# The environmental footprint of New Zealand's plantation forests: nutrient fluxes and balances

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## Abstract

Concern over New Zealand's environmental quality and the long-term impacts of agricultural sector activities on water quality is increasing. Lake and river water quality is declining as a result of past and current land use practices and national and regional initiatives are being developed to halt and reverse the declines. Plantation forestry is a low impact land use by comparison to other agricultural sectors, requiring less nutrient input in terms of fertiliser and causing less environmental impact on ground and surface water from nutrient leaching.

A nutrient balance model has been developed to predict nutrient fluxes within plantation systems, over one or more rotations. The model is a simple mass balance model; it predicts nutrient uptake by a crop and partitions nutrients into the various pools within the soil/plant system. The model predicts when there will be surpluses or deficits in the system and consequently when there is an increased risk of nutrient transfer or a need for fertiliser application. Running different scenarios demonstrates the effect of vegetation management, harvesting intensity, or change in productivity due to climate change on the pools of nitrogen during a rotation, and the effects of multiple rotations on soil phosphorus pools.

Using the model to develop various scenarios will enable the development of multiple land use scenarios, with a focus on minimising the nutrient 'footprint' or impact for a specific catchment or region. Predictions of nutrient fluxes can contribute to the development of nutrient trading models, where the value of plantation forestry as a low nutrient footprint land use may be recognised as an additional economic benefit above the value of the tree crop.


## Introduction

There is growing concern within New Zealand that our environment is becoming increasingly polluted. Our clean green image is becoming tarnished by the body of accumulating evidence of the decline in environmental quality. For example, a recent Ministry for the Environment report (2005) noted that between 40 and 71% of monitored river sites exceeded guidelines for a number of water quality indicators such as $NH_4$, *E. coli*, $NO_x$, and Dissolved Reactive Phosphate (DRP). Our iconic North Island lakes in the Taupo and Rotorua catchments are suffering from declining water quality; the Ministry for the Environment's 1997 State of the Environment report (summarised in Cameron *et al.* 2002) noted that 40% of 177 New Zealand lakes had high to very high levels of total N and P and could be considered eutrophic or hyper-eutrophic. Additionally, major recent storms in the Bay of Plenty and Manawatu have given rise to very large scale soil erosion.

The recent report by the Parliamentary Commissioner for the Environment, 'Growing for good: intensive farming, sustainability and New Zealand's environment' (PCE 2004), summarised many of the concerns over nutrient inputs to farming systems, movement of nutrients into surface and ground waters, and gave a gloomy prognosis for New Zealand's environmental quality in the future if solutions were not found.

The PCE report concentrated on those land uses contributing the most to the environmental degradation. Plantation forestry was not seen as one of these land uses, and was rarely referred to. What has been interesting in the debate on the PCE report has been the recognition that forestry is not one of the major impacting land uses, but at the same time that it is rarely seen as part of the solution for protecting and enhancing the environment. At times, forestry seems almost like a forgotten land use, and the environmental benefits of forests within the wider landscape appear overlooked.

For instance, despite the recent floods in the Manawatu, sales of seedlings do not appear to have increased over previous levels, indicating farmers are not looking to forestry as a strategic solution (D. Hocking pers. comm.) to the erosion issue. There is good reason to question why this is not the case given that afforestation is an obvious and well-proven solution to soil loss. One possible reason is that outside of the forestry sector there is poor understanding of the economic and environmental benefits of forestry. At the same time there is an inability of existing economic models to handle direct and indirect, or 'down stream'; economic benefits of the major land uses, and to recognise and incorporate the true cost of production, including environmental costs.

The environmental footprint can be defined as the scale of potential environmental impact from management practices. One component of the environmental footprint of forestry relates to nutrient impacts. In plantation forestry operations the size of the nutrient footprint depends on harvesting impacts leading to sediment generation and loss of nutrients offsite from erosion, impacts from fertiliser applications – run off by fertiliser into streams and leaching losses of nutrients from sites, and impacts of general silvicultural operations such as weed control, pruning, and thinning on nutrient cycling processes. These potential


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impacts are in addition to the nutrients removed in harvested forest products. So the overall impact of forest management on the nutrient footprint of forestry can be defined as the difference between nutrient inputs to a site and off-site removals or losses.

The purpose of this paper is to present some current thinking on defining the nutrient footprint of plantation forests, and to outline some new approaches we may adopt which could have impacts on long-term land use patterns and the valuation of plantation forests.

### Nutrient inputs

The recent report on the sustainability of intensive farming by the PCE (2004) summarised the increased use of nitrogen in farming systems. Since 1983 the amount of N applied annually as urea has increased 18 fold to 311,000 tonnes. Quantities of N used were dominated by the dairy sector with over 200,000 tonnes used in 2004, followed by sheep and beef at around 60,000 tonnes. We have no recent comparative data for urea use in plantations but estimate only 5000 tonnes were applied in 1997 (Payn *et al.* 1998) and even under greatly intensified management of our plantation forests these agricultural levels of fertiliser are unlikely to be reached. A projection of potential future fertiliser use by the forest industry (Payn *et al.* 1998) indicated in the order of 12,000 tonnes of N (~25,000 tonnes of urea) would be required to replace the quantity of nutrients removed in harvested forest products and maintain productivity at current levels.

Unlike intensive agriculture, where the use of large quantities of fertiliser results in the build up of a large nutrient capital (Skinner & Attiwill 1981a, 1981b; Edmeades & Roberts 2001), plantation forests in New Zealand in general rely on naturally occurring inputs of nutrients from atmosphere and soil weathering processes (Zabowski *et al.* 1994) and are effective scavengers for key limiting nutrients (N and P) due to the association of tree roots with ectomycorrhizal fungi. For example, N gains from natural processes, including atmospheric inputs (ca. 120 kg/ha over a 30-year rotation in Kaingaroa forest (Dyck 1982)) and biological N-fixation for species such as tree tutu (Silvester *et al.* 1979) or broom (Watt *et al.* 2003) for several years prior to suppression by canopy closure, may be sufficient to replace N losses from leaching and N removal in logs at harvest (ca. 210 kg/ha, Webber & Madgwick 1983). In recently planted forests, trees are capitalising on the higher fertility of previously marginal farmland, releasing locked up capital. This nutrient capital is a significant input and may meet the nutrient requirements of several forest rotations.

### Nutrient outputs

Forests are conservative in cycling N and other nutrients and little is lost through leaching. Nutrients are returned to the soil from the canopy as litterfall or deposited as thinning or harvesting slash (needles, branches, stem wood). These materials decompose only slowly and N is released mainly as ammonium-N (Parfitt *et al.* 2001; Girisha *et al.* 2003, 2004; Will *et al.* 1983). This contrasts with pastoral farming where N is returned mainly in concentrated urine patches and becomes available for leaching after conversion to nitrate. Some leaching loss of N from forests may occur, especially at harvest, when N uptake is disrupted and decomposition accelerated. Dyck (1982) reported leaching losses of up to 15 kg $N.ha^{-1}$ for a two-year period following harvest at Kaingaroa forest. In contrast, Parfitt *et al.* (2002) found harvesting reduced nitrate loss on a pumice soil of high

*Table 1: Summary of published and unpublished data on nutrient removals ($kg.ha^{-1}$) for stem only harvests for a range of sites in New Zealand.*

| Source | Soil type* | Stand age | Species | N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|---|---|
| Webber & Madgwick (1983) | | 29 | *Pinus radiata* | 217 | 31 | 285 | 220 | 63 |
| Berwick Forest | Mottled Fragic Pallic Soil | 31 | *Pinus radiata* | 337 | 38 | 439 | 153 | 107 |
| Canterbury Plains Forest | Pallic Orthic Brown Soil | 32 | *Pinus radiata* | 187 | 28 | 198 | 183 | 69 |
| Golden Downs Forest | Acidic Orthic Brown Soil | 45 | *Pinus nigra* | 280 | 67 | 185 | 363 | 59 |
| North West Nelson | Acidic Brown Soil | Mixed | *Nothofagus truncata* | 140 | 69 | 215 | 30 | 494 |
| Kinleith Forest | Immature Orthic Pumice Soil | 26 | *Pinus radiata* | 136 | 22 | 168 | 126 | 97 |
| Tarawera Forest | Buried-Pumice Tephric Recent | 27 | *Pinus radiata* | 187 | 36 | 302 | 237 | 80 |
| Woodhill Forest | Typic Sandy Recent Soil | 42 | *Pinus radiata* | 128 | 38 | 218 | 233 | 73 |

* *Hewitt 1993.*

natural N status at the Puruki experimental catchment site.

Significantly, Worsnop & Will (1980) found in a Taupo silty sand soil at Kaingaroa that no loss of $^{15}N$ from $^{15}N$-labelled urea applied (at 200 kg $N.ha^{-1}$) in a lysimeter study occurred for three years after the fertiliser application. Estimates of annual loadings of N to surface waters (PCE 2004) from non point sources suggest agriculture contributes ~100,000 tonnes per annum, natural forests ~15,000 tonnes per annum and plantations ~7000 tonnes per annum. This equates to approximately 8, 4 and 2 kg $N.ha^{-1}.yr^{-1}$ respectively and again demonstrates the low impact nature of plantations compared to agriculture.

Nutrient removals in harvested forest products will depend on a number of factors including species and harvesting intensity (e.g. Forest Research (Unpublished data); Hart *et al.* 2003; Webber 1978; Webber & Madgwick 1983). A comparison of data (Table 1) suggests that the quantity of individual nutrients removed will vary with site quality and stand age.

## Nutrient budgets

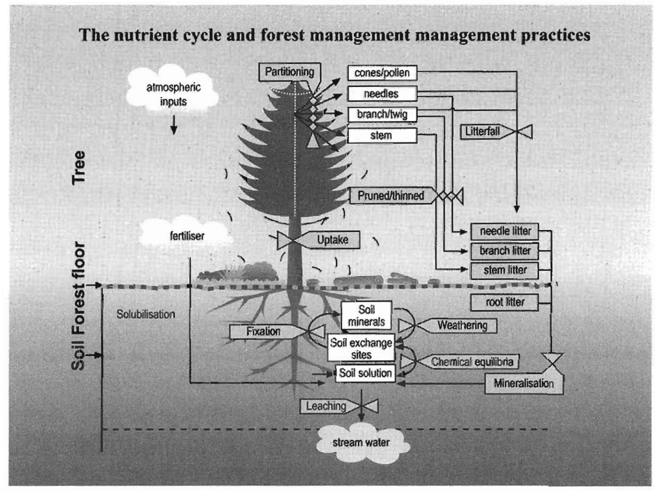
If forestry is to be part of the solution to environmental degradation by, for instance, being incorporated into future patterns of land use to offset nutrient loadings from greater impact land uses, a number of fundamental requirements need to be met that demonstrate its benefits. One of these is the ability to predict the impacts of various management regimes on the nutrient inputs and outputs of forest systems. As a first step towards this, a nutrient balance model has been developed that allows analysis of various forest management scenarios on forest nutrient budgets. In the past, simple estimates or input-output budgets have been used to assess the potential of a site to supply nutrients and hence its capacity for sustained timber production (Ranger & Turpault 1999). However, these estimates have not incorporated environmental impact components such as leaching losses or long-term changes in site quality brought about by management activities.

## The nutrient balance model

The model is based on a simplification of the forest nutrient cycle and management activities (Fig. 1) and uses a mass balance approach with an annual time step. The model uses biomass and soil nutrient pool data and tree growth data from the Long Term Site Productivity (Intensive Harvesting) trial series (LTSP1) (e.g. Dyck *et al.* 1991; Smith *et al.* 1994).

Tree growth is driven empirically using a generalised growth model for radiata pine in New Zealand. Annual increment in stem volume is calculated from stem volume data generated from the growth model. Volume increment is allocated to biomass pools using simple allocation procedures similar to those used by Beets *et al.* (1999). Nutrient concentrations of various tree components can be set by the user and are combined with biomass pools to calculate annual nutrient requirements. Stands can be thinned, and biomass and nutrients allocated to various detrital pools. Initial nutrient pools in soils and the forest floor including harvest residues, if present, as well as nutrient inputs from atmospheric sources or mineral weathering can be defined by the user. Once canopy closure is reached, foliage biomass is assumed to be a constant amount and litterfall begins at a predetermined rate. Rates of nutrient release from detrital pools can be set by the user or based on published rates (e.g. Girisha *et al.* 2003, 2004).

*Fig. 1: Components of the nutrient balance model; inputs, nutrient pools (boxes) and nutrient fluxes (shaded boxes).*




Model outputs represent the amounts of nutrients in the various pools from which annual nutrient deficits or surpluses in the plant available pool can be calculated. Deficits indicate the need for nutrient additions; surpluses can indicate the risk of nutrient leaching losses. The model can be used to examine various scenarios such as the effects on nutrient supply and demand of climate change or genetic gain on productivity, understorey vegetation management strategies, intensive forest management such as thinning or biomass harvesting for bioenergy, or multiple rotations. The model is presented in Payn *et al.* (2005). The current model is simple and does not incorporate feedback to reduce tree growth if crop nutrient demand exceeds site nutrient supply, or predict actual leaching loss as it does not yet incorporate a rainfall input and drainage component, or address physical loss of nutrients in sediment.

## Scenarios

Examples of scenarios that could affect the balance of nutrients in forests (Figs. 2 to 4) resulting in possible off-site nutrient movement are included to demonstrate the application of the nutrient balance model. Details of the scenarios are contained in Payn *et al.* (2005).

Manipulation of the understorey to reduce the impacts of competition on seedling establishment and early growth is a common practice. Fig. 2 shows how the model can be used to identify the periods (0 to 4 years and the period following the second thinning at age 13 for the weed-free site) in the rotation when nutrient supply exceeds crop demand and therefore puts the site at risk of leaching losses. The model can also be used to predict the potential size of these losses, by calculating the area under the curve. The impacts of weeds on tree growth would be greater in drier

*Fig. 2: Effect of presence or absence of a weed understorey on N supply and crop demand over one rotation of radiata pine. The weed-free site has a higher N supply until age 4.*

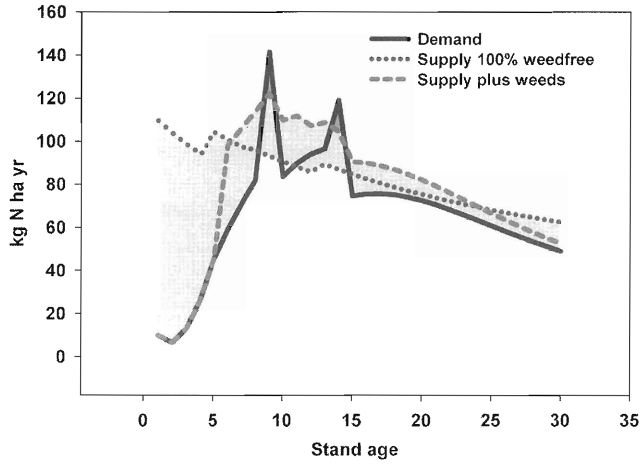
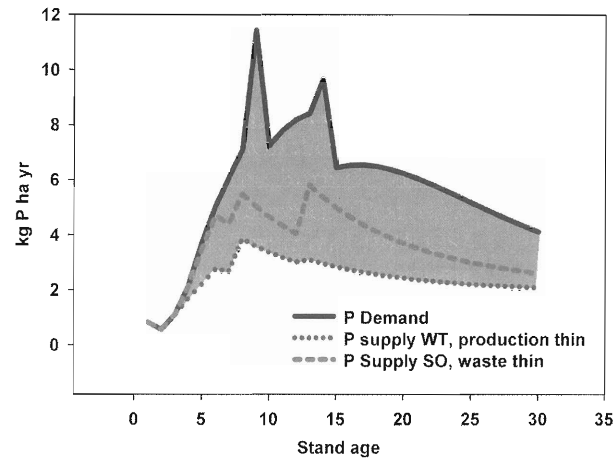



*Fig. 3: The impact of harvest intensity on P supply and crop demand during the subsequent rotation of radiata pine. The shading indicates periods when demand for P exceeds supply following whole tree (WT) harvest. The deficit is less following stem only (SO) harvest.*




climates or where weed control measures had not been effective. Under conditions of severe competition, nutrient losses are expected to be greatly reduced.

Removal of nutrients from a site due to crop harvesting or soil disturbance can have an impact on productivity of the next crop. The consequences of reduced nutrient supply early in successive rotations as a result of whole tree harvesting, as identified by Webber (1978), and the impacts of large-scale disturbance of forest floor, which can contain a large quantity of nutrients (Ballard 1978b; Ballard & Will 1981; Dyck & Beets 1987), are apparent in Fig. 3. This indicates the site's need for nutrient additions to achieve the expected level of productivity from age 3 for the whole tree harvest and age 6 for the stem only harvest, and the increased overall input required for the whole tree harvesting treatment compared to stem only removal.

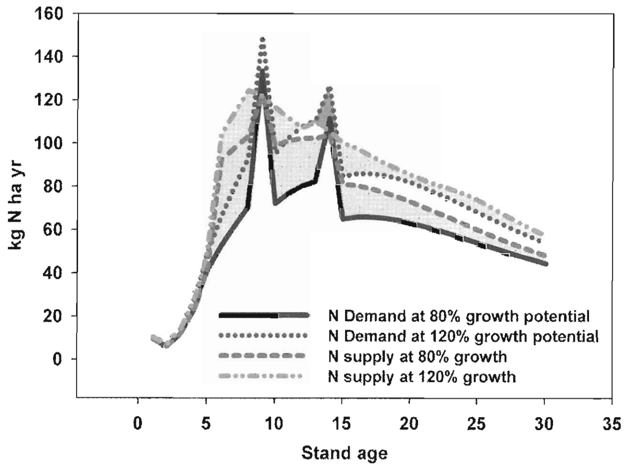
At some sites, multiple rotations may result in the depletion of site nutrient capital. This is illustrated for phosphorus (P) at six sites (Table 2). The model, run over six rotations, predicts varying levels of depletion of soil P levels, weathering inputs of P, and the amount of deficit that needs to be offset through fertilisation to achieve the required productivity. These potential declines appear large but are small compared to the quantities of nutrient inputs required to maintain agricultural production systems and the environmental risks posed by such practices. In the case where P fertiliser has been applied to correct severe P deficiency in the first rotation, or to replace P lost in harvest removals, fertiliser requirements may be reduced on some soils due to residual benefits of previous P applications (Ballard 1978a; Comerford *et al.* 2002). It should be noted that, to date, no decline in productivity due to nutrient depletion has been recorded in New Zealand plantations, some of which are in their fourth rotation.

The model can also be used to explore the impact of advances in forest management practices that may have a large impact on forest productivity. For example, predictions have been made on the effects of genetic gain on forest yields (e.g. Carson *et al.* 1999). Simulating increased growth rates of +20% as a result of genetic gain or climate change (Fig. 4) clearly illustrates that site nutrient pools will more than likely not be adequate to support the higher level of productivity. This observation may well have important implications for gains in carbon sequestration from genetic improvement of radiata pine plantations (Jayawickrama 2001). The model identifies the timing and magnitude of fertiliser additions required to support the increased growth. Conversely, an adverse climate change scenario (possibly due to pests or disease) that results in a 20% decline in

*Table 2: Summary of output of model for 6 (180 years) successive rotations of radiata pine for ecosystem pools and transfers of P (kg/ha).*

| | Site A | Site B | Site C | Site D | Site E | Site F |
|---|---|---|---|---|---|---|
| Initial total soil P | 975 | 963 | 585 | 603 | 569 | 623 |
| P weathered | 387 | 303 | 410 | 143 | 161 | 265 |
| P in wood removals | 322 | 343 | 282 | 274 | 273 | 220 |
| P deficit | 64 | -39 | 128 | -130 | -112 | 44 |
| Fertiliser addition P | 0 | 203 | 0 | 218 | 157 | 0 |
| Remaining soil P | 588 | 659 | 175 | 459 | 408 | 357 |
| Total timber production units (m3/ha) | 2151 | 1904 | 2871 | 2669 | 2601 | 2143 |

*Fig. 4: Effect of varying productivity on N balance. N demand can exceed N supply when growth rate is increased to 120%. Conversely, when growth rate is reduced to 80% there is an excess of supply over demand.*




productivity indicates an increased likelihood of leaching losses later in the crop rotation.

## Discussion

Plantation forestry has a low nutrient footprint by comparison to other productive agricultural land uses, both in terms of nutrient inputs to produce the crop, and in terms of losses to the wider environment. There is an opportunity for forestry to capitalise on this low footprint, but currently there seems little acknowledgement of the benefits of forestry in the wider community. The development of the nutrient balance model is a first step towards improving this understanding. The model has been used to predict the results of a range of scenarios on nutrient supply and demand, and possible leaching loss risks.

Developing the model to run within a spatial framework to predict what might happen when forestry is considered in a catchment context with a number of different management scenarios is a logical next step to define cumulative impacts within a catchment or region. Outputs could then be linked to outputs from similar models running on other agricultural systems to design lower impact management systems.

Currently there is significant regional and national discussion on the merits of developing nutrient trading systems for land management. Nutrient balance models can contribute to this development. A low impact land use such as forestry can be considered as complementary to high impact land uses such as dairy with their much higher nutrient inputs and impacts. There is potential for forestry to be a major financial beneficiary if trading schemes were implemented based on the actual nutrient footprints of the different sectors. This would allow the recognition of the non-timber values of plantation forests, and potentially lead to a higher economic value of plantations in New Zealand, based on these added values.

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