Modelling Nitrogen Discharge Trading Using Spatial Multi-Agent Simulation

C.K.G. Dake

AgResearch Ltd, Grasslands Research Centre, Tennent Drive, Private Bag 11008, Palmerston North, New Zealand, E-Mail chris.dake@agresearch.co.nz

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EXTENDED ABSTRACT

Nutrient discharge, e.g. nitrogen (N) leached from intensive farming is a major cause of poor water quality of rivers and lakes in catchments. Regulators have set up many schemes in some countries to manage and reduce the flow of nutrients into water ways. The include promoting the adoption of less intensive farming systems and setting up trading schemes to buy and sell nutrient discharge credits. In New Zealand a regulatory institution, Environment Waikato, has proposed a scheme to restrict N discharge from agricultural activity in the Lake Taupo catchment to improve the water quality of Lake Taupo in the central North Island region of New Zealand. Their proposal includes (a) capping of N produced by farms at current levels of N leached from farms, (b) reducing N flows into the catchment by 20% and (c) allowing the trading of N discharge allowances (NDA) between farmers in the catchment.

This study describes the use of the multi-agent simulation framework, CORMAS (Common-pool Resources and Multi-Agents Systems), to model the behaviour of key actors (regulator, auctioneer, NDA sellers and NDA buyers) who are endeavouring to improve water quality in the Lake Taupo catchment. The regulator allocates NDA to farmers and reduces total catchment NDA through purchase of NDA, the auctioneer manages a centralised contract protocol for trading in NDA and the farmer buys or sells NDA based on a farm plan that maximises the farmer's risk adjusted expected income (*RAE*)

A whole farm risk model (WFRM) is formulated for each farmer in the Taupo catchment and used to determine farm plans that maximise *RAE* for a range of risk tolerance levels, and assuming farmers are risk averse. The model assumes the farmer's utility function for net income is negative exponential and incomes are normally distributed. The farm plan options are selected from a range of pastoral (sheep, beef cattle, deer and dairy cattle) and forestry (exotic forestry, indigenous forest and scrub land) enterprises which have been matched to land use capability classes. N leached is calculated from the optimum farm plans. This is the farmer's preferred NDA.

Nitrogen discharge allowance allocated to the farmer by the regulator is determined by solving WFRM with vegetation maintained at current levels. Comparing the farmer's preferred NDA with the NDA allocated by the regulator determines whether the farmer would be a buyer or seller of NDA in the multi-agent simulation model.

Land resource data used for WFRM were combined in a GIS environment from the Landcover Database for vegetation cover, New Zealand Land Resource Inventory for land use and versatility and Agribase for farm boundaries. Enterprise gross margins were estimated using FARMAX (sheep, beef cattle and deer management), UDDER (dairy management) packages. Exotic forestry gross margins were based on the Farm Forestry "Calculators" package. N leached from farming enterprises were estimated using the OVERSEER® Nutrient Budget package.

The WFRM was developed in the Microsoft Excel spreadsheet and solved using the Frontline Solver for 100 farms in the Taupo catchment. Farmers' NDA, *RAEs* and GIS maps of the catchment were loaded into the CORMAS model. Results show the size of the market for trading in NDA, sales to the regulator to achieve their target of reducing N leached in the catchment by 20% and NDA trades through the auctioneer.

1. INTRODUCTION

Many schemes have been setup by regulators in a number of countries to manage and reduce the flow of nutrients into water ways. They have generally been promoted to allow high cost point sources (e.g. waste treatments plants) to purchase discharge credits from low cost non-point (mainly farms) sources, enabling point sources to manage their discharges below a cap. A review of about 37 prototype trading schemes in the United States by King and Kuch (2003) show that very few trades have occurred, and only one has involved trade between point and non-point sources. A number of reasons have been suggested for the failure of these trading schemes. They include the high cost of measuring nutrients discharged from farms, uncertainty in the quantity of nutrients discharged, and few willing buyers and sellers.

There is currently no nutrient discharge trading scheme in New Zealand. Recently, a regulatory institution, Environment Waikato, has proposed a scheme to improve the quality of water in an iconic lake, Lake Taupo in the central North Island of New Zealand. Their proposal is aimed at restricting nitrogen (N) discharge from agricultural activity in the Lake Taupo catchment (MAF, 2005; Environment Waikato, 2006). The proposal under consideration includes capping of N produced by farms at current levels of N leached from farms, reducing N flows into the catchment by 20% and allowing the trading of N discharge allowances (NDA) between farmers (non-point sources) within the catchment.

This study proposes:

(a) a methodology that can be used to determine the likely number of NDA traders in the catchment, and

(b) to model the behaviour of key actors (regulator, NDA sellers, NDA buyers and auctioneer) who are endeavouring to improve water quality in the Lake Taupo catchment. A multi-agent simulation framework, CORMAS (Common-pool Resources and Multi-Agents Systems) (Bousquet et al.,1998) is used to model this. CORMAS provides facilities to describe spatial entities such as landscape units, and decision making agents such as farmers and the regulatory institution.

The ability of the farmer to reduce nutrient discharged into the catchment depends on available farming enterprise options, land quality classes and the farmer's ability and willingness to trade-off financial and environmental outcomes (Ekman 2002; Dake et al., 2005; Dake et al., 2006).

The income and financial risk trade-off options available to the farmer and associated N leached can be determined from a risk efficient frontier of each farm in the Lake Taupo catchment.

A risk efficient frontier indicating the highest income that can be generated for a given level of financial risk is calculated for each farm in the Lake Taupo catchment.. The farm plan and level of N discharged can be calculated for each point on the frontier.

The best farm plan for the farmer can be determined from the risk efficient options based on the farmer's utility function with regard to wealth or income. The N leached from the farmer's best farm plan then becomes the farmer's preferred NDA. Comparing the farmer's preferred NDA with the NDA allocated to the farmer by the regulator determines whether the farmer would be a buyer or seller of NDA in the multi-agent simulation model.

2. THE SPATIAL MULTI-AGENT SIMULATION MODEL

A multi-agent simulation (MAS) can be used to describe the interaction between farmers to supply and purchase NDA within a regulatory framework, and the resulting financial, environmental and landscape impacts (Bousquet et al.,1998; Parker et al, 2001; Images Project, 2001). In this study a MAS model is developed in the CORMAS modelling framework to illustrate trade in NDA.

Entities included in the model are:

(1) Spatial - Landscape (Taupo catchment).

- Land cover.
- LUC (land use capability class).
- Land parcels (i.e. farm boundaries).

(2) Social - Communicating Agents

- Regulatory Institution – Allocates NDA to farmers and reduces total catchment NDA through purchase.
- Auctioneer - Manages a centralised contract protocol.
- Farmers – Base trade on individually optimised farm

plans. (This is discussed in detail in the next section).

- Farmer Groups (NDA buyers, NDA sellers).

(3) Passive

- Mail boxes – Used to send and respond to bids.

Trading Protocols

A number of trading protocols can be modelled using the MAS model to trade in NDA.

Purchase of NDA by the regulatory institution. The regulatory institution, in theory, knows the quantity of each farmer's NDA and would be able to identify potential sellers of NDA.

Trading of NDA by farmers using a centralised protocol. An auctioneer offers to purchase/sell NDA to all farmers. The best proposal received by the auctioneer from the farmers is then accepted.

3. WHOLE FARM RISK MODEL

Farmers must trade-off income and financial risk in their effort to implement farm plans that use resources efficiently and minimise nutrient discharges from the farm. General formulations of farm risk models recognise that farmers are risk averse, and they result in farm plans that minimise risk for a desired level of farm income (Hardaker et al. 2004). Risk programming models that specifically account for environmental emissions as outputs or constraints alongside resource constraints can be found in Teague et al. (1995), Ekman (2002) and Dake et al., (2006).

If the farmer's utility function with regard to wealth or transitory income is known, then the best farm plan can be determined from the risk efficient options (Sharpe, 1999; Hardaker et. al, 2007). Assuming that a farmer's utility function for net income is negative exponential and incomes of enterprises are normally distributed, then the utility of the portfolio (or the risk adjusted expected income (*RAE*)) of farming enterprises selected by the farmer can be approximated by $e - v/t$ where e is expected income, v is the variance of income and t is the farmers risk tolerance (Sharpe, 1999). The optimum *RAE* for the farmer can be derived from the following formulation of the whole farm risk model (WFRM):

$$\text{Maximise } RAE = e - v/t \quad (1)$$

Subject to:

$$Ax \leq b \quad (2)$$

$$Bx \leq z \quad (3)$$

$$t = 2/r \quad (4)$$

$$l \geq x \leq m \quad (5)$$

$$l \geq 0 \quad (6)$$

where:

RAE = risk adjusted expected income (portfolio utility).
e = expected farm gross margin.
v = variance of gross margin.
t = the risk tolerance.
r = the coefficient of absolute risk aversion with regard to income.
x = vector of 152 activities levels (in hectares) derived from the matrix of 19 farming enterprises and 8 land use capability classes.
A = matrix of ones.
b = land class area constraints.
B = matrix of N (kg N) leached for each x.
z = maximum limit on N leached.
l = lower bound on x.
m = upper bound on x.

Equation 1 assumes enterprise incomes are normally distributed. Where this assumption cannot be supported, Hardaker et. al. (2007) have proposed a utility efficient programming model where the negative exponential distribution of income is maximised subject to resource constraints and income equations derived from each state of nature.

The WFRM was formulated in Microsoft Excel and solved using the solver from Frontline Systems (2003).

4. DATA REQUIREMENTS FOR THE WFRM

Activities

1. Pastoral: sixteen mixed sheep/beef cattle/deer, bull beef and dairy enterprises were designed using a range of N fertilisers application rates on a

base potential ryegrass/clover pasture production that range from 6.5 t/ha to 15.6 t /ha.

2. Tree crops: Pinus radiata plantation forestry, indigenous forests and scrubland.

Constraints

3. Land use and vegetation: three data sources, Land cover Database for vegetation cover (LCDB2), New Zealand Land Resource Inventory for land use and versatility (NZLRI), and Agribase for farm boundaries were combined in a GIS environment to produce a standardised data source for the WFRM model.
4. Farm size: one hundred farms, ranging from 50 – 80,000 hectares.
5. Land use capability classes (LUCs): eight LUCs based on their suitability for cropping, pastoral and forestry production were estimated for each farm.
6. Vegetation cover: pasture, exotic forest, indigenous forest and scrubland area estimated for each LUC on a farm.
7. Potential pasture production: estimated for each LUC based on the carrying capacity of the top farmer.
8. Infeasible enterprise and LUC match. An activity value is constrained to zero if the base pasture production requirement of the activity (bullet point 1) is higher than pasture that can be supplied by the LUC (bullet point 7).

Environmental, financial and risk profile

9. Environmental. N leached from farming enterprises (Bullet point 1) were estimated using the OVERSEER® Nutrient Budget package. N leached from forestry activities was assumed to be zero.
10. Gross margins were estimated using the FARMAX sheep, beef cattle and deer management package (Farmax, 2007), and the UDDER dairy management package (Larcombe, 1999) for pastoral enterprises. Exotic forestry gross margins were estimated using data from Knowles et al. (2003). Gross margins for indigenous forest management were assigned a nominal value of $150/ha, and scrubland a low value of $10/ha.
11. Variability of gross margins of activities. These were based on inflation adjusted livestock and milk solid prices over the past 10 years for pastoral systems; the coefficients of variation (CV) ranged from 12% to 26%. The coefficient of variation for forestry stumpage was assumed to be 30%. Small CVs of 1% were assigned to gross margins from indigenous forestry and scrubland
12. Risk tolerance (Table 1): four categories of risk tolerance and suggested values of relative risk aversion with respect to wealth were adapted from Hardaker et. al. (2004). The conversion of the risk aversion coefficient from wealth to transitory income was based on an equation from Hardaker et. al. (2007) using a net farm asset level of $2,000 per hectare. (The asset value is taken as the capital value of livestock on a high intensive sheep/beef farm).
13. Assignment of risk profiles to farms. The 100 farms in the catchment were randomly assigned to the four risk profiles using arbitrary proportions shown in (Table 1). The implication is that most of the farms were medium to strongly risk averse.

Table 1 Risk profile

Risk tolerance	Relative risk aversion with respect to wealth	Relative risk aversion with respect to income	Assumed distribution of farmers
Very High	0.5	0.00025	5%
High	1	0.00050	10%
Medium	2	0.00100	43%
Low	3	0.00150	43%

Determining NDA buyers and NDA sellers

The regulatory authority proposes to cap N leached to current levels and allocate them as NDA for each farm. Without information on enterprises currently farmed by individual farmers, the regulation to cap N at current levels is interpreted in this study as the maintenance of the current vegetation cover at the LUC level on the farm (Bullet point 6 above). Solving WFRM with the current vegetation cover as constraints yields the regulator’s allocated NDA and the risk adjusted expected income (*RAE*) for the farm.

When the WFRM is solved without constraints on vegetation cover, the farmer's preferred NDA may be below or exceed their NDA allocation. A farm that exceeds its NDA will need to purchase additional NDA from farmers that have spare NDA. A third category of farmers do not need to sell or buy NDA.

The benefit to the farmers of reducing or increasing their NDA can be calculated from the difference in *RAE* of their preferred NDA and the regulators allocated NDA.

Characteristics of NDA traders

Figures 1 and 2 show farm plans, N leached and *RAE* for two example farms. The farm size of Farmer A's farm is about 1,200 hectares and the farm plan includes sheep/beef cattle/deer and exotic forests under an N cap scenario (Figure 1). The farmer can maximise *RAE* by replacing the pastoral enterprise with exotic forestry, thereby increasing the farm *RAE* by about 40% and have 3.71 tonnes N for sale.

Farmer B on the other hand needs to purchase NDA. The farm size is about 1,500 ha, carries exotic and indigenous forests, and has no NDA allocated. If the farmer is able to purchase 11.2 tonnes N leached, then the farmer's farm plan will include dairying and exotic forestry and increase *RAE* by about 190%.

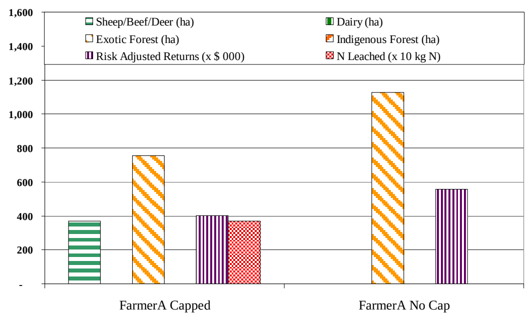

Figure 1 Example farm plans of NDA seller

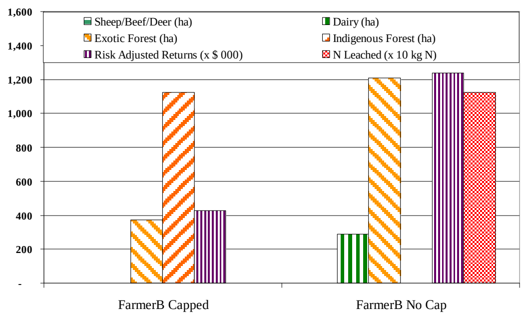

Figure 2 Example farm plans of NDA buyer

The risk relative risk aversion coefficients used in Table 1 did have an effect on the *RAE*s of a farm. However the differences were not high enough to change farm plans and N leached between risk tolerance levels.

5. IMPLEMENTING THE MAS MODEL AND RESULTS

The WFRM groups farmers into sellers and buyers of NDA, and those for whom there was no benefit to trading in NDA. The change in benefit from trading in NDA can also be calculated. This information was read into the CORMAS model and used to provide rules for trading in NDA.

Table 2 shows the size of the market for trading in NDA. There are considerably more NDA sellers (61) than NDA buyers (17). However the demand for NDA (430 tonnes N) exceeded supply (184 tonnes N).

Table 2 NDA traders, total demand and supply of N

Farmer Groups	Farms	Capped	No Cap	Net
	No	Tonnes N	Tonnes N	tonnes N
NDA Sellers	61	333	148	184
NDA Buyers	17	0	430	- 430
Non Traders	22	74	74	0
Total	100	406	652	

An integral part of the policy to regulate N leached in the Taupo catchment is to purchase 20% of the catchment's NDA from farmers. In this model this equates to purchasing about 80 tonnes N from farmers. Since the regulatory body has complete information on sellers of NDA and their net benefits, a trading protocol would simply be to buy

NDA from those farmers with the highest incentive to sell (i.e. from those with the highest change in *RAE* per unit of NDA sold).

In the CORMAS model, this can be achieved by accepting bids from farmers with the highest per unit change in *RAE.* About 47 farmers would be required to supply the regulator with its requirements leaving only 14 N sellers owning about 65 tonnes N to trade with farmers who wish to buy N.

Assuming that regulator succeeds in purchasing all its N requirements the remaining 14 N sellers may trade with the 17 farmers who wish to purchase N through an auctioneer who accepts the best proposal from the N buyers. It can be expected that the best proposal from N buyers would be made in proportion to the net benefit of obtaining the extra N. On this basis, the remaining 65 tonnes N would be purchased by the top 6 (out of 17) farmers requiring N.

Other trading protocols could be implemented in the CORMAS framework. The regulator could only decide to purchase its quota of N from farmers closest to the Lake Taupo. Farmers could also decide to buy N from only their neighbours. These protocols could easily be modelled in CORMAS since the algorithm can easily detect neighbouring properties in the spatial data for the Taupo catchment that was loaded into CORMAS trading model.

6. CONCLUSION

This study has shown how the results of an individual farm risk model can be used to characterised NDA traders in the Taupo catchment. This information was used in a multi-agent simulation model where the key actors were farmers, the regulator and an auctioneer of NDA.

The proposed allocation of NDA to farmers by regulators in a bid to improve the quality of water in Lake Taupo would result in the creation of supply of NDA which could be traded. It was expected that the ability of a farmer to trade would depend on the farmer's tolerance for risk, in a setting where the farmer is able to select the best farm plan from other risk efficient options. However even though the chosen risk tolerance levels used in the study affected the farm's *RAE*s the differences were not high enough to change farm plans.

The best farm plan maximises the farmer's utility function with regard to income. The resulting optimum *RAE* and preferred NDA, when compared with the *RAE* from regulator allocated NDA was used to group farmers in the catchment into three categories: NDA sellers, NDA buyers, and farmers for whom trading in NDA was not beneficial.

The number of farmers that may be engaged in trading, especially if the regulator authority comes into the market and buys 20% of NDA, is small. These results would seem to imply the conditions for a successful trading i.e., many willing buyers and sellers may not exist in the catchment.

There are new N mitigation strategies being developed by research organisations that are close to, or new to, the market. They include the use of feed pads that can be used to manage the spreading of nutrients onto farms and the use of nitrification inhibitors. These new technologies can be evaluated in the framework developed in this study and have the potential to significantly to redefine sellers and buyers of NDA in the catchment.

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