Title: Relationships between land use and nitrogen and phosphorus in New Zealand lakes

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Abstract

Developing policies to address lake eutrophication requires an understanding of the relative contribution of different nutrient sources and of how lake and catchment characteristics interact to mediate the source-receptor pathway. We analysed total nitrogen (TN) and total phosphorus (TP) data for 101 New Zealand lakes and related these to land use and edaphic sources of P. We then analysed a sub-sample of lakes in agricultural catchments to investigate how lake and catchment variables influence the relationship between land use and in-lake nutrients. Following correction for the effect of covariation amongst predictor variables, high producing grassland (intensive pasture) was the best predictor of TN and TP, accounting for 38.6% and 41.0% of variation respectively. Exotic forestry and urban area accounted for a further 18.8% and 3.6% of variation in TP and TN respectively. Variation in mean catchment soil P could not account for variation in TP due to the confounding effect of pastoral land use. Lake and catchment morphology (z_{max} and lake: catchment area) and catchment connectivity (lake order) mediated the relationship between intensive pasture and in-lake nutrients. Mitigating eutrophication in New Zealand lakes requires action to reduce nutrient export from intensive pasture and quantifying P export from plantation forestry requires further consideration.

Introduction

Excess inputs of nitrogen (N) and phosphorus (P) to lakes can cause eutrophication and the associated decline of water quality and ecological integrity (Vollenweider 1968; Smith 2003). Natural sources of these nutrients to freshwaters include: organic matter such as plant residues which undergo mineralisation, atmospheric di-nitrogen fixed by heterocystous phytoplankton species and P associated with apatite bearing minerals (Newman 1995; Rabalais 2002). Inputs from anthropogenic sources are, however, increasing in many parts of the world and loading associated with pollution now greatly exceeds natural N and P loads to many lakes (Smith 2003).

Lake managers require an understanding of nutrient sources and the processes that drive lake productivity before developing plans to improve water quality in eutrophied lakes (Moss 2007). Although limnologists have traditionally focussed on the study of in-lake processes (Johnes 1999), there is now widespread understanding that the successful control of nutrient pollution and its associated problems is contingent on developing a holistic and integrated understanding of lakes in the context of their wider catchments (Ferrier and Jenkins 2010). While there is limited scope to adopt an experimental approach to investigate how natural and anthropogenic factors influence nutrient loading to lakes, the empirical analysis of relationships between lake and catchment variables across different scales can advance mechanistic understanding. Geographical Information Systems (GIS) can provide a platform for the collation and integration of data relating to a wide range of bio-physical parameters at a catchment scale (Macleod *et al.* 2007; Johnson and Host 2010) and numerous studies have used GIS to investigate relationships between catchment characteristics and water quality (e.g. Arbuckle and Downing 2001; Lee *et al.* 2009; Roberts and Prince 2010).

When empirically investigating how catchment characteristics interact to influence nutrient loading to a lake, it is useful to distinguish between characteristics that are nutrient sources (or direct proxies for specific sources) and characteristics that do not represent sources yet mediate the pathway between the nutrient source and the lake (Figure 1). For example, the proportion of farmland in a catchment is a direct indicator of the amount of nutrients from agricultural sources available for export to a lake, whereas average catchment slope is an indicator of the gravitational energy available for the transfer of those nutrients via mechanisms such as overland flow. A failure to make this distinction can lead to confounding conclusions regarding the likely contribution of various nutrient sources to external lake nutrient loads. This is also complicated by covariation of natural and anthropogenic factors (e.g. land use and soil type) which is frequently encountered in landscape ecology and can make it problematic to determine whether a relationship is causal or spurious (Van Sickle 2003; Allan 2004; Daniel *et al.* 2010). For example, Liu *et al*. (2010) studied 103 lakes across China and found that natural factors, specifically variables relating to geographic location, lake morphology and climate, accounted for 13.3 – 57.5% of the variance in eutrophication parameters. As the authors concede, however, the reason why some 'natural' factors such as longitude and altitude partly determine trophic state is because these factors are probably co-related with human development and therefore anthropogenic nutrient pollution; a factor not represented in their study.

Eutrophication is a significant problem affecting freshwaters in New Zealand where an estimated 32% of lakes greater than 1 ha in area (n > 1000) are classified as eutrophic or hypertrophic and consequently have very poor water quality (Ministry for the Environment 2010). Empirical studies and experiments have shown that both N- and P-limitation of phytoplankton growth occurs widely in New Zealand lakes and this, in addition to frequent high connectivity between freshwater and marine ecosystems, supports the need for dual control of N and P export from New Zealand lake catchments (Abell *et al*. 2010). Intensification of land use resulting in increased external nutrient loads has become an increasing concern for resource managers and policy makers (Hamilton 2005; Edgar 2009). In particular, nutrient export from New Zealand's increasingly intensive agricultural land has been subject to scrutiny (Parliamentary Commissioner for the Environment 2004) and the presence of pastoral land in a catchment has been shown to correlate with the occurrence of a shift from a clear to a de-vegetated, turbid state in lakes (Schallenberg and Sorrell 2009). While the relationship between catchment land use and water quality has been investigated for streams and rivers in New Zealand (Close and Davies Colley 1990; Larned *et al*. 2004; McDowell *et al*. 2009), the contribution of catchment land use to in-lake nutrient concentrations has not been quantified at a national scale, either in New Zealand or elsewhere. In this study, we investigate how catchment characteristics relate to in-lake concentrations of total phosphorus (TP), total nitrogen (TN) and chlorophyll *a* for 101 lakes distributed throughout New Zealand. By differentiating between variables that are direct proxies for nutrient sources and those that represent other factors, we seek to highlight relationships that are significant at the national scale. For this sample, we asked: (1) to what extent do anthropogenic land uses explain variation in TN and TP concentrations? and (2) is the relationship between land use and in-lake nutrient concentrations influenced by other catchment and lake characteristics?

Methods

Data collection

Lake water quality data

Mean data relating to the trophic status parameters total phosphorus (TP), total nitrogen (TN) and chlorophyll *a* (chl *a*) were obtained from New Zealand regional councils for 101 lakes located throughout New Zealand (Figure 2). The data related to samples collected by regional environmental managers, either from the lake surface, or from integrated depths in the surface mixed layer, at monthly or quarterly intervals during 2004 - 2006 (Ministry for the Environment 2006). All samples were analysed using standard methods based on APHA (1998) and described by Burns *et al*. (2000). Each mean datum is therefore representative of at least 12 samples taken over a three-year period.

Extracting lake catchment data

A GIS map layer comprising delineated catchment boundaries in polygon format was created for the 101 lakes using ArcGIS (ESRI, version 9.3.1), based on a digital map layer of lake catchment boundaries that was provided by the New Zealand Department of Conservation. Lake catchment boundaries were originally defined by the National Institute of Water and Atmospheric Research (NIWA) as part of the development of the River Environmental Classification (REC) system. The REC system is based on a digital elevation model using a 30 m pixel size with 20 m contour data (Ministry for the Environment and NIWA 2004).

Catchment connectivity and morphology data

The following 'connectivity' parameters were calculated for each catchment: average catchment slope (in degrees), stream length (m) relative to area (km^2) of non-lake catchment and lake order. Average catchment slope was calculated using the 'slope' tool within ArcGIS which was applied to a 25 m resolution topographic raster map. Stream length was calculated using the REC line feature stream map. Lake order was defined in accordance with Martin and Soranno (2006) as the highest Strahler stream order of a lake inflow. The ratio of catchment area to lake area (A_c:A_l) was calculated for each lake and maximum depth (z_{max}) and lake altitude were obtained from Ministry for the Environment (2006).

Land use data

The area of individual land use/ land cover (hereafter 'land use') categories in each lake catchment was calculated using the New Zealand Land Cover Database version 2 (LCDB2). The LCDB2 is a GIS map layer in polygon format that has a 15 m resolution and describes the spatial distribution of 43 land use types based on Landsat 7 ETM+ imagery acquired in 2000-2001 (Ministry for the Environment 2004). Areas of the following land uses were calculated for each catchment: 'built up area' (built up area), 'exotic forest' (exotic), 'arable cultivation' (crop), 'native forest' (native), 'high-producing grassland' (high prod. grass), and 'low-producing grassland' (low prod. grass). Areas were then converted into percent coverage of non-lake catchment. The area of exotic forest was calculated by taking the sum of the six LCDB2 'planted forest' land use categories (see Ministry for the Environment 2004) while the area of native forest was defined as the sum of the 'indigenous forest' and 'broadleaved indigenous hardwoods' categories. The area of 'arable cultivation' was calculated by taking the sum of the 'short rotation cropland', 'orchard and other perennial crops' and 'vineyard' categories. The remaining three categories correspond to single LCDB2 categories. 'Low-producing grassland' comprises both native and exotic grasses that display relatively low plant vigour indicative of low soil fertility, short growing season and/or minimal fertiliser application. It is typically managed as pasture for low densities of sheep or beef cattle. 'High-producing grassland' comprises exotic grasses that are intensively managed as pasture for livestock production and receive fertiliser application.

Soil data

Area-weighted catchment mean values of soil cation exchange capacity (CEC) and drainage were calculated using digital soil fundamental data layers (FDLs). FDLs contain data for 16 key soil attributes (polygon format) for all New Zealand soils derived from stereo aerial photograph interpretation, field verification and single factor soil surveys undertaken as part of the 1:63 360/1:50 000 scale New Zealand Land Resource Inventory (NZLRI) survey (Newsome *et al.* 2000). Data are not available for soils that are permanently submerged or in urban areas. In most areas only the soil record (i.e. soil type) has been mapped in the field and data for other parameters are derived from established correlations with the mapped soil (Newsome *et al.* 2000). Mean values for CEC and drainage were calculated for 99 of the 101 catchments as two catchments had no exposed soil as they comprised urban land or exposed bedrock. The NZLRI maintains a record of data for each attribute in the form of discrete rating categories, as described in Table 1. An area-weighted mean value was calculated for the P content of the soil in each catchment using the Land Environment New Zealand (LENZ) acid soluble phosphorus data layer (polygon format). This parameter provides a measure of the natural abundance of P in the soil and does not reflect P from anthropogenic sources such as fertiliser. Soil fertility data included in the LENZ database have been developed by grouping soils together based on the nutrient status of 129 classes of parent material (Leathwick *et al.* 2002). Each group has been assigned a rating based on acid soluble P concentration, ranging from 1 (very low) to 5 (very high) (Table 1).

For each catchment, an area-weighted mean value was calculated for each of the three soil attributes using the median value of each rating category present in the catchment. For

CEC, soils with a rating of 1 were assumed to have a CEC of 40 meq $(100\ g)^{-1}$ while soils with a rating of 5 were assumed to have a CEC of 5.9 meq $(100\ g)^{-1}$.

Rainfall data

Annual mean rainfall was calculated for each catchment using monthly GIS raster layers that have been developed by Landcare Research using data collected by the New Zealand Meteorological Service from 2202 monitoring stations during 1951 – 1980 (Leathwick *et al.* 2002).

Statistical analysis

All statistical analyses were undertaken using Statistica (version 8.0; Statsoft, Tulsa, USA) and a significance level of $p < 0.05$ was adopted in all tests. Probability plots and histograms were inspected before analysis and most variables were transformed to improve normality and homogeneity of variances. Land cover percentages were converted to a proportion and then arcsine square-root transformed. The remaining variables were $\log_{10}$ transformed with the exception of 'length of stream per km^2' which was normally distributed. Data were reduced to a common scale by subtracting the mean and dividing by the standard deviation to produce standardised descriptors that allow for the calculation of meaningful covariances (Legendre and Legendre 1998). Standardised data were then used during initial data exploration and to address our first research question.

The data were initially explored by constructing a Pearson correlation matrix and then by undertaking principal component analysis (PCA) (see Figure 3 for an overview of analytical methods). PCA can be applied to multivariate data to identify a small number of transformed variables that describe most of the variation in the data. Analysis of a projection of the two principal components allowed the main relationships between lake and catchment variables to be visualised.

Linear regression analysis was then used to identify the variance in TN and TP explained by nutrient sources. Subsequently, the method for selecting predictor (independent) variables reflects this aim. Predictor variables for regression analysis were chosen by selecting variables that: (1) represent nutrient sources (anthropogenic land use proportions or soil P content) and (2) significantly positively correlate with lake TN or TP. Separate multiple linear regression functions to predict both TN and TP were developed using the chosen predictor variables. To identify the variance in TN and TP solely explained by each predictor variable, we performed partial linear regressions with and without the variable(s) of interest and partitioned variance using the method described by Legendre and Legendre (1998) and adopted in a similar study by Goldstein *et al*. (2007). Briefly, this method separates the variance in a dependent variable explained by a particular predictor variable (or set of predictor variables) (R_a^2) from the variance explained by another predictor variable (or set of predictor variables) (R_b^2) included within a multiple linear regression model that can explain variance R_{abc}^2, where R_c^2 is the combined variance explained by variables *a* and *b*. Therefore, $R_a^2 = (R_{abc}^2) - (R_{bc}^2)$. This method thus allowed us to identify the degree to which each predictor variable in the regression functions explained the variation in in-lake TN or TP by removing the effect of covariation with other predictor variables included in the regression model.

To address our second research question, we isolated a sub-sample (n = 43) of lakes that had catchments dominated by the land use type that best correlated with lake TN and TP. Based on *a priori* hypotheses (Table 2), we then tested whether eight variables influenced the relationship between land use and in-lake nutrient concentrations in our national-scale sample. To test our hypotheses, we used multiple linear regression to quantify whether the inclusion of a term to represent interaction between the land use variable and the variable of interest significantly improved the prediction of $\log_{10}$ TN or $\log_{10}$ TP. The form of the linear model was:

$$\text{NUTRIENTS} = a + (\beta_1 \times \text{LAND USE}) + (\beta_2 \times (\text{LAND USE} \times \text{VARIABLE})) + \varepsilon$$

where NUTRIENTS = transformed TN or TP concentrations; a = intercept, LAND USE = transformed land use proportion; VARIABLE = catchment characteristic variable hypothesised to mediate the relationship between land use and in-lake nutrient concentrations; ε = error term; β_1 and β_2 are regression coefficients. Separate multiple linear regression models were developed to predict both TN and TP based on land use and each of the eight variables being tested. We concluded that the relationship between in-lake nutrient concentrations and the land use variable was influenced by a catchment characteristic if inclusion of the interaction term made a significant improvement to the model prediction. Variables used in the analysis were transformed as previously described to achieve normality, which was then confirmed using a Kolmogorov Smirnov test ($p > 0.05$). Data were not standardised for this analysis.

Results

Data exploration

The sample of 101 lakes included a diverse range of lakes from a broad geographic range within New Zealand (see Table 3 and Figure 2). Lake area ranged from 0.03 - 612.6 km^2, the largest lake being Lake Taupo which is the largest lake in New Zealand. Maximum lake depth ranged from 1 – 444 m. Eighty-seven of the lakes had been categorized into broad groups based on lake formation mechanism (see Ministry for the Environment

2006), including: dune (n = 32), glacial (n = 20), volcanic (n = 14), riverine (n = 8), peat (n = 5), lagoon (n = 3), reservoir (n = 3) and landslide (n = 1). The origin of 14 lakes was undetermined. Lake trophic state varied from microtrophic to hypertrophic (see Burns *et al.* 2000 for definitions), with concomitant wide variations in the trophic status parameters TN (44.5 – 4247.5 mg m^{-3}), TP (1.5 – 440.0 mg m^{-3}) and chl *a* (0.3 – 149.0 mg m^{-3}) (Table 3). The land use composition of the lake catchments was broadly representative of the overall land use composition of New Zealand (Table 4).

Significant ($p < 0.05$) Pearson's correlation coefficients (Table 5) show that as expected, the parameters TN, TP and chl *a* were highly positively inter-correlated. Total nitrogen provided a better predictor of chl *a* ($r = 0.85$, $p < 0.001$) than TP ($r = 0.80$, $p < 0.001$). Comparison of correlations between catchment land use and lake eutrophication parameters showed that TN was positively correlated with % high prod. grass ($r = 0.62$, $p \leq 0.001$) and weakly positively correlated with % built up area ($r = 0.20$, $p < 0.05$). Total phosphorus was positively correlated with % high prod. grass ($r = 0.57$, $p < 0.001$) and % exotic forest ($r = 0.32$, $p \leq 0.001$). There was a significant ($p \leq 0.05$) negative correlation between % low prod. grass and both TN ($r = -0.43$) and TP ($r = -0.55$) and % native also correlated negatively with both TN ($r = -0.36$) and TP ($r = -0.31$). Chlorophyll *a* was positively correlated with % high prod. grass ($r = 0.60$) and % built up area ($r = 0.20$), while it correlated negatively with % low prod. grass (-0.46) and % native ($r = -0.20$). Catchment soil P correlated negatively with in-lake TP ($r = -0.52$) and also TN ($r = -0.48$). Chlorophyll *a* declined both with increasing lake altitude ($r = -0.60$) and maximum depth (z_{max}, $r = -0.57$), both of which were positively correlated ($r = 0.66$).

The results of PCA (Figure 4) helped to characterise the inter-relations between lake and catchment variables. The Eigenvalues of the two principal components were 3.86 and 2.17 respectively and cumulatively they accounted for 40.2 % of the variance in the lake and catchment variables that were analysed. The first component, represented on the horizontal axis of the ordination diagram, is most strongly loaded with the variables of slope (-0.42), soil P (-0.39), z_{max} (-0.35), lake order (-0.34) and % high prod. grass (0.29). The second component is represented on the vertical axis and is most strongly loaded with the variables mean annual rainfall (0.45), A_c:A_l (-0.44), % native (0.38) and % low prod. grass (-0.34). Different lake types are relatively evenly distributed along both axes, however glacial lakes are predominantly in the negative sector of the horizontal axis whereas dune lakes are predominantly in the positive sector of the horizontal axis.

Quantifying land use effects

To address our first question (to what extent do anthropogenic land uses explain variation in TN and TP concentrations?), we computed separate linear regression models for TN and TP using predictor variables that represented nutrient sources and significantly positively correlated with lake TN or TP, respectively. Individual predictor variables were not inter-correlated (Table 6).

A multiple linear regression model to predict TN from % high prod. grass and % built up area was highly significant ($p < 0.001$, SE = 0.77). Following partitioning of variance by subtraction, % high prod. grass accounted for 38.6% of the variation in in-lake TN while % built up area accounted for 3.7% of the variation in in-lake TN.

A multiple linear regression model to predict TP from % high prod. grass and % exotic was also highly significant ($p < 0.001$, SE = 0.70). Following partitioning of variance by subtraction, % high prod. grass and % exotic accounted for 41.0% and 18.8%, respectively, of the variation in in-lake TP.

The effect of catchment characteristics on the relationship between land use and in-lake nutrients

To address our second question (is the relationship between land use and in-lake nutrient concentrations influenced by other catchment and lake characteristics?), we focused on the catchments comprising high prod. grass as the dominant land use, i.e. catchments where the proportion of high prod. grass in the non-lake area of the catchment was greater than the proportion of any of the other 40 LCDB2 land use types present in our sample. Accordingly, a sub-sample of 43 lakes was identified with catchments comprising 28.7 % - 99.8 % high prod. grass. These lakes were distributed throughout New Zealand with North Island lakes (69.8 % of the sub-sample) being marginally better represented than in the whole sample (65.2 %).

Regression of TN on % high prod. grass yielded a significant function ($p < 0.001$, $r^2 = 0.27$, SE = 0.31). This regression model was significantly improved by the addition of interaction terms that included the product of % high prod. grass and A_c:A_l and z_{max} (Table 7). The addition of an interaction term to represent the influence of z_{max} yielded the greatest improvement to the predictive power of the model ($r^2 = 0.43$) and the standardised regression coefficient for this term had a negative value, while the coefficient for the interaction term to represent the influence of A_c:A_l was positive.

Regression of TP on % high prod. grass also yielded a significant function ($p < 0.01$, $r^2 = 0.16$, SE = 0.43). Like TN, this regression model was significantly improved by the addition of interaction terms to represent the influence of A_c:A_l and z_{max} with the terms having a positive and a negative coefficient respectively (Table 7). The addition of an interaction term to represent the influence of lake order also significantly improved the regression model and this term had a positive coefficient.

Discussion

We sought to quantify the relationship between anthropogenic land use and in-lake N and P concentrations at the national scale in New Zealand. We have shown that, following correction for the effect of co-variation between land use types, the proportion of high intensity pasture in a lake catchment accounted for more variation in our national dataset than any other land use, explaining 38.6 % of the variation in TN and 41.0 % of the variation in TP. The proportion of exotic forestry explained 18.8 % of the variation in TP and the proportion of built up (urban) area explained 3.7 % of the variation in TN. To qualify whether a range of catchment characteristics influence the relationship between anthropogenic land use and in-lake nutrient concentrations, we then focused on lakes where high production grassland was the dominant land use type in the catchments. For this sub-sample, we showed that lake and catchment morphology variables (A_c:A_l and z_{max}) and a catchment connectivity variable (lake order in the TP model) influenced the relationship between the proportion of high intensity grassland in a lake catchment and in-lake nutrient concentrations. Increasing maximum lake depth (z_{max}) reduced the influence of high intensity grassland on in-lake TN and TP concentrations while increasing catchment area to lake area ratio (A_c:A_l) had the opposite effect. Lake order (LO) had a positive interactive effect indicating that increasing lake order resulted in an increasingly positive relationship between high intensity grassland and in-lake TP concentrations.

Land use effects at the national scale

A positive relationship between pastoral agriculture and nutrient concentrations in freshwaters has generally been established in New Zealand (McColl 1972; Larned *et al.*

2004; Parliamentary Commissioner for the Environment 2004; Galbraith and Burns 2007; McDowell 2009). Larned *et al*. (2004) analysed data for 229 stream sites throughout New Zealand and found that median dissolved reactive P and dissolved N concentrations from pastoral sites exceeded recommended guidelines in all stream orders sampled, and concentrations of these nutrients were significantly higher in samples obtained from pastoral sites than in those from native and exotic forest sites. Likewise, Galbraith and Burns (2007) found that the proportion of pasture in a catchment was positively related to TN and TP in 45 water bodies in the Otago region. Elsewhere, other landscape-scale studies have established links between agricultural land use and elevated nutrients in freshwaters. For example Hooda *et al.* (1997) attributed elevated P in streams in the west of Scotland to intensive dairy farming in the catchments and Tong and Chen (2002) concluded that N and P losses from agriculture in Ohio watersheds were seven and six times higher, respectively, than the second-most polluting land use (impervious urban).

The strength of the positive relationship that we have found between high producing grassland and in-lake TN and TP concentrations is particularly significant given the scale of our study. Goldstein *et al.* (2007) found that the relationship between land use and physical stream habitat condition characteristics became weaker with increasing spatial scale from regional to national level. By distinguishing between low and high producing grassland, we have shown that the intensity of pastoral land use has a significant bearing on the magnitude of nutrient losses to lakes. The major pastoral-related nutrient sources include urine and N fertiliser in the case of N, and faeces and superphosphate fertiliser in the case of P (Monaghan *et al.* 2007). The magnitude of nutrient loss is broadly related to stocking rate (*ibid.)* and therefore increasing intensity results in greater nutrient loss. Whilst research into management options to mitigate nutrient losses from pasture has been an active field (see Cherry *et al.* 2008), it is clear that a significant change in practices is required if productivity is to be decoupled from nutrient loss. The contrast in nutrient losses between low and high productivity grassland is further emphasised by the fact that even though low intensity pasture and mean catchment soil P content were positively correlated (see Figure 4 and Table 5), both correlated negatively with in-lake P due to the opposing influence of high producing grassland. Although our estimates of mean acid-soluble P content for catchment soils are derived from relatively broad categories, we had expected to find a positive relationship between soil P and in-lake TP concentrations, especially given the range in the soil P values (4.0 – 47.1 mg $(100\ g)^{-1}$) and the fact that unusually high concentrations of P in igneous rocks in New Zealand have been shown to be associated with elevated P concentrations in freshwaters at a regional scale (Timperley 1983) and a local scale (Quinn and Stroud 2002). The fact that our results are contrary to this expectation indicates that, at the national scale, anthropogenic sources of P exert a greater influence on in-lake TP concentrations than naturally occurring edaphic sources.

The magnitude of variance (18.8 %) in in-lake TP explained by the proportion of exotic forestry in a catchment was appreciably high. Exotic forests in New Zealand comprise 90% radiata pine (*Pinus radiata* Dons) (Fahey *et al*. 2004) and, while it has been noted that pine plantations have the potential to export P at a greater rate than native forests in New Zealand (Hamilton 2005), a knowledge gap exists regarding nutrient export from plantation forests (Drewry 2006). Intriguingly, export coefficients used to estimate P loss from exotic forests in New Zealand can be less than those for native forests (Ministry for the Environment 2002), however, these are based on a limited number of studies. Cooper and Thomsen (1988) estimated TP export from pine-forested catchments at 9.5 kg $km^{-2}\ yr^{-1}$; lower than their estimate for either native forest (12 kg $km^{-2}\ yr^{-1}$) or pasture (167 kg $km^{-2}\ yr^{-1}$). Similarly, Quinn and Stroud (2002) compared a stream draining pine forest with two streams draining native forest and found that average dissolved reactive P concentrations were significantly lower in the stream draining pine forest. Analysis of land use effects in the previously cited study was based, however, on monthly sampling; a frequency that may not be sufficient to derive precise estimates of P export due a failure to obtain accurate data for P loss during high-flow events (Johnes 2007). Studies have shown that TP exported from plantation forest catchments predominantly comprises particulate phosphorus (PP) (Zhang *et al.* 2007; Luz Rodriguez-Blanco *et al.* 2009) which can be higher in storm flow than in base flow by a factor of ten (Ellison and Brett 2006). The export of PP from sources in exotic forests such as exposed soil in clear-felled areas and logging roads may therefore be underestimated due to the spatial heterogeneity of such critical source areas and the temporally variable nature of losses from these sources. Although PP that enters streams draining exotic forest may not be immediately available for plant uptake (and thus would appear not to promote eutrophication), for example due to pH constraints (McDowell *et al.* 2004), PP which enters downstream lentic receiving systems may become available following early diagenesis processes at the sediment-water boundary (Pacini and Gachter 1999; Sondergaard *et al.* 2003). Sediment flux (but not necessarily P export) has been shown to be greatest following initial native forest clearance and to then steadily diminish following afforestation (Kasai *et al.* 2005). It is therefore possible that P in lakes that have catchments containing substantial proportions of exotic forest is in part a legacy of PP export during historic land clearance and not associated *per se* with ongoing forestry operations. Clearly, our finding that a substantial proportion of the variance in in-lake TP can be attributed to the extent of exotic forest in a catchment elicits the need for further research to quantify P export from this source, and, underlines the importance of considering the potential for P loss when making decisions regarding aspects of forestry management such as felling regimes and the maintenance of riparian buffers within the forested hydrological landscape (Quinn 2005).

The relatively small proportion of the variance in in-lake TN explained by the proportion of built up area (3.7 %) is indicative of the predominantly rural nature of the lake catchments (and therefore New Zealand as a nation); only 2.3 % of the lake catchments on average comprised this land use (Table 3). High rates of N export from urban land (for example in storm drainage), are well established (e.g. Line *et al.* 2002; Allan 2004; Dietz and Clausen 2008) and therefore urbanization in a catchment has the potential to greatly increase nutrient loads to lakes that are hydrologically connected.

Factors that mediate the relationship between land use and in-lake nutrients

Our finding that lake and catchment morphology variables mediate the relationship between pastoral land use and in-lake nutrients is consistent with other studies. Deeper lakes have greater volume relative to their area than shallow lakes and, therefore, lake depth has been shown to have a buffering effect on nutrient inputs (Nixdorf and Deneke 1997; Nõges 2009; Liu *et al.* 2010). Furthermore, both wind driven resuspension of sediment (Hamilton and Mitchell 1997) and internal loading of P (Sondergaard *et al.* 2003) are more prevalent in shallow lakes than in deep lakes, thereby providing mechanisms for nutrients in lake sediments that originate from agricultural sources to be recycled in the water column. The positive interactive effect of the catchment to lake area ratio is in accord with empirical analysis undertaken by Håkanson (2005) which showed that TP was significantly related to this variable. This result reflects the fact that external N and P loads to lakes will typically be greater in a lake with a relatively large catchment compared to a lake with a relatively small catchment but the same proportion of land use (Nõges 2009).

Although intuitive, there is limited precedent in the literature for our finding that a variable (lake order) related to hydrologic connectivity in catchments mediates the relationship between land use and in-lake nutrient P concentrations. Fraterrigo and Downing (2008) used temporal variation in in-lake TN and TP concentrations as a proxy for ‘watershed transport capacity’ which is equivalent to ‘catchment connectivity’ referred to in our study. Using an equivalent sample size (101) to our study, these authors established that the influence of land use on in-lake nutrient concentrations varied with watershed transport capacity, with near-shore land use being more influential in determining nutrient concentrations in lakes with low watershed transport capacity than in lakes with high transport capacity where nutrient concentrations were more closely related to land use throughout the whole catchment. Buck *et al.* (2004) obtained a similar result for streams, finding that the proportion of pasture in a catchment related better to water quality in fourth order than in second order streams. The finding that lake order has a positive interaction on the relationship between land use and TP, but not TN concentrations, is likely to be a reflection of the variation in the transport mechanisms of the two nutrients. Relative to P, surface transport of N in stream channels accounts for a lower proportion of total nutrient flux in many catchments due to the high mobility of nitrate which results in a high proportion of N-transport via subsurface hydrological pathways (Petry *et al*. 2002).

Implications for lake water quality policy

It is reasonable to conclude that our results provide an approximation of the relative contribution made by major land uses to explaining variation in nutrients in New Zealand lakes, given the range of lake types and the representative land use composition of the catchments included in our study (Table 4). Also, our sample size would seem appropriate for a national scale study; Liu *et al*. (2010) analysed 103 lakes to characterise relationships amongst lake and catchment variables at the national scale in China and Van Sickle (2003) notes that watershed studies rarely have a sample size exceeding 50 and a sample of 20 - 30 is common. Our findings therefore provide an evidence base to guide water quality policy at the national level. On this basis, our results indicate that actions are required to reduce nutrient pollution from intensive pastoral farms to mitigate lake eutrophication in New Zealand. Furthermore, by highlighting the potential for significant interactive effects, our study emphasises the importance of considering individual lake and catchment characteristics when assessing the likely vulnerability of lake ecosystems to land use change.

Following free market reforms, agricultural productivity has increased markedly in New Zealand in recent decades, however, this expansion has had an associated environmental cost (Parliamentary Commissioner for the Environment 2004; Barnett and Pauling 2005). Further development of the industry requires that these costs be explicitly recognized and mitigated, if this development is to be sustainable. Our analysis indicates that land use effects on lake nutrients may be non-linear (note use of log-transformed nutrient concentrations in linear models), thus suggesting that the relationship with in-lake nutrient concentrations may exhibit a threshold response (Gergel *et al.* 2002), possibly in relation to the observed propensity for lakes to shift from clear water to turbid equilibria (Sorrell and Schallenberg 2009). This possibility mandates a precautionary approach to agricultural expansion in the catchments of lakes with significant ecological value and warrants further research into the form of the relationship between agricultural land use and lake water quality. Our results also highlight the potential for P export from plantation forests to contribute to eutrophication in lakes and we recommend that this issue is the focus of further research. Finally, our results indicate that lake and catchment morphology, and catchment connectivity need to be considered when strategically assessing and planning for the potential impact of land use on lake water quality.

Given the national scale of our study, care should be taken when extrapolating our results to smaller scales. The results reflect the subset of New Zealand lakes included in our study and, while we believe that the range of lakes in our sample is broadly representative of those in New Zealand, it would clearly not be appropriate to apply the empirical relationships that we have derived at the scale of individual lakes. In particular, we note that the inverse correlation between z_{max} and high prod. grass in our sample (Figure 4; Table 5) may cause the variance in the nutrient concentrations that we have attributed to high prod. grass to be greater than would be obtained at a scale where this correlation is not present. Our aim when using regression analysis to address the first of our two questions was to seek explanatory insight, as opposed to predictive power which is a disparate objective of environmental modelling (Mac Nally 2000; Beven 2001). It is likely therefore that the inclusion of more predictor variables in the regression models would have yielded higher predictive power, however, this gain would be at the expense of understanding the relative contribution of anthropogenic land uses. For example, including variables which were also *negatively* correlated with lake nutrient concentrations (e.g. '% native') may have resulted in better predictive power (e.g. higher r^2) but less explanatory depth due to the opposing influences of natural and anthropogenic land uses in determining lake nutrient concentrations. We also acknowledge that lake nutrient concentrations are a function of both historic and contemporary catchment land use (Johnes 1999) and therefore the respective land use proportions that we have calculated for each catchment are a simplification of land use pressures on lake water quality as we have not accounted for historic land use, nor have we considered land use change that may have occurred between 2000-2001 (land use imagery acquisition) and 2004-2006 (water sampling).

Similarly, our analysis of factors that potentially mediate the land use - water quality relationship was undertaken at a broad spatial scale and several studies have highlighted the importance of aligning the scale at which relationships between catchment variables are analysed to the scale of the study (Buck *et al.* 2004; Daniel *et al.* 2010). For instance, it is possible that analysis at finer spatial scales would yield significant relationships between the effect of land use on lake nutrients and variables such as slope, as have been established in other studies (Kamenik *et al.* 2001; Chang *et al.* 2008). A worthwhile subject for further research is to undertake finer scale spatial analysis to better define relationships between land use and nutrients in New Zealand lakes, and to investigate how factors such as the spatial configuration of land use (Lee *et al.* 2009), biological diversity and abundance (e.g. macrophyte coverage), lake mixing status, historic land use and future climate scenarios mediate this relationship. Finally, future studies with larger sample sizes may wish to investigate higher (second and greater) order interactions between variables to provide greater insight into catchment interactions.

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List of Figures

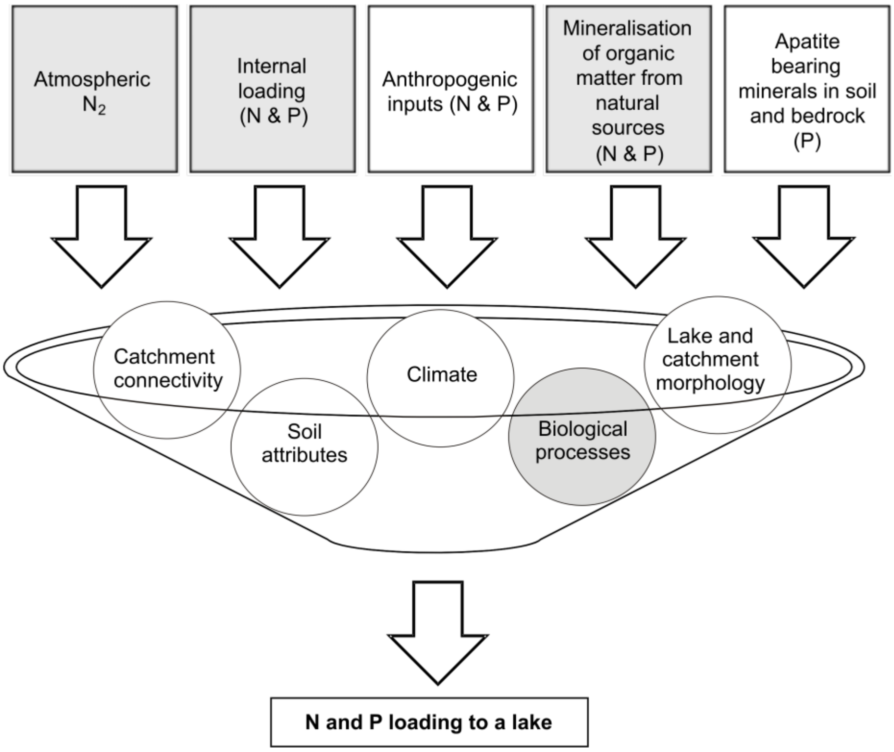
Atmospheric N2
Internal loading (N & P)
Anthropogenic inputs (N & P)
Mineralisation of organic matter from natural sources (N & P)
Apatite bearing minerals in soil and bedrock (P)
Catchment connectivity
Soil attributes
Climate
Biological processes
Lake and catchment morphology
N and P loading to a lake

Figure 1

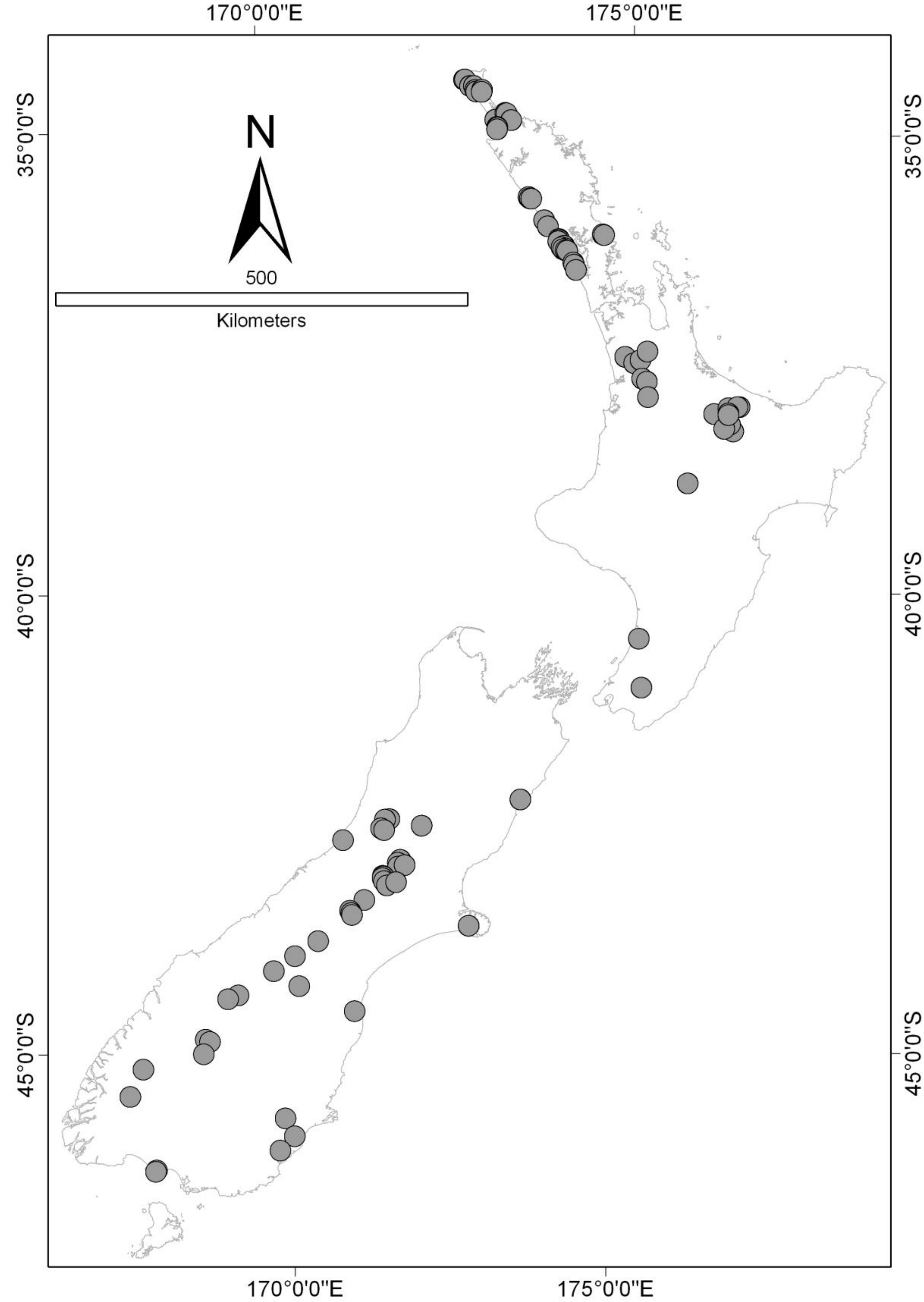

Figure 2

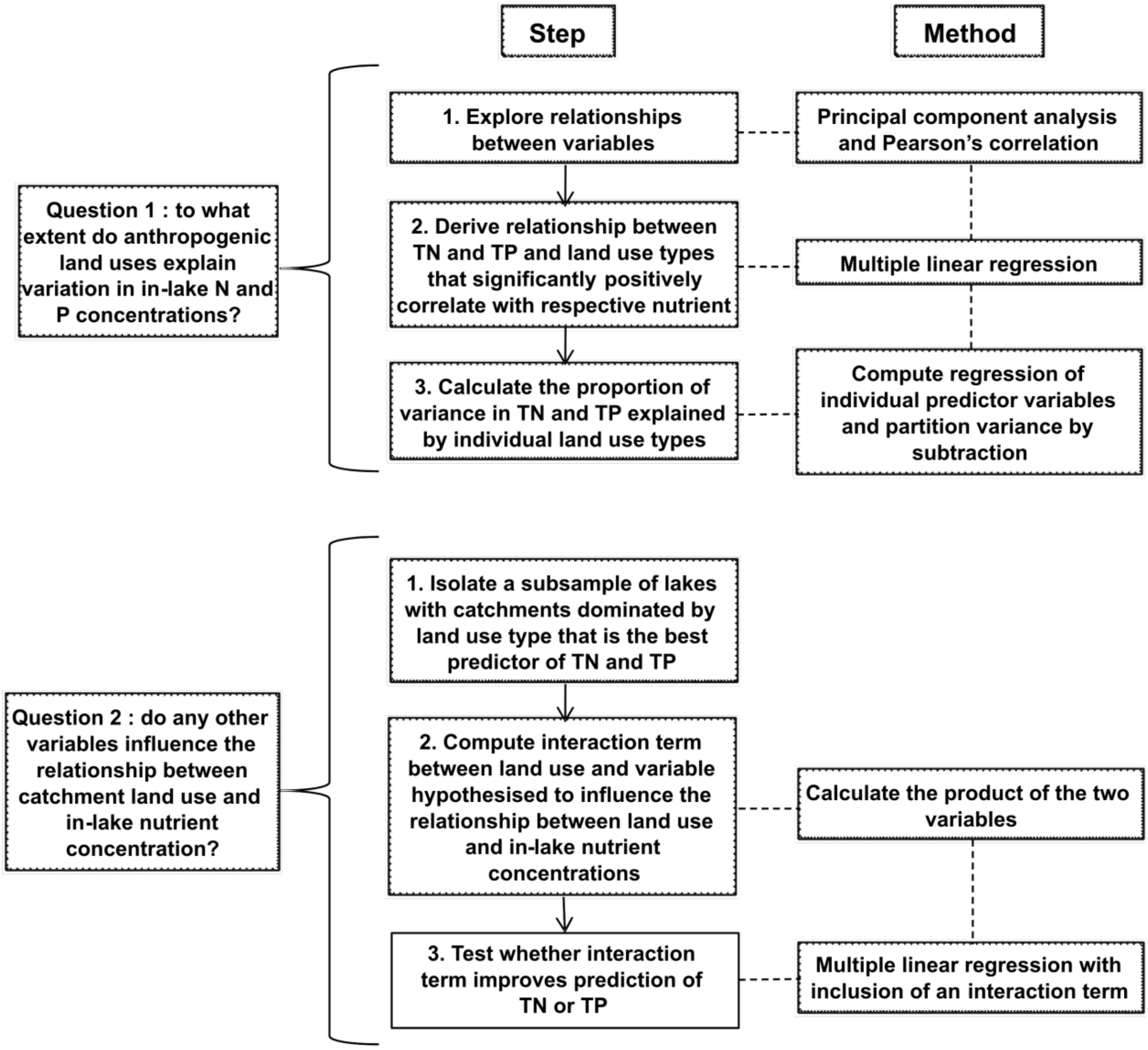
Step
Method
Question 1 : to what extent do anthropogenic land uses explain variation in in-lake N and P concentrations?
1. Explore relationships between variables
Principal component analysis and Pearson's correlation
2. Derive relationship between TN and TP and land use types that significantly positively correlate with respective nutrient
Multiple linear regression
3. Calculate the proportion of variance in TN and TP explained by individual land use types
Compute regression of individual predictor variables and partition variance by subtraction
Question 2 : do any other variables influence the relationship between catchment land use and in-lake nutrient concentration?
1. Isolate a subsample of lakes with catchments dominated by land use type that is the best predictor of TN and TP
2. Compute interaction term between land use and variable hypothesised to influence the relationship between land use and in-lake nutrient concentrations
Calculate the product of the two variables
3. Test whether interaction term improves prediction of TN or TP
Multiple linear regression with inclusion of an interaction term

Figure 3

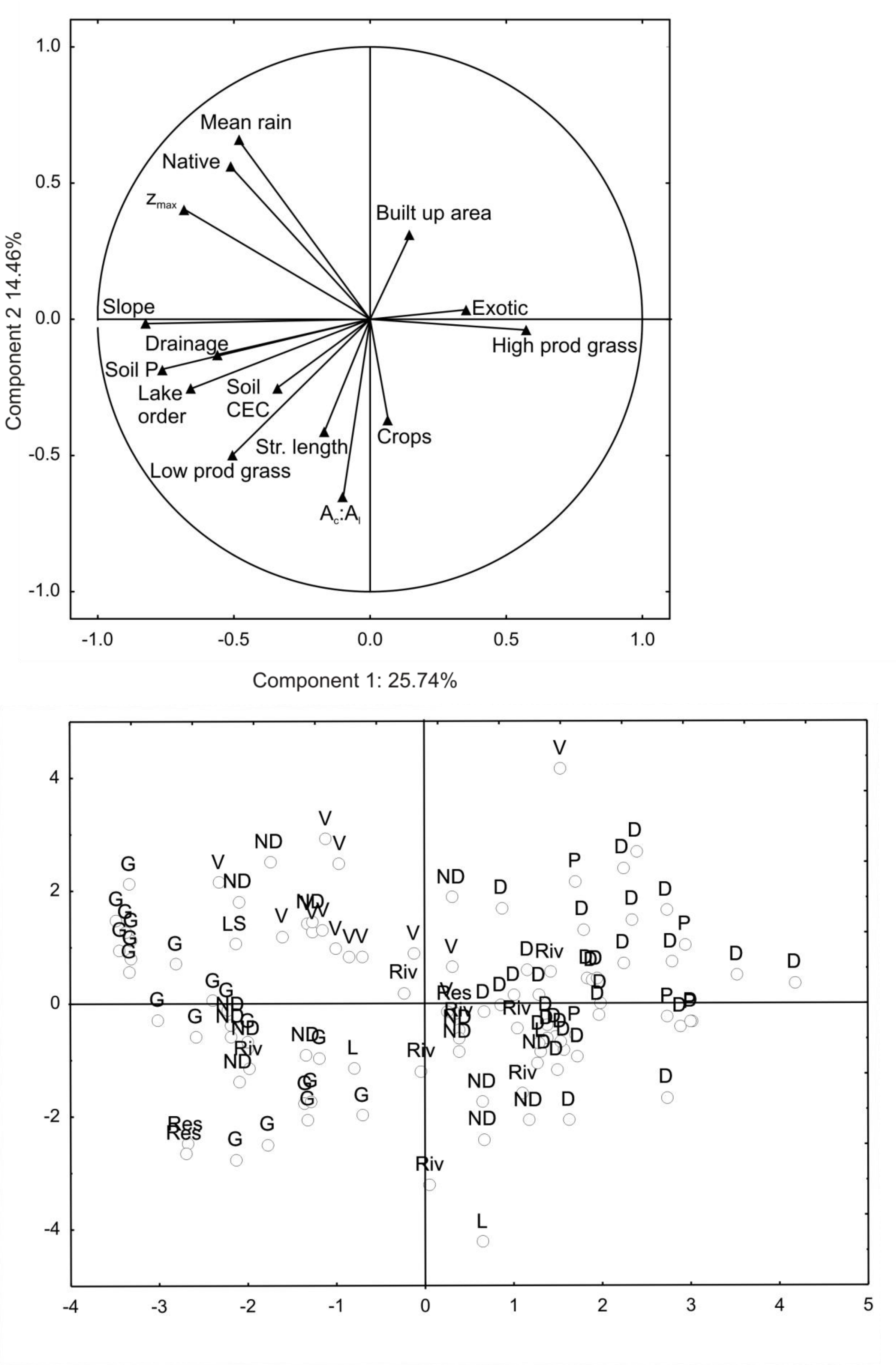
Mean rain
Native
z_{max}
Built up area
Slope
Exotic
Drainage
High prod grass
Soil P
Lake order
Soil CEC
Crops
Str. length
Low prod grass
$A_c:A_l$
Component 2 14.46%
Component 1: 25.74%

Figure 4

List of Tables

Table 7 Multiple linear regression models to predict in-lake total nitrogen (TN) and total phosphorus (TP) concentrations from the percentage of high producing grassland in a lake catchment (% high prod. grass) and an interaction term that represents the hypothesised interaction between the land use variable and other catchment characteristics. a = intercept; ε = error; β_1 and β_2 are regression coefficients. Model statistics are only reported in cases where the interaction term (β_2) is statistically significant ($p < 0.05$). Variable abbreviations are defined in Table 3.

Table 1

Soil parameter	CEC (0 – 0.6 m)	Drainage	Acid soluble P content
Unit	meq $(100\ g)^{-1}$	Class	mg $(100\ g)^{-1}$
Rating			
1	> 40	Very poor	0–7
2	25 – 39.9	Poor	7–15
3	12 – 24.9	Imperfect	15–30
4	6 – 11.9	Moderately well	30–60
5	< 5.9	Well	60–100

Table 2

Catchment characteristic	Variable analysed	Hypothesed influence on the relationship between anthropogenic land use and in-lake nutrient concentrations	Reason (hypothesised)
Lake/catchment morphology	Catchment to lake area ratio	**Positive**	High catchment to lake ratio will yield a high nutrient load per unit of lake area.
	Maximum lake depth	**Negative**	Shallow lakes less able to buffer nutrient inputs than deep lakes.
	Average catchment slope	**Positive**	Rate of nutrient flux associated with hydrological flows (e.g. overland flow) will be higher in steeper catchments due to higher gravitational energy.
Catchment connectivity	Stream length per km^2 catchment	**Positive**	More hydrologically connected catchments have greater capacity to transport nutrients.
	Lake order	**Positive**	More hydrologically connected catchments have greater capacity to transport nutrients.
Soil attributes	Cation exchange capacity (CEC)	**Negative**	Greater mobility of mineral nutrients with decreasing soil CEC.
	Drainage	**Positive**	Rate of nutrient flux associated with hydrological flows will be higher in well drained catchments.
Climate	Mean rainfall	**Positive**	Rate of nutrient flux associated with hydrological flows (e.g. throughflow) will be higher in wetter catchments.

Table 3

Characteristic	Variable	N	Unit	Abbreviation	Range	Mean
Trophic status parameters	Total nitrogen	101	mg m^{-3}	TN	44.5 – 4247.5	687.1
	Total phosphorus	101	mg m^{-3}	TP	1.5 – 440.0	64.3
	Chlorophyll *a*	101	mg m^{-3}	Chl *a*	0.3 – 149.0	17.7
Land use	% low producing grassland	101	%	% low prod. grass	0.0 – 90.0	9.4
	% high producing grassland	101	%	% high prod. grass	0.0 – 99.8	33.1
	% built up area	101	%	% built up area	0.0 – 73.8	2.3
	% arable cultivation	101	%	% crops	0.0 – 19.8	0.4
	% exotic forestry	101	%	% exotic	0.0 – 98.3	15.1
	% native forest	101	%	% native	0.0 – 80.0	13.3
Lake/catchment morphology	Max lake depth	101	m	z_{max}	1 – 444	44.1
	Lake area	101	km^2	A_l	0.02 - 612.6	26.2
	Catchment area (m^2) to lake area (m^2) ratio	101	-	A_c:A_l	1.5 - 451.3	28.4
	Altitude	101	m a.s.l	Alt	1.26 - 826.0	200.0
	Average catchment slope	101	Degrees	Slope	0.4 – 32.2	10.8
Catchment connectivity	Lake order	101	-	LO	0 - 7	2.8
	Stream (m) per km^2 of catchment	101	m	Str. length	225.6 – 3015.0	1245.3
Catchment soil attributes	Cation exchange capacity	99	meq (100 g)$^{-1}$	Soil CEC	4.9 – 40.0	15.1
	Acid soluble phosphorus content of the soil	101	mg (100 g)$^{-1}$	Soil P	4.0 – 47.1	16.6
	Drainage score (1 = very poor, 5 = well drained)	99	Nominal score	Drainage	1.3 – 5.0	4.1
Climate	Mean annual rainfall	101	cm	Mean rain	53.2 – 355.9	128.5

Table 4

LCDB 2 Land use type	High producing grassland	Exotic forest	Native forest	Low producing grassland	Built up area	Arable cultivation
Mean proportion in 101 catchments studied (%)	33.1	15.1	13.3	9.4	2.3	0.4
Proportion in New Zealand (%)	33.1	7.3	26.1	6.2	0.6	1.5

Table 5

	TN	TP	Chl *a*	Alt	z_{max}	A_c:A_l	Str. length	Slope	% low prod. grass	% high prod. grass	% built up area	% crop	% exotic	% native	Soil CEC	Soil P	Drain -age	Mean rain
TN	-	**.87**	**.85**	**-.71**	**-.76**	.11	.01	**-.62**	**-.43**	**.62**	**.20**	.12	.11	**-.36**	-.16	**-.48**	**-.31**	**-.45**
TP		-	**.80**	**-.75**	**-.64**	**.21**	.09	**-.56**	**-.55**	**.57**	.09	.19	**.32**	**-.31**	**-.21**	**-.52**	**-.29**	**-.40**
Chl *a*			-	**-.60**	**-.57**	.17	.13	**-.46**	**-.45**	**.60**	**.20**	.18	.06	**-.20**	-.09	**-.39**	**-.27**	**-.28**
Alt				-	**.66**	-.15	-.01	**.59**	**.53**	**-.44**	-.15	-.16	**-.22**	.17	.11	**.44**	**.35**	**.28**
z_{max}					-	-.19	.03	**.48**	.15	**-.43**	-.03	-.11	-.12	**.43**	.07	**.32**	**.28**	**.56**
A_c:A_l						-	**.27**	.09	.12	-.02	**-.25**	.12	.07	-.17	-.01	.07	.19	**-.22**
Stream length							-	-.02	.03	.09	**-.24**	.14	-.07	.04	.18	.07	.03	-.02
Slope								-	**.40**	**-.36**	**-.29**	-.07	**-.30**	**.42**	.16	**.60**	**.43**	**.33**
% low prod. grass									-	**-.50**	-.20	0.01	**-.27**	**-.22**	.14	**.55**	**.31**	**-.20**
% high prod. grass										-	.01	.14	-.18	-.14	-.07	**-.36**	**-.50**	**-.22**
% built up											-	.11	-.17	.06	**.40**	.06	-.06	-.02
% crop												-	-.03	-.08	.09	.05	-.05	**-.24**
% exotic													-	-.17	**-.39**	**-.49**	.16	-.14
% native															.11	**.29**	.18	**.60**
Soil CEC															-	**.36**	.18	.12
Soil P																-	**.37**	.13
Drainage																	-	.11
Mean rain																		-

Table 6

Dependent variable	Predictor variable	β	r^2	Standard error of estimate	p	Variance (%)
TN	% high prod. grass	0.62	0.39	0.79	<0.001	38.6
	% built up area	0.20	0.04	0.99	0.05	3.7
	% high prod. grass, % built up area	0.62, 0.19	0.42	0.77	<0.001	-
TP	% high prod. grass	0.57	0.33	0.79	<0.001	41.0
	% exotic	0.32	0.11	0.95	<0.001	18.8
	% high prod. grass, % exotic	0.65, 0.44	0.52	0.70	<0.001	-

Table 7

Dependent variable	Model	p-value of interaction (β_2)	β_2 (standardised)	r^2
TN	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * mean rain) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * A_c:A_l) + ε	**< 0.05**	0.41	0.38
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * z_{max}) + ε	**< 0.01**	- 0.41	0.43
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * slope) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * CEC) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * drainage) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * stream length) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * LO) + ε	> 0.05	-	-
TP	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * mean rain) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * A_c:A_l) + ε	**< 0.01**	0.49	0.31
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * z_{max}) + ε	**< 0.05**	- 0.36	0.28
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * slope) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * CEC) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * drainage) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * stream length) + ε	> 0.05	-	-
	$a + \beta_1 *$ % high prod. grass + $\beta_2 *$ (% high prod. grass * LO) + ε	**< 0.01**	0.39	0.30