Roger L Parfitt evidence

Paragraph 42

Question from Commissioner van Voorthuysen about why we used 24 degree slope.

We made the following assumption:

- To reduce erosion, pine is planted on soils on soft rock with slopes >24%, so pine plantations increase from 2 million ha to 2.9 million ha, farm and pasture ha decrease by 0.9 million ha, SU decrease by 5 for each ha of pine

This assumption was copied from our paper - Parfitt RL, Schipper LA, Baisden WT, Mackay AH. 2008. Nitrogen inputs and outputs for New Zealand at national and regional scales: past, present and future scenarios. Journal of the Royal Society of New Zealand 38: 71–87.

It should read 24 degree slope.

The assumption was a simple pragmatic assumption to set up a part of our national cap-and-trade scenario.

Ron De Rose reviewed previous work in this area for the POP in his paper “Slope limitations to sustainable land use in hill country prone to landslide erosion”. He gives a range of 20 to 33 degrees where slope are prone to landslide erosion; so we are near the middle of the range.

SLOPE LIMITATIONS TO SUSTAINABLE LAND USE IN HILL COUNTRY PRONE TO LANDSLIDE EROSION

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Introduction

The identification and implementation of sustainable land use is currently a major challenge for land researchers and planners in New Zealand. Unfortunately this process is hindered by confusion about the meaning of sustainability. Many definitions exist and these tend to conflict because of different emphasis on either, biophysical (ecological), or socioeconomic aspects (Blaschke *et al.* 1991). The New Zealand Resource Management Act (1991) provides a useful definition, with the central concept being "managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their health and safety while: (a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; (b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems, and (c) avoiding, remedying, or mitigating any adverse effects of activities on the environment". In agricultural systems, one aspect of resource management involves sustaining the biological and physical resources on which farm productivity depends, while at the same time minimizing detrimental effects to the environment. It is important, therefore, to identify those land use practices which lead to degradation of natural and physical resources.

One study in eastern Taranaki hill country (Blaschke *et al.* 1992a, DeRose *et al.* 1993) identified sustainable land use classes on the basis of slope. These classes reflected increased slope instability after deforestation, and decline in potential pasture production caused by subsequent landslide erosion. This was a natural consequence of the relationship between landslide activity and slope angle which is well established in the literature on both theoretical (slope mechanics) and empirical grounds (Crozier *et al.* 1980). Hillslopes with an average slope above 28° were identified as being particularly prone to landslide erosion (DeRose *et al.* 1993, DeRose 1994). Further slope division was somewhat arbitrary, although slopes above 32° had a much higher landslide density, compared with the modal class of slopes between 28 and 32°. While these results have been particularly useful in helping to define land use sustainability on hard Tertiary sandstone lithologies (Blaschke *et al.* 1992b) they cannot be applied without qualification in other regions. This partly reflects the spatial limitations of extrapolating results from small experimental basins, but also reflects the fact that other adverse land use effects (i.e., nutrient runoff) may be as, if not more, important than landslide erosion. A classification of landforms based on nutrient runoff, for example, may not necessarily co-inside with a classification based on erosion potential.

Regional Councils now intend to adopt slope angles as a means of controlling land use activities on steep hill country (TRC 1993, MWRC 1993). This may be appropriate, but only once all aspects of sustainability have been considered, and where slope angles are based on sound research findings on the adverse effects of current land use activities. The purpose of this article is to review current information on the slope dependency of landsliding for other regions in the North Island.

Spatial patterns of landslide erosion

Hill country, below 1000 m in elevation, occupies over 40 % of New Zealand's land area (Blaschke *et al.* 1992a), and shallow landsliding has been recognised here as a major process leading to soil depletion, to decline in the productive potential of farmland (Lambert *et al.* 1984, Douglas *et al.* 1986, DeRose *et al.* in press), and to increased sediment and nutrient loadings in waterways. The density of shallow landslides is typically 3 to 10 times greater under pasture than under either native or exotic forests (Laffan 1979, Salter *et al.* 1981, Blaschke *et al.* 1992a, Hicks 1990, 1991, Hicks *et al.* 1993, DeRose *et al.* 1993, 1995, Phillips *et al.* 1990, Marden *et al.* 1989, 1992, Bergin *et al.* 1993, Marden and Rowan 1994). In specific situations, 20 fold increases in landslide density have been observed following deforestation (O'Loughlin and Pearce 1976). Increased landslide occurrence reflects decreased slope stability due to removal of the reinforcing strength of tree roots (O'Loughlin and Ziemer 1982), and due to changes in slope hydrology. Those results are also consistent with sediment yields from paired catchments (Hicks 1988) and studies of long-term lake sedimentation (Page and Trustrum *in prep.*), which suggest increases in sediment production from drainage basins of 6 to 8 times under pasture.

Landslides tend not to be evenly distributed within regions, and are often clustered into 'families' related to specific triggering events. These are usually high intensity storms (Eyles and Eyles 1981) producing rainfall depths above certain critical threshold values (Crozier 1986) that vary according to local pre-conditions to failure. In a number of storm damage assessments, Hicks (1990, 1991) and Hicks *et al.* (1993) repeatedly demonstrated that the way in which landslide are distributed on hillslopes is much the same between different regions. That is, most hillslopes have little or no erosion, and progressively fewer hillsides have increasingly higher levels of erosion. In statistical terms this pattern of erosion follows a bimodal distribution. Comparisons of rainfall depths to area eroded for individual storm events (Salter *et al.* 1981, Crozier 1986, Eyles and Eyles 1981, Eyles *et al.* 1978) show that, in general, the highest levels of erosion tend to correspond with storm centres where rainfall densities and totals were highest. Furthermore, site specific studies which have compared the same hillsides under different rainfall conditions (Eyles 1971, DeRose 1994) have shown that landslide densities tend to be higher in storms with higher total rainfalls. Page *et al.* (1994a) also inferred increasing erosion with increasing storm intensity from the thickness of individual sediment pulses, which showed good correlation with total rainfall for individual storms over the last 100 years.

Within areas that have had the same total rainfall, there is usually a great deal of variation in landslide densities, with intact hillsides interspersed among others that have eroded (Hicks *et al.* 1993). This variability can be attributed to the different susceptibility of individual hillslopes to failure. Controlling factors are likely to be those that influence slope stability by altering the balance between shear strength (resistance) and stress (shearing) forces (Crozier 1986). These include vegetation type (root strength), soil cohesion, internal angle of friction of soil, slope angle, weight of soil (depth, bulk density), and slope hydrology (development of pore water pressure) which is in turn controlled by drainage characteristics of the soil. Most landslides would be expected to occur in regions where soils are 'weakest' and prone to frequent soil saturation: on steep hillsides that are convergent in form, lacking a forest cover, and where soils are deep and underlain by rocks which weather to produce a regolith with low friction angle and soil cohesion when saturated. There are very few studies in New Zealand that have examined in any detail the relationship between landslide density and variation in critical factors for slope stability across a range of landforms, although the effect of root strength on slope stability has been investigated (O'Loughlin and Ziemer 1982, Phillips and Watson 1994). Some studies have examined in detail the relationships between slope form and landslide form and location (Eyles 1971, Blong 1974, Eyles *et al.* 1978, Crozier *et al.* 1980, DeRose *et al.* 1991, DeRose 1994). A larger number of studies (Selby 1979, Appendix 1) have measured the slope angle of landslide failures, but not all have measured a sufficient number, to construct slope distributions for large areas of hill country.

Slope frequency distributions

There is usually a well-defined limiting slope for a given set of lithological, soil, hydrological, and climatic conditions below which landslides do not occur. Figures 1, 2 and 3 show frequency distributions of slope angle for landslides (usually shear plane slope) which have been summarised from various surveys. These show that the limiting slope for landslide occurrence is between 18 and 24° for most areas of hill country in the North Island. Above this limiting slope, there is an increase in the frequency of landslides, reaching a maximum between 26 and 40°. The frequency distribution of slope for landslides is similar to that of slope for the hillslopes on which landslides occur (i.e., parent slope). Consequently, the decrease in frequency of landslides on steeper slopes reflects a decreasing proportion of these hillslopes within drainage basins, and there is usually an upper slope limit of between 50 and 60°. The mean slope of landslide distributions is typically between 29 and 39° (Appendix 1), with the notable exception of greywacke lithologies in the Wellington region (Lawrence *et al.* 1982). Slope angle distributions (Figs. 1 to 3) also show that few landslides occur at, or immediately above, limiting slopes. For the purpose of comparison between regions, it is more useful to consider a threshold slope above which 95% of landslides occur (Appendix 1). In this case most landslides occur on slopes above 20 to 33° for most hill country areas.

The majority of surveys investigating landslide slope have been conducted on pasture hillslopes, and while some have been conducted under forest (Pain 1968, Laffan 1979, Jane and Green 1983, Blaschke 1988), results are often not directly comparable because forested areas invariably remain on steeper landforms. Any difference in slope frequency distributions usually reflects a difference in the frequency distribution of parent slopes. For example, Pain (1968) showed that the mean slope for landslides was 4.4° steeper under forest, but indicated that forested areas were on steeper hillslopes. Similarly, Blaschke (1988) measured a steeper mean for landslides under forest compared with surveys by DeRose *et al.* (1993), but there was also a similar difference in the mean slope of hillslopes on which the surveys were conducted (Appendix 1). Hence, although landslide densities are clearly lower under a forest cover, there is no evidence to suggest that the slope distribution, or limiting slope, for landslides is any different between forested or pasture hillslopes.

The results summarized in Appendix 1, however, suggest that differences in slope distributions may relate to lithology. Landslides occur on gentlest slopes where hillslopes are underlain by soft Tertiary mudstone and sandstone lithologies. These rock types occur extensively along the east coast of the North Island and have been studied in the following catchments: Pakaraka (Crozier 1980), Tangoio (Eyles 1971), Lake Tutira (Page *et al.* 1994b), Otoi (Harmsworth *et al.* 1987), and Emerald Hills and Arai Matawai (in 't Veld and de Graaf 1990). O'Byrne (1967) considered that, on soft calcareous mudstone, serious slipping started on moderately steep slopes between 20 an 25°. Lowest overall slope angles have been measured for landslides triggered during Cyclone Bola, probably one of the most extreme rainfall events to occur this century. Mean slopes were 27.4° (in 't Veld and de Graaf 1990) and 30.6° (Page *et al.* 1994), and 95% threshold slopes were 18 and 21°, respectively, for landslides triggered during this Cyclone. Eyles (1971), whose survey at Tangoio included the 1938 ANZAC Day event (of similar recurrence interval to Cyclone Bola), measured a mean slope of 32.4°, and 95 % of landslides occurred on slope segments steeper than 24°. For less intense, more frequent storm events, mean slopes for landsliding range from 33° (Crozier 1980) to 36°

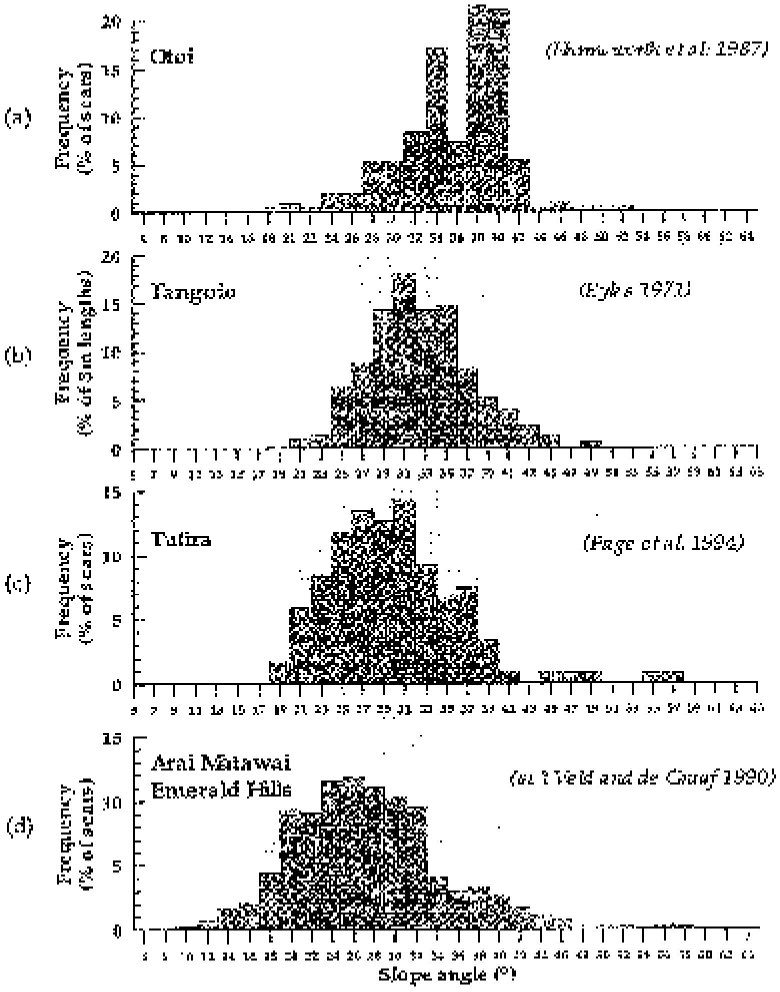

Fig 2: Frequency distribution of landslide slope angle on soft Tertiary mudstone and sandstone.

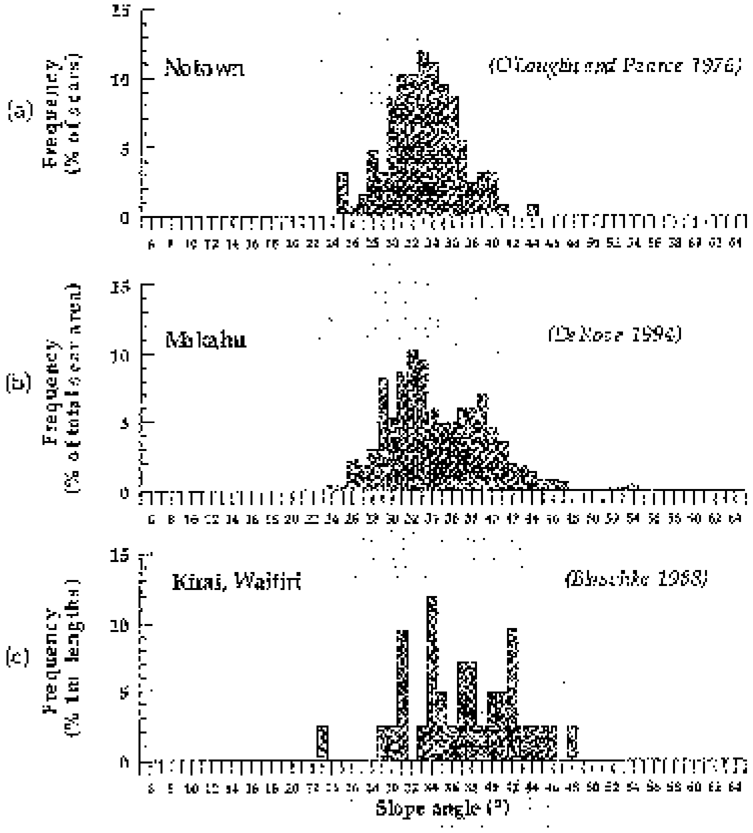

Fig. 2: Frequency distribution of landslide slope on hard Tertiary sandstone lithologies.

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underestimate the extent of landsliding on steeper hillslopes (>32°). However, landslide density information (Fig.4) confirms that slope frequency data (Fig 2b) can be used to establish approximate slope threshold conditions for landsliding, but suggests that further slope sub-division is somewhat arbitrary.

Similar conclusions can be drawn from other surveys. Eyles (1971) indicated an increase in the proportion (20 and 56 %) of hillslope profiles covered by landslide scars when slope increased from 24 to 30°. In addition, hillslope segments steeper than 30° had most of their length covered by landslide scars, suggesting a high density of landsliding. Salter *et al.* (1981) showed that the density of landsliding was greatest for 21-25°, and 26-35° slope classes. These results are not particularly useful, however, because of the broad slope intervals. Laffan *et al.* (1979) proposed a classification of landslide potential in the Charleston-Punakaiki region based on slope angle of landforms: flat to rolling hillslopes (0-12°) had a negligible or slight potential; moderately steep to steep hillslopes (13-30°) had a moderate potential; and steep and very steep hillslopes (>30°) had a severe to very severe potential for landsliding.

Conclusions

Previous research has established that landslide erosion in many areas of steep hill country is much more extensive on pasture hillslopes than under either exotic or native forests. The results summarized in this article, show that in addition, landslide erosion is confined to hillslopes above certain slope angles. While it is clear that hillslopes steeper than 30° are particularly prone to landslide erosion in most areas of hill country, hillslopes gentler than 20° remains largely unaffected, and hillslopes between 20 and 30° may have different landslide susceptibility, and resultant landslide densities, depending on the local soil and hydrological conditions that affect slope stability. In particular, threshold slopes for landsliding vary according to lithology as follows: above 20° on hillslopes underlain by soft Tertiary mudstone and sandstone, Miocene andesite, and deeply weathered greywacke; above 27-28° on hillslopes underlain by hard sandstone; and above about 33° on hillslopes underlain by hard greywacke. Where deep colluvial fills overlie greywacke rocks, the slope limitations may be similar to Tertiary lithologies.

In order to reduce soil erosion and mitigate the hazard from landsliding, reforestation of steep slopes should be considered as a preferred land use option. Landslide erosion, however, is only one aspect of sustainability in hill country, and all aspects of land management should be examined before considering slope angle as a means to regulate particular land use activities. The surveys summarised in this article, nevertheless, provide useful information about slope susceptibility to landslide failure that could help set guidelines for future effective sustainable land use in North Island hill country.

Slope defined sustainability criteria for landslide risk

Frequency distributions of landslide slope angle are by themselves insufficient for defining limitations to land use in steep hill country. Additional information is required about the density of landsliding in relation to slope angle of hillslopes, and this may not be apparent from frequency distributions for landslides alone. Unfortunately, very few surveys have measured this relationship. One example in Taranaki hill country (DeRose 1995), showed a linear increase in the average density of landslides on hillsides, with increasing mean slope above 27-28°. These results (Fig 4) suggest that frequency distribution of landslide slope angles (Fig. 2b) tends to over-estimate the extent of landsliding on the modal class (28-32°) of hillslopes, and greatly

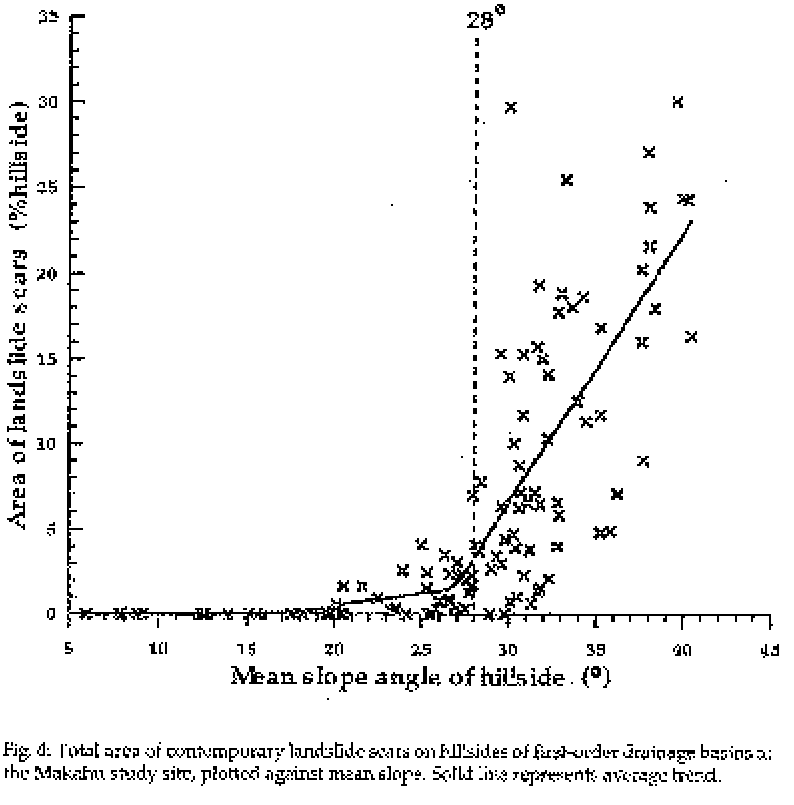

Fig. 4: Total area of contemporary landslide scars on hillsides of first-order drainage basins at the Makahu study site, plotted against mean slope. Solid line represents average trend.

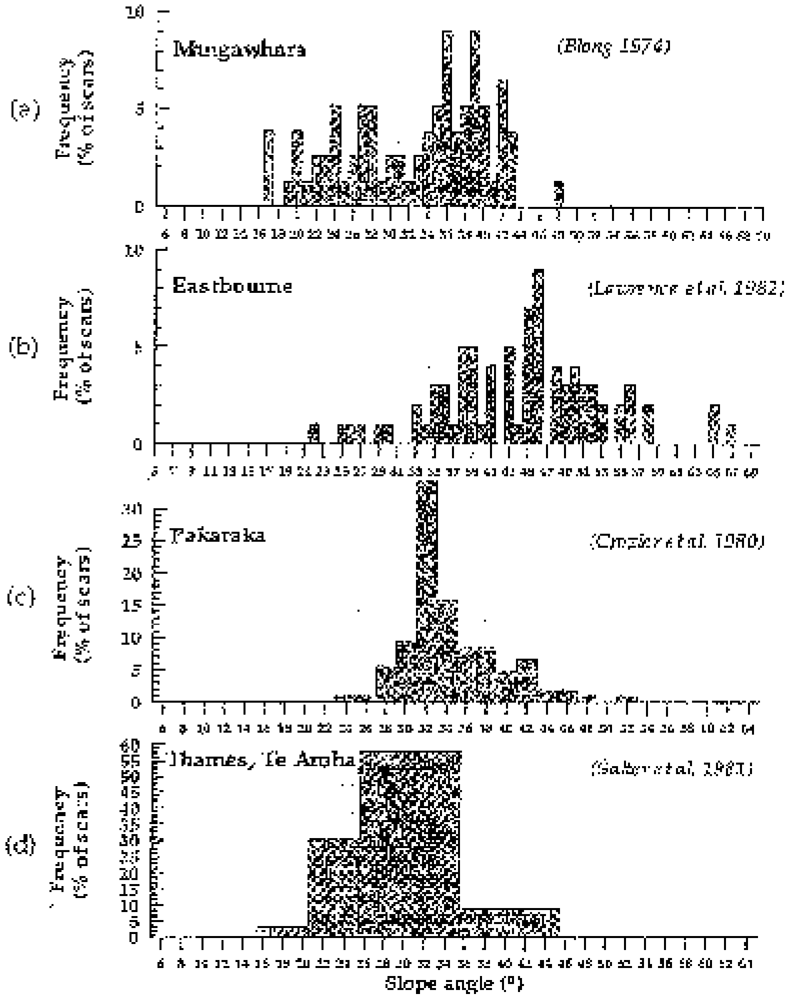

Fig. 3: Frequency distribution of slope angle for various lithologies: (a) weathered greywacke; (b) hard greywacke; (c) soft Tertiary mudstone/sandstone; and (d) Miocene andesite.

(Harmsworth et al. 1987), and threshold slopes range from 24 to 28°. Clearly, slope distributions of landslides relate to rainfall conditions, with the larger magnitude rainfall events producing a greater number of landslides on gentler slopes.

Slope angle distributions appear to be similar for crushed Cretaceous sandstones and alternating mudstone and sandstone lithologies. O'Loughlin and Zhang (1986) indicated that shallow debris slides and avalanches at Mangatu Forest occur predominantly on slopes over 25°. Phillips (1988) measured a mean slope of 35° for landslides in the Waitahaia catchment. The standard deviation for the slope distribution was 7°, suggesting that most landslides occurred above 21°.

On hillslopes underlain by hard Tertiary sandstone lithologies, landslides occur more frequently on steeper slopes when compared to softer lithologies (Fig 1). Mean slopes for landslides are 32 to 35° with 95 % of landslides occurring on slopes above 27-28° (DeRose 1994, O'Loughlin and Pearce 1976). The threshold slope for landsliding was found to decrease from 35 to 28° with increasing rainfall intensity (DeRose 1994) at Makahu.

Research on hillslopes underlain by hard Jurassic greywacke (Eyles *et al.* 1978, Lawrence *et al.* 1982) indicates, that although some landslides occur down to 20°, 95% of landslides occur on natural slopes (as opposed to cut and fill) above 33 to 36°, indicating an even steeper threshold slope compared with hard Tertiary sandstones. Mean slopes for landsliding were 44.5° in Eastbourne (Lawrence *et al.* 1982), and 49° in and about Wellington city (Eyles *et al.* 1978). Crozier *et al.* (1990), investigating the stability of colluvium-filled bedrock hollows in the Belmont area, found that slopes failed in CBDs where colluvial fills were deeper than 1.5 m and slope in most cases exceeded 25°. Where greywacke rocks are deeply weathered and have altered to clay rich regolith, landslides occur more frequently on gentler slope angles, and frequency distributions are more comparable with soft Tertiary lithologies (Fig. 3a). Mean slope for landslides vary from 28.6° (Pain 1968) to 34° (Selby 1976), and a threshold slope of 20° is interpreted from slope data in the Mangawhara Catchment (Blong 1974)

Few other lithologies have been investigated which yield suitable slope information. Salter *et al.* (1981) investigated landslide density on hillslopes underlain by predominantly weathered soft Miocene andesite over a large area in the Thames - Te Aroha region. Although slope intervals were broad (Fig.3d), being derived from the dominant slope in the NZLRI, most landslides occurred on slopes exceeding 20°. The slope angle distribution is similar to those from soft Tertiary lithologies. Landslides on Miocene andesite in the Kaimai Range (Jane and Green 1983) have a limiting slope of 15°, and mean slopes of 31 to 42°, depending on landform elevation.

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Appendix 3: Landslide surveys

Author	Site	Lithology	Vegetation	Survey type	Period covered (Date)	Area surveyed (ha)	Area eroded (%total)	Landslide scar				Parent slope (°)
								N	Mean slope (°)	Range (°)	95% slope (°)	
Blong (1971)	Mangawhara Valley	Weathered Mesozoic greywacke	Pasture	Profiles	1966-67	-	-	27	32.4	17-48	20	29.5
Blaschke (1989)	Waihi-Kirai, Taranaki	Tertiary Sand-Slst	Native forest	Plots	c.1000-1986	1	30	8	38.7	23-53	30	35.0
Crozier et al. (1980)	Pakuratahi, Wairarapa	Tertiary Mst,Slst	Pasture	Point/seg	1977	24	9.7	110	c.33-34	20-58	28	31
DeRose et al. (1993)	Makahu, Taranaki	Tertiary Sand Sslst	Pasture	Profiles	1965-90	80	21	50	33.3	21-49	28	32.2
DeRose (1994, 1995)	Makahu, Taranaki	Tertiary Sand Sslst	Pasture	DEM	1905-90	120	6.5	620	33.6	21-54	28	26.5
Eyles (1971)	Tangoio Reserve	Pleistocene Ss:Slst	Pasture	Profiles	1938-71	162	17	~250	32.4	21-49	24	24.4
Eyles et al. (1978)	Wellington City	Jurassic greywacke	Gorse-scrub	Geol/map, slope profile, air photo	1974 1976	- -	- -	30/1149 400	39	27-59	31	41
Harmsworth et al. (1987)	Otoi Catchment	Tertiary Mst,Sst,Sslst	Pasture	Transect	1988	156	2.2	205	c36	18-61	24	-
Harvey (1975)	Port Hills, Canterbury	Loess/Basalt	Pasture	Point/area	1975	-	0.0-1.2	513	c35	25-60	c.28	20-40
ter Veld and De Graaf (1989)	Emerald Hills-Arai Te Marawai	Tertiary Mst,Sdst	Pasture	Transect	1988	333	4.3	567	27.4	6-62	15	-

Jane and Green (1983)	Kaimai Range	Miocene andesite	Native forest	Aerial dot grid	1948-71	-	0.1-20	>159	31.5-62	15->60	-	-
Loftus (1979)	Punakaiki-Charleston	Tertiary sst Granite/gneiss /greywacke	Forest-clear fell	Air photo	-	2,050	0.1-5	>63	>30	17->30	-	-
Lawrence et al. (1982)	Eastbourne, Wellington	Loess/Greywacke	Gorse-scrub	point/scar	1977 cut/fill natural cliff			76 31 12	50 42.5 99	28-80 29-58 30-65	53 56 41	- - -
McConchie (1977, 1980)	Stokes Valley		Urban		1976	1270	0.3		>33	15-		
O'Loughlin and Pearce (1976)	Mokihinui, West Coast	Tertiary hard Mst, Slst	Clear fell	Point/scar	1965-75	350	<10	127	32	25-44	27	-
Page et al. (1994)	Tutira, Hawke's Bay	Tertiary Sst, Mst	Pasture	Air photo dot grid	1988	5206	4	126	30.6	24-59	33	-
Pain (1968)	Tararua Range	Greywacke	Forest/pasture					29 25	33.2 28.6			
Phillips (1988)	Waitahaia, East Cape	Cretaceous Sst, Sst/Mst	Pasture/scrub/forest	Air photo point/scar.	1980-82	1670	0.5-1.6	116	25	-	21	-
Salter et al. (1981)	Tauranga-Te Aroha	Miocene andesite	Pasture/scrub /forest	Air photo	1981	81,000	-	2090	-	5->15	30	-
Selby (1976)	Hapuakohe Range	Weathered greywacke	Pasture	point/scar	1973	-	4.4	50	36	-	-	-

Sdst = sandstone, Sst = siltstone, Mst = mudstone, *DEM = digital elevation model

TREES FOR SURVIVAL - SO WHAT

Trees for Survival has grown from a 3 year trial project, involving 3 schools producing only 2000 plants per year, into a national programme with units in 40 schools growing at least 25,000 plants per year. In addition, although it still often involves Rotary and other service clubs, it is now a Charitable Trust, rather than a Rotary Programme.

Now that the project is no longer a "Rotary Project", placement of a unit in a school is not necessarily reliant on involvement of a Rotary Club. What is critical, is that there is a commitment by some group to provide ongoing support to the school - that group may be a Regional Council, Landcare Group, another Service Club etc. Such a group will meet the initial cost of placing a Plant Growing Unit in a school ($3,000), plus the ongoing costs of growing seedling ($2-300 per year), and show ongoing interest and support of the project.

The Trees for Survival Management Committee has been established to provide ongoing coordination and assistance to all those involved with the project. This includes a regular newsletter, a "Growing Plants Successfully" video, and provision of 'trouble shooting' advise for units.

REGIONAL COUNCIL'S BENEFIT

Because the aim of Trees for Survival is to plant trees for erosion control, rather than straight beautification or revegetation, Regional Councils and other agencies can benefit from support of the units, in getting trees planted for erosion control, at a minimum financial cost to the agency.

For example, in the Auckland Region, the Soil Conservator assists the schools involved with the programme to identify farms to plant on, helps coordinate the planting day, and provides advise on species selection, establishment methods, and other issues. This requires a commitment of time, but very little financial input.

In addition, the ARC have partially sponsored the placement of a unit in a school associated with a Landcare Group, with the allocation of the plants grown by the unit being the responsibility of the Landcare Group. This would also tie in well with Beachcare / Coastcare / any Care Group.

In the Bay of Plenty, Environment BOP River Engineers have placed a unit in the Galatea School, to grow

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Nitrogen inputs and outputs for New Zealand at national and regional scales: past, present and future scenarios

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Abstract The Nanjing Declaration on Nitrogen Management calls for national governments to optimise N management by several strategies including assessment of N cycles. In New Zealand, reactive N continues to be added to the environment mainly by biological N fixation, and increasingly from N fertiliser additions. Here, we extend our work on N budgets in 2001/02 for New Zealand (267 000 km^2), at both national and regional scales, to 1861, 2020 and 2050. We first attempt to estimate the N cycle for 1861, the year of the first census and when European settlers were beginning to clear large areas of forest for agriculture in some regions. For the future, we adopt two scenarios: agricultural production increasing at 3% p.a., and a "cap and trade" scheme for N. These scenarios provide instructive results by projecting two very different potential policy directions into the future; they do not represent predictions. The 3% growth scenario warns of ever-increasing N loads on the environment. The cap and trade scenario (such as may be introduced by regional councils) supports the development of a mechanism by which farmers might constrain N losses without regulations being introduced. These scenarios seek to provide farmers, industry and regulators with an understanding of the large range of future possibilities. This paper highlights the urgency with which primary industry must move away from increased production *per se* to systems where value is added to products.

Keywords ammonia; clover; denitrification; erosion; nitrate; rivers; sediment

INTRODUCTION

Much of the New Zealand economy depends on agriculture and this, in turn, largely depends on the nitrogen (N) status of the soils. The Nanjing Declaration on Nitrogen Management, signed in Nanjing in October 2004, calls for national governments to optimise N management by several strategies including assessment of N cycles (Iniforum 2004). Here, we make scenario-driven projections of the national and regional N cycles out to 2050 to provide farmers, industry and regulators with an understanding of a range of future possibilities. We deliberately select two very different scenarios to bracket the large range of future environmental outcomes. Scenario approaches are now well known in the context of Intergovernmental Panel on Climate

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Change (IPCC) climate change assessments, and the evaluated scenarios are intended to represent projections of plausible, simple and transparent assumptions. Individual scenarios constructed in this context should never be interpreted as predictions of the future.

New Zealand is unusual in that the agricultural sector, a large part of which is pastoral farming, is deregulated, unsubsidised, highly profitable, and accounts for 55% of exports and 17% of the gross domestic product. There is a drive towards increasing "value-added" food exports. Since the removal of subsidies in 1984, production has greatly increased, and the value of economic activity in the farm sector has increased by over 40% up to 2000 (Federated Farmers 2002). Over this period, lamb weights have increased by 13%, ewe fecundity has increased by 25%, and the average milk fat yields from dairy cows have increased by 20%. The increased production in dairy farms is partly due to the increased use of N fertiliser. Nationally, this increased rapidly from 50 Gg in 1989 to 350 Gg in 2005, as opposed to the trends reported by most OECD countries (OECD 2001). The average dairy farm is approaching the use of about 150 kg N/ha fertiliser per year. If the New Zealand economy is to continue to achieve growth through the agricultural sector growing more forage, then more N inputs will be required. Here, we consider a scenario with 3% annual growth in animal production. This is a conservative position of the goal of 4% growth in returns set by the national dairy cooperative (Fonterra) which also involves growth in animal production.

On the other hand, since export of nutrients from land to water is increasing (Hamill & McBride 2003; Vant & Smith 2004; Scarsbrook 2006) some regional councils are introducing schemes that call for assessment of nutrient budgets on farms. Environment Waikato is introducing the Lake Taupo Variation where N inputs will be capped for the Lake Taupo catchment, and Horizons Regional Council has introduced in their draft One Plan, the requirement for a Farmer Applied Resource Management strategy to establish limits on the N and phosphorus leakage from intensive land uses in priority catchments, based on the natural capital of soils in the catchment. Both regional councils are recommending that farmers use the Overseer® (AgResearch 2005) model to obtain nutrient budgets.

Our work also follows that of Galloway et al. (2004) who assessed global N cycles for 1860, 1990 and 2050. Galloway et al. (2004) used global scenarios generated for the IPCC to bracket a range of realistic projections. It is critical to understand that scenario-based projections presented here and by Galloway et al. (2004) are not predictions. Instead, we develop model-based projections based on clear and explicit assumptions that bracket the range of possible futures. For this work, no predetermined economic scenarios were available for New Zealand. Thus, we define two future scenarios designed to illustrate the potential differences resulting from very different environmental policies. Neither scenario represents "business-as-usual" or a baseline. Instead, we use our models to project an aggressive intensification of agricultural production as well as a "cap and trade" approach to N management.

We estimate flows of N into and out of regions in the North and South Islands of New Zealand for the years 1861 (the year of the first census), the season 2001/02, the last year for which there are many complete datasets, and the years 2020 and 2050. The 2020 and 2050 projections represent two scenarios: (1) annual agricultural production growth of 3%, and (2) capping and trading of allowable N inputs. Some of the data we have used for 2001/02 are an average of several years, ranging from 3 to 20 years. We include annual flows into and out of plant and soil ecosystems, including livestock, 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 livestock grazing systems. Losses go to the groundwater, to the oceans, to the atmosphere, as exported produce, and by burial. We highlight those N stocks and flows that are reasonably well understood or at least well constrained, and also identify those that are poorly known, to point to areas for further research.

BACKGROUND INFORMATION FOR THE N CYCLE IN NEW ZEALAND

Climate and regions

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 one year in three over one-third of the pastoral land, generally on the East Coast.

New Zealand's 16 regional authorities (councils) were established in 1989, and their boundaries are based on water catchment areas (Fig. 1).

Wet and dry deposition

There is little data available for deposition of N in rainfall over New Zealand but where measurements are available they are generally in the range 1–5 kg N/ha per year (Nichol et al. 1997; Vant & Gibbs 2006). There are some notable exceptions. Where the rainfall is over 2 m, the input is in the range of 3–6 kg N/ha per year (Neary et al. 1978; Mosley & Rowe 1981; Baker et al. 1985; Oyarzún et al. 2004) and it probably increases with rain. These values have been used here for regions of high rainfall. The general input of N by wet deposition is taken to be 1.5 kg N/ha per year in the absence of contributions from sources such as agriculture within a region.

Ammonia is emitted by volcanoes and fumaroles, the amount emitted at the Wairakei geothermal field being about 2 tonne of N per year (Ellis & 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 estimate that 50% is added by dry deposition onto forests and trees (Parfitt et al. 2006).

Erosion

Erosional losses from soils delivered to the ocean, lakes and reservoirs were estimated for 2001/02 by multiplying the national erosion C loss surface averaged over 12–20 years (Scott et al. 2006) by a national soil C:N ratio surface in ArcGIS. The model of Scott et al. (2006) is consistent with the recent erosion model of Dymond & Betts (unpubl. data) and gives us more confidence in the numbers we have used. 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 Project (all held at Landcare Research). Burial in rivers and on hill slopes also removes N from the terrestrial environment, and we assumed burial is equivalent to the losses to the sea. For the West Coast of the South Island, however, the Alps are adjacent to the ocean, and because of the steep slopes we assume there are no zones for burial of sediments. For the Gisborne region, a correction has been made to recognise that half the eroded C and N is derived from deep bedrock (Gomez et al. 2003).

Denitrification

The annual loss for indigenous forest is 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 per year (Groffman 1994). Pro-rata amounts have been calculated for regions based on areas of Histosols and wet soils.

SCENARIOS

N inputs and outputs for 1861

In 1861 the indigenous population (Maori) was 56 000 (McKinnon 1997) and the population of settlers was 99 021 (Evans 1956); 30 000 of the settlers were in six towns. There were 2.76 million sheep, 193 285 cattle, 43 270 pigs and 28 275 horses. The settlers had planted 19 735 ha of grain crops and 5247 ha of root crops, and had established 63 940 ha of sown pastures (Evans 1956). The Maori people were growing commercial crops as well as cultivating crops in gardens. The area of forest was estimated to be 13 million ha, the area of "open" land was 11 million ha, and tussock grassland was 3 million ha (McKinnon 1997).

N deposition was estimated from Parfitt et al. (2006). About half the deposition would have been on forest in the west of the South Island, where the rainfall is often >2 m. Legumes had probably been introduced by 1861 but the P status of much of the cleared land was low (Walker & Syers 1976). Therefore, the average input of N from legumes on this land was assumed to be 5 kg N/ha per year, though there is considerable uncertainty in this number. The amounts of N lost by erosion processes were estimated from the amounts lost in kg/ha per year for forest and for pasture in 2001/02 (Parfitt et al. 2006). These rates were then applied to areas of forest and cleared land in 1861 (McKinnon 1997). Since grazing was more extensive and there was less pressure on the land, these values may be overestimates. Nevertheless, large amounts of erosion were occurring in 1861 (Kettner et al. 2007).

Leaching of N in low-fertility ecosystems occurs mainly as dissolved organic N (DON) (Perakis & Hedin 2002; Oyarzún et al. 2004; McGroddy et al. 2008). Nitrate-N is also leached from soil; for land with low inputs of N it is usually between 1 and 4 kg/ha per year (Neary et al. 1978; Mosley & Rowe 1981). As soil fertility and inputs of N increase, leaching of N increases (Galloway et al. 2003). In 1861 it is assumed to have been 2.5 kg/ha per year in lower rainfall areas, and 4 kg/ha per year for the West Coast region which has greater rainfall and consequent leaching volumes.

Within New Zealand native forests, N is fixed by a few native species such as *Coriaria arborea* Lindsay, lichens, algae and free-living microorganisms. Data suggest this can range from 1 to –10 kg N/ha per year for conifers and montane forests (Sollins et al. 1980; Matzec & Vitousek 2003), and that it varies with rainfall and soil fertility (Benner et al. 2007). McGroddy et al. (2008) suggest that the N status of New Zealand native forests is generally low, so we assume N fixation is 1.5 kg N/ha. Denitrification was assumed to be 1 kg N/ha for forest, 1 kg N/ha for cleared land, and 10 kg N/ha for wetlands and organic soils.

N inputs and outputs for 2001/02

We have previously reported on the N budgets for the regions of New Zealand for the season 2001/02 (Parfitt et al. 2006). Briefly, we used spatial information, population data and inputs and outputs for grazing animals, based on stock units (SU) equivalent to the number of breeding ewes per hectare in 1980. We used the following factors for SU: beef cattle, 4.83; cows and heifers (over 1 year, 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. There are several minor modifications to the Parfitt et al. (2006) results. We now set N fertiliser inputs at 309 Gg (MFE 2005) and ammonia-N volatilisation from N fertiliser at 10%. We have allowed for a decrease in N fixation arising from the increased use of N fertiliser since 1985 (Parfitt et al. 2006). We have also allowed for a decrease in N fixation of 1% p.a. arising from the infestation of pastures with the clover root weevil (*Sitona lepidus* Gyllenhal) since 1996.

Fig. 1 Boundaries of the 16 regional councils.

Here, we have used the Overseer® model to estimate the N leaching for dairy, sheep and beef land for slope classes above 15° and below 15° for each region. We used national average SU and fertiliser rates. We have measured leaching losses of DON under pasture in the range 4–8 kg N/ha per year (Parfitt et al. 2007) and here use a figure of 5 kg N/ha for pastures.

N inputs and outputs for 2020 and 2050—3% growth scenario

By 2050 the human population is projected to increase from 3.7 to 4.8 million, with 2 million living in Auckland; more people will live in the North Island and fewer in the South Island (MED 2003).

In this scenario, with 3% growth per year in animal production, the largest pressure is the requirement to feed the animals; a three-fold increase is generally needed by 2050. It is assumed that 8 million ha out of the total 12 million ha of grassland are available for improvement since 4 million ha are steep land with low-producing grasses. Projections for the N cycle are based on the following assumptions. For sheep (on 4 million ha), the number of lambs surviving, from a fixed number of ewe SU, increases by 3% p.a. until all ewes have surviving triplets (2033); thereafter ewe SU increase at 2% p.a. The utilisation of feed (i.e., percentage of above ground net primary production consumed by stock) increases by 2% a year from 65% up to a maximum of 85% (by 2020). The feed required for these animals is also met by increasing pasture production using N fertiliser up to 100 kg N/ha per year (by 2035), and then (since all available land is used and increased pasture production is not possible) by importing feed from overseas. All calculations were based on SU where 550 kg dry matter per year are required for each SU.

For beef (on 2 million ha), the stock units increase by 2% pa, and the utilisation of feed increases by 2% a year from 65% up to a maximum of 85%. The feed required for these animals is also met by increasing pasture production using N fertiliser up to 100 kg N/ha per year (by 2022), and then by importing feed from overseas.

For dairy cows (on 2 million ha), the production increases by 3% p.a., and the utilisation of feed increases by 2% a year from 70% up to a maximum of 90% (by 2015). The feed required for these animals is also met by increasing pasture production using N fertiliser up to 200 kg N/ha per year (by 2011), and then by importing feed from overseas. Using these models, the inputs and outputs for 2001/02 have been extrapolated out to 2020 and 2050, generally using the methods developed for 2001/02 (Parfitt et al. 2006). 2020 was chosen because it represents an inflection point where feed has to be imported.

We assumed the following: all pastures produce an extra 15–20 kg DM for each kg N fertiliser added (AgResearch 2005); the N concentration of imported feed is 2% (Parfitt unpubl. data); denitrification from pasture soils will be 35 kg N /ha per year (Barton et al. 1999). Estimates of ammonia volatilisation are based on SU (Parfitt et al. 2006), with 10% volatilisation occurring directly from fertiliser. Clover N fixation is reduced as a result of N fertiliser additions (Parfitt et al. 2006), and the effect of the clover root weevil. The infestation of pastures with the clover root weevil is expected to spread nationwide by about 2010, and N fertiliser will be needed to compensate for the decrease in N fixation by clovers in pasture. The amount of fertiliser required will depend on the impact of the weevil, but it may be 100 to 250 Gg N; it should compensate closely, and approximately equal the loss from damage to clovers (NZIER 2005). We have assumed a low impact scenario here, because the effect of infestations since 1993 appears to have been overcome with small applications of N fertiliser.

We estimated leaching losses and gaseous losses by running the Overseer® model for each region for highly developed dairy, sheep and beef farms in 2020 and 2050 using the SU and N fertiliser rates derived from our 3% growth models. For dairy farms in 2050 the growth model showed that 780 kg N in imported feed would be added per ha together with 200 kg N fertiliser; Overseer® predicted the nitrate-N leaching would be 350 kg N/ha and atmospheric losses would be 320 kg N/ha. While these data are extreme and unlikely to ever be permissible, they do serve to highlight the outcome of the 3% growth model projection.

N inputs and outputs for 2050—cap and trade scenario

We designed a simple cap and trade scheme for New Zealand, to limit the quantity of reactive N in water. Since diffuse discharge to water cannot be traded using current scientific knowledge, we impose a cap on N fertiliser of 472 Gg N; projections suggest this amount will be sold in 2011. The simple approach allows a sensible scenario to be calculated but may differ from more politically realistic cap and trade schemes in which adjustments to the cap can be made at regional or catchment levels based on environmental quality.

We make the following assumptions:

- To reduce erosion, pine is planted on soils on soft rock with slopes >24%, so pine plantations increase from 2 million ha to 2.9 million ha, farm and pasture hectare decreases by 0.9 million ha, SU decreases by 5 for each hectare of pine
- Other animal numbers and SU stay the same as in 2001/02

  Farmers will grow more maize to feed the livestock, and the N concentration in animal excreta will therefore be reduced
- Most dairy farms will use winter feed pads (some of which may include a "herd home") so N waste can be better managed, leaching of N is halved from dairy farms, and denitrification is increased from 10 (in 2001) to 20 kg N/ha
- Emissions of ammonia will increase from 2.1 kg N/SU to 3 kg N/SU, as a result of larger concentrated areas of animal waste
- N_2O emissions from animal excreta decrease by 30%
- Nitrate leaching in pasture under sheep and beef increases from 2001/02 by 30% as a result of increased N inputs

Unresolved gains and losses

The difference between outputs and inputs of N for New Zealand is estimated at 133 Gg for 1861, 82 Gg in 2001/02, and 79 Gg in 2020. It is in balance for 2050 since inputs are predicted to be so large that they generate losses of similar magnitude. The cap and trade scenario generated a net annual loss of 82 Gg N. There is considerable uncertainty in some of the inputs and outputs, whereas others are well constrained. The largest uncertainties arise in the estimation of N fixation by pasture legumes. Not only is there a large year-to-year variation, because of different weather conditions, but there are almost no data on the effect of the clover root weevil on N fixation. The outputs are constrained to some extent by the inputs. The amount of N that is immobilised by soil is unknown; indeed, there are indications that the N is being remobilised with net losses of total soil N for some lowland pasture soils (Schipper et al. 2007). There is uncertainty therefore as to how much N is lost by leaching, denitrification, volatilisation and erosion.

RESULTS

1861

Inputs of N into New Zealand were dominated by deposition (63 Gg), from legumes in cleared land (51 Gg) and other biological N fixation (BNF) (20 Gg), giving a total of 133 Gg (Table 1).

The N outputs would have been erosion (153 Gg), especially in Hawke's Bay, Tasman, Southland and the West Coast, leaching (72 Gg), denitrification (27 Gg), fires (11 Gg), exports of N in wool (1 Gg), ammonia volatilised from animal excreta (1 Gg), and effluent (1 Gg); giving a total of 266 Gg (Table 2). This suggests there was net export of N, occurring mainly as erosion in the areas where there was large scale clearance and burning of tussock grassland and forest. Export of N from the West Coast, although it was naturally forested, was also high,

Table 1 Annual inputs of different categories of nitrogen (N) for New Zealand by region for 1861.

		Area (sq km)	Legumes (Gg N)	Other BNF (Gg N)	Atmosphere (Gg N)	Fertiliser (Gg N)	Imports (Gg N)	Total (Gg N)
1	Northland	12 696	3	1	2	0	0	6
2	Auckland	5104	2	0	1	0	0	3
3	Waikato	24 500	6	2	4	0	0	12
4	Bay of Plenty	12 271	2	1	2	0	0	5
5	Gisborne	8361	0	1	1	0	0	3
6	Hawke's Bay	14 172	6	0	2	0	0	8
7	Taranaki	7256	1	1	1	0	0	3
8	Manawatu-Wanganui	22 211	3	2	3	0	0	9
9	Wellington	8125	2	0	1	0	0	4
10	Tasman	9654	1	1	5	0	0	7
	Nelson	424	0	0	0	0	0	0
12	Marlborough	10 494	1	1	2	0	0	4
13	West Coast	23 363	1	3	14	0	0	18
14	Canterbury	45 039	10	2	7	0	0	19
15	Otago	31 922	7	1	5	0	0	13
16	Southland	31 775	5	3	13	0	0	20
	Islands		nd	nd	nd	nd	nd	nd
	Total	267 367	51	20	63	0.0	0.04	133

Table 2 Annual outputs of different categories of nitrogen (N) for New Zealand for 1861.

	Produce (Gg N)	Leaching (Gg N)	Denitrification in soil (Gg N)	Other effluent (Gg N)	Ammonia volatilisation (Gg N)	Erosion, burial (Gg N)	Fires (Gg N)	Total (Gg N)
Northland	0.0	3	2	0.1	0.0	5	2	11
Auckland	0.0	1	1	0.0	0.0	0	0	3
Waikato	0.0	6	4	0.3	0.0	7	1	18
Bay of Plenty	0.0	3	1	0.0	0.0	7	1	12
Gisborne	0.0	2	1	0.0	0.0	11	0	15
Hawke's Bay	0.1	4	1	0.0	0.1	33	0	39
Taranaki	0.0	2	1	0.0	0.0	7	0	10
Manawatu-Wanganui	0.0	6	2	0.0	0.0	12	1	21
Wellington	0.0	2	1	0.0	0.1	5	1	9
Tasman	0.0	2	1	0.0	0.0	19	1	23
Nelson	0.0	0	0	0.0	0.0	0	0	1
Marlborough	0.1	3	1	0.0	0.1	1	1	5
West Coast	0.0	9	3	0.1	0.0	18	0	30
Canterbury	0.2	11	3	0.1	0.4	4	1	21
Otago	0.1	8	2	0.1	0.3	4	0	15
Southland	0.0	10	4	0.1	0.0	20	2	35
Total	1	72	27	1	1	153	11	266

but this was probably matched by the high N rates of deposition from the Tasman Sea to the west.

2000/01

The national N inputs were estimated to be 1023 Gg (Table 3), mainly from biological N fixation, but also from fertiliser application and atmospheric deposition. The outputs were estimated at 1105 Gg (Table 4). 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. Pastoral agriculture accounts for 85% of the inputs and 80% of the outputs. These results are consistent with minor methodological changes introduced since the Parfitt et al. (2006) N budget for the same period.

2020 and 2050 growth scenarios

The growth scenarios suggest total inputs of N increase from 1023 Gg in 2001/02 to 1482 Gg in 2020 to 3565 Gg in 2050 (Tables 5 and 6). Inputs of N into New Zealand will be dominated by fertiliser and clover up to 2020 and then by imported feed and fertiliser in 2050. Fertiliser use reaches about 1000 Gg by 2035 and it is assumed N fertiliser then remains constant as a result of agreements between land owners and local government. The input of N from pasture legumes consequently falls from 461 Gg in 2001/02 to 383 Gg in 2020 to 355 Gg in 2050. Import of feed increases from 187 Gg N in 2020 to 1610 Gg N in 2050. Deposition, mainly from ammonia from animals, increases from 175 Gg N in 2001/02, to 238 Gg in 2020 and to 532 Gg N in 2050.

The total annual outputs of N increase from 1105 Gg in 2001/02 to 1561 Gg in 2020 and to 3550 Gg in 2050 (Tables 7 and 8). Outputs of N increase significantly for produce, leaching, denitrification and ammonia volatilisation. Overseer® predicted a leaching loss from pasture

Table 3 Annual inputs of different categories of nitrogen (N) for New Zealand by region for 2001/02.

	Pasture legume (Gg N)	Other BNF (Gg N)	Atmosphere (Gg N)	Fertiliser (Gg N)	Imports (Gg N)	Total (Gg N)
Northland	22	3	9	17	1	53
Auckland	6	1	3	7	11	28
Waikato	67	5	26	76	4	178
Bay of Plenty	17	4	7	17	2	48
Gisborne	15	2	5	4	0	27
Hawke's Bay	32	3	10	13	1	59
Taranaki	22	1	7	19	1	50
Manawatu-Wanganui	68	3	18	31	2	122
Wellington	18	2	5	7	4	37
Tasman	5	2	4	5	0	17
Nelson	0	0	0	0	0	1
Marlborough	9	1	4	3	0	17
West Coast	5	3	14	9	0	31
Canterbury	69	4	24	60	5	162
Otago	52	2	16	17	2	89
Southland	53	3	22	24	1	103
Total	461	39	175	309	38	1023

of 370 Gg N for 2020. The average leaching loss from dairy farms was 88 kg N/ha per year, for beef was 35 kg N/ha per year, and for sheep was 18 kg N/ha per year. Our leaching loss of 468 Gg N also includes losses from farms under cropping. Denitrification is the process that largely removes reactive N from the environment, but denitrification only increases its removal

Table 4 Annual outputs of different categories of nitrogen (N) for New Zealand for 2001/02.

	Produce (Gg N)	Leaching (Gg N)	Denitrification in soil (Gg N)	Other effluent (Gg N)	Ammonia volatilisation (Gg N)	Erosion, burial (Gg N)	Trees, fires (Gg N)	Total (Gg N)
Northland	9	19	9	2	14	6	1.3	60
Auckland	4	8	4	5	4	3	1.0	28
Waikato	34	48	20	8	44	13	2.1	169
Bay of Plenty	8	12	5	2	11	6	1.4	45
Gisborne	4	8	5	0	7	32	0.9	58
Hawke's Bay	9	16	10	1	16	22	1.3	76
Taranaki	11	20	6	3	12	16	0.4	67
Manawatu-Wanganui	19	29	17	2	30	21	1.3	120
Wellington	5	9	5	2	8	5	0.8	36
Tasman	2	5	3	0	3	14	0.7	28
Nelson	0	0	0	0	0	0	0.1	1
Marlborough	2	7	5	0	4	1	0.8	21
West Coast	2	12	4	1	4	18	0.4	42
Canterbury	24	51	27	4	35	6	2.6	150
Otago	14	32	19	2	23	5	1.4	96
Southland	16	28	15	2	25	20	1.0	107
Total	165	304	153	35	241	190	17	1105

Table 5 Annual inputs of different categories of nitrogen (N) for New Zealand by region for 2020 using the 3% growth model.

	Pasture legume (Gg N)	Other BNF (Gg N)	Atmosphere (Gg N)	Fertiliser (Gg N)	Imports (Gg N)	Total (Gg N)
Northland	21	3	14	45	13	97
Auckland	6	1	5	14	20	46
Waikato	63	5	39	125	51	282
Bay of Plenty	15	4	9	22	12	63
Gisborne	13	2	7	16	1	39
Hawke's Bay	28	3	14	32	4	81
Taranaki	21	1	11	50	17	100
Manawatu-Wanganui	52	3	26	69	14	163
Wellington	14	2	8	19	7	49
Tasman	4	2	5	8	2	22
Nelson	0	0	0	0	0	1
Marlborough	7	1	5	21	1	36
West Coast	5	3	15	14	4	41
Canterbury	54	4	33	91	20	202
Otago	39	2	21	69	8	139
Southland	41	3	27	40	11	121
Total	383	39	238	635	187	1482

of reactive N by about 300 Gg N. The output of reactive N (all N except for N_2 gas) therefore increases from about 900 Gg in 2001/02 to 3000 Gg in 2050. Nearly all of the increase comes from pastoral farming since the 3% pastoral growth scenario is much greater than for any other land use; it leads to an 80% increase in land use by 2020 and a 340% increase by 2050.

Table 6 Annual inputs of different categories of nitrogen (N) for New Zealand by region for 2050 using the 3% growth model.

	Pasture legume (Gg N)	Other BNF (Gg N)	Atmosphere (Gg N)	Fertiliser (Gg N)	Imports (Gg N)	Total (Gg N)
Northland	20	3	35	57	123	238
Auckland	6	1	13	18	63	101
Waikato	59	5	102	152	432	750
Bay of Plenty	15	4	22	26	87	155
Gisborne	12	2	15	41	31	101
Hawke's Bay	26	3	33	74	75	211
Taranaki	19	1	18	56	78	172
Manawatu-Wanganui	48	3	62	127	176	416
Wellington	13	2	18	36	50	118
Tasman	4	2	9	11	20	46
Nelson	0	0	0	0	1	1
Marlborough	6	1	9	45	16	78
West Coast	4	3	19	15	31	73
Canterbury	50	4	76	164	200	494
Otago	36	2	47	149	98	333
Southland	37	3	53	58	127	278
Total	355	39	532	1029	1610	3565

Table 7 Annual outputs of different categories of nitrogen (N) for New Zealand for 2020 using the 3% growth model.

	Produce (Gg N)	Leaching (Gg N)	Denitrification in soil (Gg N)	Other effluent (Gg N)	Ammonia volatilisation (Gg N)	Erosion, burial (Gg N)	Trees, fires (Gg N)	Total (Gg N)
Northland	15	30	12	3	24	6	1.3	93
Auckland	6	13	5	7	9	4	1.1	45
Waikato	55	95	28	12	70	15	2.1	277
Bay of Plenty	12	24	7	3	14	6	1.4	67
Gisborne	6	12	8	0	11	32	0.9	70
Hawke's Bay	13	24	15	1	24	22	1.2	101
Taranaki	17	37	8	4	20	17	0.4	104
Manawatu-Wanganui	28	50	25	3	45	22	1.3	173
Wellington	8	15	7	2	13	5	0.8	51
Tasman	3	7	3	1	4	15	0.6	34
Nelson	0	0	0	0	0	0	0.1	1
Marlborough	3	11	7	0	6	1	0.8	30
West Coast	4	15	5	1	6	18	0.4	50
Canterbury	34	58	38	5	53	7	2.5	198
Otago	19	36	27	2	33	5	1.4	125
Southland	23	40	20	3	34	21	1.0	142
Total	246	468	216	48	367	198	17	1561

Table 8 Annual outputs of different categories of nitrogen (N) for New Zealand for 2050 using the 3% growth model.

	Produce (Gg N)	Leaching (Gg N)	Denitrification in soil (Gg N)	Other effluent (Gg N)	Ammonia volatilisation (Gg N)	Erosion, burial (Gg N)	Trees, fires (Gg N)	Total (Gg N)
Northland	35	95	24	7	66	8	1	237
Auckland	14	35	10	10	25	5	1	100
Waikato	130	315	52	27	196	24	2	746
Bay of Plenty	26	73	12	6	41	8	1	168
Gisborne	12	21	15	0	28	33	1	110
Hawke's Bay	30	45	28	2	62	23	1	191
Taranaki	41	126	15	5	34	18	0	239
Manawatu-Wanganui	65	118	49	7	118	24	1	382
Wellington	17	36	15	3	33	6	1	111
Tasman	7	19	6	1	12	15	1	61
Nelson	0	0	0	0	0	0	0	1
Marlborough	7	22	13	1	15	2	1	61
West Coast	9	38	8	2	16	19	0	92
Canterbury	78	149	74	10	139	10	3	463
Otago	44	95	56	4	85	6	1	291
Southland	53	90	39	6	87	23	1	298
Total	568	1279	417	91	956	222	17	3550

Table 9 Annual inputs of different categories of nitrogen (N) for New Zealand by region for 2050 using the "cap and trade" model.

	Pasture legume (Gg N)	Other BNF (Gg N)	Atmosphere (Gg N)	Fertiliser (Gg N)	Imports (Gg N)	Total (Gg N)
Northland	21	4	12	26	2	65
Auckland	7	1	4	11	17	39
Waikato	66	5	33	116	4	224
Bay of Plenty	16	4	9	27	3	59
Gisborne	9	4	6	7	0	26
Hawke's Bay	26	4	14	20	1	65
Taranaki	20	1	8	29	1	60
Manawatu-Wanganui	53	5	24	47	2	130
Wellington	13	3	7	11	4	38
Tasman	5	2	5	7	0	19
Nelson	0	0	0	0	0	1
Marlborough	7	1	4	4	0	18
West Coast	5	3	14	13	0	36
Canterbury	56	4	32	91	4	188
Otago	41	2	21	26	2	92
Southland	42	3	27	37	1	111
Total	386	48	221	472	44	1171

Table 10 Annual outputs of different categories of nitrogen (N) for New Zealand for 2050 using the "cap and trade" model.

	Produce (Gg N)	Leaching (Gg N)	Denitrification in soil (Gg N)	Other effluent (Gg N)	Ammonia volatilisation (Gg N)	Erosion, burial (Gg N)	Trees, fires (Gg N)	Total (Gg N)
Northland	10	17	13	3	20	3	1.6	68
Auckland	4	8	6	9	6	4	1.2	37
Waikato	34	47	31	12	58	12	2.2	197
Bay of Plenty	8	12	8	3	15	6	1.4	53
Gisborne	5	3	4	0	10	23	1.9	47
Hawke's Bay	10	13	14	1	23	16	1.9	79
Taranaki	11	19	8	4	13	15	0.5	71
Manawatu-Wanganui	20	25	25	3	41	12	2.1	129
Wellington	6	7	7	2	12	2	1.2	37
Tasman	2	5	4	1	4	14	0.6	31
Nelson	0	0	0	0	0	0	0.1	1
Marlborough	2	7	8	0	6	1	0.8	26
West Coast	2	12	6	1	5	18	0.4	45
Canterbury	24	51	45	6	51	6	2.5	186
Otago	14	32	33	2	33	5	1.4	120
Southland	16	28	24	3	35	20	1.0	128
Total	168	287	236	51	332	158	21	1253

We also ran models that included increased use of irrigation to produce more grass in summer. This delayed the import of feed for sheep from 2035 to 2042, for beef from 2022 to 2029, and for dairy from 2011 to 2018. The N imported in 2050 fell from 1610 to 1411 Gg.

Cap and trade

The national inputs of N increase by about 20% from 1023 Gg in 2001/02 to 1171 Gg (Table 9). Most of the increase comes from N fertiliser and from the subsequent deposition of ammonia-N as more ammonia becomes volatilised. Smaller increases come from the increased area of BNF in pine plantations (Parfitt et al. 2006) and from imports. Clover N fixation is reduced to 386 Gg as a result of both N fertiliser additions and the effect of the clover weevil.

The national outputs of N increase by about 14% from 1105 Gg in 2001/02 to 1253 Gg (Table 10) since fertiliser use increases from 309 to 472 Gg. Outputs of ammonia-N increase significantly to 332 Gg as a result of increased concentrations of animal waste on dairy farms, but this is balanced by increases in denitrification to 236 Gg N, mainly as N_2—the form of N that is not reactive. The output of reactive N, therefore, is about the same as in 2001/02.

As a result of reforestation in hill country, the loss of N by erosion is reduced by about 20% to 158 Gg. Leaching of N is increased from sheep and beef farms because of the higher N status of the pastures, but is reduced from dairy farms in winter as a result of using feedpads, giving a small net reduction in leaching (to 287 Gg).

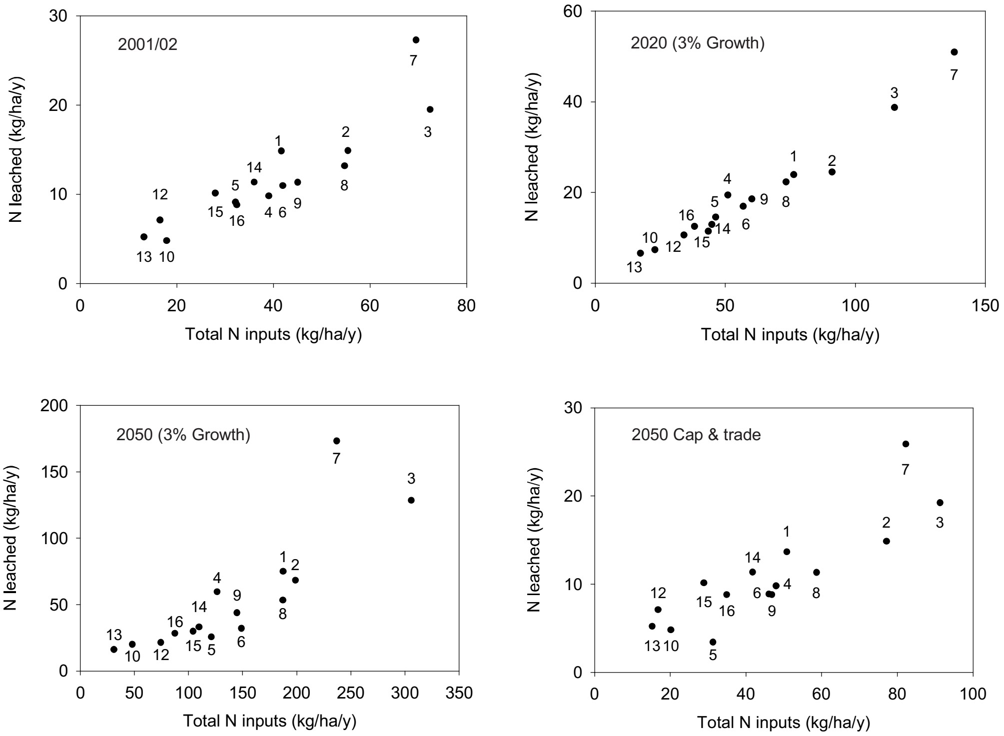

Fig. 2 Nitrogen (N) leached plotted against N inputs for each region (kg N/ha). The numbers refer to the regional councils listed in Table 1.

DISCUSSION

There is increasing concern about the N loads on the environment in New Zealand; indeed, the Parliamentary Commissioner for the Environment has outlined issues associated with agricultural intensification and increasing N fertiliser use (McLeod & Moller 2006), calling for redesign of farm systems (PCE 2004). While New Zealand regional councils have the authority to introduce regulatory controls over land, none presently control the rate at which fertiliser can be applied. Currently, the regional councils aim to work with farmers to optimise the use of N on different land and farming systems, rather than use regulatory limits as a primary tool. However, the Lake Taupo Variation will effectively cap N inputs for catchments and this may lead to a cap and trade scheme. In the draft One Plan (Manawatu-Wanganui Region), it is proposed to set N leaching loss limits, based on the natural capital of soil, above which mitigation would be required to offset any additional N losses.

Our scenarios seek to provide farmers, industry and regulators with an understanding of the wide range of future possibilities for New Zealand agriculture. The scenario approach projects the relatively simple and transparent assumptions we have described into the future using an existing national N budget (Parfitt et al. 2006). We emphasise that the two scenarios do not represent predictions, but serve the purpose of projecting two very different plausible sets of assumptions into the future. Under the 3% growth scenario, increases in N losses to the environment are considerably more serious than in the cap and trade scenario. As an example, we show the increase in N leaching for each region in Fig. 2. Generally, as total N inputs increase, the amount lost by leaching increases. Ammonia volatilisation (not shown) follows the same pattern. Overall, the large differences in N budgets between the two scenarios emphasise the value of these scenario projections as an exercise in understanding the range of possible futures. It appears that N loads in some regions of New Zealand (Taranaki and Waikato) have already reached the levels found in Europe and the United States, where regulation has been introduced to cap the N inputs (Parfitt et al. 2006). It is unlikely these regions can absorb further increases in N loads without environmental impacts.

We emphasise that neither scenario represents a prediction of future economic or policy states for New Zealand. Indeed, while growth in agricultural production remains a stated target, industry is taking steps to reduce environmental impacts in ways that are likely to reduce N losses. In 2003, the national dairy cooperative (Fonterra) signed the "dairying and clean streams accord", and there has been considerable progress towards keeping cows out of water bodies (MAF 2005); dairy farmers are gradually moving towards nutrient management plans and some are introducing mitigation options, e.g., nitrification inhibitors or alternative animal management (Monaghan et al. 2007). There has been little consideration given, however, to the effects of increasing N loads as a result of the ongoing lift in total cow and per cow production, and the trend of bringing more imported feed onto the milking platform. This paper highlights the urgency with which primary industry must address the issue of N loads on the environment, and move away from continued increase in production *per se* to systems where value is added to products. Indeed, the annual growth model appears to be unsustainable in the long term, unless there are radical changes in the farming systems.

Further work to examine policy options will require more detailed scenarios. The work we present is limited in many ways by the lack of detailed scenarios, equivalent to the IPCC SRES (Special Report on Emissions Scenarios) (e.g., Galloway et al. 2004) downscaled for New Zealand. Such scenarios are only available internationally for very large regions and nations (such as the United States). The development of downscaled scenarios at the resolution of the New Zealand economy would make it possible to undertake integrated studies combining climate and water quality mitigation policies. For example, the impact of rising energy prices on the cost and use of N fertiliser could be studied. However, the ability to address more detailed questions such as the economics of N fertiliser use will require integrated models of economic and biophysical processes. Although the short-term benefits of integrated modelling may be questioned, our results demonstrate that over the timespan of c. 50 years policy settings can make a large difference in environmental outcomes.

CONCLUSIONS

This study provides a preliminary analysis of N inputs and outputs for New Zealand, both in the past and under two widely differing future scenarios. We find large differences in N budgets between the two future scenarios examined. Despite the large uncertainty in some aspects of the N cycle and the preliminary nature of this analysis, the large differences between scenarios demonstrate that the range of plausible policy settings can have a profound impact on future environmental outcomes over c. 50 years.

The construction of national N budgets, as completed in this study, should be an important component of N management as outlined under the Nanjing Declaration. For New Zealand, most of the large inputs are from pastoral farming and these are now well constrained by the Overseer® model. The inputs also constrain the outputs such as products, leaching and volatilisation. This exercise, however, indicated that there is large uncertainty in parts of the N cycle under pastures, including ammonia volatilisation, denitrification to nitrogen gas, and attenuation of soluble N in subsoils and headwater streams. These are areas that require further research.

A variety of additional policy tools and farm-based mitigation technologies can potentially be included in similar scenarios, when it is possible to construct robust models for these options. We note the potential benefit of developing a range of scenarios, following the IPCC approach, applicable to modelling New Zealand's potential environmental and economic trajectories. Further refinement of these N budgets and scenarios should enable New Zealanders to make informed decisions regarding the trade-off between economic growth of the agricultural sector and the impacts of reactive N on the environment, and the degree of regulation that is required.

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