Land use impacts on nutrient export in the Central Volcanic Plateau, North Island

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Abstract

Different land uses are increasingly being scrutinised for their impacts on downstream waterbodies, particularly in relation to rates of nutrient export. Phosphorus export varies mostly with sediment erosion but nitrogen export is mostly associated with nitrate leaching to groundwater, which is highly variable under different land uses. Both plantation and native forests leach a fraction of the nitrate of most pastoral lands except perhaps just after harvest, but particularly compared with modern farming regimes of addition of labile nitrogenous fertilisers to increase pasture growth and support higher stock numbers.

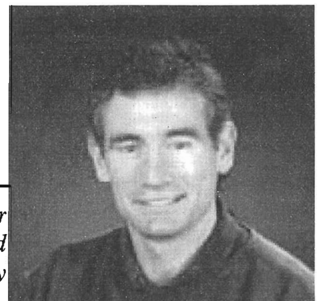
Recent use of dating techniques to 'age' stream inflows to Lake Taupo and the Rotorua lakes suggest that the effects on stream nitrate concentrations of past conversions of forest to pastoral land and more recent intensification of pastoral land are only partially expressed, as stream inflows are mostly several decades old. Use of riparian buffers, nitrification inhibitors and in-stream and in-lake flocculants may partially offset intensification of land use, but forward thinking is required to mitigate for effects of lag times and achieve a holistic balance of economic, environmental and social aspirations.

Introduction

The natural composition of water on the landscape is altered by a variety of human activities which influence its quality (Peters & Meybeck 2000). Recent and widespread decline in quality of New Zealand waterbodies as a result of human activities indicates that modification or regulation of land use may be required to preserve water quality, at least in catchments that contribute to high value waterbodies. For example, a 20% reduction in nitrogen loads from manageable sources (not including forestry) has been proposed by Environment Waikato to protect water quality of Lake Taupo (Environment Waikato 2003).

Further, Environment Bay of Plenty proposes under its Regional Land and Water Plan that a change of land use should not increase nutrient loads by more than 10% in catchments of Rotorua lakes where there is declining water quality (Environment Bay of Plenty 2004). Time series data for nutrients, transparency and algal biomass in the Rotorua lakes are synthesised using the Tropic Level Index (Burns *et al.* 2000), which indicates that five out of twelve major Rotorua lakes show a significant trend of declining water quality.

Different land uses are increasingly being scrutinised for the rate at which they export nutrients. There is now some urgency to these evaluations as a result of dramatic increases in fertiliser additions to pastoral lands (Parliamentary Commissioner for the Environment 2004) and degradation in water quality of significant lakes and rivers (Hamilton 2003; Larned *et al.* 2004; Vant & Smith 2004).



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The objective of this paper is to review some of what is known about different New Zealand land uses in terms of nutrient export, and to examine the possibility for mitigation measures to attenuate nutrient loads. The primary focus is on lakes of the Central Volcanic Plateau (CVP) of the North Island but the information is pertinent to other areas of New Zealand. Specifically, there is a need for regulators to address long response times of receiving waters to land use change, and to integrate science, policy, planning and education in order to develop long-term visions for balancing economic, environmental and social aspirations for catchments.

Soil nutrients in the CVP

Soils of the CVP are characterised by comparatively recent volcanic activity that has produced a permeable surface tephra layer of pumice that readily allows rainwater recharge to penetrate deeper, mostly unconfined aquifers. Water derived from these volcanic soils is comparatively rich in phosphorus (P), so that primary production in receiving waters is frequently limited by nitrogen (N) rather than phosphorus (White *et al.* 1985).

Globally, nutrient management strategies for waterbodies are generally predicated upon control of phosphorus as nitrogen tends to be limiting only infrequently in the Northern Hemisphere where much of the information on nutrient control strategies has originated. The increased prevalence in eutrophic Rotorua lakes of blooms of blue-green algae (cyanobacteria), some of which fix atmospheric N dissolved in the water column, is a reminder that control of P should still be an integral part of nutrient management strategies for all catchments (Hamilton 2003).

Limitation by N is also partly a response to comparatively low rates of atmospheric nitrogen deposition in the Southern Hemisphere. Typical rates of atmospheric nitrogen deposition are 3-4 kg N $ha^{-1} yr^{-1}$ (Schouten 1983; Timperley *et al.* 1985; Nicol *et al.* 1997) and for phosphorus, 0.17 kg P $ha^{-1} yr^{-1}$ (Schouten 1983). For Lake Taupo, where the ratio of catchment area (2800 km^2) to lake surface area (616 km^2) is comparatively small (~4.5), atmospheric deposition contributes a substantial nutrient load; around 19% of N and 6% of P. This figure demonstrates the reasoning behind lake-specific strategies that delineate manageable nutrient sources (e.g. from pastoral farming) from unmanageable sources (e.g. from the atmosphere) in evaluating realistic nutrient load reduction strategies for lakes.

Lag times

Waterbodies respond only slowly to changes in catchment land use, at time scales which mostly reflect hydrologic transport times. Tritium and CFC compounds have been released to the atmosphere as a result of human activities and their analysis in groundwater or near spring sources can be used to provide an indication of the length of time since the water was last exposed to the atmosphere, i.e. transport times, whilst acknowledging that the water will still have an 'age distribution' corresponding to preferential flow paths within the aquifer system (Hadfield *et al.* 2001). Using tritium and CFC analyses, streams that constitute the majority of the inflow to Lake Taupo have been estimated to range from <30 to >80 years (Vant & Smith 2002), with a median age around 45 years.

Hamurana Springs, the highest discharge of any single inflow to Lake Rotorua, has a median age of 145 years, while there are other inflows at least several decades old (Morgenstern *et al.* 2004). In addition, in a large lake such as Taupo, where the water residence time is approximately 10 years, it takes about 25 years for conservative solutes (e.g. chloride) to attain 95% of equilibrium levels based on stream inflow concentrations (see Hamilton & Wilkins 2004) and a further 1-5 years for the biological response to be fully expressed.

As a result of the lag times in groundwater transport, water composition from many of the CVP catchments does not reflect either the full extent of conversion of forest and scrub land to pasture (Hadfield *et al.* 2001) or recent increases in intensity of pastoral land use associated with increasing fertiliser additions (Parliamentary Commissioner for the Environment 2004). This issue is most relevant to nitrate, which is readily leached through the soil profile, while phosphorus in groundwater is associated mostly with dissolution of minerals. There are no clear trends in phosphorus concentration in selected stream inflows to Lakes Taupo and Rotorua, but for some of these streams there have been several-fold increases in nitrate concentration in the past 2 to 3 decades (Vant & Smith 2002; Rutherford *et al.* 2003).

Land use impacts and nutrient export

The recent trend of widespread increase in reactive nitrogen fertiliser applications and reduced reliance on clover for nitrogen fixation (Parliamentary Commissioner for the Environment 2004) may also lead to considerable disparity in nitrate export between traditional and intensive farming types. There is inevitably some direct leaching of nitrogenous fertilisers to groundwater but much of the leaching is associated with 'patches' of animal excreta, particularly urine, that can leach nitrate at rates equivalent to 500 to 1000 kg ha^{-1} yr^{-1}. Thus increasing fertiliser additions have been used to stimulate greater pasture productivity and to support more animals on the land, with corresponding increases in excreta and nitrate leaching. Additions of phosphorus also remain fundamental to this intensification, in order to achieve balanced nutrition for optimal pasture growth.

Nitrogen budgets based on land uses in different catchments in the CVP have used a range of areal export rates, primarily to reflect land use effects on nitrate leaching. Variations in export rates will also be contributed by lag times as nitrate concentrations in streams equilibrate to the prevailing land use (e.g. conversion of forest to pasture), differences in soil properties, intensity of specific land uses, and land management practices. For different pastoral systems at equilibrium, N export rates may be around 10 to 16 kg ha^{-1} yr^{-1} for sheep and beef farms, and 30 to 70 kg ha^{-1} yr^{-1} for dairy farms. Elliot & Stroud (2001) used mid-range *equilibrium* values of 14 kg ha^{-1} yr^{-1} for non-dairy farms and 52 kg ha^{-1} yr^{-1} for dairy farms in applying the catchment nutrient model GLEAMSHELL to Lake Taupo.

Groundwater in the CVP that is uninfluenced by pastoral land use or geothermal activity has total N concentrations around 0.1 to 0.2 g m^{-3}, generally equating to areal export rates of 1.5 to 3 kg ha^{-1} yr^{-1}; Quinn & Stroud (2002) estimated the nutrient yield from a native forest catchment to be 2.1 kg N ha^{-1} yr^{-1}. Total nitrogen yields for native forest or scrub catchments may in some cases exceed those of plantation forests, but are also highly variable depending on species present, forest age structure and the way in which these species influence soil composition. Nodulated plants and free-living bacteria in leaf litter may fix up to 10 kg N ha^{-1} yr^{-1} in native forests (Silvester & Musgrave 1991) and export considerable dissolved organic nitrogen, whereas nitrogen fixation is absent or low in the forest floor beneath pine.

Mylechreest (1988) stimulated considerable debate with an unpublished report that suggested that pine plantations were more efficient at nitrogen uptake than native forest, and that this would enhance nitrogen limitation in Rotorua lakes, ultimately favouring formation of blooms by nitrogen-fixing blue-green algae. In a reply to the Mylechreest report, Silvester (2001) pointed to limited empirical evidence for higher nitrogen yields from pine forest relative to podocarp hardwood forest, but also highlighted the high degree of heterogeneity of native catchments.

By contrast, differences in nutrient yields between pasture and both pine and native forests are well established and provide a far more definitive measure of the benefits, in terms of nutrient export, of conversion of pasture to forestry (Wilcock 1986; Cooper & Thomsen 1988; Menneer *et al.* 2004), with flow-on benefits of reduced trophic status in receiving waters. Conversely conversion of forest to pasture will be associated with increased nutrient export and concomitant decline in water quality.

Most of the data assembled for comparisons of native, pine and pasture catchments has been when pine catchments have been in a phase of active growth or when the canopy has been closed and approaching harvesting.

At the time of canopy closure (9 to 12 years after planting) in the steep (mean slope 17°) Purukohukohu catchment near Rotorua, Cooper & Thomsen (1988) found that nitrogen exports from a pine subcatchment were lower than those from a native forest subcatchment, but the pine subcatchment was less retentive of total phosphorus (4-fold difference). Quinn & Ritter (2003) produced evidence to show that nutrient export from the same pine plantation as it approached maturity was higher than from the native forest; nitrate c. 2-fold, total Kjeldahl nitrogen (TKN) c. 6-fold and total phosphorus c. 14-fold.

Nutrient yields through the logging and regeneration phases in pine catchments of the CVP are of particular interest because of the large amount of plantation forest that is of harvestable age. Quinn & Ritter (2003) found that total phosphorus yields were 24-fold higher in the pine subcatchment in the year following harvesting and then decreased to 3-fold higher four years after harvest. Comparable figures for nitrate and TKN were c. 4-fold and 26-fold higher, respectively, one year after logging, followed three years later by nitrate yields less than one-fifth and TKN c. 2-fold higher than the native forest control.

Generalisations of nutrient export from pine plantations are difficult to make as there are wide variations attributable to harvesting and regeneration techniques, tree age, soil type and topography. Export rates of nitrogen vary from 3 to 28 kg ha^{-1} yr^{-1} (Menneer *et al.* 2004) and may approach 10 kg ha^{-1} yr^{-1} within two years after harvesting, but are mostly at the lower end of the range in undisturbed plantations (3 to 5 kg ha^{-1} yr^{-1}; Parfitt *et al.* 1997) unless there are exceptional circumstances related to plantation soils with high N, applied wastewater or fertilisation. Other estimates applied to Lake Taupo have adopted lower rates of N export; 1.5 kg ha^{-1} yr^{-1} (Elliot & Stroud 2001; Vant & Smith 2002) and 2 to 2.5 kg ha^{-1} yr^{-1} (Vant & Huser 2000) that may reflect losses of N in stream and riparian zones.

Phosphorus export from plantation forests (0.07 to 0.1 kg ha^{-1} yr^{-1}; Menneer *et al.* 2004) generally falls outside of the range for pastoral systems but is also variable (Cooper & Thomsen 1988), particularly in relation to amount of sediment eroded, which is affected by factors such as harvesting techniques and topography (Quinn & Ritter 2003).

It may be surmised from these results and from comparisons with other native forest types that there is increased export of nitrogen and phosphorus as pine forests approach maturity, that relative to pastoral land there are substantially lower nutrient yields from plantation forestry over the full rotation cycle, and that there is a rapid return to low nitrogen yields, but less so for phosphorus, around 2 years after harvesting and replanting of pine.

Catchment scale

The study by Quinn & Ritter (2003) highlights the importance of long-term data collection in order to more fully understand the nutrient yield dynamics of pine plantations over a rotation cycle. The effects of forestry on stream water quality in the Taupo catchment have been examined for the Waimarino River (1994-present; 36% *Pinus radiata*) and Mangakowhitiwhiti Stream (1996-present; 75% *P. radiata*) (Rodgers 2003). Concentrations of total nitrogen and total phosphorus in these streams remain low (generally <150 mg total N m^{-3} and <15 mg total P m^{-3}), while ratios of total N to total P, relative to requirements for balanced growth, indicate a slight tendency for nitrogen deficiency (Rodgers 2003). While no significant impact of harvesting operations on water quality has been demonstrated at the whole stream scale, there are temporary (c. 2 year) increases in concentrations of total and dissolved nutrients in subcatchments where there are harvesting operations.

Dilution of runoff from the harvested subcatchment as well as in-stream processing may mitigate the adverse effects of harvesting, but this will also be specific to harvesting methods and intensity, and site characteristics (e.g. rainfall, slope). Pine forest may be slightly more conservative of nitrogen than phosphorus compared with native forest, but differences in nutrient yield between pine and native forests are not consistent, nor easily resolved, compared with the magnitude of changes in N yield, and to a lesser extent P yield, with conversion of pasture to forest (Wilcock 1986). By contrast, there is a sound scientific basis to predict that planned conversion of plantation forest to pastoral land use between Taupo and Reporoa will substantially increase nutrient loads to the receiving waters of the Waikato River, with concomitant deterioration of river water quality.

The development of knowledge about catchment scale implications of forestry on nutrient yields requires data to be collected over rotation cycles (e.g. Rodgers 2003), targeted research to understand relevant processes operating before, during and after harvesting operations, and modelling to estimate catchment scale nutrient yields from plantations, particularly in the current phase of high harvesting intensity. This knowledge will indicate whether re-evaluation is required in treating nutrient yields from pine plantations as an 'unmanageable' source of nutrients in the nitrogen reduction targets imposed for Lake Taupo (Environment Waikato 2003).

Riparian strips

The use of riparian buffer strips alongside streams is widely promoted as a mitigation measure for the effects of sediment and nutrient runoff from land use intensification (Collier *et al.* 1995) or forest harvesting operations (Collier 2001). The success of these buffers will be highly reliant on the area dedicated for riparian processing of sediment and nutrients relative to the load. Pastoral areas have considerably higher areal loads of sediment and nutrients than pine forests, and will therefore require larger riparian areas to be devoted for plant nutrient uptake, as well as denitrification to remove nitrogen. Maturity of riparian areas (i.e. progression to canopy closure and invasion of large woody vegetation) will progressively reduce nutrient uptake (Howard-Williams & Pickmere 1999) but may be offset by pro-active management to maintain an open canopy and through harvesting of some riparian plants such as water cress (*Nasturtium officinale*) or raupo (*Typha orientalis*) to maintain nutrient processing capacity. Calculations of carbon increments for vegetation in riparian areas and stoichiometric approximations of associated N and P uptake should be used to ensure that there is sufficient riparian area dedicated for nutrient processing in the first place.

At a catchment scale it is generally difficult to model the effects of riparian buffer zones because of the small spatial scales on which these zones operate relative to the sub-catchment grid scale used for most catchment models (e.g. GLEAMSHELL). The wide range in riparian areas relative to nutrient load, variations in in-stream nutrient processing, areas of anoxic (generally boggy) zones for denitrification, and the stage of maturity of riparian plants are some of the reasons why the success of riparian areas is somewhat equivocal, with nutrient removal rates ranging from highly efficient (Smith 1989) to modest (Cooper *et al.* 1990).

Other approaches to mitigation

There is active research on other methods to offset increasing nitrate levels in runoff from pastoral land. OVERSEER is a model that is intended to be used mostly at an individual farm scale, as a tool for evaluating both incoming and outgoing nutrient fluxes and efficiency of nutrient uptake into economic produce (Ledgard 2000). It can also be adapted to a range of land uses such as pasture, crop and horticulture. For a dairy farm OVERSEER includes input data such as fertiliser application rates, soil type, annual rainfall, stocking rate (cows per hectare) and animal production (milk solids per hectare), and generates nutrient export rates on an areal basis. The model allows various dairy management options such as winter feed pads and grazing management techniques to be evaluated quantitatively in terms of their effects on farm nitrogen export (Menneer *et al.* 2004).

Another area of development is in nitrification and urease inhibitors to restrict microbial nitrification that would otherwise render applied inorganic nitrogen in the readily leached form, nitrate. This work is in its infancy and while small-scale results are promising, there is a need to evaluate performance of these products at a whole paddock or farm scale (Edmeades 2004). Use of flocculants or filtration materials is also a highly promising technique for removal of phosphorus, and a range of traditional flocculants (e.g. alum) and new materials (see Yang *et al.* 2004) may offer opportunities for separation and removal of P from streams, or permanent sedimentation and burial of P when applied at the whole lake scale.

The use of nitrification inhibitors or flocculants offers an opportunity to offset some of the effects of increasing nutrient export from land use intensification, generally at considerable cost, but cannot be used as a substitute for land uses that minimise nutrient export and are also profitable. Indeed, there is likely to be an increase in regulation and incentives to promote land uses that reduce nutrient exports in catchments where there are waterbodies of national or regional significance.

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