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Nitrogen inputs and outputs for New Zealand in 2001 at national and regional scales

R.L. PARFITT[1,]*, L.A. SCHIPPER[2], W.T. BAISDEN[1] and A.H. ELLIOTT[3]
*[1]Landcare Research, Private Bag 11052, Palmerston North, New Zealand; [2]Department of Earth Sciences, University of Waikato, Private Bag 3105, Hamilton, New Zealand; [3]National Institute of Water and Atmospheric Research, POBox 11115, Hamilton New Zealand; *Author for correspondence (e-mail: parfittr@landcareresearch.co.nz; phone: 64-6-356-7154; fax: 64-6-355 9230)*

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Abstract. The Nanjing Declaration on Nitrogen Management, signed in Nanjing in October 2004, calls for national governments to optimize N management by several strategies including assessment of N cycles. Here we develop a first N budget for New Zealand (267,000 km^2), at both national and regional scales. The national inputs are estimated to be 36.5 kg/ha, mainly from biological N fixation, but also increasingly from fertilizer application and atmospheric deposition. The outputs are estimated at 40.5 kg/ha. Biological N fixation from legumes in pasture was the most important input in most regions. Exceptions were Auckland, with a large urban population, and the West Coast of the South Island, with large tracts of rain forest. Outputs were distributed in the order leaching > ammonia volatilisation > erosion = produce = denitrification. These outputs are very different from global averages because of the large numbers of grazing animals on pasture. A large loss occurs between the subsoil and the oceans, and further research is needed to identify these pathways. Riverine export of N was generally well correlated with inputs.

Introduction

Humans have dramatically altered the global nitrogen (N) balance, breaking into the vast reservoir of inert N_2 gas in the atmosphere, and releasing reactive forms of N into the environment (Galloway et al. 2003). This has been achieved through crops that promote N fixation to sustain food production, through industrial processes that produce ammonia, some of which is used as fertilizer, and through fossil fuels that burn to produce NO_x gases. This reactive N can cascade through a variety of environmental systems causing significant damage to water bodies, forests, biodiversity and human health (Galloway et al. 2003). The Nanjing declaration in 2004 is a recent response that calls for national governments to optimize N management by several strategies including assessment of N cycles (www.iniforum.org/fileadmin/user_-upload/nanjing/nanjing_declaration-041016.pdf). Herein, we assess New Zealand's N budget in response to this call.

Extensive land clearing for agriculture in New Zealand began only in the 1850s, and large areas of native forest still remain in mountain areas. The New Zealand environment is considered by some to be a low N environment, since streams in these mountains have low concentrations of N (Stenzel and Herrmann 1990), and N inputs from rain water are estimated at only 1–2 kgN/ha/y (Baker et al. 1985; Nichol et al. 1997). Until the late 1980s, New Zealand was one of a few temperate countries where much of the agricultural production depended on biological N fixation (BNF) as the source of reactive N. This BNF arises mainly from white clover in pastures that are grazed for 12 months of the year. In 1980 about 50% of the land area was under pastoral farming; there were 70 million sheep and 8 million cattle, and movement of waste-N from these animals to water bodies had been observed (Sharpley and Syers 1979). Outputs of N from farms, although generally lower than from European farms, are still considerable (Ledgard et al. 1999; Jarvis and Ledgard 2002). This includes emissions of ammonia, which the IPCC default approach (O'Hara et al. 2003) suggest is at least 10 kg N/ha over the entire nation, but which is not found in wet deposition. This is a topic that has received little attention in New Zealand.

New Zealand's N fertilizer use is changing rapidly, increasing from 50 Gg in 1989 to 342 Gg in 2003, increasing the load of N in the New Zealand environment. For example, in the Waikato region 17% of groundwater samples have nitrate-N concentrations exceeding the WHO limit of 11.3 mg/l (Environment Waikato 2005). Some lakes in the Rotorua region have algal blooms, and N concentrations are increasing in Lake Taupo, New Zealand's largest lake. Groundwater residence times to some lakes are in excess of 40 years so the effects of recent intensification in land use have not yet become apparent. Trends in water quality, however, are generally downward (Hamill and McBride 2003; Larned et al. 2004; Vant and Smith 2004). To address the issue of reactive N in the environment, The Parliamentary Commissioner for the Environment has a called for a redesign of New Zealand farm systems (PCE 2004).

Our work is a preliminary effort in response to calls for better national N budgets (Galloway et al. 2004). We recognise this effort can be improved, but this preliminary budget indicates where the focus of work needs to go in future. We estimate flows of N into and out of regions in the North and South Islands of New Zealand for the season 2001–2002, the last year for which there are many complete data sets. Erosion data and climate data, however, are an average of several years, with the term of the average ranging from 3 to 20 years. We include annual flows into and out of plant and soil ecosystems, and also flows involving waste treatment, cities and towns. The boundaries are the oceans, the atmosphere above plant canopies, and the aquifers. We do not include the internal cycling of N from soil to plant, and plant to soil that occurs several times within a given year, particularly with grazing animals. Losses go to the groundwater, to the oceans, to the atmosphere, as exports of produce (meat, wool, milk, etc), and by burial. We highlight those stocks and flows that are reasonably well understood or at least well constrained, and also identify those that are poorly known, to highlight areas for further research.

Methods

New Zealand has an average air temperature of around 13 °C, and for most populated areas, annual rainfall varies between 800 and 1500 mm, evenly distributed throughout the year. However, mountains greatly affect rainfall in some areas and the range of annual rainfall is 400–11,000 mm. Summer drought occurs about 1 year in three over one-third of the pastoral land, generally on the east coast. However, during summer in these regions, dairy pasture is irrigated.

In New Zealand the 16 regional authorities (Councils) were established in 1989, and their boundaries are based on water catchment areas (Figure 1). Statistical data are collected regularly for each Regional Council. Timely information was available for recent years in the Ministry of Agriculture and Forestry (MAF) Agricultural Production Census June 2002 (MAF 2003), from the New Zealand Climate Change Office, Ministry for the Environment (MfE) National Inventory Report 1990–2002 (MfE 2004), and in the 2001 Census of Population and Dwellings (Statistics New Zealand 2004). In this study we used several excellent spatial databases such as Land Research Inventory (LRI), which contains soil polygons, Land Environments NZ (LENZ), which contains rainfall and water balance, and Land Cover Database 2 (LCDB2) (MAF 2004), which contains vegetation. Data for the smaller islands has not been presented, and graphs for the small Nelson region (42,000 ha) are not shown.

Several of our calculations involved the number of grazing animals in a region. These were measured in stock units (SU) defined as the number of breeding ewes per hectare in the year 1980. Animal weights in 2001 were considerably larger, therefore we have used the following factors: beef cattle, 4.83 SU; cows and heifers (over 1 y, usually Friesian/Holstein) in milk or in calf, 7.3 (Taranaki region, 6.7; usually Jersey); other cows, 4.2 (Taranaki, 3.9); breeding ewes, 1.18; other sheep, 0.7; deer, 1.8; goats, 0.9; and horses, 4.0 (H. Clark personal communication). This gave a total of 98.6 million stock units. Regional distribution of stock units was taken from MAF (2003) and from AgriBase, a spatial database of farm type.

The data presented in this paper are for the season 2001–2002, assuming it was a year with 'average' weather conditions. We recognise many of the N flows will change with weather conditions such as drought or periods of above average rainfall. Much of the statistical data is for the calendar year 2001, and this has been assumed to apply to the agricultural season 2001–2002.

Figure 1. Map of regional boundaries – these are generally catchment boundaries.

Inputs of N

Fertilizer N inputs for each region were taken from tonnes fertilizer sold in 2001–2002 (MAF 2003). Imports of N in grain and in animal feed were estimated from imported tonnage for 2001.

N fixation by pasture legumes

Because N is the major limitation for pasture growth (Haynes and Williams 1993) and animal numbers depend on pasture growth, there is a relationship between N fixation per ha and SU for a farm. This relationship is supported by 4 sets of data from 3 contrasting catchments where no N fertiliser was used (Figure 2) (Power et al. 2002). In New Zealand farms, the management practice is one of rotational grazing, where live-stock are moved from paddock to paddock to efficiently use the pasture growth. These data enabled us to assess N fixation, using animal numbers for each region (MAF 2003) based on the equation in Figure 2. Phosphate and sulphur also limit legume growth, but farmers generally have used superphosphate to raise soil P and S status to adequate levels (Wheeler at al. 2004). Ledgard et al. (1999) found N fixation in an N-unfertilised farmlet fluctuated over 3 years from 99 to 231 kg/ha/y according to the weather patterns. There is therefore considerable uncertainty in our estimate for the season 2001–2002.

Since 1988, increasing amounts of N fertiliser have been applied to dairy pastures, which has led to a reduction in N fixation by legumes in pastures (Crush et al. 1982; Ledgard et al. 1999). In 2001–2002, 60% of the N fertiliser was applied to dairy farms (MAF 2003); the average application rate was 67 kg N/ha. Using data from a research dairy farm (Ledgard et al. 1999), we estimated N fixation by legumes has been reduced by 13% (Figure 3), leading to a reduction of 13% of N fixed by clover for each dairy cow in each region. In Waikato and Bay of Plenty regions, however, the average application rate was 113 kg N/ha (Singleton 2003), and we estimated N fixation has been reduced by 21% on dairy farms in these regions. We assume N fixation by legumes has not been reduced significantly on other farms (e.g., sheep and beef), because smaller rates of N fertilizer have been used. The effect of the clover weevil (*Sitona lepidus* Gyllenhal), which was introduced into New Zealand in the early 1990s and has spread throughout North Island, has been ignored at this stage.

Other biological N fixation, and deposition from the atmosphere

Orchards usually have a grass strip that contains clover in the rows between the trees; the strip is either grazed by sheep or is mown. The areas were obtained from LCDB2, and the N fixed by this clover is assumed to be 30 kg N/ha/y (Goh and Ridgen 1997).

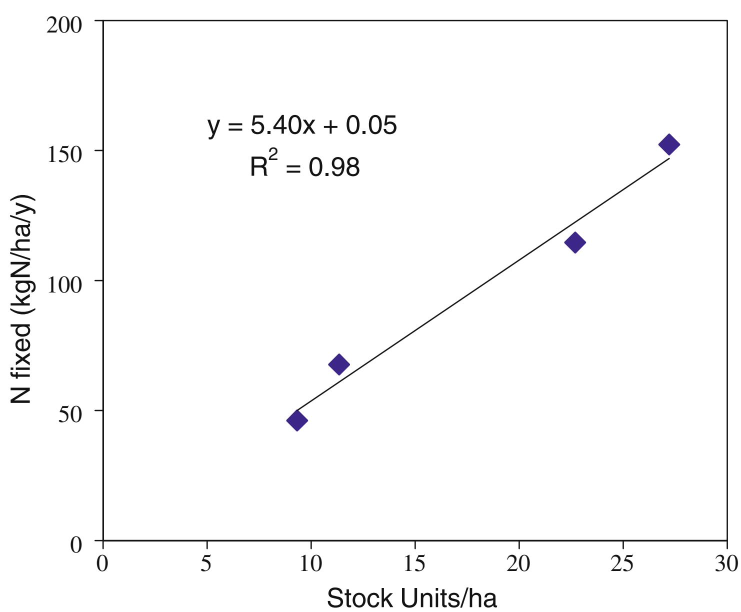

Figure 2. Relationship between stock units and N fixation based on the isotopic dilution method (Power et al. 2002).

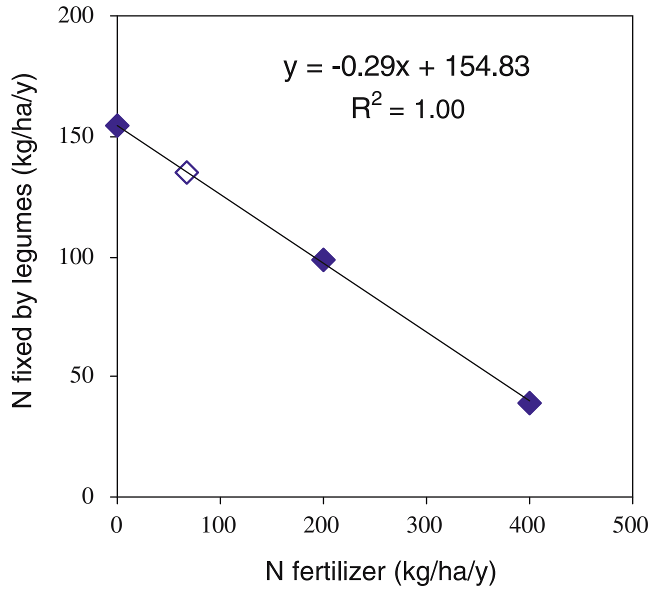

Figure 3. Relationship between N fixation and N fertilizer (Ledgard et al. 1999).

Plantation forests occupy about 1.6 million ha (MAF 2004), and are harvested about once every 25 years. Legumes are often sown, and are actively fixing N between the young trees for 5 years until the canopy closes; i.e., 5/25 of the land in plantation forestry will have legumes present. The average N fixation by these legumes is 40 kg N/ha each year for 5 years (Watt et al. 2003).

There are two major exotic N fixers – Broom (*Cytisus scoparius* L) and Gorse (*Ulex europaeus* L) – that have become widely distributed in most regions in New Zealand, and colonise nutrient-poor pastures. N fixation by broom in New Zealand is about 110 kg N/ha/y, and by gorse is estimated to be 20 kg N/ha/y (Watt et al. 2003; M. Watt personal communication). LCDB2 gives the area of gorse plus broom in New Zealand (200,000 ha), but since gorse makes up the greater proportion, the N fixation by gorse and broom is assumed to average 30 kg N/ha/y.

Within New Zealand native forests, N is fixed by *Coriaria arborea*, lichens, algae and free-living micro-organisms. Outputs of N from these forests by erosion, leaching and denitrification are estimated to be about 3 kg N/ha/y; the area is 6.5 million ha MAF 2004). Atmospheric inputs in rain generally are about 1.5 kg N/ha/y except for regions of high rainfall and cloud, where with deposition on the canopy they can be >5 kg N/ha/y (Neary et al. 1978; Mosley et al. 1981; Baker et al. 1985; Nichol et al. 1997; Oyarzún et al. 2004). Input rates used were: 5 kg/ha for West Coast, 3 kg/ha for Tasman and 1.5 kg/ha for the remainder. We assume the N cycle of native forests for 2001 is at close to steady state (Richardson et al. 2004), and therefore the biological N fixation in forests is assumed to average 1.5 kg N/ha/y.

Ammonia is emitted by volcanoes and fumaroles, the amount emitted at the Wairakei geothermal field being about 2 tonne of N per year (Ellis and Mahon 1977), and these data have been extrapolated, assuming there are 50 similar geothermal emitting areas. This ammonia from volcanoes, along with the much larger quantities of ammonia volatilised from pastures can be re-deposited onto land, and we present methods for calculating the proportions of ammonia deposition onto forests and trees in the section on ammonia outputs.

Total national emissions of NO_x gases are 196 Gg NO_x; 189 Gg are from fossil fuel combustion (MfE 2004). The N content of NO_x is 0.30, and since most fossil fuel is burned in the urban centres on the coast, and prevailing winds remove most of the combustion products to the oceans, we assume only 25% gets added to the New Zealand ecosystems. The input of NO_x was apportioned to regions based on the population of the regions (Statistics New Zealand 2004).

Outputs of N

Ammonia volatilisation and redeposition

Ammonia volatilisation occurs not only when N fertiliser is added to soil but also when animal excreta are deposited on soil. The ammonia-N volatilised from New Zealand pastures has been estimated to be 9.1 kg N/y per cow over 3 years on dairy farms on Allophanic soils (Jarvis and Ledgard 2002) or 1.3 kg N/y for each SU. Ammonia is volatilised from urine spots when temperatures are high, and because soil pH increases when urea is hydrolysed (Clough et al. 2003). Carran et al. (1982) gave a value of 2.1 kg/SU for silty (loess derived) soils, and Ruz-Jerez (1991) estimated >3 kg N/SU was volatilised on sandy alluvial soils that are very poorly buffered against pH change. The Allophanic soils, however, are well buffered against pH change (Parfitt 1980), and this is consistent with the lower value of Jarvis and Ledgard (2002). This value (1.3 kg/SU) has been used for pastures on the Allophanic soils. The proportion of pasture-land that has Allophanic soils was obtained from the LRI and LCDB2 (20% of North Island) and SU were allocated based on this proportion. These soils occur mainly in the Waikato and Taranaki regions. Since silt loam soils are very common in New Zealand, a value of 2.1 kg/ha/SU has been used for all other soils under pasture.

Due to a lack of published data for ammonia concentrations in the bulk atmosphere over New Zealand, and subsequent deposition rates to forests, a simple model was used to calculate atmospheric concentrations and dry deposition based on the following mass balance relationship, assuming that most ammonia emission occurs during dry conditions (Andersen and Hovmand 1999).

$$U\frac{dM_{NH_3}}{dx} = E - v_d\frac{M_{NH_3}}{H} \qquad (1)$$

Equation (1) describes the inputs and outputs of ammonia (M_{NH_3}, g N/m^2) as an atmospheric column with the thickness of typical planetary boundary layer (H, assumed to be 500 m) advancing across the landscape due to average prevailing wind (U, ~4.5 m/s^1) in the absence of precipitation. Emissions are represented by E (g/m^2/s^1), while deposition is driven by the right-hand term. Taking typical deposition velocities (v_d, m/s^1) for gaseous and ammonia-bearing aerosols as 0.02 m/s^1 for forests and values <0.01 m/s^1 for grazed pasture, literature values suggest most deposition in New Zealand occurs to forests.

The model yielded atmospheric concentrations typically reaching 1000–2000 ng N/m^3, consistent with the limited data reaching 930 ng N/m^3 at Baring Head despite the low exposure of this site to agriculture (Allen et al. 1997). Results obtained from integrating Eq. (1) suggest forests consume approximately 2/3 of atmospheric ammonia per 100 km. The average width of forests downwind of major agricultural regions is 50 km or less, with the exception of the ~120 km North Island Central Plateau, but we also note the likely importance of precipitation and montane clouds (Heath and Huebert 1999) in depositing ammonia in downwind terrestrial locations. These factors suggest approximately 50% of the ammonia emitted from agriculture is redeposited on land in New Zealand. Although the factors influencing wet, dry and cloud deposition vary spatially, an effort to determine the regional difference in deposition was beyond the scope of this work. We have thus assumed 50% of emitted ammonia is redeposited, and included deposition as an input since deposition can occur outside of the site and region of emission. This is consistent with 74% estimated to be deposited in the continents that have larger land masses (Galloway et al. 2004).

Produce exported overseas and consumed in NZ

The N exported in 2001 has been calculated from the N concentration and tonnes of exported produce (I. Parminter personal communication). The exports containing N are meat, casein, milk powder, cheese, wool and hides, and to a lesser extent butter, wood products, grain and fruit. The various products have been apportioned to the regions based on the number of cows and sheep, and on the area of forests, crops and horticultural land. The N consumed by the New Zealand population has been apportioned to the regions by population.

Loss of N by erosion to ocean and by burial in landslides

Erosional losses from soils delivered to the ocean, lakes and reservoirs were estimated by multiplying the national erosion C loss surface averaged over 12–20 years (Scott et al. 2004) by a national soil C:N ratio surface in ArcGIS. The national soil C:N ratio surface (0–10 cm) was generated through multiple regression using LENZ climate data and soil order as predictor variables explaining the variation in C:N in the 0–10 cm range in the National Soils Database, Soil Carbon Monitoring System database, and 500 soils database (all held at Landcare Research). Burial in rivers and on hill slopes also removes N from the terrestrial environment, and as a first approximation we assumed burial is equivalent to the losses to the sea (Page et al. 2004). For the West Coast of South Island, however, the Alps are adjacent to the ocean, and we assume there is no zone for burial of sediments. For the Gisborne region, a correction has been made to recognize that half the eroded C and N is derived from deep bedrock (Gomez et al. 2003). Some underestimation may arise from the greater probability of erosion on agricultural land relative to forested land, since agricultural land has lower C:N. For instance, during a 100+ year flood in the Manawatu River, sediment had a C:N ratio of 11 (Parfitt and Baisden unpublished data), while the estimated average C:N for the catchment is 16. The estimate of eroded N delivered to the ocean reflects the use of long-term data, including major flood events, and can be viewed as a true long-term average preceding 2002. The estimate is constrained by the total N exported by rivers (see Elliott et al. 2005), which represents a direct measurement of all dissolved and particulate N over 12 years without direct efforts to capture flood events.

Leaching, loss to aquifers, attenuation in water, and export of solutes in rivers to oceans

Leaching of N from pasture soils is very difficult to assess for whole regions since rainfall and drainage vary considerably both for the region, and within regions. It is also influenced by the size of the grazing animal, feed intake, N content of the feed, and farm management in winter. The concentration of nitrate-N in soil solution under dairy cattle can vary from 25 mg/l in autumn to 2 mg/l in spring (Monaghan et al. 2002; Houlbrooke et al. 2003), and from 0.5 to 7 mg/l for sheep (Sakadavan et al. 1993; Magesan et al. 1996). For this exercise, we have assumed the average N concentration in soil solution is 9 mg N/l for dairy (10 mg/l in Waikato and Bay of Plenty), 6 mg N/l for beef, 3 mg N/l for sheep/deer, and 4 mg N/l for sheep/beef. Based on the water balance in LENZ, we have estimated the drainage for each land use in each 100-m cell in each region (from AgriBase and LCDB2) averaged over 20 years. Multiplying drainage by soil solution concentration gives an estimate for nitrate-N leaching and runoff under grazed pasture for the year. Houlbrooke et al. (2003) showed the dissolved organic N (DON) in water draining from pasture under dairy was about 1 mg N/l, and this has been added to the leaching data for pastures. For other livestock we have assumed the DON concentrations are between 0.3 and 0.6 mg N/l.

We also assume nitrate-N leached from soil is 40 kg/ha/y under cropping, 60 kg/ha/y for horticulture including vegetables (Webb et al. 2001; MAF 2003), and 1 to 4 kg/ha/y for other land uses (Neary et al. 1978; Mosley et al. 1981; Parfitt et al. 1997). Losses from point sources (sewage, dairy factories, abattoirs) have been taken from Elliott et al. (2005). The National Institute for Water and Atmospheric Research has taken water samples at 77 river sites each month since 1989, and has analysed them for total N concentration and nitrate-N and ammonium-N (Elliott et al. 2005). The amount of dissolved N (nitrate-N, ammonium-N and DON) exported to oceans by rivers was estimated from these data.

N_2O emissions and denitrification

Data for N_2O losses were taken directly from New Zealand's Greenhouse Gas Inventory 1990–2002 (MfE 2004). Other denitrification losses from agriculture and forests were based on the review of rates of loss in agricultural and forest soils by Barton et al. (1999). The mean loss for unfertilized agricultural soil is 3.2 kg N/ha/y and for fertilized agricultural soil is 13.4 kg N/ha/y. We have assumed a loss of 13 kg N/ha/y for cropping soils and 10 kg N/ha/y for pasture soils. These rates could be conservative as they are predominantly measured using acetylene inhibition methods, which can underestimate denitrification particularly in nitrate-limited environments (Bollmann and Conrad 1997). These values are not unreasonable, since N_2O losses alone can be 10 kg N/ha/y for New Zealand pastures that are grazed by dairy cows (Bolan et al. 2004b). Soils in New Zealand are generally not frozen in winter, and emissions are likely to be high both in wet winters when soils are saturated, and for poorly drained soils.

Horticultural soils are often fertilized with 200 kg N/ha N, and denitrification losses are assumed to be 50 kg N/ha/y (Barton et al. 1999). The annual loss for a pine forest soil in New Zealand was reported to be 1.7 kg N/ha, and losses for indigenous forest are likely to be about 1 kg N/ha (Barton et al. 1999). Nitrogen loss from inland and coastal wetlands not connected to agriculture is assumed to be 10 kg N/ha/y (Groffman 1994); the area of wetlands is given in LCDB2. These numbers have been summed for the different land-uses in the regions (MAF 2003). Pro rata amounts have been calculated for regions based on regional numbers of animals, areas of Histosols, and N applied.

The main sources of effluent in New Zealand are derived from dairy cows and people. The amount of N added to effluent ponds on dairy farms is 21 Gg N/y, calculated from the 5.9 kg of N produced in effluent per cow per year (Dairying and the Environment Committee 1996) multiplied by the 3.5 million milked cows. Human sewage produces 20 Gg N/y, based on an intake of 90 g protein/person/day (MOH 2000). We assume approximately 30% of effluent is denitrified, and this denitrification loss has been apportioned to regions based on the number of dairy cows milked, and on the human populations, respectively. A further 60 Gg N/y is deposited on tracks on dairy farms (Ledgard et al. 1999; O'Hara et al. 2003) and it is assumed that 15 Gg N is transformed to ammonia, 15 Gg is buried in the tracks, 15 Gg goes to waters and 15 Gg N is denitrified.

Fires

The loss of N from burning cereal residue is reported in MfE (2004). This has been apportioned to regions according to the area of cropland. Wood burned for heating contains 372 Gg C (MfE 2004) and about 0.6 Gg N; other fires are assumed to release 1.2 Gg N. This has been apportioned to regions according to population.

Forest storage

Since 1980, 900,000 ha of plantation forest have been established. The N stored is estimated to be 15 kg N/ha/y. All other forests and shrubland, which occupy 32% of the land area, have been assessed to be at steady state in terms of their carbon and N storage (C. Trotter personal communication).

Results and discussion

Here we present data giving the first N budget for New Zealand. Nitrogen inputs and outputs are summarised by region in Tables 1 and 2 and summed up nationally (Figures 4 & 5). We limit our discussion to larger inputs and outputs of N and highlight areas of uncertainty rather than to an exhaustive examination of the data collected.

Inputs of N

The total annual input of N for New Zealand is estimated as 976 Gg, or 36.5 kgN/ha/y (Figure 4). The average inputs for each region (total ha basis), however, covered a wide range (12–69 kg N/ha) (Figure 6). The largest input of N for New Zealand was fixation by pasture legumes – mainly white clover; this was estimated at 503 Gg for 2001 (Table 1). This input varied from 29 kg N per ha of pasture in Marlborough, where there are many farms in hill country with extensive grazing, to 75 kg N/ha in Bay of Plenty where

Table 1. Annual inputs of N for New Zealand by region; assuming 2001 was an 'average' year.

	Area Sq km	Pasture legume Gg N	Other BNF Gg N	Atmosphere Gg N	Fertilizer Gg N	Imports Gg N	TOTAL Gg N
Northland	12 696	28	3	8	13	1	53
Auckland	5 104	8	1	3	5	11	27
Waikato	24 500	80	5	22	58	4	168
Bay of Plenty	12 271	20	4	6	13	2	46
Gisborne	8 361	18	2	5	3	0	28
Hawke's Bay	14 172	38	3	10	10	1	62
Taranaki	7 256	27	1	6	15	1	50
Manawatu–Wanganui	22 211	69	3	17	23	2	114
Wellington	8 125	18	2	5	6	4	35
Tasman	9 654	6	2	4	4	0	16
Nelson	424	0.2	0.2	0.1	0.1	0.4	1
Marlborough	10 494	9	1	3	2	0	17
West Coast	23 363	6	3	13	7	0	29
Canterbury	45 039	71	4	22	46	5	147
Otago	31 922	52	2	15	13	2	85
Southland	31 775	54	3	21	19	1	97
Islands	65	nd	nd	nd	nd	nd	nd
TOTAL	267 367	503	39	161	236	36	976

there is intensive dairy farming. The annual reduction in N fixation on dairy farms was estimated at 28 Gg as a result of fertiliser N inputs.

New Zealand is unusual, compared with other temperate countries, in that biological fixation makes up such a large part of the N budget. A series of papers in 1979 assessed this N fixation (e.g., Ball et al. 1979), and these data have been extrapolated to the land classes of New Zealand, to obtain a national figure for N fixation by pasture legumes. Early estimates of N fixation by clovers were 1000 Gg (Syers 1982; Ball and Field 1985) and 1570 Gg (Caradus et al. 1996). Other recent estimates of N fixation for New Zealand pastures were 900 Gg (O'Hara et al. 2003) and 1100 Gg (Bolan et al. 2004a). Our estimate differs from those made previously by recognising the relationship between animal stock units and N-fixation to directly account for the large areas of low-producing pasture and tussock grassland. This approach calculates a lower N fixation by clover in areas that support lower stock numbers. These areas include pastures in hill country, where slope and aspect of the land lead to extremes of wetting and drying, and where there are many steep gullies and terrace scarps. The low N fixation for some of the regions in South Island (Table 1) probably arises from large areas of montane forest and tussock grasslands, together with some areas of low rainfall. Biological N fixation in non-pasture land was relatively small at 39 Gg (comprised of 3 Gg in orchards, 15 Gg in plantation forests, 5 Gg in exotic fixers, and 15.5 Gg in other forests). Due to the uncertainty inherent in N-fixation estimation, and New Zealand's high pastoral N-fixation rates, this term represents a large source of uncertainty in New Zealand's budget relative to other areas of the world (e.g., Boyer et al. 2002).

The use of N fertilizer in New Zealand increased from about 50 Gg in 1989 to 236 Gg in 2001 (Table 1). Most of this increased use, however, has been on pastures on flat to rolling land. The average rate of application of N fertilizer per farm covers a wide range for different regions, with the lowest in Marlborough (3 kg/ha) and highest in Waikato (34 kg/ha) where there is intensive dairy farming. Preliminary data for 2003–2004 show that sales had increased to 342 Gg, and future N budgets would need to take account of this change in N inputs, together with the suppressive effects of N fertilizer on N fixation by pasture legumes. Also, the clover root weevil, an exotic pest, reached New Zealand in 1996, and its range has been increasing throughout the country with resultant decreases in N fixation. Its total impact on the N budget presently, and into the future, is unclear.

Atmospheric inputs of N in rainfall were estimated to be 55 Gg. There have been relatively few measurements, however, of N in rain and by dry deposition in agricultural areas. Data for an area of dairy,

Table 2. Annual outputs of N for New Zealand by region; assuming 2001 was an 'average' year.

	Produce Gg N	Leaching Gg N	Denitrification in soil Gg N	Denitrification in waters Gg N	Ammonia volatilization Gg N	Erosion, burial Gg N	Trees, fires Gg N	TOTAL Gg N
Northland	9	24	9	2	13	6	1.3	61
Auckland	4	7	4	5	4	3	1.0	25
Waikato	34	62	20	8	36	13	2.1	169
Bay of Plenty	8	16	5	2	9	6	1.4	45
Gisborne	4	11	5	0	7	32	0.9	60
Hawke's Bay	9	15	10	1	15	22	1.3	73
Taranaki	10	28	6	3	10	16	0.4	71
Manawatu–Wanganui	19	30	17	2	27	21	1.3	115
Wellington	5	8	5	2	8	5	0.8	33
Tasman	2	7	3	0	3	14	0.7	29
Nelson	0.1	0.1	0.1	0.1	0.1	0.2	0.1	1
Marlborough	2	7	5	0	4	1	0.8	19
West Coast	2	29	4	1	3	18	0.4	57
Canterbury	24	28	27	4	30	6	2.6	119
Otago	14	16	19	2	21	5	1.4	77
Southland	16	19	15	2	23	20	1.0	95
Islands	nd	nd	nd	nd	nd	nd	nd	nd
TOTAL	165	307	153	35	212	190	17	1079

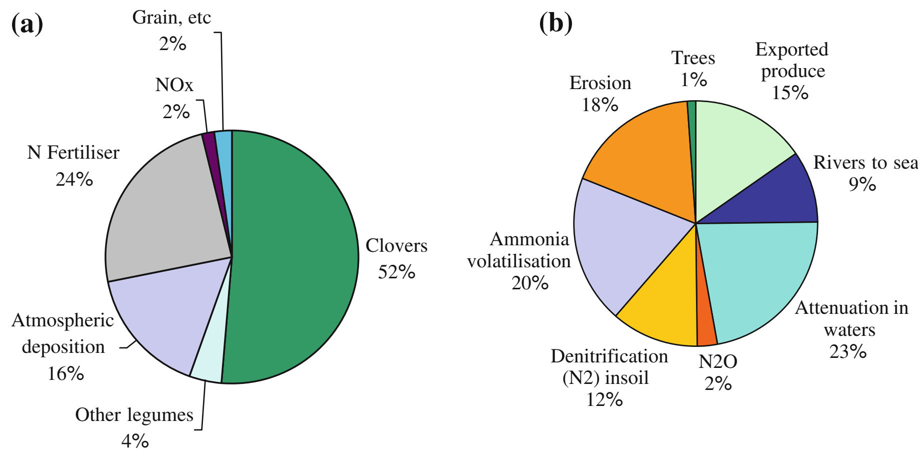

Figure 4. Estimates of (a) nitrogen sources and inputs – total 976 Gg N (36.5 kg N/ha) and (b) nitrogen storage and losses – total 1079 Gg N (40.5 kg N/ha).

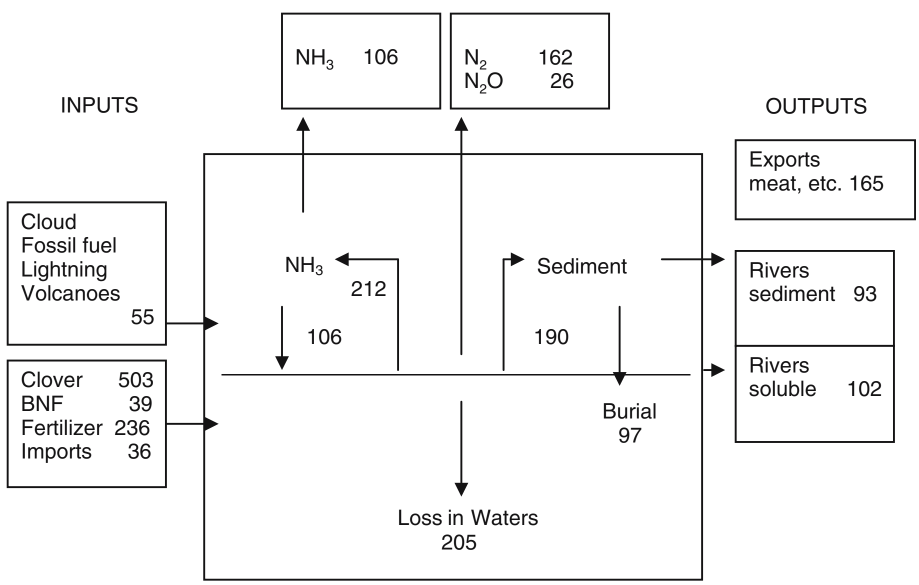

Figure 5. Inputs and outputs of N for New Zealand in 2001, Gg N/y.

sheep and crop farming in Manawatu region showed that up to 5 kg N/ha/y ammonia-N are present in rainfall, and ammonia was also present on diffusion (oxalic acid) collectors (A. Carran personal communication). This suggests ammonia volatilisation occurs in this region, and wet and dry deposition may be more than 1.5 kg N/ha/y. The deposition is more likely to occur in forests, woodlots and shelter belts where there is greater interception of aerosols and gases (Lovett 1994). Ammonia emitted by volcanoes and fumaroles is estimated to be about 0.1 Gg N. Atmospheric inputs of ammonia are discussed further in the section on outputs; the total for New Zealand is estimated to be 106 Gg. When added to N in rain the total is 161 Gg (Table 1). The atmospheric inputs for the regions (total ha basis) vary from 3 kg/ha in Marlborough to 9 kg/ha in Waikato. These atmospheric inputs are generally lower than many places in Europe and North America (Boyer et al. 2002), reflecting New Zealand's lower intensity of livestock and industry. Furthermore, because of the proximity of agriculture to the coast, there is opportunity for ammonia to be deposited into the surrounding ocean rather than on land.

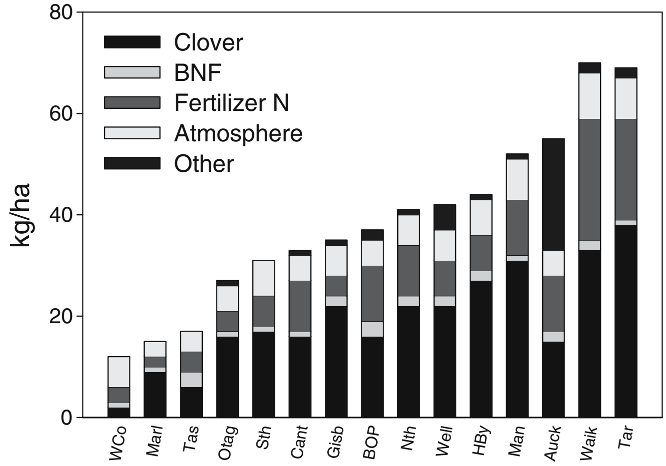

Figure 6. Annual N input for regions of New Zealand (kg/ha).

There are few data on imported N in food and in feed for animals; they are estimated from import data to be about 8 Gg and 2 Gg, respectively (Statistics New Zealand 2004). The 8 Gg compares with the estimated human intake of 20 Gg N for 2001. Agriculture within New Zealand would supply the remaining 12 Gg of N in protein; this has been included as an input to regions with cities (based on population), because N in food is transported from regions to cities. This 12 Gg is also included as an output from the producing regions (within exported produce). The estimated 2 Gg N in imported feed is apportioned to regions based on animal numbers. The input of NO_x from fossil fuel combustion to ecosystems is estimated at 16 Gg N. Since a large proportion of the New Zealand population live in the Auckland region, the food and NO_x inputs for this region make up 11 Gg N of the total 36 Gg N imported (Table 1, Figure 6).

Outputs of N

There are six output categories where the output is >90 Gg Table 2). These include losses from soil to oceans and other waters (102 Gg and 205 Gg), ammonia volatilisation (212 Gg), erosion (190 Gg), exports of produce (165 Gg), and denitrification in soil (153 Gg). Generally the N outputs for each region follow the order leaching > ammonia volatilisation > produce = denitrification = erosion (Figure 7).

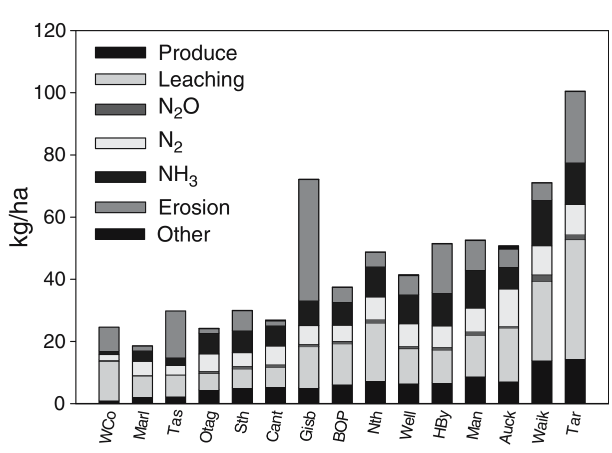

Figure 7. Annual N loss for regions of New Zealand (kg/ha).

Leaching, erosion and transport to oceans

Runoff and leaching of nitrate-N in soils was estimated as 246 Gg (of which 22 Gg was dissolved organic N) from pasture, 17 Gg for crops, 6.5 Gg for horticulture, 14 Gg for native forests and shrubland, and 2 Gg for plantation forests. Since this was an estimate of leaching and runoff, it was generally greater than previous estimates of N 'loads to surface water' of 110 Gg from agriculture, 15 Gg from native forests, and 8 Gg from plantation forests (Cooper (1992). Point sources (sewage, dairy factories, abattoirs) were assumed to be 6.7 Gg (Elliott et al. 2005), and farm tracks generated 15 Gg. Erosional losses of N from soils delivered to the ocean, lakes and reservoirs were estimated as 93 Gg, while losses by burial were estimated as 97 Gg. The Gisborne region has large erosion losses averaged over 20 years due to large areas of steep mudstones under pasture, and several high rainfall events (Gomez et al. 2003).

The total loss of soluble N from soils was 307 Gg. The N leaching (loss to oceans plus attenuation) varied from 5 kg/ha for Otago (a low rainfall region) to 36 kg/ha for Taranaki (a region with high rainfall, porous soils, and intensive dairying). The N leached through subsoils is transported to rivers and aquifers. Some N is lost between the vadose zone and the ocean by attenuation processes such as denitrification, chemical reduction and biological uptake, but there are almost no quantitative data about the rates and distribution of these processes. The amount of dissolved N exported to oceans by rivers was estimated at 102 Gg, with a further 93 Gg exported by erosion. This compares well with the data of Elliott et al. (2005) who reported total N exported to oceans by rivers at 160 Gg N (soluble and particulate N). The difference between N leached and exported to the oceans (307–102 = 205 Gg) could result from denitrification to N_2 in subsoil, denitrification and attenuation in waters, together with N exported to the oceans by direct groundwater discharge. Where streams flow through pasture, there can be considerable attenuation of N; losses of 50% have been observed in streams just 500 m below spring outlets Parfitt et al. 2002). There can also be a considerable temporal difference between N leaching from topsoil and appearance in surface waters. For example, groundwater retention times of more than 40 years occur in Lake Taupo region and other parts of New Zealand. As a consequence, the N loads in rivers in 2001 could originate from potentially lower N inputs in previous decades. The difference between N leaving the topsoils and entering the ocean could be due to all of the possible reasons given above, and it is not possible to estimate how these losses might be spread.

Gaseous losses

Total annual N losses from ammonia volatilisation were estimated at 212 Gg. We estimated half was exported beyond the coastline, and half was retained in a region where it is added to atmospheric inputs. There is a very large uncertainty in this estimate for indigenous forests and alpine zones; this deposition represents a threat to biodiversity in these ecosystems mainly through favouring invasive species (Balmford et al. 2005).

Data for N_2O losses were taken directly from New Zealand's Greenhouse Gas Inventory 1990–2002 (MfE 2004). Losses were given as 41.3 Gg N_2O or 26.3 Gg N. Our estimates of total N losses by denitrification in soil were 153 Gg. Our estimate of denitrification losses (to N_2) at 10 kg N/ha/y for pasture soils accounted for most of the denitrification losses. Again, because of variability of soil type and weather there is a very large uncertainty in this estimate.

Denitrification is assumed to be 1 Gg N from inland and coastal wetlands not connected to agriculture, approximately 22 Gg from effluent ponds and tracks, and about 7 Gg from human sewage. Sewage sludge that is buried is assumed to be 5 Gg giving a total for other effluent losses as 35 Gg.

The loss of N from burning cereal residue is 2.2 Gg, and from wood burned for heating about 0.6 Gg N; other fires are assumed to release 1.2 Gg N.

Produce exported overseas and consumed in New Zealand

Exports of produce containing protein have been a main part of the New Zealand economy since refrigeration was introduced in the 1890s, and today, much of the New Zealand economy depends on agricultural exports. The N exported in 2001 has been calculated as 165 Gg N.

Forest storage

900,000 ha of plantation forest have been established since 1980, and the N stored is estimated to be 13 Gg/y. It is probable this N arises mainly from mineralization of soil N (Giddens et al. 1997), and therefore shows up in the loss from the soil organic matter pool.

Unresolved gains and losses

The difference between outputs and inputs of N for New Zealand was 102 Gg (Tables 1 and 2). For all New Zealand this is 10% of the inputs, and includes unknown soil gains and losses. In NE USA, van Breemen et al. (2002) were able to assess soil storage due to change in land cover, but finally had unresolved gains and losses of +7 to −19% for the different catchments. From our review of the New Zealand literature we believe there are large uncertainties associated with estimating the ammonia and N_2 gas losses, and we may have underestimated these losses. We are confident with our assessment of fertilizer N inputs, and the N fixation inputs are largely constrained by the data in Figures 2 and 3, and also Figure 8 discussed in the next section. Although there is a large uncertainty in our mass balance, soil storage is likely to be finite (Schipper et al. 2004), and may have reached upper limits under high producing pastures. This is consistent with recent measured losses of total soil N under pastoral farming that makes up about 40% of the land area (Schipper et al. submitted). Forest soils on the other hand may be gaining N, from wet and dry deposition of ammonia.

Comparisons with other countries

For 2001, the input of N for New Zealand's two main islands averaged 36.5 kg/ha (range 12–69 kg/ha), which is remarkably similar to the average value (34 kg/ha; range 9–63 kg/ha) for watersheds in the NE USA that have quite different agriculture and population densities (van Breemen et al. 2002). Atmospheric

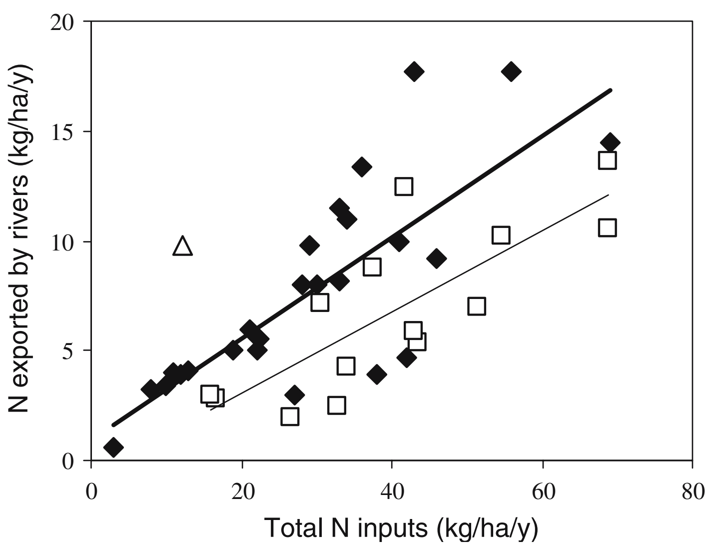

Figure 8. N losses in rivers plotted against N inputs for North Atlantic (diamonds) (Howarth et al. 1996; Boyer et al. 2002) and New Zealand catchments (open squares). The bold line is the regression line for North Atlantic data ($R^2 = 0.61$); the light line is for New Zealand data ($R^2 = 0.63$). The data point for West Coast (triangle) has been omitted from the regression (see text for further explanation).

deposition and import of food and feed, however, were proportionally greater for the US watersheds. The greatest losses in the USA were from denitrification in the landscape (37% of the total losses). For New Zealand, there is considerable uncertainty in the amount of N denitrified in soil and waters. Our estimate is 12% for soils, and up to 20% in waters. The export of N as volatilised ammonia in the USA is estimated at 3% compared with 20% for New Zealand; the difference probably arises from the large numbers of grazing animals in New Zealand. Riverine export is 20% of the total losses for USA (van Breemen et al. 2002), and 10% for New Zealand. At least some of this difference may be accounted for by the fact that New Zealand is a net exporter of 6 kg/ha/y in food and feed, while the NE US is estimated to import 7 kg/ha/y in food and feed.

The riverine data for New Zealand regions (as a proportion of inputs) are shown in Figure 8 together with data for large catchments draining into the North Atlantic (Howarth et al. 1996; Boyer et al. 2002). The West Coast is an outlier, probably because the region has very high rainfall (3 m plus) and a large area of rain forest; this data point was excluded from the regression. The riverine data for New Zealand catchments (as a proportion of inputs) are lower (17%) than data for catchments draining into the North Atlantic (25%). This could arise from New Zealand having lower population densities, less discharge of effluent to rivers, fewer feedlots, and less cropping. New Zealand has also had extensive agriculture for less than 150 years; intensification has increased in the past 10 years with greater fertiliser inputs. The effects of this land use change may not yet be apparent in New Zealand rivers as groundwater retention times can be decades. The relationships between N inputs and riverine export of N across both our geographical regions and those of Howarth et al. (1996) and Boyer et al. (2002) are quite similar, suggesting that the underlying drivers, such as leaching and runoff are similar. There are, however, differences in the emphases of the different processes since they vary with climate and land use. For the regions of New Zealand generally, the regions with the greatest inputs and losses (kg/ha) are those with intensive land use. For example, Taranaki and Waikato regions have large area of high producing pasture. For Auckland, however, the N budget is strongly influenced by the large human population.

Only about one third of the reactive N added to New Zealand ecosystems is transformed back to N_2 gas (denitrification in soil and water). Further denitrification may occur once rivers discharge to sea but this is unquantified. This suggests reactive N is accumulating in New Zealand's productive and indigenous ecosystems and aquifers, like many other parts of the world. Impacts of this excess N are seen in some parts of New Zealand, such as Taupo and Rotorua lakes. As the global focus on N increases, it is likely we will need a better understanding of the stocks and flows of N. While we have not looked at temporal trends of N, it would appear N inputs are increasing as greater amounts of fertiliser are being applied.

Conclusions

We have completed a preliminary N budget for New Zealand, and have apportioned the national budget across regions. Inputs of N are key to New Zealand's food production and play an important role in the economy. Major N inputs were BNF, fertiliser and atmospheric deposition. Major fluxes out were leaching and attenuation, ammonia volatilisation, erosion, export of produce, and denitrification in soil. A major source of N loss in grazed pastures was derived from deposited dung-N and urine-N that was leached, volatilized and denitrified. More work is needed on the relative contribution of dung and urine to these pathways (Bolan et al. 2004b).

More work is also needed on spatial representation and temporal variability of N flows and associated problems. In particular, there has been little work on scaling the data on ammonia and N_2 to the regions. Important issues requiring further research are the N losses in subsoils and groundwater, and the relative losses by leaching, denitrification and volatilisation on different soils types and in hill country, taking into account drainage, slope and aspect. For this preliminary budget we have not attempted to derive errors but this should be a focus of future investigation. While N budgeting may demonstrate the scale and location of possible imbalances, there is also an urgent need for practical solutions to manage N and/or reduce inputs while maintaining production.

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