions on the optimised land-use pattern and its performance, the LUMASS optimisation framework enables Monte-Carlo-style variation of input performance scores or constraint thresholds (Herzig et al. 2013b). Also, uncertainties affect the decision-making of farmers in land-use allocation. The risk-averse farmers would select less risky land use than the risk-neutral farmer. Therefore, having risk aversion in the model might be useful to understand the decision making of different risk-averse farmers to uncertain outcomes of policies.

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