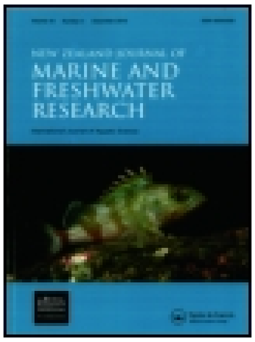

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Nitrogen yields from New Zealand coastal catchments to receiving estuaries

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Abstract A model to estimate nitrogen loads from coastal catchments to New Zealand estuaries is presented. The Sub-Catchment to Estuary Nitrogen Yield (SCENY) model estimates total nitrogen inputs from atmospheric deposition, fertiliser application, and biological nitrogen fixation for catchments with different land use practices. Nitrogen losses in the vadose zone and aquifers were assessed, and the net nitrogen yield that enters estuaries was quantified. The model was applied to 13 sub-catchments in the South Island, which encompass 0–91% agricultural land use. Nitrogen yields to the study estuaries ranged from 0.6 kg N ha^{-1} yr^{-1} to 17.0 kg N ha^{-1} yr^{-1}, with nitrogen flux increasing directly with the percentage of agriculture in the catchment. Moreover, fertiliser contribution to nutrient loading increased proportionately with increased nitrogen yields. The model was in close agreement with other New Zealand nitrogen yield models and confirms that management of water quality for estuaries surrounded by agricultural catchments should be targeted at the local level, with improved measures for controlling fertiliser run-off.

Keywords nitrogen loading model; agricultural land use; water quality management

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INTRODUCTION

Excessive nitrogen inputs from land practices have degraded water quality and caused ecological shifts in many coastal and estuarine ecosystems world wide (Howarth et al. 1996). In particular, the rapid intensification of agriculture has increased nitrogen yields and caused eutrophication of aquatic bodies in New Zealand (Pridmore et al. 1985; Galbraith & Burns 2007) and globally (e.g., Smith 2003). The historical conversion of approximately 14 million hectares (140 000 km^2) of indigenous vegetation to cropland or pasture (Parliamentary Commissioner of the Environment 2004), along with the removal of riparian zones and wetlands increased the flux of reactive nitrogen and accelerated water quality degradation in surface waters in New Zealand (Taylor & Smith 1997; Hamill & McBride 2003; Larned et al. 2004). More recently, high fertiliser application and stocking rates (Hamill & McBride 2003; Wilcock et al. 2006) and an increase in dairying (Elliott et al. 2005) have increased non-point agricultural sources to an estimated 75% of the total nitrogen load to estuaries in New Zealand (Ministry for the Environment 1997). Consequently, nutrient budgets in New Zealand have focused on quantifying nitrogen flows and losses in agricultural lands (Ledgard et al. 1999; Jarvis & Ledgard 2002; Wheeler et al. 2003; Monaghan et al. 2007).

The first national budget for New Zealand apportioned nitrogen loads across regions and estimated an average input of nitrogen of 36.5 kg ha^{-1} for 2001 whilst regional yields ranged between 12 and 69 kg ha^{-1} (Parfitt et al. 2006), similar to values for the northeast United States (9–63 kg ha^{-1}; Boyer et al. 2002; van Breemen et al. 2002). However, these nitrogen yield estimates are based on whole regions (Parfitt et al. 2006) or large catchments (Boyer et al. 2002; van Breemen et al. 2002) and do not examine flux from individual catchments, which is the scale that is relevant for ecological studies and of interest for environmental managers.

OVERSEER® (AgResearch 1999; Ledgard et al. 1999) was the first empirical, annual time-step nutrient budget model that quantified nitrogen inputs and outputs at an individual farm scale in New Zealand. The model provides quantitative information on leaching and the relative impact of different on-farm nutrient uses. Case studies that used OVERSEER® and similar models to estimate nutrient yields for small to medium-sized catchments (0.1–100 km^2) in New Zealand illustrate how non-point source run-off from catchments, particularly from agricultural-dominated catchments, can affect nutrient yields to lakes and, in turn, water quality (Wilcock 1986; Elliott & Sorrell 2002). By contrast, the model SPARROW (Spatially Referenced Regression on Watershed Attributes) was developed for large catchments—in the order of thousands of square kilometres (Alexander et al. 2002; Elliott et al. 2005); however, the model was based on only two land-use classes, pasture and non-pasture (Alexander et al. 2002), or the dominant (>85%) land cover (Elliott et al. 2005). Further, SPARROW was developed principally to estimate the supply of nutrients to streams, with nutrient yields to estuaries only approximated as a fraction of the load entering streams (Elliott et al. 2005). Other New Zealand nutrient loading models were designed to address specific components of broader models, such as GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) and AquiferSim, which assess the impact of agricultural land use on nitrate transport in groundwater (Knisel 1993; Webb et al. 2001). The recent model, CLUES (Catchment Land Use for Environmental Sustainability), is the first model to integrate multiple components from the aforementioned models to link community, social and economic inputs to assess the effects of land use on water quality (Woods et al. 2006). Therefore, although some models have been developed for New Zealand, most cannot be applied to catchments of varying land use. Moreover, these previous models were developed to estimate nutrient yields to streams and freshwater ecosystems. To date, there are no models that have focused on nitrogen loading rates to New Zealand estuaries from small catchments with a mosaic of land-use classes.

This study addressed this knowledge gap and presents a model designed specifically to predict total dissolved nitrogen yields to shallow New Zealand estuaries from individual sub-catchments. An empirically developed model, NLM (Nitrogen Loading Model) (Valiela et al. 1997), is used as a guideline for the present model as NLM provides a comprehensive analysis of total nitrogen loads from multiple land-use classes. NLM has accurately predicted total dissolved nitrogen loads to shallow estuaries from suburban catchments in the United States (Carmichael et al. 2004; Valiela et al. 2000, 2004). The current study is the first application of the NLM to a more pastoral setting compared to the urbanised catchments for which it was developed. The original NLM was calibrated to the New Zealand environmental setting, using national values for atmospheric deposition and fertiliser use. In addition, a quantitative formula was created to include biological nitrogen fixation (BNF) as a source of nitrogen input to account for the reliance on N_2 fixation by white clover (*Trifolium repens*) in pastures (Ledgard et al. 1999) and the presence of invasive nitrogen-fixers (e.g., *Cytisus scoparius*, *Ulex europaeus*) in estuarine catchments in New Zealand. Thus, the aim of this study was to apply the adjusted NLM, which we hereafter refer to as the SCENY (Sub-Catchment to Estuary Nitrogen Yield) model, to estimate nitrogen loading from individual sub-catchments in Otago and Southland, South Island, New Zealand. The estimated nitrogen yields from the SCENY model were compared with those from other models developed in New Zealand.

METHODS

The SCENY model estimates nitrogen inputs from three major sources: (1) atmospheric deposition, (2) fertiliser inputs, and (3) BNF into each type of land use. SCENY tracks the fate of nitrogen as it traverses the various ecosystem components (the catchment surfaces, vadose zone (the unsaturated zone between the land surface and water table), aquifer, and freshwater ponds and lakes) and undergoes complex losses (Fig. 1). Thus, the model estimates total dissolved nitrogen loads to estuarine receiving water and can be used to evaluate the relative importance of different diffuse sources of nutrient loading to an estuary in New Zealand. The values used in the model (Table 1) are specific to New Zealand, in particular the South Island. Specifically, local values were used in the model whenever possible except for atmospheric deposition where a single national value was more reliable than a local value. While it would be desirable to incorporate nutrient inputs from small streams into the model, this input was excluded owing to insufficient data or a lack of long-term data for the study sites.

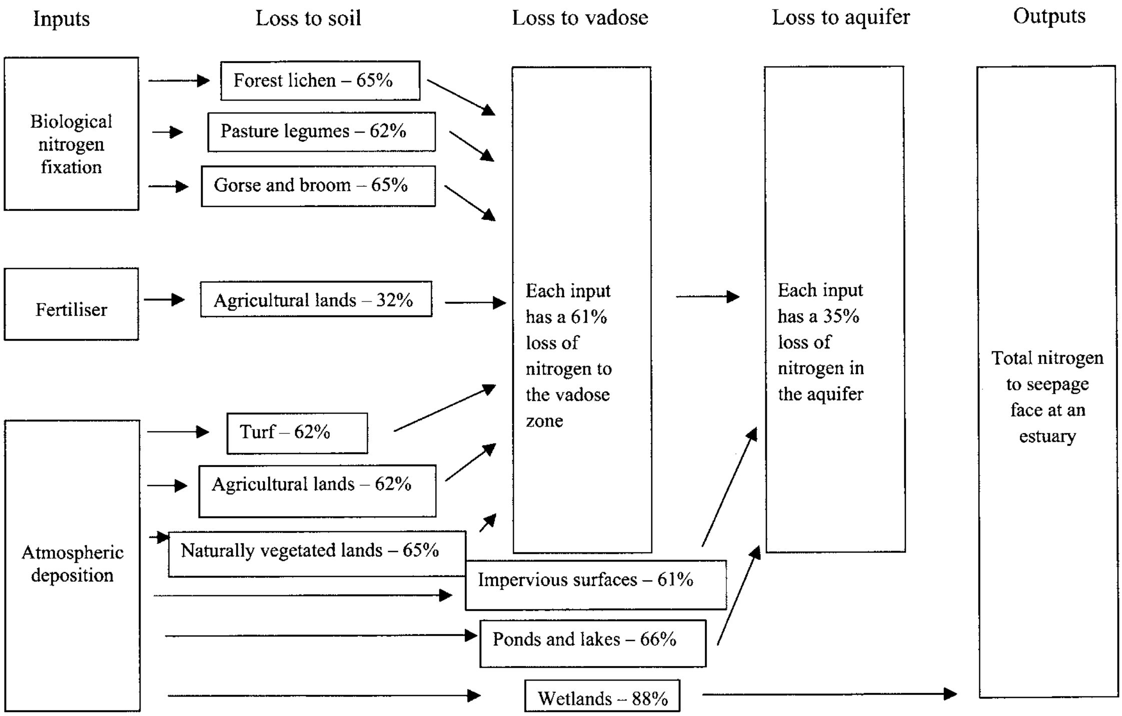

Fig. 1 Diagram of the Sub-Catchment to Estuary Nitrogen Yield (SCENY) model for New Zealand estuaries showing nitrogen inputs of fertiliser, biological nitrogen fixation and atmospheric deposition to the catchment and the percentage losses as nitrogen percolates into land parcels and traverses soils, the vadose zone and aquifers on its way to recipient estuaries.

Inputs and loss components included in the SCENY model

Atmospheric deposition

Atmospheric deposition includes wet deposition and dry deposition (Lovett 1994). Nitrogen inputs from wet deposition (rainfall) are estimated as 1–2 kg N ha^{-1} yr^{-1} for New Zealand (Baker et al. 1985; Nichol et al. 1997; Parfitt et al. 2006). By contrast, there are few national estimates for dry deposition (the accumulation of nitrogen by particles and by absorption of NO_x gasses and ammonia through vegetation, soil or surface water; Lovett 1994; Valiela et al. 1997). Measurements of atmospheric gas exchange in New Zealand estimate that ammonia volatilisation is 8 kg N ha^{-1} yr^{-1} (Parfitt et al. 2006) with about 50% re-deposited onto land or surface waters within 50 km downwind of the source (Heath & Huebert 1999). Therefore, we estimated dry deposition of ammonia as 4 kg N ha^{-1} yr^{-1}. When added to total nitrogen from wet deposition, the atmospheric input for New Zealand is estimated as 6 kg N ha^{-1} yr^{-1} (Parfitt et al. 2006), which is within the range of the lower values reported for catchments in North America and Europe (5.75–12.12 kg N ha^{-1} yr^{-1}; Boyer et al. 2002).

The fate of atmospheric nitrogen varies depending upon different land covers and their respective losses (natural vegetation, turf, agricultural land, impervious surfaces). Therefore, leaching of total dissolved nitrogen (TDN) delivered by wet and dry deposition to different land parcels was assessed individually.

Atmospheric nitrogen deposited onto vegetated parcels is partially intercepted by vegetation and soils. Aggrading forests retain between 65% (Valiela et al. 1997; Scott et al. 1998) and 80–90% (Aber et al. 1993) of atmospheric nitrogen in trees, soils and lichens. In a study of fertiliser-nitrogen applied to *Pinus radiata* plantations in coastal sand dunes near Christchurch (South Island, New Zealand), nitrogen retention was between 54–67% (Thomas & Mead 1992). Therefore, we used 65% retention of atmospheric nitrogen for forested land and natural

Table 1 Summary of the Sub-Catchment to Estuary Nitrogen Yield (SCENY) model, which estimates nitrogen (N) delivery to and through catchment surfaces, losses in the vadose and aquifer zones, and calculates resulting nitrogen loads to receiving coastal waters. *New Zealand-specific values: †nitrogen removed as crop (export–import). (Numbers in parentheses are terms in the model used in calculations.) Nitrogen loading to estuary (kg N yr): sum of items 11–14. (NA, not applicable.)

To and through catchment surfaces (kg N yr^{-1})			To and through vadose zone and aquifer (kg N yr)
via atmospheric deposition to:	via fertiliser application to:	via biological nitrogen fixation to:	via diffuse percolation:
Natural vegetation (1): *atmospheric deposition × area (ha) of naturally vegetated land × 35% not retained in plants and soil	*Agricultural land* (7): *crop fertilisation rate × area (ha) under cultivation × *68% not lost as gases—nitrogen removed as crop†	*Pasture legumes* (8): *fixation by pasture legumes × area (ha) of pasture legumes × 38% not retained in plants and soil	*from catchment surface* (11) [sum of 1–4 + 7–10] × 39% not lost in vadose × 65% not lost in aquifer
Turf (2): *atmospheric deposition × area (ha) of turf × 38% not retained in plants and soil		*Ulex europaeus and Cytisus scoparius* (9): *fixation by gorse and broom × area (ha) of pasture legumes × 35% not retained in plants and soil	*through ponds and lakes* (12): [5] × 44% not lost in vadose × 65% not lost in aquifer
Horticultural land (3): *atmospheric deposition × area (ha) of horticultural land × 38% not retained in plants and soil		*Native forest lichen* (10): *fixation by native forest lichen × area (ha) of pasture legumes × 35% not retained in plants and soil	*through wetlands* (13): [6] × 22% not lost in vadose
Impervious surfaces (4): *atmospheric deposition × area (ha) of roads and commercial areas			*Via wastewater from wastewater treatment plants* (14): NA
Ponds and Lakes (5): *atmospheric deposition × area (ha) of ponds and lakes			
Wetlands (6): *atmospheric deposition × area (ha) of wetlands			

vegetation since this value is consistent with local studies and commonly reported in similar models (e.g., Valiela et al. 1997; Scott et al. 1998)

Pasture, soils and roots on agricultural land in New Zealand retain between 55–67% of atmospheric nitrogen (Silva et al. 2005), with regional variation owing to drainage and rainfall. Since there were no data available for the study region, atmospheric nitrogen retention in agricultural land and turf was estimated as 62%, which agrees with other studies (Valiela et al. 1997) and is close to the national average (61%) for agricultural land (Silva et al. 2005).

Atmospheric nitrogen deposited on impervious surfaces including roads and other human-made structures in urban areas generally evaporates or is channelled into gutters and drains and accumulates in the vadose zone (Valiela et al. 1997). Thus, the fraction of atmospheric nitrogen that is deposited onto impervious surfaces is not exposed to losses in the soil like other land parcels, but is passed straight to the vadose zone in the model.

Fertiliser applications

The SCENY model calculates inputs of agricultural fertiliser as the product of crop fertilisation rate, area (in hectares) of land under cultivation, and fertiliser retention following gaseous losses, minus nitrogen removed from the catchment as a crop. On average, 85 kg fertiliser N ha^{-1} is applied to a variety of crops produced in New Zealand (Ministry of Agriculture and Forestry 2007). Fertiliser nitrogen delivered to pastoral lands is stored, transported to groundwater, or lost as gas. The model assesses actual losses of nitrogen as gasses since nitrogen assimilated by plants and soil eventually leaches into the subsoil. Ammonia volatisation can be important in nitrogen loss pathways, with losses typically ranging between 5% and 15% of nitrogen applied as fertiliser (Black et al. 1985; Monaghan et al. 2007), although greater losses (up to 23%) have been reported during warm summer conditions (Silva et al. 2005). Denitrification in agricultural soils causes a further loss of c. 12% (Barton et al. 1999; Legard et al. 1999; Parfitt et al. 2006). Therefore c. 32% of fertiliser nitrogen is lost through gaseous processes, leaving a surplus of 68% fertiliser nitrogen to reach the subsoil below horticultural lands. To account for fertiliser nitrogen that is assimilated by crops but not consumed locally and thus exported from the catchment, the model includes a loss term for fertiliser nitrogen that is exported as crops from the catchment. On average, the total nitrogen exported from New Zealand catchments in food items is 6 kg N ha^{-1} yr^{-1} (Parfitt et al. 2006) and imports are 1.5 kg N ha^{-1} yr^{-1} (Statistics New Zealand 2004). Therefore, there is a net output of 4.5 kg N ha^{-1} yr^{-1} of fertiliser nitrogen that does not enter the vadose zone and aquifer in the local catchment.

BNF

BNF, the fixation of dinitrogen gas (N_2) by the symbiotic relationship between plants and N_2-fixing organisms (Freiberg et al. 1997), represents an important source of nitrogen in agriculture, yet it is often under-represented or excluded in ecosystem models. The present model accounts for nitrogen fixation in pasture legumes, invasive plants and forest organisms and thus includes an input term that was not incorporated in the original NLM (Valiela et al. 1997).

Legume-based pastures in Australasia are dominated by perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*), and more recently also mixed herb leys (Goh & Bruce 2005). Nitrogen fixation rates of pasture legumes are considerably varied (Table 2) ranging from 43 to 581 kg N ha^{-1} for leguminous trees and 15 to 210 kg N ha^{-1} for grain legumes (Zahran 2001). Recent estimates of nitrogen fixation for New Zealand pastures demonstrated fixation rates of 19–41 kg N ha^{-1} yr^{-1} (O'Hara et al. 2003; Bolan et al. 2004; Goh & Bruce 2005; Parfitt et al. 2006), with most studies reporting average fixation rates of 30–40 kg N ha^{-1} yr^{-1}. Consequently, the model included the assumption that pasture legumes fixed 35 kg N ha^{-1} yr^{-1} (the average of 30 and 40 kg N ha^{-1} yr^{-1}).

Table 2 Estimates of nitrogen (N) fixation by *Trifolium* spp. (clover) in New Zealand and Australasian studies. (* = pasture legumes without irrigation, † = pasture legumes with irrigation.)

Clover fixation (kg N ha^{-1} yr^{-1})	Reference
37	Ball & Field 1985
59	Caradus et al.1996
27–41*; 52–179†	Goh & Bruce 2005
36	O'Hara et al. 2003
41	Bolan et al. 2004
29–75	Unkovich et al. 1995; Parfitt et al. 2006
40	Watt et al. 2003
30	Goh & Ridgen 1997

There is a paucity of information on the contribution of invasive leguminous plants such as gorse *U. europaeus* and broom *C. scoparius* to surface water nitrogen yields despite their extensive occurrence in New Zealand. Initial calculations of nitrogen fixation rates for *U. europaeus* and *C. scoparius* estimated rates as high as 100–200 kg N ha^{-1} yr^{-1} (Egunjobi 1969; Watt et al. 2003). However, in a more recent study, nitrogen fixation rates of 8.1 to 57.4 kg N ha^{-1} yr^{-1} were recorded for *U. europaeus* (Augusto et al. 2005). Since the Land Cover Database 2 (LCDB2) spatial database (Terralink 2004) in New Zealand does not distinguish between the land area of gorse or broom, the areal extent of these invasive species were analysed collectively and a nitrogen fixation rate of 30 kg N ha^{-1} yr^{-1} used in the model, which is the average value used by Parfitt et al. (2006).

BNF in native forests is small in comparison to the contribution from pastoral legumes and invasive plants. Nitrogen is fixed by *Coriaria arborea* and other lichens, algae and free-living microorganisms in New Zealand native forests (Parfitt et al. 2006). Owing to the lack of measurements, we estimated BNF in native forests using a mass balance approach. Since atmospheric deposition contributes about 1.5 kg N ha^{-1} yr^{-1} and nitrogen outputs (leaching) from native forests have been estimated as 3 kg N ha^{-1} yr^{-1} (Parfitt et al. 2006), we estimated BNF in indigenous forests as c. 1.5 kg N ha^{-1} yr^{-1}, assuming that the nitrogen cycle of native forests is close to steady state (Richardson et al. 2004).

Nitrogen sources excluded from the SCENY model

Livestock are considered important sources of nutrients to coastal catchments and receiving waters (Ryther & Dunstan 1971; Postma et al. 1991). However, livestock fed on locally grown pastures do not contribute new sources of nitrogen to the catchment as the nitrogen in their faeces derives from BNF or fertilisers applied to that parcel of land (Valiela et al. 1997). Therefore, since the nitrogen passing through livestock has been accounted for in BNF and fertiliser input, waste from livestock is not included as a new source of nitrogen in the SCENY model.

Wastewater nitrogen was also excluded from the model since small amounts of wastewater nitrogen reach an estuary—approximately a third of the concentration of wastewater nitrogen that enters leaching fields, plumes, and the aquifer is lost in each compartment (Valiela et al. 1997). Moreover, wastewater treatment facilities remove urban wastewater kilometres from recipient water bodies, and there are negligible on-site wastewater treatment sites in rural areas in New Zealand. Consequently, wastewater nitrogen was omitted as a source of new nitrogen to receiving waters in the model. However, in areas where leaching from septic tanks contributes wastewater nitrogen into the vadose zone, wastewater nitrogen should be included using either a "per capita" or "water use" method, analogous to the original NLM (Valiela et al. 1997).

Fate of nitrogen in vadose zones and aquifers

Nitrogen delivered to the catchment surface by atmospheric deposition, fertiliser use and BNF permeates the vadose where it undergoes further attenuation processes. Nitrogen is lost from the vadose zone by denitrification, chemical reduction, and biological uptake, however there is a lack of quantitative data about the rates and distribution of these processes (Korom 1992; Valiela et al. 1997; Parfitt et al. 2006). Valiela et al. (1997) calculated that the vadose zone in all land-use types, on average, removes 61% nitrogen, allowing 39% to pass into the aquifer.

Quantitative data on nitrogen losses within aquifers is generally the largest unknown parameter in nitrogen loading models, with its importance still contentious (Valiela & Costa 1988; Postma et al. 1991; Weiskel & Howes 1991; Cherkauer et al. 1992; Starr & Gillham 1993). In the SCENY model, we used an estimate of 35% loss of nitrogen through biological processes, namely vadose uptake and denitrification in the aquifer (Valiela et al. 1997).

Study estuaries

The SCENY model was applied to three South Island study estuaries and coastal inlets containing 13 sub-catchments. These study estuaries and inlets were Waikouaiti (Otago), Otago Harbour (Otago), and Freshwater River catchment (Stewart Island, Southland). Land use was mapped using the LCDB2 classification of land cover (Terralink 2004) and land parcels assigned into eight categories according to similar land-use practices that affect the flux of nutrients (Fig. 2). Area of each land-use type was calculated using a geographical information systems (GIS) mapping programme ArcMap 9.2 (Environmental Systems Research Institute (ESRI) ARC/INFO software). The land-use data within each sub-catchment were used as input variables for the model.

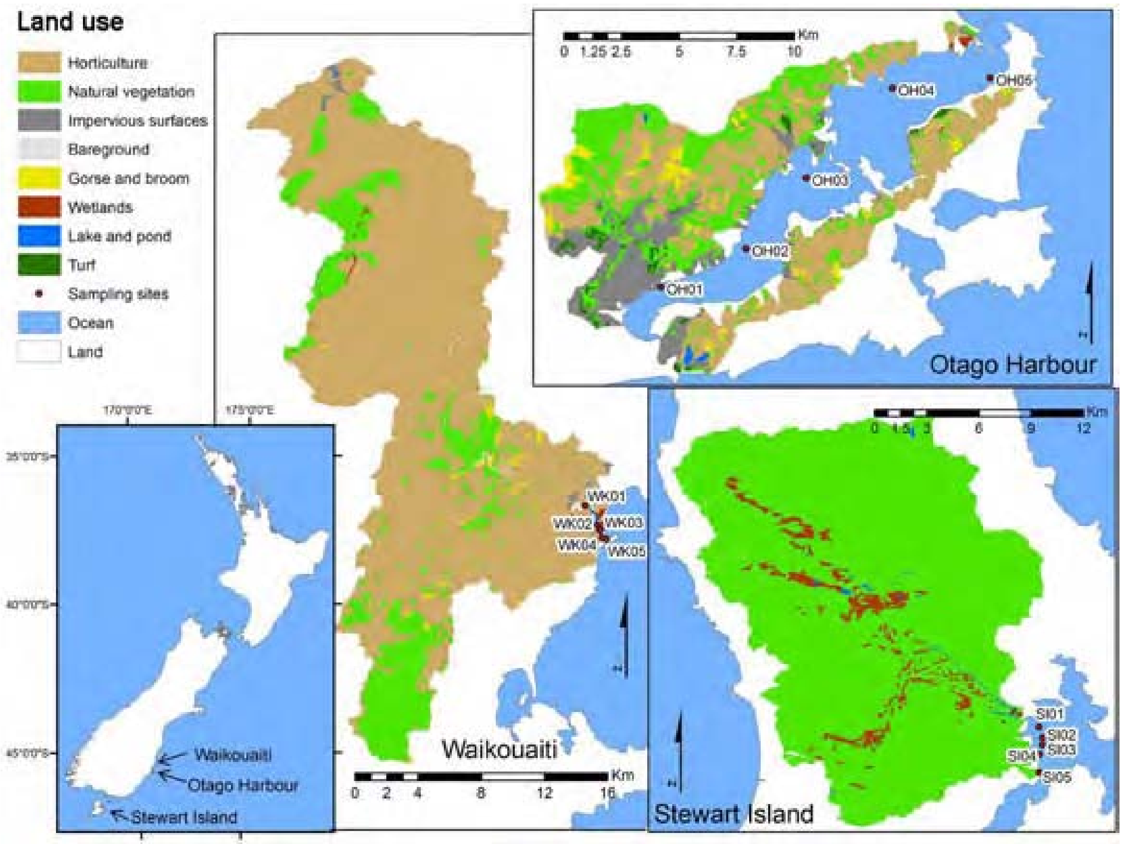

Fig. 2 Geographical information system (GIS) data on land use in the three New Zealand study sites classified into eight categories based on land-use practices that affect the nitrogen flux in comparable ways. Horticulture includes pastoral lands (sheep, beef, deer, arable and other farming practices), short rotation cropland, vineyards, orchards, and other perennial crop.

Data analysis

Linear and logarithmic regressions were applied to the data using JMP 7.0 (SAS Institute Inc.) to test the relationships between the predicted nitrogen yield from the model and catchment variables. Further, the model outputs from the SCENY model were compared to nitrogen yield estimates from other relevant New Zealand models.

RESULTS

The three study estuaries encompassed a mosaic of land-use combinations, with estimated total nitrogen loads from sub-catchments to recipient estuaries ranging between 26.2 kg N yr^{-1} and 43001.9 kg N yr^{-1} (Table 3). Land-derived nitrogen loading rates normalised to catchment area (i.e., yields) varied from 0.6 kg N ha^{-1} yr^{-1} in pristine catchments to 17.0 kg N ha^{-1} yr^{-1} in catchments dominated by agricultural practices.

The percentage of agricultural land in sub-catchments ranged from 0 to 91%, with estimated nitrogen yields increasing directly with the fraction of agricultural land area in the catchment (Fig. 3A; $r^2 = 0.99$, $F = 20903.28$, $P < 0.0001$). The model predicted that nitrogen yields can be approximated by the percentage agriculture in the catchment by the empirical relationship, $y = 0.1796x + 0.7056$, with a SE of 0.84. As agricultural land practices increased, both the resulting nitrogen loads to estuaries and the percentage contribution from fertiliser increased (Fig. 3B). The relationship between nitrogen yields and percentage contribution of fertiliser exhibited an asymptotic relationship, $y = 25.6706\ln(x) + 15.2046$, with a SE of 0.28.

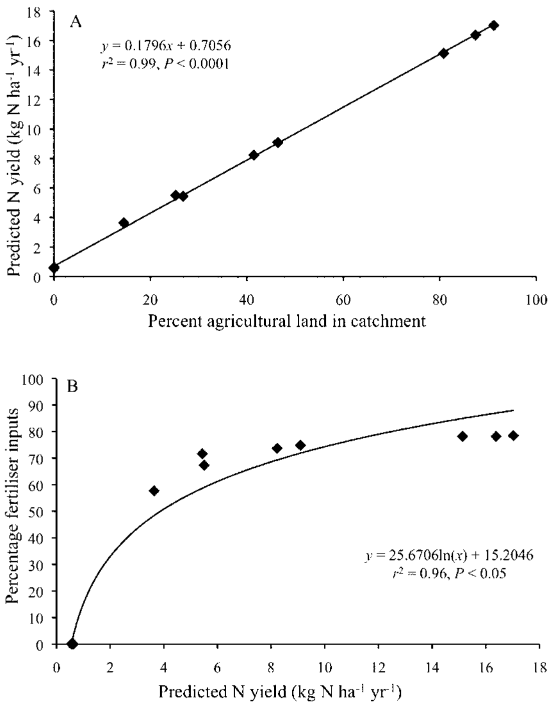

Fig. 3 Relationship between modelled **A**, land-derived nitrogen yields and percentage agricultural land, and **B**, percentage of fertiliser inputs from individual sub-catchments in the three study estuaries with different nitrogen (N) loading rates.

The relative importance of the different nitrogen sources varied among the sub-catchments in association with different land-use practices (Fig. 4). For example, Freshwater River sub-catchments were dominated by natural vegetation and atmospheric nitrogen deposition. By contrast, the Waikouaiti sub-catchments were dominated by agricultural landscapes with the contribution of fertiliser to nitrogen yields greater than 70% for all sub-catchments. Similarly, in Otago Harbour, fertiliser contributed between 50 and 80% of total nitrogen loads in the outer harbour. Thus, fertiliser inputs became proportionately more important at high nitrogen loads, contributing between 58 and 79% of the total nitrogen yield. In contrast, the relative contribution by atmospheric deposition decreased exponentially at high nitrogen loads, whereas the contribution by BNF to nitrogen yields did not change proportionately with increasing nitrogen load.

The relationship between predicted total nitrogen yield (kg N ha^{-1} yr^{-1}) and the proportion of nitrogen yields from pastoral land use (kg N ha^{-1} yr^{-1}) was significant when the values for SCENY were combined with those from other New Zealand models (Alexander et al. 2002; Parfitt et al. 2006) ($r^2 = 0.93$, $F = 300.10$, $P < 0.0001$, SE = 3.98; Fig. 5). The pasture nitrogen yield estimates included both the contribution of BNF from pasture legumes and fertiliser application to agricultural lands.

Table 3 Catchment land area and calculated nitrogen (N) loading rates for Freshwater River/Stewart Island (SI), Otago Harbour (OH), and Waikouaiti (WK) estuaries (New Zealand) and their individual sub-catchments.

	Watershed		Calculated N loads		
Site	Area (ha)	% agriculture	Total N load (kg N yr^{-1})	% fertiliser	Total N yield (kg N ha^{-1} yr^{-1})
SI04	47.3	0.0	26	0	1
SI02	54.6	0.0	34	0	1
SI05	43.9	0.0	27	0	1
SI03	409.5	0.0	258	0	1
SI01	31 792.9	0.0	20 048	0	1
OH05	50.2	14.5	182	58	4
OH02	42.1	26.7	229	72	5
OH01	4841.5	25.3	26 628	67	5
WK02	92.6	41.4	761	74	8
OH03	1174.8	46.4	10 682	75	9
OH04	69.5	80.8	1051	78	15
WK01	2625.5	87.4	43 002	78	16
WK04	396.1	91.2	6744	78	17

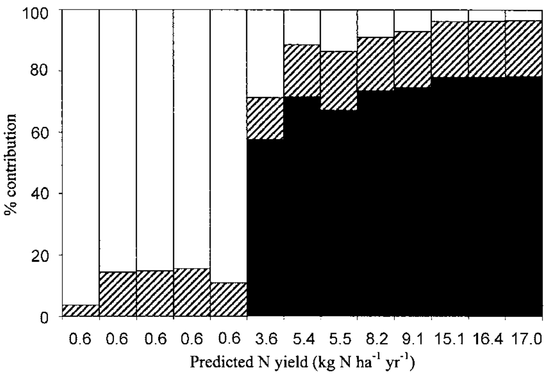

Fig. 4 Percentage contribution of different nitrogen (N) sources, including atmospheric deposition (open bars), fertiliser inputs (closed bars) and biological nitrogen fixation (cross-hatched bars), to total nitrogen loads predicted using the Sub-Catchment to Estuary Nitrogen Yield (SCENY) model.

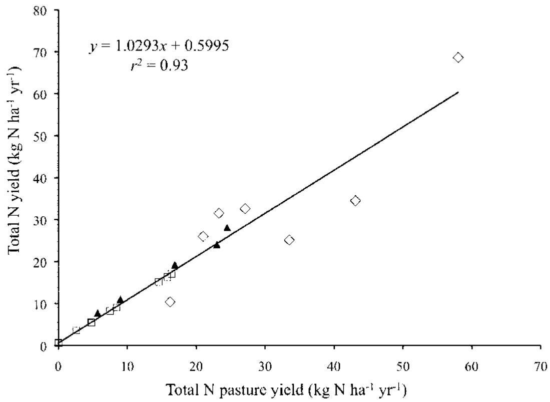

Fig. 5 Relationship between modelled total nitrogen (N) yields (three different models) and total nitrogen yield from agricultural land ($P < 0.0001$), where pasture nitrogen includes biological nitrogen fixation and fertiliser inputs. Different models are: SPARROW (triangle), Alexander et al. 2002; Parfitt et al. 2006 (diamond); and the Sub-Catchment to Estuary Nitrogen Yield (SCENY), current study (square).

DISCUSSION

The current study demonstrates a strong linkage between land use and nutrient levels of surface waters and thus agrees with other New Zealand (e.g., Quinn & Stroud 2002; Galbraith & Burns 2007) and international studies (e.g., Valiela et al. 1997; Bowen et al. 2007). In particular, the SCENY model showed a significant relationship ($r^2 = 0.99$, $P < 0.0001$) between total nitrogen yields to coastal inlets and estuaries in New Zealand and agricultural land use in surrounding catchments. Thus, the results of this study confirm that nitrogen flux to coastal waters in New Zealand is generally dominated by non-point sources (Howarth et al. 1996; Parfitt et al. 2006), and highlight the importance of managing land-derived nutrient run-off to avoid or mitigate nutrient enrichment of New Zealand estuaries.

The SCENY model estimated that between 0.6 and 17.0 kg N ha^{-1} yr^{-1} entered the three study estuaries in Otago and Southland from agriculture, BNF, and atmospheric inputs. These nitrogen yield estimates agree closely with nitrogen yields for New Zealand catchments calculated using SPARROW, which range from 0.5 to 20.0 kg N ha^{-1} yr^{-1}, with highest yields in areas dominated by dairying in the southeast South Island (Elliot et al. 2005). Moreover, the nitrogen yields estimated with SCENY are similar to estimates of the annual total nitrogen input for the entire Otago region (26 kg N ha^{-1} yr^{-1}; Parfitt et al. 2006). However, the greatest nitrogen yields estimated in this study and other New Zealand models are considerably lower than the average values for catchments in the northeast United States, where reported land-derived nitrogen yields range from 25 to 199 kg N ha^{-1} yr^{-1} in Cape Cod, Massachusetts (Carmichael et al. 2004) to 2–10 253 kg N ha^{-1} yr^{-1} in Narragansett Bay, Rhode Island (Wigand et al. 2003; Chintala et al. 2006). The relatively lower nitrogen loading rates for New Zealand estuaries are most likely owing to a combination of significantly lower population densities, less discharge of urban wastewater to surface waters, and less cropping as New Zealand has had extensive agriculture for less than 150 years (Parfitt et al. 2006).

Despite the relatively low nitrogen yields to New Zealand estuaries compared with highly urbanised catchments in the United States, the recent decline in water quality of New Zealand surface waters (Larned et al. 2004; Wilcock et al. 2006) has highlighted the impact of land use in surrounding catchments on nutrient export. This study supports this relationship between land use and nutrient run-off, showing a close relationship ($r^2 = 0.99$, $P < 0.0001$) between agricultural land use and nitrogen yields to estuaries in the South Island. The intensification of agricultural development in some New Zealand catchments has increased the flux of nitrogen to aquatic ecosystems, providing both nutrient subsidies and stresses to biodiversity, primary production, invertebrate and fish production, and other ecosystem processes (Quinn 2000; Niyogi et al. 2003; Niyogi et al. 2007). It is hypothesised that the present nitrate concentrations and negative impacts of excess nitrogen in Lake Taupo and the Rotorua lakes (North Island) only partially reflect the past conversions of forest to pastoral land and intensification of agricultural practices (Rutherford 1984; Elliot & Stroud 2001). Moreover, with the widespread increase in reactive nitrogen fertiliser and reduced reliance upon BNF (Parliamentary Commissioner for the Environment 2004), it is anticipated that nitrate export and leaching rates from intensively cultivated land will be exacerbated. Although there are few studies in New Zealand which have quantified the eutrophication status of estuaries (e.g., McLay 1976), there are indications that some estuaries experience excessive nitrogen loads and exhibit symptoms of nutrient enrichment. Eutrophication in estuaries causes a suite of effects that can cascade through the estuarine food web (Rabalais 2002; Bowen et al. 2007). Consequently, being able to evaluate the relative importance of different land-derived nitrogen sources to groundwater, and ultimately to recipient estuaries before eutrophication effects are fully expressed, can facilitate management priorities relating to water quality.

The current study, and all nitrogen yield models presently developed for New Zealand, show agreement that the intensification of farming practices increases nutrient export to surface water. Although some nitrogen budgets emphasise the importance of BNF by pasture legumes (Parfitt et al. 2006), most models identify fertiliser nitrogen inputs as the principal component of total nitrogen inputs to aquatic ecosystems (Alexander et al. 2002; Elliot et al. 2005; this study). Therefore, the remediation of incipient nutrient enrichment in estuaries surrounded by farms ought to focus on the control of land-derived nitrogen loads while simultaneously preserving fringing wetlands and riparian vegetation to reduce nitrogen flux to receiving estuaries.

Unresolved gains and losses in the SCENY model

The SCENY model does not include livestock since it is not a new source of nitrogen. This assumption is also used in the original NLM (Valiela et al. 1997). Nevertheless, to account for shifts in stocking density or grazing management that may affect nitrogen yields, it would be preferable to include a term that quantifies stocking type and intensity. It was beyond the scope of this study to include individual farm stocking information (e.g., AgriBase™ database, Sanson 2005). The SCENY model could underestimate nitrogen yields from intensively farmed land parcels. Therefore, future directions include the use of a soil leaching model to derive load adjustment factors that can be incorporated into the SCENY model to refine source predictions. Other uncertainties in the model include unknown soil gains and losses. As the storage capacity of nitrogen within the soils declines, nitrate leaching is likely to increase with an associated risk to the environment (Schipper et al. 2004). Moreover, different pasture management regimes can affect the amount of nitrate leached from soils and whether the loss is by leaching or run-off (Woods et al. 2006). Therefore, additional information on soil nutrient levels and pasture management would further refine estimates of nitrogen flux into groundwater and ultimately estuaries. Nitrogen lost from surface run-off can also be significant, especially in conditions where fertiliser application and stocking rates are high, and following heavy rainfall. However, these pulse events are relatively short-lived, disappearing within weeks. Moreover, the processes that mobilise nutrients into water are still largely unresolved. Hence nitrogen from surface run-off was excluded from the model, which focused instead on longer-term, more integrated sources of nutrients derived from catchments. An additional caveat is that although the SCENY model attempts to account for local variations by working at the individual catchment level, we used national values in the model when local values were unavailable or unreliable. For example, after literature review on ammonia volatisation and NO_x gas losses, a single national value showed a better fit than a local value. However, as more data become available, the model should be updated accordingly to reflect local values. Finally, to validate the effects of land-derived nitrogen yields predicted by the SCENY model on estuarine ecosystems, nitrogen yields need to be translated into a measure of nitrogen concentration in the water column. At present, there is insufficient quantitative data on losses of land-derived nitrogen during downstream transport and on the additional losses and gains of nitrogen within the estuary to accurately relate modelled nitrogen yields (kg N ha^{-1} yr^{-1}) to measured water column concentrations of dissolved inorganic nitrogen (μg $litre^{-1}$) in estuaries. Nevertheless, the close agreement between the modelled estimates of nitrogen yields from the SCENY model and other New Zealand nutrient models confirms that the

SCENY model accurately predicted total nitrogen yields and agricultural-derived nitrogen loading for a range of land-use practices.

In conclusion, as burgeoning human populations and economic drivers continue to drive intensification of agricultural practices in New Zealand, land-derived nitrogen yields to estuaries are likely to increase further, causing deteriorating water quality and posing ecological challenges. Consequently, the management of estuarine water quality should focus on limiting nitrogen inputs from surrounding catchments to receiving aquatic ecosystems. A nitrogen yield model, such as SCENY, can be used to evaluate the relative magnitude and fates of nitrogen inputs from fertiliser applications, atmospheric deposition and BNF to estuarine and coastal ecosystems, and will provide valuable information for the management of New Zealand estuarine ecosystems.

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