Does Complex Hydrology Require Complex Water Quality Policy?

NManager Simulations for Lake Rotorua

Simon Anastasiadis, Marie-Laure Nauleau, Suzi Kerr, Tim Cox, and Kit Rutherford

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Author contact details

Simon Anastasiadis
Motu Economic and Public Policy Research
simon.anastasiadis@motu.org.nz

Marie-Laure Nauleau
ENSAE ParisTech
marie-laure.nauleau@ensae.fr

Suzi Kerr
Motu Economic and Public Policy Research
suzi.kerr@motu.org.nz

Tim Cox
NIWA
t.cox@niwa.co.nz

Kit Rutherford
NIWA
k.rutherford@niwa.co.nz

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Motu Economic and Public Policy Research

PO Box 24390
Wellington
New Zealand

Email	info@motu.org.nz
Telephone	+64 4 9394250
Website	www.motu.org.nz

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Abstract

This paper examines six different approaches to nutrient management, and simulates the economic costs and environmental impacts associated with them using NManager, a partial equilibrium simulation model developed by Motu and NIWA, the National Institute for Water and Atmospheric Research. We focus on Lake Rotorua in the Bay of Plenty in New Zealand, where the regional council is concerned with the decline in the lake's water quality and has set a goal to restore the lake to its condition during the 1960s.

Reaching this goal will require significant reductions in the amount of nutrients discharged into the lake, especially from non-point sources such as farm land. Managing water quality is made difficult by the presence of groundwater lags in the catchment: nutrients that leach from the soil arrive at the lake over multiple years. The mitigation schemes we consider are land retirement, requiring best practice, explicit nitrogen limits on landowners, a simple nutrient trading scheme, and two more complex trading schemes that account for groundwater lags.

We demonstrate that best practice alone is not sufficient to meet the environmental target for Lake Rotorua. Under an export trading scheme, the distribution of mitigation across the catchment is more cost effective than its distribution under explicit limits on landowners or land retirement. However, the more complex trading schemes do not result in sufficient, or sufficiently certain, gains in cost effectiveness over the simple trading scheme to justify the increase in complexity involved in their implementation.

JEL codes

C69, Q53, Q57, Q58

Keywords

Groundwater, Lake Rotorua, model, nutrients, nutrient trading, water quality, non-point source pollution

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1. Introduction

Non-point source water pollution is a serious problem in most developed countries, including New Zealand, and in an increasing number of developing countries (Sutton et al., 2011; Parliamentary Commissioner for the Environment, 2006).[1] It is frequently considered intractable because it is so hard to regulate large numbers of small sources and because the science associated with it is so complex. New Zealand has demonstrated that it is possible to implement a cap-and-trade system to comprehensively cover nutrient leaching from farms (Duhon et al., 2011). This paper tackles a further question: are complex regulatory systems required when the situation they address is complex?

The "enabling myth" of the United States Acid Rain program, one of the most recognised tradable permit markets, was that the environmental impact of emissions was not spatially differentiated. The simplicity this allowed may have contributed to the successful legislation and implementation of the program (Stavins, 1997). More recently Muller and Mendelsohn (2009) argue for environmental regulations that match the marginal damages of pollution across space to the marginal costs of abatement. They estimate large gains in the cost effectiveness of regulation from spatially differentiated air quality policies in the United States. While obviously analytically correct, spatially differentiated policy is significantly more demanding of science and more complex to implement; whether the gain in efficiency justifies this additional complexity is an empirical question.

The literature on the design of environmental markets is now extensive and sophisticated.[2] The literature on markets for water quality is mostly more recent. Shortle and Horan (2008) provide a recent summary. Hung and Shaw (2005) consider a trading ratio system which takes into account differentiated marginal damages and Prabodanie et al. (2010) discuss an offset approach. In terms of actual policy development, Selman et al. (2009) identified 57 trading systems focused on water quality worldwide, most of which were inactive. Of these, the majority are concerned with point sources, though some allow point sources to purchase reductions from non-point sources. Our paper both explores a more ambitious, but already implemented, approach to non-point source pollution and provides the first empirical estimates of the effects of regulatory complexity in a water quality cap-and-trade market.

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[1] "Inorganic nitrogen pollution of inland waterways has increased more than twofold globally since 1960 and more than tenfold for many industrialised parts of the world" (Millennium Ecosystem Assessment, 2005).

[2] Tietenberg (2006) provides an excellent introduction to the literature.

When nitrogen moves through groundwater to a lake, the damage it causes is not spatially differentiated but is temporally differentiated. For a given series of lake water quality targets, it is more efficient to focus effort on abating nitrogen that will reach the lake rapidly. We build an integrated model of one catchment, Lake Rotorua in New Zealand, to estimate the efficiency gain from a sophisticated nitrogen trading program that incorporates the temporal differentiation caused by groundwater, relative to simple nitrogen regulation that does not.

We find that, in this instance, the gains from the more sophisticated regulation are tiny and cannot possibly justify the additional complexity required. We also show that requiring best practice is insufficient to meet the challenging abatement targets and that relying purely on land retirement is an expensive option.

1.1. Water quality in Lake Rotorua and New Zealand

Lake Rotorua is one of thirteen major lakes in the Bay of Plenty region of New Zealand. It has significant cultural value and provides numerous tourism opportunities. Te Arawa (the local iwi, or tribe) have ancestral ties to the lake and surrounding land that reach back more than 600 years, and today 35% of residents are of Māori ancestry. The Tourism Strategy Group, of the Ministry of Economic Development, estimates the region attracts three million visitors annually, a quarter of whom are from overseas.

Land use in the catchment surrounding the lake has intensified since the 1960s, resulting in increased discharges to the lake of nitrogen (Rutherford, 2003; 2008) and phosphorus (Rutherford et al., 1989). These nutrient discharges have caused eutrophication, toxic algal blooms, a decline in water quality, and the intermittent closure of the lake due to health risks (Parliamentary Commissioner for the Environment, 2006).

Through discussion with the Rotorua District Council, Te Arawa and the community, the Bay of Plenty Regional Council (BoPRC)[3] set a target for water quality to be the same as it was in the 1960s (Environment Bay of Plenty et al., 2009). This involves reducing lake loads (the amount of nitrogen arriving at the lake) to 435 tonnes of nitrogen per year (tN/yr). As a result of groundwater lags, the time taken for nitrogen to move through the groundwater, not all exports reach the lake at once but will be realised as lake loads over multiple years. In 2009 total nitrogen exports were estimated to be 771 tN/yr, of which 73 percent comes from rural land; total lake loads were estimated to be 593 tN/yr (Environment Bay of Plenty et al., 2009).

[3] Bay of Plenty Regional Council was, until 2010, named Environment Bay of Plenty.

The BoPRC has begun to address the decline in water quality. Their initiatives include upgrades to the sewage and storm water system and to septic tanks, and addressing land management practices (Environment Bay of Plenty et al., 2009). In 2005 they introduced Rule 11, designed to freeze nutrient loss from land use at 2001–2004 levels (Environment Bay of Plenty, 2008).[4] Despite these initiatives, further intervention will be necessary to meet lake quality targets.

A nitrogen trading system is expected to be a cost effective approach to control leaching into the lake. Lock and Kerr, (2008) design a trading system for Lake Rotorua that incorporates the temporal lags. New Zealand has some experience with allowance trading systems, namely the Individual Transferable Quota (ITQ) system used to manage marine fisheries (Newell et al., 2005); the New Zealand Emissions Trading Scheme (NZETS) used to manage greenhouse gases covered by the Kyoto Protocol (www.climatechange.govt.nz/emissions-trading-scheme/); and a nitrogen trading system that was recently established by Waikato Regional Council[5] to manage the Lake Taupō catchment.

In the Lake Taupō catchment, farms occupy about 20 percent of the land; however, they contribute more than 90 percent of the manageable nitrogen load (Rutherford and Cox, 2009). Waikato Regional Council has implemented a cap-and-trade scheme to prevent nutrients in the lake increasing beyond their present levels and has overseen the creation of a charitable trust, the Lake Taupo Protection Trust, charged with the permanent removal of 20 percent of the manageable nitrogen (Young et al., 2010). Although groundwater lags are present in the Lake Taupō catchment, the Waikato Regional Council chose not to implement regulation that incorporated groundwater lags or attenuation, both because of uncertainty in the underlying biophysics and because of the likely complexity of the regulatory and trading schemes. Some farmers lobbied for both attenuation and groundwater lags to be considered. However, it was felt that this was unnecessary (Environment Waikato, 2003). In contrast to Taupō's 20 percent reduction, Rutherford et al. (2011) calculate that in the case of Lake Rotorua, exports need to be reduced by around 320 tN/yr, or 69 percent of the manageable exports, in order to meet the load target. Hence more severe intervention will be needed for Lake Rotorua than was necessary for Lake Taupō – this requires an even more efficient response.

The paper is set out as follows: section 2 gives an overview of the models that support our research and section 3 introduces the NManager model. Different regulatory approaches are

[4] A review of Rule 11 suggests that there is little quantitative evidence of its effectiveness and that more active enforcement is required (Foster and Kivell, 2009). Anecdotal evidence suggests that Rule 11 has helped prevent an increase in dairy farming in the Lake Rotorua/Rotoiti catchment (Maki, 2009).

[5] Waikato Regional Council was, until 2011, named Environment Waikato.

introduced in section 4 and methods of solving them in section 5. The performance of different regulations is discussed in section 6. Section 7 concludes the paper.

2. Supporting Models

NManager combines data from several external models with its own internal calculations. This section gives an overview of the different models, and the inputs they provide to NManager.

2.1. ROTAN

The Rotorua and Taupō Nutrient model (ROTAN) is a geographic information system-based catchment hydrology and water quality model developed by NIWA (Rutherford et al., 2008).

ROTAN simulates the hydrogeology of the Lake Rotorua catchment. It distinguishes between nutrient exports and nutrient loads. Nutrient exports are the quantity of nutrients discharged from the land; nutrient loads are the quantity of nutrients reaching the lake. The translation from exports to loads is neither complete nor immediate due to attenuation and groundwater lags (Kerr and Rutherford, 2008).

Attenuation is the temporary storage and/or permanent removal of nutrients from runoff, groundwater or stream flow. Some nutrients are taken up by plants before reaching the lake. However, this uptake is temporary: the nutrients are released following the death of the plant. Permanent removal of nitrogen occurs principally through denitrification, the conversion of nitrate into nitrogen gas. Attenuation has been found to be minimal in most of the Lake Rotorua catchment, with the exception of the Puarenga Stream (Rutherford et al., 2009; 2011).

Groundwater lags are present across the Lake Rotorua catchment due to the presence of large underground aquifers. When nitrogen leaches off farmland, a certain amount is carried by surface water (streams) and enters the lake directly. The remainder enters the groundwater system, modelled as a series of well-mixed bucket aquifers, which slowly releases the nitrogen into the lake. ROTAN simulations suggest that 47 percent of nitrogen reaches the lake via surface water and 53 percent via groundwater (Rutherford et al., 2011). Groundwater lags determine the speed at which the nitrogen in the aquifers arrives at the lake. They depend on the distance of the exports from the lake, the size and speed of surface water streams, and the geology of the soil and underlying rock. For land close to the lake, groundwater lags are small. The lags increase the further land is from the lake and probably exceed 200 years for nitrogen emitted at the edge of the catchment.

NIWA has extensively calibrated ROTAN to historical data from the Lake Rotorua catchment, using information about groundwater lags estimated using tracers and aquifer boundaries provided by GNS Science (Rutherford et al., 2009; 2011). GNS Science is using a detailed finite-element model to refine the current estimates of aquifer boundaries, flow pathways and travel times (Dr Chris Daughney, GNS Science, pers. comm.). Refinement of aquifer boundaries and associated residence times within ROTAN are the subject of ongoing NIWA and GNS Science research (Rutherford et al., 2008).

2.2. Farmax

Farmax is a decision support model developed by AgResearch. It has been designed to assist dairy and sheep-beef farmers to maximise their productivity by simulating the profitability of farms under different management scenarios. Farmax has been evaluated against two independent New Zealand data sets (Bryant et al., 2010).

Management decisions affect not only the profitability of a farm but the amount of nutrient that leaches from it. In Farmax these decisions include: farm type (for dairy farms, milking herds and dry stock were treated differently), stocking rate, fertiliser use, supplementary feed use, the choice of winter fodder crops, and whether animals are grazed on or off the land (Bryant et al., 2010). Clearing gorse has been shown to mitigate nitrogen leaching (Male et al., 2010), however this is not yet included in Farmax.

Outputs from Farmax are used, in conjunction with those from OVERSEER, to give feasible and realistic combinations of profit and nutrient exports. From these we express profit per hectare per year as a function of mitigation per hectare per year. Further details are given in section 3.4 and Appendix B. For the simulations run in Farmax we direct the reader to Smeaton et al. (2011).

2.3. OVERSEER

OVERSEER is a farm management tool developed by AgResearch to help farmers maximise the productivity of their land (AgResearch, 2009). It also calculates nutrients lost to the environment, which has drawn the attention of regulatory bodies.

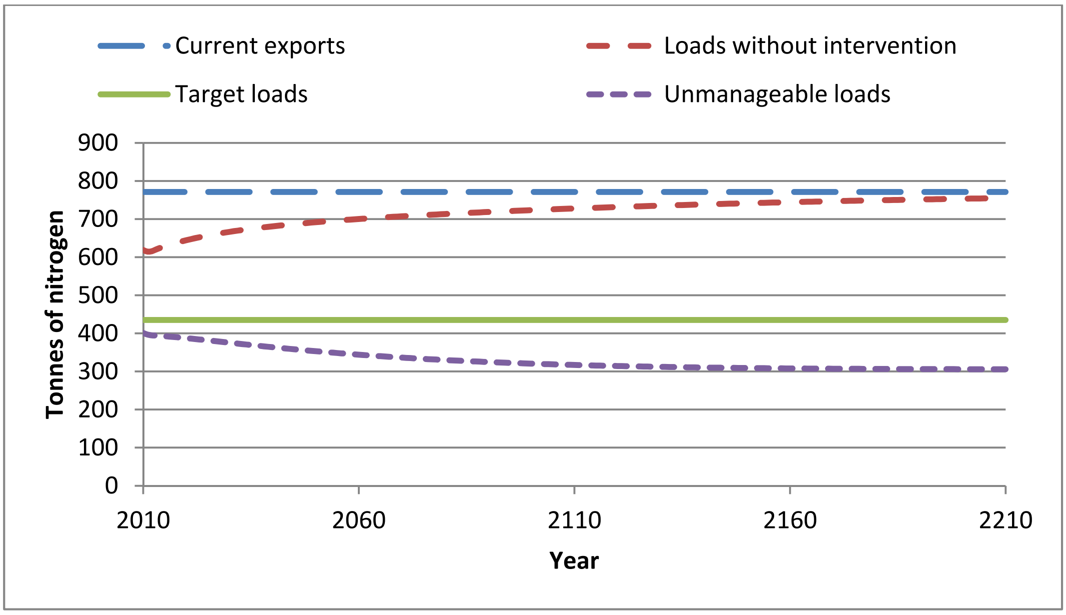
The data inputs for OVERSEER are extensive and include: farm type, productivity (e.g., tonnes of milk solids per year for dairy farms), soil type, soil drainage class, slope, rainfall, stocking rate, fertiliser use, supplementary feed and area for effluent irrigation. The use of nitrogen inhibitors is included for on-farm mitigation. Changes in any of these inputs affect nutrient loss.

3. Using NManager to Model Lake Rotorua

NManager is intended to reflect the complex biophysical properties of the catchment and the behaviour of landowners under regulation. This section details how the reality of the catchment is represented in NManager.

Figure 1 shows the nitrogen exports and loads in the Lake Rotorua catchment used in NManager assuming current land use and farming practices continue, compared to the target of 435 tN/yr, and the unmanageable nitrogen loads used in NManager.

Figure 1: Exports and lake loads with no change in land use



At present NManager assumes that 771 tN/yr are exported from the catchment but only 593 tN/yr are currently realised as lake loads; this difference is due to the rate at which nitrogen moves through the groundwater. Unmanageable loads are those arising from nutrients already in the groundwater (legacy loads) and exports that cannot be controlled via land management. How NManager handles groundwater flows is described below. The unmanageable exports consist of 4 kg N/ha/yr across the entire catchment (excluding Waipa forest, where leaching is 2 kg N/ha/yr) and all nitrogen from sewage, septic tanks, the RLTS and geothermal and urban areas. NManager considers 308 tN/yr to be unmanageable exports.

3.1. Modelling the transportation of nutrients to the lake

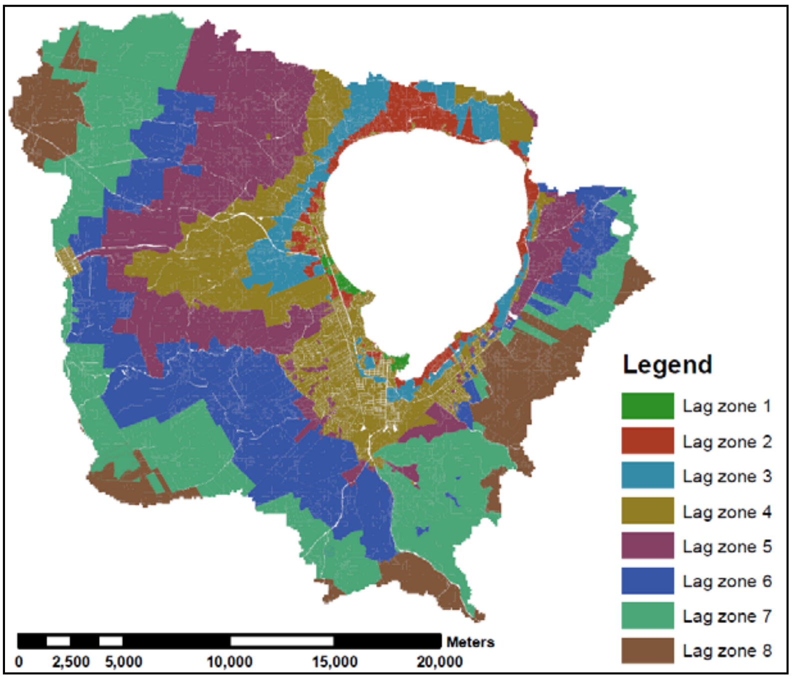
Groundwater lags are defined for each parcel of land in the catchment. The lags are described by their mean residence time (MRT), the mean time that nitrogen spends in the groundwater. For ease of analysis, parcels were aggregated into eight groundwater lag zones based on their MRTs. All parcels within the same zone were treated as having the same MRT.

Lag zone 1, the closest to the lake, has the lowest MRT and lag zone 8, the farthest from the lake, has the highest MRT. Table 1 gives the MRT, size and percentage of nutrients in the catchment for each lag zone. Figure 2 shows the catchment by groundwater lag zone.

Table 1: Overview of the groundwater lag zones

Lag Zone	1	2	3	4	5	6	7	8
MRT (years)	2.5	8	15	30	50	70	90	110
Number of ha	150	1,390	2,335	6,855	8,290	9,440	11,610	5,090
Nutrients transported (%)	0.2	3.4	5.1	12.8	19.0	25.5	24.7	9.3

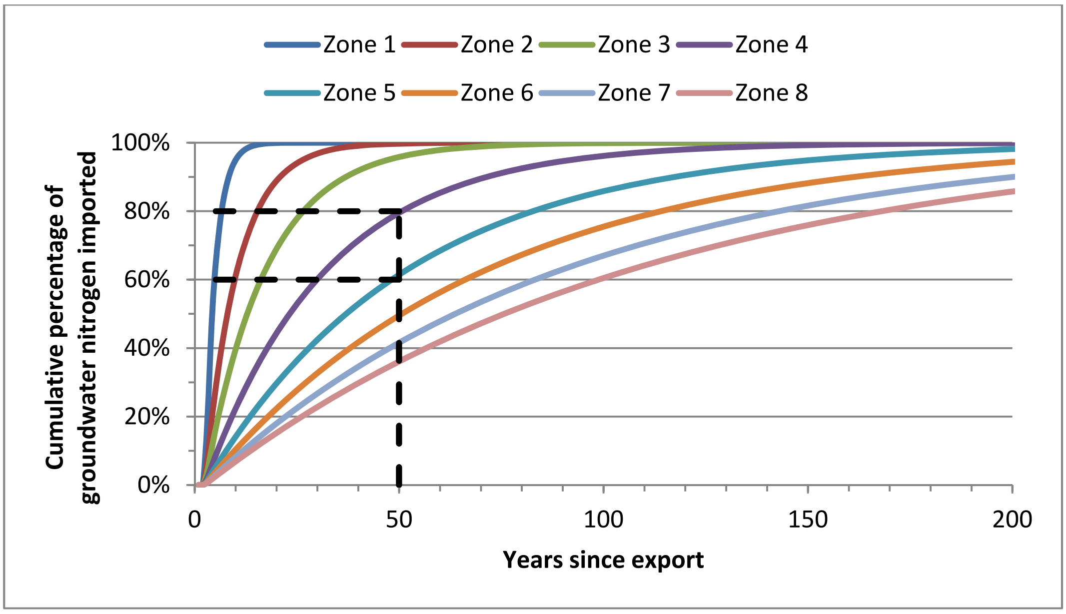
Figure 2: NManager groundwater lag zones



In NManager groundwater lags are described by a series of Unit Response Functions (URFs), one URF for each lag zone. URFs describe the nitrogen loads from a single unit of nitrogen entering the groundwater as a function of time since export. Each URF is constructed according to the behaviour of a single aquifer with steady flow as an approximation to ROTAN.

Figure 3 gives the cumulative sum of the URFs used by NManager. Each curve gives the percentage of nitrogen from the groundwater, exported at time zero that has since arrived in the lake. For example, if nitrogen is exported from lag zones 4 and 5, then after 50 years 80 percent of the nitrogen from lag zone 4 and 60 percent of the nitrogen from lag zone 5 that entered into the groundwater will have reached the lake.

Figure 3: Cumulative sum of Unit Response Functions by groundwater lag zone



Nitrogen exports from a single year result in loads to the lake over multiple years as expressed by the URFs. These loads are additive across time and across different locations in the catchment. The nitrogen load at time t, from parcel i, delivered via groundwater can be expressed as follows:

$$Load_{GW}^{i}(t) = \rho_{GW} \sum_{\tau=0}^{\tau=t} f^{i}(\tau)\, h^{i}(t-\tau)$$

where ρ_{GW} is the proportion of nitrogen exports delivered to the lake via groundwater (ROTAN suggests $\rho_{GW} = 57\%$), $f^{i}(\tau)$ is the quantity of nitrogen exported from parcel i at time τ; and $h^{i}(\cdot)$ is the URF for the lag zone associated with the parcel. NManager evaluates this sum using an annual time step for each time t.

Nitrogen loads delivered via surface water arrive in the lake in the same year they are exported. The load from parcel i, delivered via surface water at time t, can be expressed as follows:

$$Load_{SW}^{i}(t) = (1 - \rho_{GW}) f^{i}(t)$$

And the total load to the lake at time t can be expressed as:

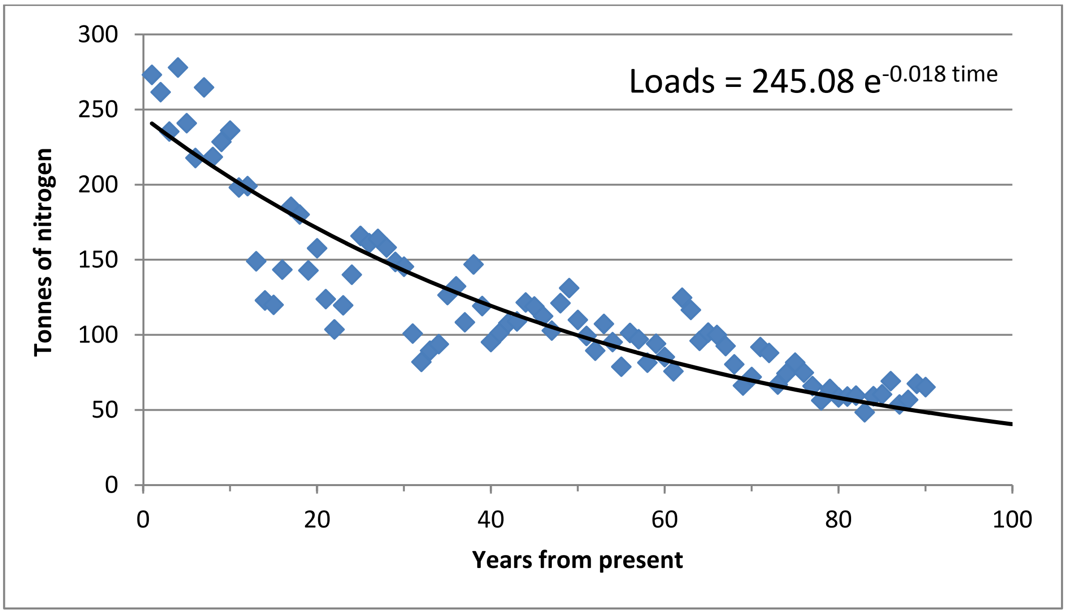
$$Load_{tot}(t) = \sum_{i=1}^{i=n} \left(Load_{GW}^{i}(t) + Load_{SW}^{i}(t) \right)$$

3.2. Legacy loads

Legacy loads are the nitrogen loads already present in the Lake Rotorua groundwater that will be realised as inputs to the lake in future years. These loads are the result of groundwater lags acting on historic exports from agricultural land use and septic tanks. They are independent of future land use and cannot be targeted by mitigation.

Legacy loads and those arising from unmanageable exports contribute to the total lake load and must therefore be adjusted for when considering which loads can be targeted by changes in land management practices (the total unmanageable loads are shown in Figure 1). Figure 4 gives the legacy loads estimated by ROTAN. These are incorporated into NManager using the exponential curve fitted to the results.

Figure 4: Legacy loads: ROTAN results from 2009



3.3. Modelling the use of land in the catchment

Landowners' responses to regulation will depend on their current land use. We are interested in the various types of land use and where the uses occur. Land use and location are specified in NManager using the ROTAN map for current land use (National Institute of Water and Atmospheric Research, dataset, 2011). This map was constructed in two steps: a 2005 land-use map was constructed by BoPRC based on 2003 aerial photographs of land cover and results from a land-use questionnaire sent to landowners in 2005. The map was updated to a 2010 land-use map using 2007 aerial photographs, a map of dairy land cover and local knowledge

(Rutherford et al., 2011). Table 2 gives the land areas, leaching and total exports of the different land types included in NManager.[6]

Table 2: Land area and base leaching in NManager

	Land area	Leaching per hectare (kg N / ha / yr)	Exports to the lake (t N / yr)
Dairy	5,363	56	300
Sheep/beef	15,375	16	246
Forestry	21,023	4 [7]	81
Urban			28
Geothermal areas			30
Sewage, septic tanks and RLTS [8]			86
Total	45,185		771

Due to similarities between leaching rates some land-use categories were merged. Bare ground, horticulture, lifestyle, dairy dry stock and different types of sheep and cattle farming were merged into a sheep-beef category. Scrub, wetlands and different types of forest were merged into a forestry category. Cropping was merged with dairy. The resulting land-use categories in NManager are: Dairy, Sheep-beef, Forestry, the Rotorua Land Treatment System, Septic tanks, Tikitere geothermal area, Whakarewarewa geothermal area, Urban and Urban open space. These are estimated at a 1 hectare spatial scale.

Leaching from forestry and scrub land is small and cannot be further mitigated via land management. However, some land classified as scrub is covered in gorse and has a high rate of nitrogen loss. Replacing gorse land with forestry is expected to result in a 40 tN/yr reduction in nitrogen leaching (Male et al., 2010). Separating gorse from other scrub land has been left for future research.

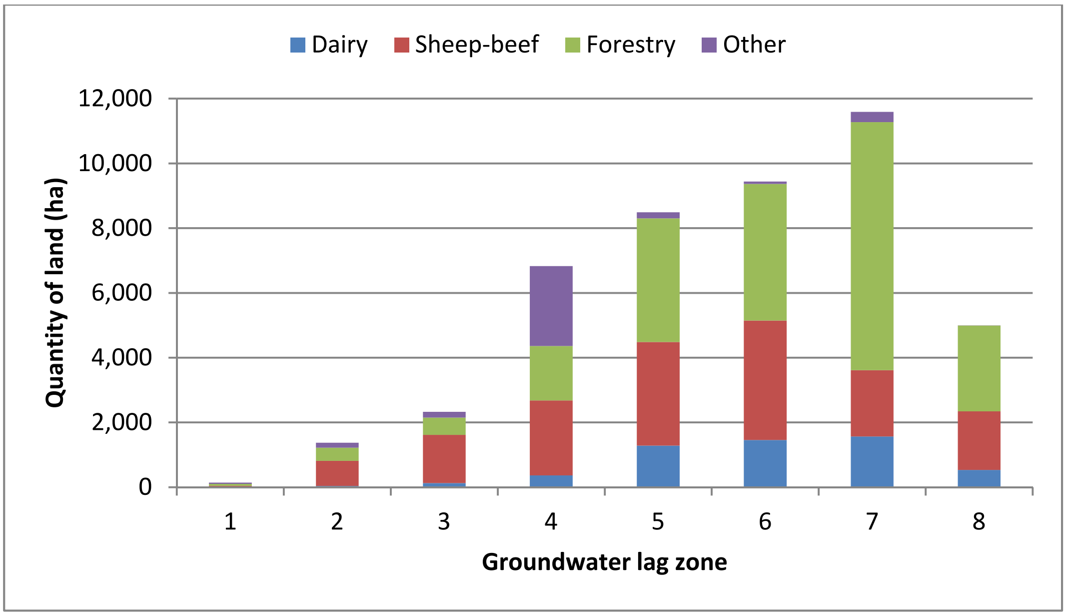
Figure 5 gives the distribution of land use in each lag zone. We have combined the smaller land uses into a single category labelled "other". We observe that there is very little land in the first three lag zones, dairy is concentrated in lag zones 4 to 7, and sheep-beef farming is spread across all lag zones.

[6] The Rotorua and Taupō Nutrient Model (ROTAN) suggests some nitrogen reaches the lake, via groundwater, from land outside the surface water catchment (Rutherford et al., 2011). This has not been included in NManager.

[7] All forestry, other than the Waipa forest, an area of about 1,500 hectares, is estimated by ROTAN to have leaching of 4 kg N/yr. Leaching for the Waipa forest is estimated to be 2 kg N/yr.

[8] Rotorua Land Treatment System: Treated effluent from the Rotorua Wastewater Treatment Plant is sprayed onto land in the Whakarewarewa Forest.

Figure 5: Proportion of land use by groundwater lag zone



3.4. The shape of the profit functions

We model landowners' land management practices using profit functions. These express the profit of a farm, per hectare per year, as a function of mitigation and land use change, per hectare per year. Mitigation occurs via changes in stocking rates, fertiliser and nitrogen inhibitor usage, and farm management.

NManager distinguishes between land initially used for dairy farming and sheep-beef farming by representing each with a different profit function. All farms of each type are assumed to be homogeneous and have the same leaching and profit per hectare before regulation. These are shown in Table 3, along with the minimum leaching possible for each land use according to Smeaton et al. (2011). As 4 kg N/ha/yr is the minimum leaching possible under any land use, we define manageable leaching, the leaching a landowner can control via mitigation, as 4 kg N/ha/yr less than the corresponding leaching value.

Table 3: Leaching and profit by land use

Land use	Dairy	Sheep-beef	Forestry
Leaching (kg N/ha/yr)	56	16	4
Manageable leaching (kg N/ha/yr)	52	12	0
Minimum leaching (kg N/ha/yr)	28	10	4
Minimum manageable leaching (kg N/ha/yr)	24	6	0
Profit ($/ha/yr)	1,345	470	105

Under regulation landowners may choose to convert their land to less nitrogen-intensive land uses. This is represented in NManager by profit functions that span the different uses of land.

Where our results suggest a level of leaching that is less than the minimum leaching for one land use but greater than the maximum leaching for the next less intensive land use, we assume a landowner will have minimised the leaching of their current land use and then converted a proportion of their land to the less intensive land use in order to satisfy the leaching reduction on average across their farm. For example: a landowner with a leaching of 20 kg N/ha/yr is assumed to have 33 percent of their land as dairy (leaching 28 kg N/ha/yr) and 67 percent of their land as sheep/beef (leaching 16 kg N/ha/yr).

Figure 6 and Figure 7 give the profit functions for dairy farm land and sheep-beef farm land respectively. These are fitted as quadratic curves to simulation results from Farmax and OVERSEER (Smeaton et al., 2011). The "X"s in these figures mark the base and minimum leaching levels for dairy and sheep/beef farming. As the curves are concave, the marginal cost of mitigation increases as mitigation increases.

Note that the profit curve for dairy farms spans the simulation results for sheep-beef farms and intersects the result for forestry profit, and that the profit curve for sheep-beef farms intersects the result for forestry profit. Some results were included even though they were dominated by other results, in an attempt to recognise heterogeneity between farmers, so the curves are more reflective of an average farmer.

Figure 6: Dairy land profit function

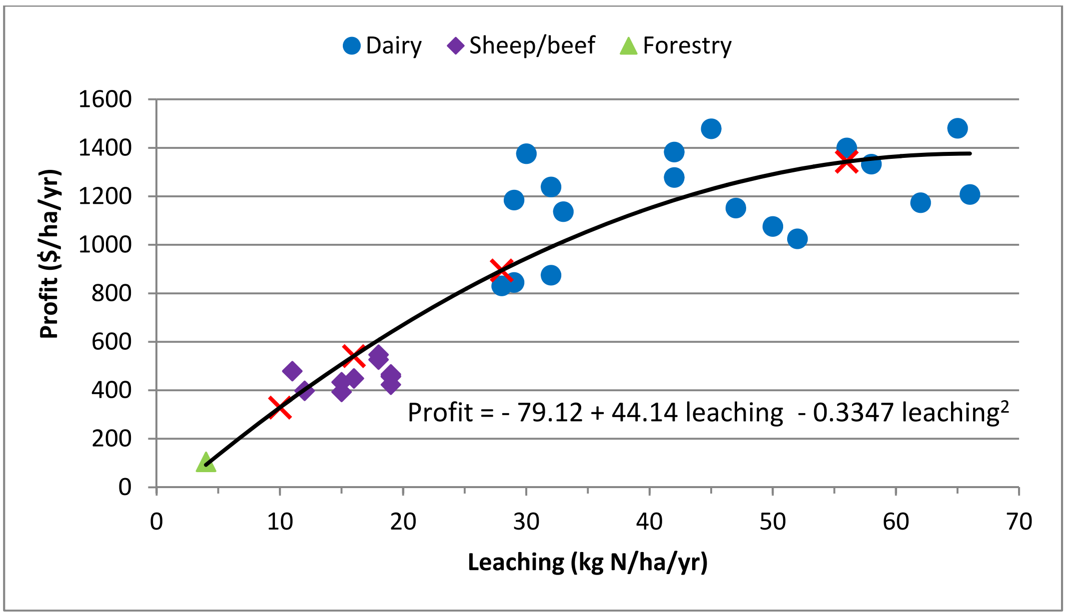
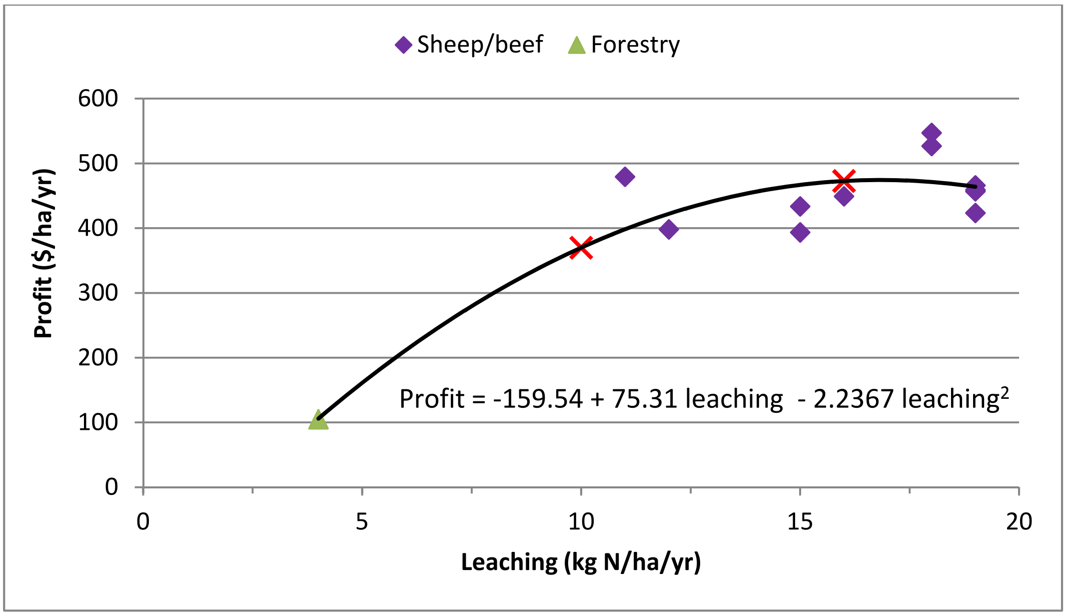


Figure 7: Sheep-beef land profit function



These profit functions include capital costs and the cost of converting land to forestry. They assume present conditions persist. Abnormal weather conditions (e.g. droughts) and changes in commodity prices may give significantly different results from those predicted.

4. The Design of Regulation

Regulation aims to control landowners' behaviour or to provide financial incentives for landowners to manage and reduce their nitrogen exports to meet the objectives of society. We are interested in the implications of different regulations and their cost effectiveness for reaching the mitigation targets. In this section we specify six approaches available to BoPRC. In order of complexity they are: requiring best practice; land retirement; an export trading scheme where landowners must hold sufficient allowances to cover nitrogen exports from their property each year; and two vintage trading schemes which attempt to incorporate the timing of nitrogen loads, via groundwater, into the regulatory scheme in a simple way. The trading schemes follow the design given in Lock and Kerr (2008) and Kerr et al. (2007). These approaches are simulated using NManager in section 6.

4.1. Best practice

Output from Farmax and OVERSEER estimates minimum possible leaching for dairy and sheep-beef farming. We model the adoption of best practice by assuming leaching is reduced to the minimum leaching given in Table 3 without changes in land use.

This is modelled as a step change from business as usual in 2015. Leaching from all dairy land is reduced to 28 kg N/ha/yr and leaching from all sheep-beef land is reduced to 10 kg N/ha/yr. We assume that there is no change in land use.

4.2. Land retirement

For modelling land retirement we assume all mitigation comes from some landowners changing their land use to a less nitrogen-intensive use. There is no change in the leaching rates per hectare for each land use.

In NManager, sheep-beef land is initially retired to become forest before dairy land is retired to new sheep-beef land. If necessary, this new sheep-beef land is then retired into forestry. We assume that land is retired equally across the catchment, hence land retirement in each year can be described by three percentages: the percentage of initial sheep-beef land that has been retired into forestry, the percentage of dairy land that has been retired into new sheep-beef land, and the percentage of this new sheep-beef land that has also been retired into forestry.

4.3. An export trading scheme

The environmental targets for Lake Rotorua are specified in terms of acceptable nitrogen loads to the lake. However, landowners manage the amount of nitrogen they put onto the land, from which it is relatively easy to estimate exports from their property (for example, using OVERSEER), but difficult to estimate loads reaching the lake. This suggests that regulation that targets exports will be more straightforward than regulation that targets lake loads.

Under an export trading scheme the regulator provides a supply of annual export allowances. At the end of each year landowners must surrender sufficient allowances to cover the nitrogen leaching from their property for that year. Landowners who do not have sufficient allowances to cover their leaching will have to either purchase unused allowances from landowners with excess allowances, reduce their exports, or risk non-compliance. By controlling the supply of export allowances a regulator can manage the amount of nitrogen that reaches the lake. The Lake Taupō scheme has this form.

A trading scheme is desirable, as it encourages mitigation to occur where it is most cost effective. Profit-maximising landowners will mitigate as long as it costs less than the allowances they would otherwise have to hold. The price of allowances will be such that all allowances are used and each landowner is indifferent between further mitigation and purchasing additional allowances. It follows that under a trading scheme the least costly mitigation activities will take place first.

In this study all farms with the same land use have the same mitigation costs. Hence trading encourages mitigation on the land use where it is cheapest. In reality, there *are* large differences among farms of the same type, so trading will encourage mitigation on farms where it is cheapest.

A trading scheme is not without administrative difficulties. Successful implementation of a trading scheme requires good monitoring and enforcement. Furthermore, the regulator must determine the initial allocation of allowances. This can be an extensive political process with high potential costs. A trading system that has lower overall cost and is perceived to be fair may, however, be easier to enforce.

4.4. Vintage trading

Groundwater lags are a major feature of the Lake Rotorua catchment. Taking account of groundwater lags in the design of regulation can result in more cost-effective mitigation as landowners will surrender allowances that better correspond to their effect on lake loads. Under a vintage trading scheme, additional gains in cost effectiveness can arise from trades between lag zones that change the timing of mitigation. A landowner at the back of the catchment can either mitigate now or pay another farmer to increase mitigation at the front of the catchment in the future (by buying allowances from them). This delay in mitigation makes no difference to the nitrogen load reaching the lake. However, because it defers the cost of mitigation, it reduces the net present value of the cost of mitigation. We consider two simple vintage trading schemes that attempt to reflect the timing of nitrogen loads to the lake. These schemes attempt to link lake loads to exports via vintage allowances.

A vintage trading scheme works in a similar way to an export trading scheme. The main difference is that vintage allowances permit landowners to release nitrogen into the lake, rather than to export it from their land. Therefore landowners are trading rights for lake loads not exports. Under regulation, landowners must surrender allowances at the end of each year to cover the lake loads that will be caused by the nitrogen leaching from their property from that year.

Although groundwater leaching is a continuous process, some approximation is required to implement a vintage trading scheme. The design of regulation must provide some convention that specifies for landowners the vintage allowances they must surrender in each year. We consider two possible regulatory conventions: a two-pulse vintage scheme that closely approximates the ideal situation, and a one-pulse vintage scheme that might be more likely in practice. These follow the design of a vintage scheme given in Kerr et al. (2007).

The one-pulse vintage scheme allocates each lag zone a lag time that approximates its mean groundwater lag time. In each year, landowners must surrender allowances of the vintage that corresponds to the current year plus their lag time. For example, suppose a landowner with a lag time of six years exports nitrogen in 2020. Under the one-pulse trading scheme they must surrender vintage allowances for the year 2026.

Table 4 summarises the lags for the one-pulse vintage scheme. These lags were selected as the average travel time for all water (47 percent of the surface water time (zero) plus 53 percent of the groundwater time, represented by the MRTs for each lag zone given in Table 1).

Table 4: Lag times for the one-pulse vintage scheme

Groundwater lag zone	1	2	3	4	5	6	7	8
Lag times	1 yr	4 yrs	8 yrs	16 yrs	27 yrs	37 yrs	48 yrs	58 yrs

In the two-pulse vintage scheme, each year landowners surrender current-year allowances to match 47 percent of their exports (to cover nitrogen that travels through surface water); the other 53 percent of exports is matched from the vintage that corresponds to the current year plus their lag time (to cover nitrogen that travels through groundwater). It specifies lag times that apply only to groundwater leaching (the MRTs from Table 1). For example, suppose a landowner with a lag time of 6 years exports 100 kg of nitrogen in 2020. Under the two-pulse trading scheme he must, in 2020, surrender 47 kg of 2020 vintage allowances and 53 kg of 2026 vintage allowances.

Table 5: Lag times for the two-pulse vintage scheme

Groundwater lag zone	1	2	3	4	5	6	7	8
Lag times	2 yrs	8 yrs	15 yrs	30 yrs	50 yrs	70 yrs	90 yrs	110 yrs

Unlike export trading schemes, vintage trading schemes have never been implemented. The complexity of these schemes makes them difficult to implement and administer. Landowners also face a more obviously complex challenge to optimise their response to the regulation. They need to manage their holdings of allowances (which would be issued many years in advance of use) anticipating their future needs. Although allowances of all vintages could be traded from the first year, markets for vintages many years out are likely to be thin so prices may not be very informative. Prices across different vintages will be interdependent, making them hard to predict (see Appendix C). A time inconsistency problem may also arise. If landowners use all future vintages early in the program the only way future farmers will be able to mitigate sufficiently may be to stop farming. The future regulator is unlikely to find this acceptable and may change the policy. Thus constraints may need to be placed on the use of future allowances.

Finally, regulation that targets lake loads will involve more apparent scientific uncertainty than regulation that targets exports. Landowners manage the amount of nitrogen they put onto the land, from which it is relatively easy to estimate exports from their property (for example, using OVERSEER), but difficult to estimate loads reaching the lake because we must also estimate the length of ground water lags.

5. Simulating Landowner Behaviour under Regulation

For a specified regulatory system, NManager determines the pattern of nitrogen exports that will be chosen by profit-maximising landowners. Furthermore, for a specified set of environmental targets and a given regulatory scheme, NManager can determine the stringency of regulation necessary to meet those targets. These solutions are unique. This section specifies how NManager solves for the optimal pattern of nitrogen exports to meet given targets under different regulatory schemes. Non-technical readers may wish to skip forward to section 6.

5.1. Solving for cost-effective land retirement

For a specified series of environmental targets, the acceptable levels of lake loads for some times $t \in [0, T]$, NManager determines the percentage of land retired under land retirement regulation necessary to ensure nitrogen targets are met.

Let $y_{s,t}^{i}$ be the amount of manageable nitrogen that leaches from land use i at time s and arrives in the lake at time t ($y_{s,t}^{i} = 0$ if $s > t$). The lag for a unit of nitrogen represented by $y_{s,t}^{i}$ is $s - t$. Before the introduction of regulation, we can therefore express the manageable lake loads without regulation in year t as:

$$\text{manageable loads w/out regulation}_t = \sum_{s>0} \sum_{i} y_{s,t}^{i}$$

Let d_s^i be the percentage of land, from land use i, that has been retired by year s. For land retirement regulation, we consider three land uses: current sheep/beef farming ($i = SB$), which is retired to forestry at a cost of c^{SB}; dairy farming ($i = D$), which is retired to new sheep/beef farming at a cost of c^{D}; and new sheep/beef farming ($i = nSB$), which is retired to forestry at a cost of c^{nSB}.

We therefore determine d_s^i (for all i and s) in order to minimise the total cost of land retirement given by:

$$\text{total cost} = \sum_s d_s^{SB} c^{SB} + d_s^D c^D + d_s^{nSB} c^{nSB}$$

subject to:

$$\text{target manageable loads}_t = \sum_s (1 - d_s^{SB}) y_{s,t}^{SB} + (1 - d_s^D) y_{s,t}^D + (1 - d_s^{nSB}) y_{s,t}^{nSB}$$

$$d_s^D \geq d_s^{nSB}$$

Given these equations, we can formulate a constrained optimisation problem. As the costs and effects of land retirement are constant over time and between farmers, we can reduce the constrained optimisation model to three sequential simultaneous equations (one equation for each land use). As $y_{s,t} = 0 \text{ if } s > t$ and $y_{s,t} \neq 0 \text{ if } s = t$ these simultaneous equations, and therefore the constrained optimisation problem, will always have a unique solution.

5.2. Solving a trading scheme

For a trading scheme with given allowance caps, NManager determines landowners' profit-maximising quantity of nitrogen exports, in each time period, by finding the allowance price under which the supply of allowances equals the demand. This price will equal the cost of the last unit of mitigation. The algorithm mimics the behaviour of a decentralised market by updating the price of allowances in response to excess supply and demand.

We next give a formal presentation of the model used in NManager. Profit for landowner i $(i = 1, \dots, M)$ at time t depends on their quantity of nitrogen exports x_{it}. The profit for landowner i at time t is:

$$\pi_{it} = f_i(x_{it}), f_i' > 0$$

Let P_t be the current price of allowances in year t. Profit-maximising landowners will choose x_{it}^* the quantity of nitrogen exports that maximises their profit, less the opportunity cost of holding allowances[9] as follows:

$$x_{it}^*(P_t) = \textbf{arg max } [f_i(x_{it}) - x_{it} P_t]$$

The total demand for allowances of year t is given by:

$$\mathrm{D}(P_t) = \sum_i x_{i,t}^* (P_t)$$

[9] We consider only the holding of allowances. By the Coase Theorem, our final results and costs of mitigation are independent of the initial allocation of allowances, and who buys and sells allowances.

For a specified path of environmental targets, NManager determines the unique set of allowance caps for each year $\{S_t\}$ that ensures all nutrient targets are met. The market-clearing prices will be $\{P_t\}$ such that for all allowances:

$$\mathrm{D}(P_t) - S_t \leq 0 \; and \; (\mathrm{D}(P_t) - S_t)\, P_t = 0 \; \forall \, \mathrm{t}$$

We use an iterative numerical method (the Newton-Raphson algorithm) to solve for the prices of allowances in equilibrium. See Appendix A for further details.

5.3. Solving the vintage trading schemes

The basic approach is the same as above but two critical features differentiate it: caps are on loads, not exports, and prices are interdependent across vintages.

Let $\{v_{ik}\}$, $k = 1, \dots, K$, be the lag times specified by the regulatory scheme for landowner i. The percentage of exports it models as carried to the lake at lag time k is given by θ_k. In the one-pulse vintage scheme $K = 1$ and $\theta_1 = 1$. In the two-pulse vintage scheme $K = 2$, $\theta_1 = 0.47$ and $\theta_2 = 0.53$. The surface water flow has a lag time of zero for all lag zones ($v_{i1} = 0$).

For each lag time landowners must surrender $\theta_k x_{it}$ allowances of vintage $t + v_{ik}$. Profit-seeking landowners will choose x_{it}^*, the quantity of nitrogen exports that maximises their profit net of allowance holdings, as follows:

$$x_{it}^* = x_{it}^*(P_t, \dots, P_{t+v_{iK}}; r, \theta_1, \dots, \theta_K) = \mathbf{arg\,max}\left[f_i(x_{it}) - x_{it}\Big(\sum_k \theta_k \frac{1}{(1+r)^{v_{ik}}} P_{t+v_{ik}}\Big)\right]$$

where r is the discount rate and P_t is the price at time t of allowances of vintage t. Vintage trading schemes require landowners to surrender allowances of the same vintage in different years. Because allowances are an asset, by the Hotelling rule, their value should be expected to rise at the real market rate of return. Mitigation each year is determined by the price of the relevant vintage allowances in that year; therefore NManager discounts the price of each allowance into the year of surrender. Results in this paper use a seven percent real interest rate. This is the rate used by BoPRC.

The total demand for allowances of vintage t is given by:

$$\mathrm{D_t}(P_{t-v_{iK}}, \dots, P_t, \dots, P_{t+v_{iK}}; r, \{v_{ik}, \theta_k\}) = \sum_i \sum_{k=1}^{K} \theta_k \, x_{i,t-v_{ik}}^*$$

As in the export trading system, the market-clearing price in each market will depend on the supply and demand in that market but in this case it will also depend on the prices, and hence indirectly the demand and supply, in all other markets. We use an iterative numerical method to determine the equilibrium set of prices of all vintage allowances simultaneously.

5.4. Handling boundary conditions

Incorporating groundwater lags in the vintage trading schemes requires landowners to hold allowances of the same vintage in different years. Unless these schemes have a fixed duration, finding an exact solution would require solving over an infinite length of time.

We may find a finite approximation to the solution under two assumptions: the first is weak dependence between markets: if we choose ω sufficiently large then the dependence between markets at time t and $t + \omega$ is weak. The second is price convergence: all the prices beyond some time T are constant and equal to price P_T. This assumption is reasonable so long as the number of allowances is constant many periods before time T.

Assuming convergence of vintage prices may introduce error into the results by creating artificially stable prices. Testing of different thresholds suggests that $T = 400$ is sufficient to minimise any artificial stability if we limit our results to the first 200 years.

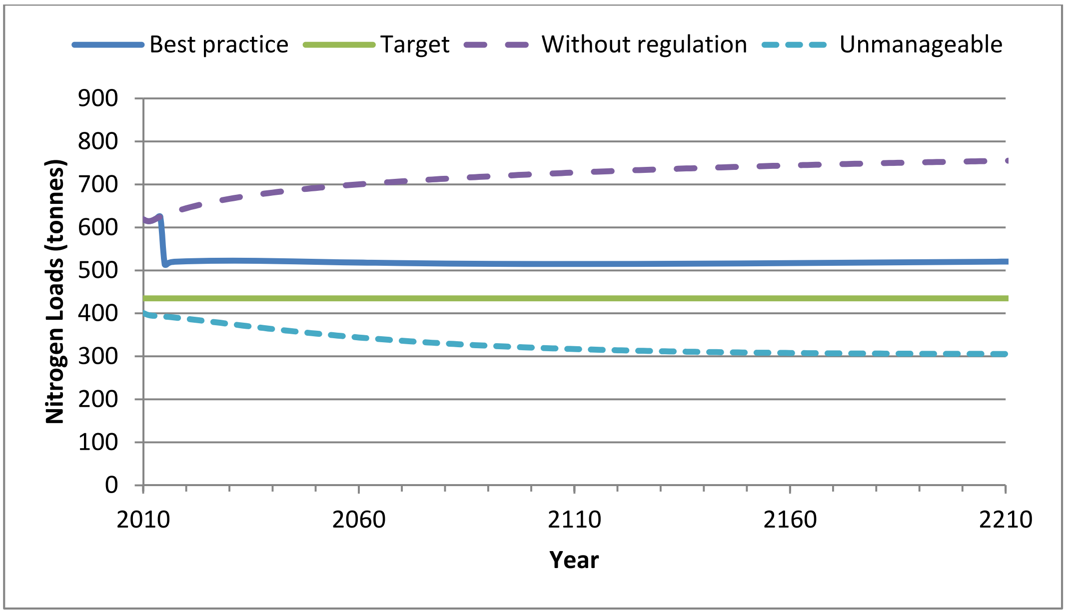
6. The Performance of Different Regulatory Schemes

This section presents simulation results from NManager for the regulatory schemes introduced in section 4. We compare and discuss the results for the different schemes.

6.1. Requiring best practice

We first consider the environmental outcome of best management practice. Figure 8 gives the total lake loads under best practice regulation modelled as a step change in land use, and hence exports, in 2015. If this regulation were to be implemented in the Lake Rotorua catchment, we would most likely observe a more gradual decrease in exports and hence lake loads as landowners would need a transition period toward full regulation.

Figure 8: Nutrient loads under best practice regulation



Under regulation, we observe a step decrease in lake loads due to surface water in 2015, followed by loads tending towards their long-run values. Requiring landowners to implement best practice on their land reduces nitrogen exports by 242 tN/yr and results in long-run loads of 529 tN/yr. This is not sufficient to meet the environmental target, suggesting that some land retirement will be necessary to ensure acceptable lake quality in the long run.[10]

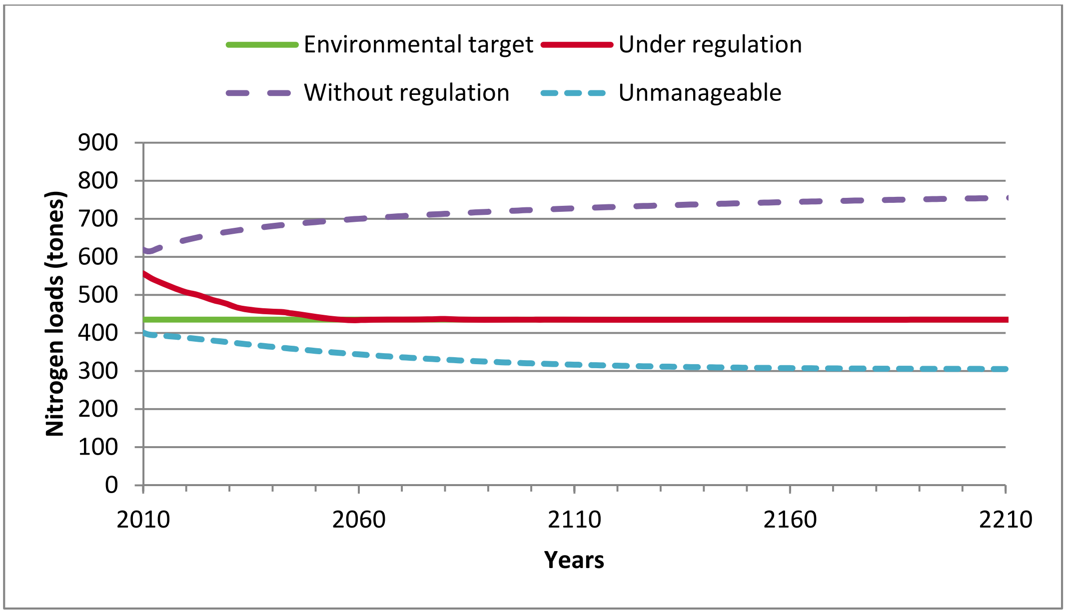
6.2. The performance of regulation that meets the target

We now consider the effects of land retirement, export trading and two forms of vintage trading regulation. For these approaches NManager requires that regulation results in the lake loads under regulation given in Figure 9.

The load path under regulation was specified so that the long-run environmental target for the lake would be reached in 50 years and nitrogen loads would remain constant from then onwards. The lake loads under the different regulatory schemes were matched to the specified load path by controlling the stringency of the regulation.

[10] This assumes that nutrient leaching per hectare stays constant within each land use.

Figure 9: Nutrient loads required for regulation comparison



Despite these regulatory approaches having identical environmental outcomes, the cost of mitigation under the schemes is not the same. The land retirement scheme will equalise the marginal costs of land use change but on-farm mitigation costs will not be equalised. The export scheme will equalise marginal costs of land-use change and on-farm mitigation within and between farms. Thus the export scheme will have lower total mitigation costs.

Our estimates of costs and prices are likely to be underestimates because they assume that farmers respond instantly and efficiently to the regulation. In reality this is unlikely because they will face some regulatory uncertainty, farmers may take time to work out an optimal response, the market or retirement scheme may not operate efficiently, they may have objectives other than profit maximisation, and some farms may be excluded from direct regulation due to their small size. As our current model is static, it also ignores any costs associated with restricting nitrogen to current levels and costs from changes in commodity prices. On the other hand it ignores the possibility of technology change.

Table 6: Net present value of the cost of mitigation for straightforward regulation

Scheme	Land retirement	Export trading
Cost on dairy farms ($ millions)	58.3	47.7
Cost on sheep-beef farms ($ millions)	26.5	20.5
Total cost ($ millions)	84.8	68.2

Table 6 gives the Net Present Value (NPV) in 2010 of the cost of mitigation, estimated by NManager, under each of the schemes.[11] The cost of mitigation under the export trading scheme is estimated to be 20 percent less than under land retirement.

Figure 10: Allowance prices and percentage mitigated

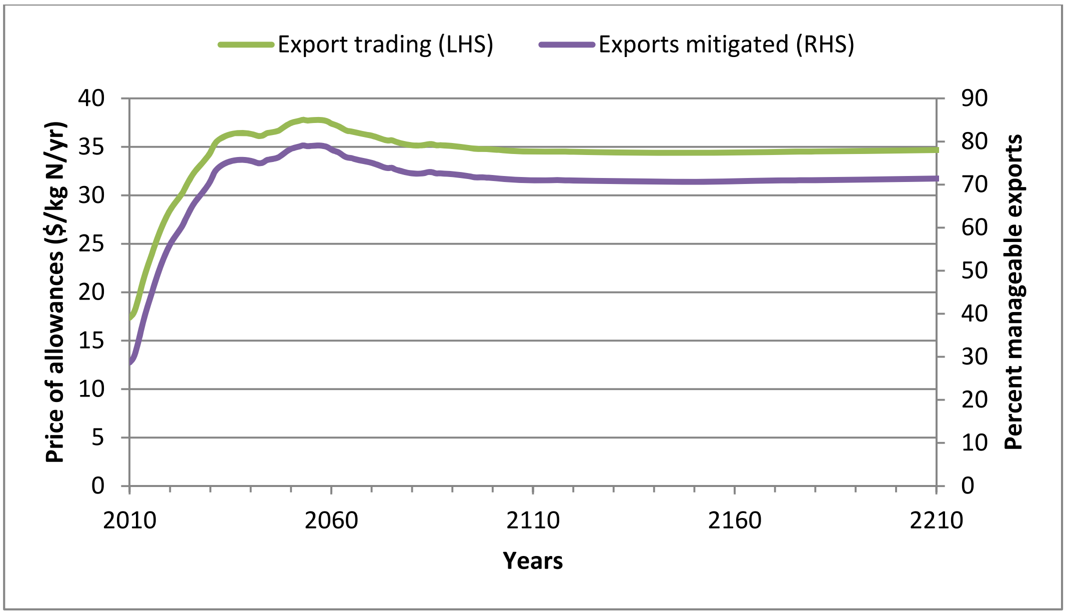


Figure 10 gives the price of allowances and the percentage of exports mitigated in each year under export trading regulation. The price of allowances is equivalent to the marginal cost of leaching, and will be equivalent to the marginal cost of mitigation for all landowners who are yet to convert their land to forestry, and are therefore still able to mitigate further. The yearly price of allowances given by NManager suggests that the net present value of a stream of export allowances is approximately $460. This is consistent with the trading price of allowances in the Lake Taupō catchment reported by Duhon et al. (2011).

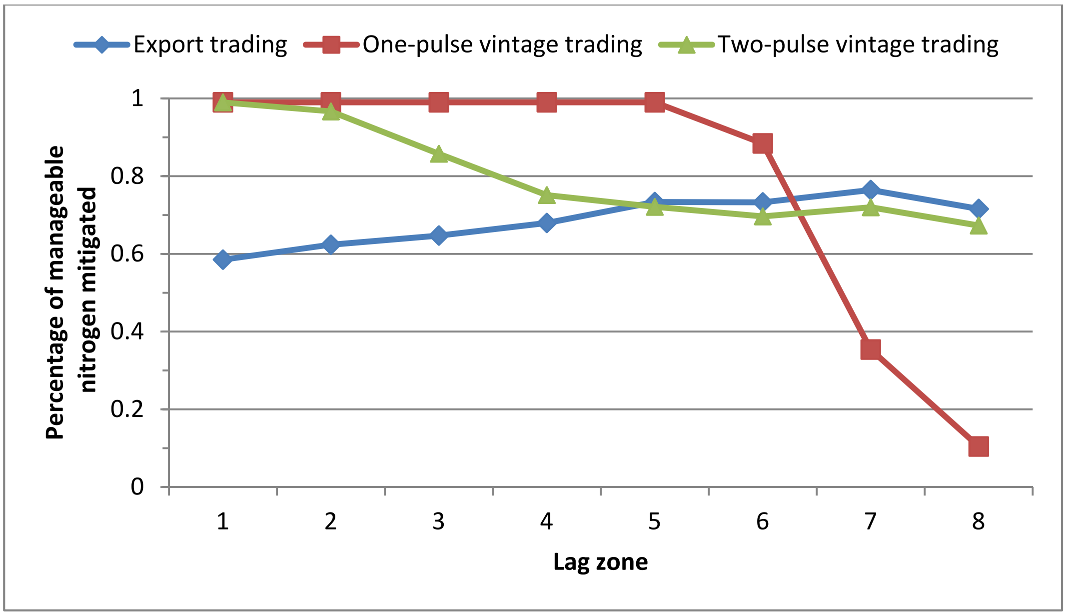
6.2.1. Cost under more complex trading schemes

We now consider the vintage trading schemes to determine whether further gains in cost effectiveness are possible from changes in the distribution of mitigation across lag zones. Under a vintage trading scheme, the set of allowances farmers must surrender to match their loads differs around the catchment. As a result, there are possible benefits from landowners at the back of the catchment delaying mitigation at first and paying for increased mitigation at the front of that catchment in the future. Ideally the marginal cost of mitigation effort should be matched to the present value of the environmental benefits (in terms of avoided future mitigation).

[11] In this section dairy land and sheep-beef land refers to the land use before regulation.

Figure 11 gives the percentage of pre-regulation manageable nitrogen within each lag zone that is mitigated under regulation.[12] Approximately 75 percent of all manageable nitrogen must be mitigated to reach the environmental target. Under an export trading scheme this mitigation is relatively evenly distributed across the catchment; any differences are driven only by the initial land use mix. Both the vintage schemes result in an increase in the percentage of mitigation for lag zones closer to the lake and a decrease in mitigation for the lag zones further from the lake. For example, 68 percent of the nitrogen in lag zone 4 is mitigated under an export trading scheme. This rises to 75 percent under the two-pulse scheme and to 100 percent under the one-pulse vintage scheme.

Figure 11: Percentage of nutrients mitigated within each lag zone



These differences are largely due to the relative vintage prices faced by landowners in different lag zones. Under the export trading scheme landowners in all lag zones face the same price for allowances in each year and therefore each lag zone will carry out a similar percentage of mitigation. However, due to intertemporal trading under the vintage schemes landowners in lag zones further from the lake face lower marginal costs for the set of allowances they must surrender in the year they export nitrogen than land owners closer to the lake; therefore they will carry out a smaller percentage of mitigation.

[12] For each lag zone: percentage mitigated = (exports before regulation – exports after regulation) / exports before regulation.

Figure 12: Nominal and discounted vintage allowance prices

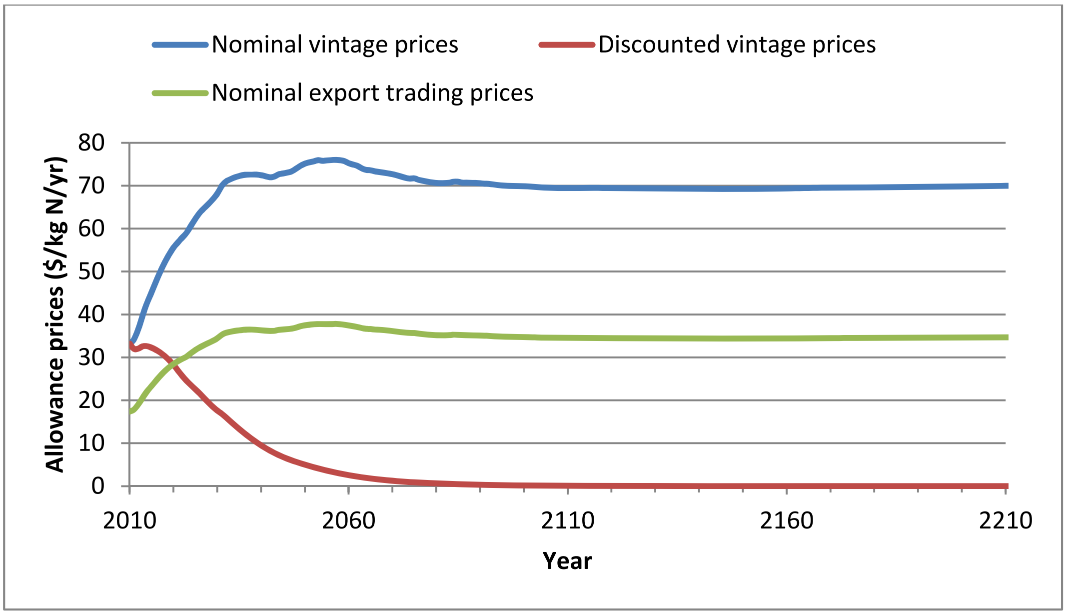


Figure 12 gives the nominal prices of vintage allowances (i.e. the price in the year the load reaches the lake) and the price of these allowances discounted to the year 2010 under the two-pulse vintage trading scheme. For comparison we include the price of allowances under the export trading scheme.

We observe that the nominal price of allowances under the two-pulse vintage trading scheme is significantly greater than the nominal price of allowances under the export trading scheme. As vintage prices are discounted depending on lag times, the nominal price of vintage allowances must be higher than the nominal price of export trading allowances, so that after discounting the two approaches result in similar marginal costs of leaching.

Table 7: Marginal cost of leaching by lag zone in 2010

Lag zone	1	2	3	4	5	6	7	8
Marginal cost of leaching two-pulse vintage scheme	32.61	31.70	27.58	20.66	16.97	15.95	15.70	15.64

Table 7 gives the marginal cost of leaching in 2010 for landowners in each lag zone under the two-pulse vintage trading scheme. These are calculated as 47 percent of the price of 2010 allowances plus 53 percent of the discounted price of allowances corresponding to the lag times given in Table 5. Under the export trading scheme the marginal cost of leaching is $17.40 for all lag zones. This is similar to the average of the marginal costs of leaching under the two-pulse vintage trading scheme, weighted by land area.

Table 8 gives the NPV of the cost of mitigation under each of the trading schemes.

Table 8: Comparison of costs of different trading schemes

Scheme	Export trading	One-pulse vintage trading	Two-pulse vintage trading
NPV ($ millions)	68.2	75.5	67.7

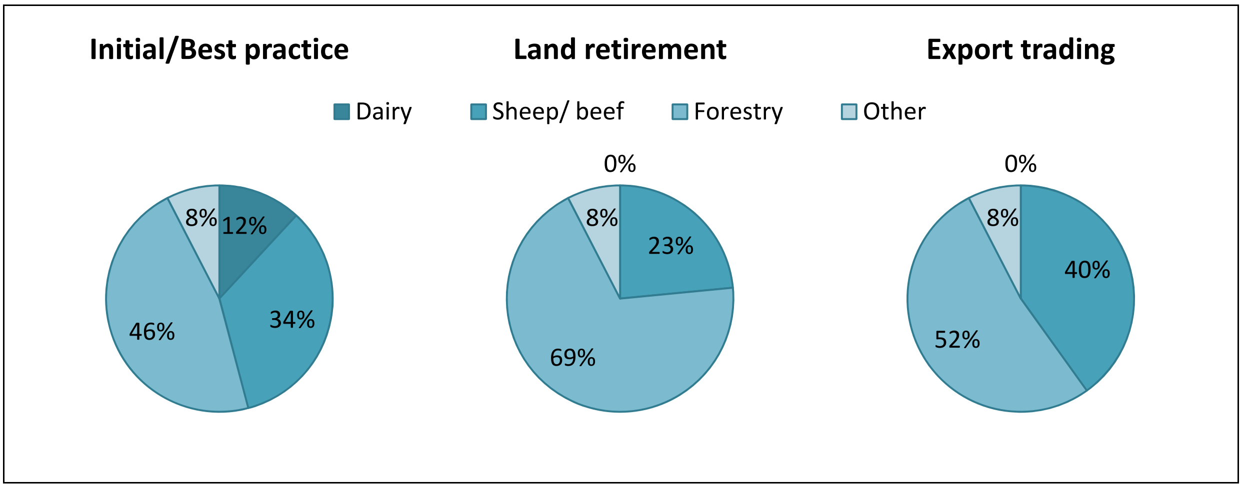
While both vintage schemes reduce the amount of mitigation that takes place at the back of the catchment, they increase the amount of mitigation that takes place at the front of the catchment. The net effect is that the one-pulse vintage scheme is less cost effective than the export trading scheme and that the two-pulse vintage scheme has only a slightly lower cost of mitigation than the export trading scheme. These results suggest that there are not significant gains in cost effectiveness from introducing a more complex regulatory scheme for Lake Rotorua and that a poor choice of regulatory lag times may result in less cost-effective regulation.

The allowances surrendered by landowners even under a two-pulse vintage scheme will still be an approximation to the lake loads they are responsible for. A vintage trading scheme that better approximates lake loads would be more cost effective. We also considered a nine-pulse vintage scheme but found that despite the increase in the accuracy with which it captured lake loads it resulted in a net present value for the cost of mitigation of $67.5 million; a less than 0.2 percent reduction in the cost of mitigation.

6.2.2. Implications of different regulations for land use change

Figure 13 gives estimates for the long-run proportion of land in each of the land uses under the different regulatory approaches.

Figure 13: Distribution of land under different regulatory schemes



Unsurprisingly, the land retirement scheme sees significant change in land use, since it produces all of its mitigation by changes from nutrient-intensive land uses to less nutrient-intensive land uses. In this scenario, all dairy land is retired to sheep/beef, and less productive sheep/beef land is retired into forestry.

The trading schemes see a different pattern of land-use change, because they allow a mixture of best-practice land management reforms and land retirement.[13] This means that, although all dairy land is still retired in the long term, by improving land management practices more land can be maintained, particularly in the short term, in the more nitrogen-intensive (and more profitable) uses.[14] The incentives to improve management rather than retire land to a less profitable use are large. These results are sensitive to the assumed profitability of forestry; under the emissions trading system, more sheep/beef land may be converted to forestry and some dairy may be sustained in the long run.

7. Discussion and Conclusions

We have created a model, NManager, and used it to evaluate a range of possible designs of regulations to improve water quality. Our key results are that only requiring best practice will probably not be sufficient to meet the environmental target for the lake. Land retirement regulation could meet the targets but a large share of the pastoral land in the catchment would need to be retired into forestry. It is likely that a mixture of these two approaches, as represented by export or vintage trading regulation, would be preferable.

By controlling the stringency of regulation we were able to ensure that the land retirement, export trading and vintage trading schemes resulted in the same path of environmental outcomes that achieve the lake load target of 435 tN/yr from land use within fifty years. This allowed us to compare costs across outcomes. We found that export trading reduced cost by 20 percent relative to land retirement only. In exploring more complex trading systems, however, we found very small gains from an efficient system that reflects groundwater lags. We also found that a plausible approximation to the efficient system that might better reflect a real regulatory response to groundwater lags actually increased costs relative to the simple export system. These results suggest that, in the case of Lake Rotorua, the extra complexity associated with accounting for groundwater lags would at best not be worth the additional difficulties associated with implementation, and at worst could be counterproductive.

[13] The two-pulse vintage trading scheme reports similar land use to the export trading scheme, but with 55 percent of the catchment in forestry, from the retirement of more low-quality sheep/beef land.

[14] Under land retirement regulation, NManager estimates than all dairy land will be retired to sheep/beef farming within seven years, while under export trading regulation this takes twenty years.

The result on the value of complexity is an empirical one and hence specific to the Lake Rotorua catchment. Non-rigorous exploration of sensitivity to key model and scenario features suggest that it is driven by a high percentage of nitrogen flowing through surface water – which implies that all mitigation has some immediate effect; by the stringency of regulation – because in the extreme, all nitrogen must be mitigated so there is no flexibility; by the specific local distribution of groundwater lags – in Rotorua there seems to be very little land with short groundwater lags; and with the discount rate – a higher discount rate makes the price of future vintages very low so the current price of allowances to cover surface water flows dominates farmers' responses. These factors may be different in another catchment.

These empirical results complement a series of papers on various aspects of design: monitoring, transaction costs, scope/participation, legal/compliance, and cost-sharing, for a nutrient trading system (www.motu.org.nz/research/detail/nutrient_trading). Many Regional Councils around New Zealand are faced with water quality challenges and nutrient sources similar to those in Rotorua, and operate under the same legal framework. With attention to differences among catchments, including the severity of the problem, rivers versus lakes, attenuation, land uses, and economic conditions, this work can provide a good starting place for more in-depth local analysis.

These initial results could be extended in several ways. Farmers can be made heterogeneous; this would allow us to better compare administrative allocations (export capping) to a trading scheme. The model could be made dynamic, allowing for changing economic conditions and also for explicit investment. NManager is a partial equilibrium model. Its solutions assume that regulation within the catchment does not affect input prices.[15] This may not be reasonable in the short run when workers are immobile and capital for investments in mitigation is scarce. NManager also ignores the pressure imposed on land outside the catchment as land use within the catchment changes under regulation.

The value of complex regulatory systems could also be more deeply assessed. We could rigorously explore the conditions under which complexity would be valuable. We could also more realistically model the value of complexity. As more complex regulatory schemes have higher costs of information, landowners will be more likely to seek satisfactory rather than optimal solutions. There will be a range of satisfactory solutions, many of which will be similar to the optimal solution. Complex vintage trading systems, with allowances for loads many years in

[15] It also assumes that output prices are unaffected. Given that most output is exported this is a reasonable assumption.

the future, are also likely to lead to strategic behaviour where the credibility that a regulation will still be enforced, and hence allowances still have value, many years in the future is low. Some limitations on current use of long vintages would probably be necessary in reality.

Finally, the current version of NManager ignores uncertainty as it assumes landowners have perfect information and the foresight required to plan 100, or more, years ahead. Landowners are in fact unlikely to plan more than 10 years ahead due to uncertainty and bounded rationality (the longest bond offered by the New Zealand Treasury is 12 years). Uncertainty could be introduced into the model by considering landowners' expectations of future leaching and land use.

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Appendix A: Solving Trading Schemes Numerically

A solution over T time periods may be found using the Newton-Raphson algorithm: Starting from an initial price vector $[P_t]^0$ iterate, until all prices satisfy the market clearing conditions, updating the prices at each iteration as follows:

$$[P_t]^{i+1} = [P_t]^i - \left[\frac{\partial g_j}{\partial P_\delta}\right]^{-1} [F_t]^i$$

where $[P_t]^i$ and $[F_t]^i$ are column vectors and $\left[\frac{\partial g_j}{\partial P_\delta}\right]$ is the $T \times T$ derivative matrix.

The vector $[F_t]^i$ is calculated numerically as given above. An approximation to the $(j, \delta)^{th}$ entry of the derivative matrix is calculated as follows:

$$\frac{\partial g_j}{\partial P_\delta} = \frac{\left(g_j^*([P_k]^i; r, \{v_{ik}\})\right) - \left(g_j^*([P_k]^i + \partial P_\delta; r, \{v_{ik}\})\right)}{\partial P_\delta}$$

Where ∂P_δ is a vector of zeros except for the δ^{th} entry which suitably small, and $g_j^*([P_k]^i; r, \{v_{ik}\})$ is the demand for allowances of vintage j if landowners have optimised their allowance holdings.

We include an adjustment to handle the situation where the vintage caps are non-binding. This occurs where $P_t = 0$ and $F_t < 0$. In this situation we wish to prevent any further decrease in the price of the vintage. This can be done by deleting the rows of $[P_t]^i$ and $[F_t]^i$ and the rows and columns of $\left[\frac{\partial g_j}{\partial P_k}\right]$ that correspond to the non-binding vintage caps before updating $[P_t]^i$ to generate $[P_t]^{i+1}$.

Appendix B: The Input for the Profit Functions

The profit functions used in NManager were fitted to estimated profit and mitigation points for dairy, sheep-beef farming and plantation forestry. This section explains how these points were estimated.

Profit and leaching for dairy and sheep-beef farming

Output from Farmax was used to determine the profitability and leaching of different farm management practices for dairy and sheep-beef farming. Farmax works from baseline scenarios provided by monitor farms. Monitor farms are theoretical farms, constructed from current data, designed to represent a typical farm in a specific region (Ministry of Agriculture and Forestry, 2010b).

The Waikato/Bay of Plenty dairy monitor farm is representative of approximately 5,060 dairy farms in the Waikato and Bay of Plenty regions. The monitor farm has 110 hectares of land, milks 310 cows (heifers are grazed off the farm for 12 months), and produces around 97,000 kg of milk solids in a normal season. This implies a gross profit of around $127,000 in 2009 (Ministry of Agriculture and Forestry, 2010a).

The Waikato/Bay of Plenty sheep-beef monitor farm is representative of approximately 720 sheep-beef farms in the Waikato and Bay of Plenty regions. The monitor farm has 300 hectares of land, 2,900 stock units, and a gross profit of around $53,000 in 2009 (Ministry of Agriculture and Forestry, 2010a). [16]

Different scenarios for the dairy model included various combinations of changes in cow stocking rates, wintering patterns, imported feed usage, and nitrogen fertiliser usage. Different scenarios for the sheep-beef model included changes to stocking rates, animal ratios (sheep : cattle; bulls : cows) and nitrogen fertiliser usage. Although Farmax is designed to assist the user to maximise their profit per hectare, the model relies on the user to propose and assess the feasibility of different management decisions. We recognise and thank Smeaton, who used his farming knowledge and expertise in attempting to define profit-maximising strategies for landowners while maintaining specified leaching targets (see Smeaton et al., 2011).

Profit and leaching for forestry

Forestry is the least nutrient-intensive land use considered for the Lake Rotorua catchment. Landowners may choose to convert land to forestry as part of managing their nutrient leaching.

Annual profits per hectare from forestry were calculated for all parcels in the catchment identified as forestry by the Land Use and Carbon Analysis System (LUCAS). Profit for each parcel was calculated according to Olssen et al. (2010). This considers information on land slope, soil type and the distance from the nearest port. These measures were used to estimate wood yield and the costs of planting, pruning and logging. Lastly, profit for each land parcel was averaged over the entire catchment.

[16] The Farmax simulations treat interest and the cost of capital differently to the monitor farm reports. Hence, the values for profit per hectare reported in Table 3 differ from those implied by the monitor farm reports.

New Zealand has implemented an emissions trading scheme. Under this scheme the profitability of forestry is expected to increase. However, landowners are currently behaving as though the effective long-term price for carbon is close to zero. This is probably largely due to uncertainty in the future price of carbon (Karpas and Kerr, 2011). The potential gain in profits from forestry under New Zealand's emission trading scheme is therefore not included in NManager.

Appendix C: Risks of the Two-Pulse Vintage Scheme

We observed that under the two-pulse vintage scheme the price of each vintage allowance depends on the prices of all other allowances. This is because landowners demand allowances of two different vintages to cover leaching from a single year of production.

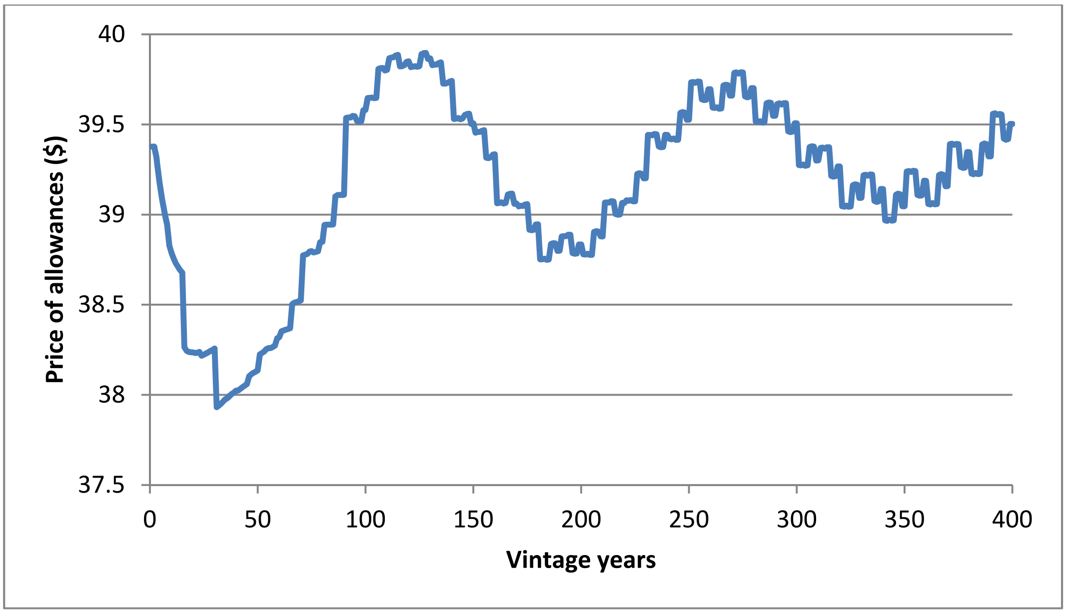
In NManager we observe that a two-pulse vintage scheme can result in short-term oscillations in the equilibrium price of vintages.[17] This is a sporadic phenomenon: certain combinations of allowance caps and lag times result in price oscillations, while other combinations do not. We do not observe price oscillations with any of the results elsewhere in this paper.

Regulatory schemes that result in price oscillations may have additional associated costs. There may be adjustment costs in responding to changes in vintage prices, or the cost effectiveness gains of the trading scheme may decrease if allowance trading is discouraged.

Figure 14 gives an example of price oscillations arising from the two-pulse vintage scheme. We observe short-run oscillations in prices with a period of 20 years and long-run oscillations with a period of 150 years.

[17] In fact, any regulatory scheme where landowners must surrender allowances of more than one vintage can result in price oscillations.

Figure 14: Oscillations in the equilibrium price of vintages under the two-pulse scheme



The short-run oscillations arise from regularities in the lag times. Consider the differences between the lag zones as given in Table 5. There is a 20-year difference between consecutive lag times for the five lag zones at the back of the catchment (lag zones 4–8). This corresponds perfectly to the 20-year periodicity of the short run price oscillations.

Experiments suggest that the long-run oscillations are independent of the timing of pulses. As the long-run cycle has minimal affect on allowances prices between years (less than a $1 or two percent effect over the entire cycle) we do not consider this cycle to be worrisome and do not investigate it any further.

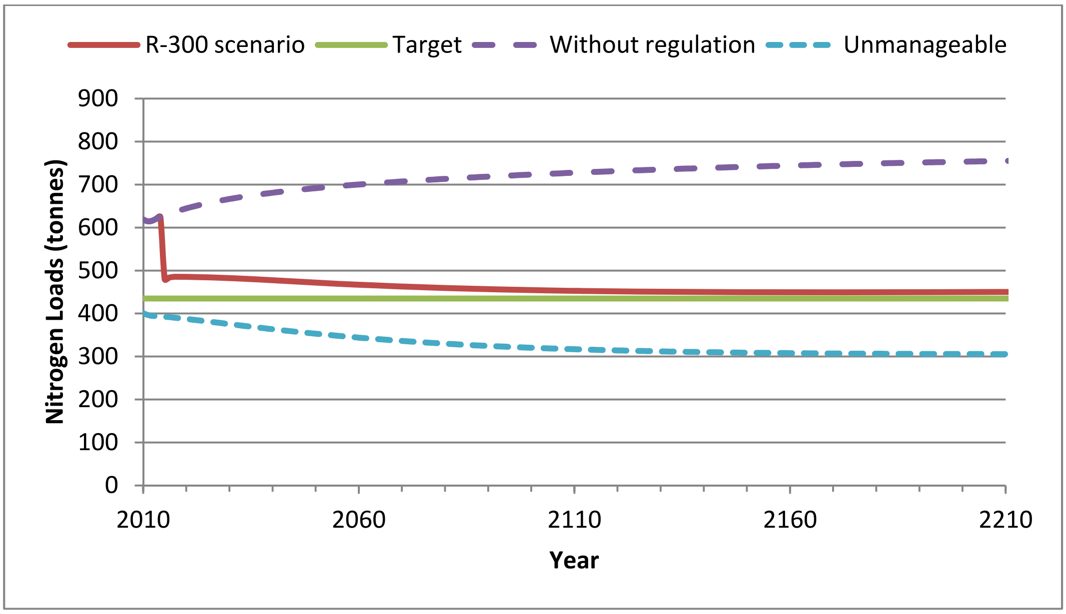
The price oscillations demonstrated here occur under the assumption that each landowner's mitigation decisions are independent across time. However, if landowners have adaptive price expectations or the cost of changing mitigation practices is significant, then landowners will have incentives to keep the same mitigation practices over several years. This may reduce the magnitude of the price oscillations (Krugman, 1991).

Appendix D: Simulating the R-300 Scenario

To help compare the results from ROTAN and NManager, we consider the retirement of land and mitigation specified in the R-300 ROTAN scenario which reduces exports from their current level by 300 tN/yr by a step change in 2015. The R-300 scenario details that all dairy land is converted to sheep-beef, and around 16 percent of the sheep-beef land is converted to new lifestyle blocks or forestry (Rutherford et al., 2011). The manageable leaching from sheep-beef land decreases to 10.4 kg N/ha/yr and the leaching from new lifestyle blocks is 6 kg N/ha/yr. Note that the R-300 scenario does not quite reach the target lake load; a reduction of 320 tN/yr is needed to reach the target.

Figure 15 gives the total lake loads under best the R-300 scenario. The load path without regulation and the unmanageable loads are provided for comparison.

Figure 15: Nutrient loads under R-300 scenario



Under regulation, we observe a step decrease in lake loads due to surface water in 2015, followed by loads tending towards their long-run values. The R-300 scenario results in long run loads of 454 tN/yr and has a net present value of the cost of mitigation of $76.4 million. As this cost arises from different environmental outcomes to the designs of regulation considered in section 6 it is not directly comparable.

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