

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

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18 **Abstract**

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

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36 **Introduction**

37 Excess inputs of nitrogen (N) and phosphorus (P) to lakes can cause eutrophication and the  
38 associated decline of water quality and ecological integrity (Vollenweider 1968; Smith  
39 2003). Natural sources of these nutrients to freshwaters include: organic matter such as  
40 plant residues which undergo mineralisation, atmospheric di-nitrogen fixed by  
41 heterocystous phytoplankton species and P associated with apatite bearing minerals  
42 (Newman 1995; Rabalais 2002). Inputs from anthropogenic sources are, however,  
43 increasing in many parts of the world and loading associated with pollution now greatly  
44 exceeds natural N and P loads to many lakes (Smith 2003).

45 Lake managers require an understanding of nutrient sources and the processes that  
46 drive lake productivity before developing plans to improve water quality in eutrophied  
47 lakes (Moss 2007). Although limnologists have traditionally focussed on the study of in-  
48 lake processes (Johnes 1999), there is now widespread understanding that the successful  
49 control of nutrient pollution and its associated problems is contingent on developing a  
50 holistic and integrated understanding of lakes in the context of their wider catchments  
51 (Ferrier and Jenkins 2010). While there is limited scope to adopt an experimental approach  
52 to investigate how natural and anthropogenic factors influence nutrient loading to lakes,  
53 the empirical analysis of relationships between lake and catchment variables across  
54 different scales can advance mechanistic understanding. Geographical Information  
55 Systems (GIS) can provide a platform for the collation and integration of data relating to a  
56 wide range of bio-physical parameters at a catchment scale (Macleod *et al.* 2007; Johnson  
57 and Host 2010) and numerous studies have used GIS to investigate relationships between  
58 catchment characteristics and water quality (e.g. Arbuckle and Downing 2001; Lee *et al.*  
59 2009; Roberts and Prince 2010).

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60           When empirically investigating how catchment characteristics interact to influence  
61 nutrient loading to a lake, it is useful to distinguish between characteristics that are nutrient  
62 sources (or direct proxies for specific sources) and characteristics that do not represent  
63 sources yet mediate the pathway between the nutrient source and the lake (Figure 1). For  
64 example, the proportion of farmland in a catchment is a direct indicator of the amount of  
65 nutrients from agricultural sources available for export to a lake, whereas average  
66 catchment slope is an indicator of the gravitational energy available for the transfer of  
67 those nutrients via mechanisms such as overland flow. A failure to make this distinction  
68 can lead to confounding conclusions regarding the likely contribution of various nutrient  
69 sources to external lake nutrient loads. This is also complicated by covariation of natural  
70 and anthropogenic factors (e.g. land use and soil type) which is frequently encountered in  
71 landscape ecology and can make it problematic to determine whether a relationship is  
72 causal or spurious (Van Sickle 2003; Allan 2004; Daniel *et al.* 2010). For example, Liu *et*  
73 *al.* (2010) studied 103 lakes across China and found that natural factors, specifically  
74 variables relating to geographic location, lake morphology and climate, accounted for 13.3  
75 – 57.5% of the variance in eutrophication parameters. As the authors concede, however,  
76 the reason why some ‘natural’ factors such as longitude and altitude partly determine  
77 trophic state is because these factors are probably co-related with human development and  
78 therefore anthropogenic nutrient pollution; a factor not represented in their study.

79           Eutrophication is a significant problem affecting freshwaters in New Zealand  
80 where an estimated 32% of lakes greater than 1 ha in area ( $n > 1000$ ) are classified as  
81 eutrophic or hypertrophic and consequently have very poor water quality (Ministry for the  
82 Environment 2010). Empirical studies and experiments have shown that both N- and P-  
83 limitation of phytoplankton growth occurs widely in New Zealand lakes and this, in  
84 addition to frequent high connectivity between freshwater and marine ecosystems,

85 supports the need for dual control of N and P export from New Zealand lake catchments  
86 (Abell *et al.* 2010). Intensification of land use resulting in increased external nutrient loads  
87 has become an increasing concern for resource managers and policy makers (Hamilton  
88 2005; Edgar 2009). In particular, nutrient export from New Zealand's increasingly  
89 intensive agricultural land has been subject to scrutiny (Parliamentary Commissioner for  
90 the Environment 2004) and the presence of pastoral land in a catchment has been shown to  
91 correlate with the occurrence of a shift from a clear to a de-vegetated, turbid state in lakes  
92 (Schallenberg and Sorrell 2009). While the relationship between catchment land use and  
93 water quality has been investigated for streams and rivers in New Zealand (Close and  
94 Davies Colley 1990; Larned *et al.* 2004; McDowell *et al.* 2009), the contribution of  
95 catchment land use to in-lake nutrient concentrations has not been quantified at a national  
96 scale, either in New Zealand or elsewhere. In this study, we investigate how catchment  
97 characteristics relate to in-lake concentrations of total phosphorus (TP), total nitrogen (TN)  
98 and chlorophyll *a* for 101 lakes distributed throughout New Zealand. By differentiating  
99 between variables that are direct proxies for nutrient sources and those that represent other  
100 factors, we seek to highlight relationships that are significant at the national scale. For this  
101 sample, we asked: (1) to what extent do anthropogenic land uses explain variation in TN  
102 and TP concentrations? and (2) is the relationship between land use and in-lake nutrient  
103 concentrations influenced by other catchment and lake characteristics?

104

## 105 **Methods**

106

### 107 Data collection

108

#### 109 *Lake water quality data*

110 Mean data relating to the trophic status parameters total phosphorus (TP), total nitrogen  
111 (TN) and chlorophyll *a* (chl *a*) were obtained from New Zealand regional councils for 101

112 lakes located throughout New Zealand (Figure 2). The data related to samples collected by  
113 regional environmental managers, either from the lake surface, or from integrated depths  
114 in the surface mixed layer, at monthly or quarterly intervals during 2004 - 2006 (Ministry  
115 for the Environment 2006). All samples were analysed using standard methods based on  
116 APHA (1998) and described by Burns *et al.* (2000). Each mean datum is therefore  
117 representative of at least 12 samples taken over a three-year period.

118

#### 119 *Extracting lake catchment data*

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

128

#### 129 *Catchment connectivity and morphology data*

130 The following 'connectivity' parameters were calculated for each catchment: average  
131 catchment slope (in degrees), stream length (m) relative to area (km<sup>2</sup>) of non-lake  
132 catchment and lake order. Average catchment slope was calculated using the 'slope' tool  
133 within ArcGIS which was applied to a 25 m resolution topographic raster map. Stream  
134 length was calculated using the REC line feature stream map. Lake order was defined in  
135 accordance with Martin and Soranno (2006) as the highest Strahler stream order of a lake  
136 inflow. The ratio of catchment area to lake area ( $A_c:A_l$ ) was calculated for each lake and

137 maximum depth ( $z_{\max}$ ) and lake altitude were obtained from Ministry for the Environment  
138 (2006).

139

140 *Land use data*

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

161

162 *Soil data*

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

183

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



186 CEC, soils with a rating of 1 were assumed to have a CEC of 40 meq (100 g)<sup>-1</sup> while soils  
187 with a rating of 5 were assumed to have a CEC of 5.9 meq (100 g)<sup>-1</sup>.

188

### 189 *Rainfall data*

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

194

### 195 *Statistical analysis*

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

206         The data were initially explored by constructing a Pearson correlation matrix and  
207 then by undertaking principal component analysis (PCA) (see Figure 3 for an overview of  
208 analytical methods). PCA can be applied to multivariate data to identify a small number of  
209 transformed variables that describe most of the variation in the data. Analysis of a

210 projection of the two principal components allowed the main relationships between lake  
211 and catchment variables to be visualised.

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

230 To address our second research question, we isolated a sub-sample ( $n = 43$ ) of  
231 lakes that had catchments dominated by the land use type that best correlated with lake TN  
232 and TP. Based on *a priori* hypotheses (Table 2), we then tested whether eight variables  
233 influenced the relationship between land use and in-lake nutrient concentrations in our  
234 national-scale sample. To test our hypotheses, we used multiple linear regression to

235 quantify whether the inclusion of a term to represent interaction between the land use  
236 variable and the variable of interest significantly improved the prediction of  $\log_{10}$  TN or  
237  $\log_{10}$  TP. The form of the linear model was:

$$238 \quad \text{NUTRIENTS} = a + (\beta_1 \times \text{LAND USE}) + (\beta_2 \times (\text{LAND USE} \times \text{VARIABLE})) + \varepsilon$$

239 where NUTRIENTS = transformed TN or TP concentrations; a = intercept, LAND  
240 USE = transformed land use proportion; VARIABLE = catchment characteristic variable  
241 hypothesised to mediate the relationship between land use and in-lake nutrient  
242 concentrations;  $\varepsilon$  = error term;  $\beta_1$  and  $\beta_2$  are regression coefficients. Separate multiple  
243 linear regression models were developed to predict both TN and TP based on land use and  
244 each of the eight variables being tested. We concluded that the relationship between in-  
245 lake nutrient concentrations and the land use variable was influenced by a catchment  
246 characteristic if inclusion of the interaction term made a significant improvement to the  
247 model prediction. Variables used in the analysis were transformed as previously described  
248 to achieve normality, which was then confirmed using a Kolmogorov Smirnov test ( $p >$   
249 0.05). Data were not standardised for this analysis.

250

## 251 **Results**

### 252 *Data exploration*

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

258 2006), including: dune (n = 32), glacial (n = 20), volcanic (n = 14), riverine (n = 8), peat (n  
259 = 5), lagoon (n = 3), reservoir (n = 3) and landslide (n = 1). The origin of 14 lakes was  
260 undetermined. Lake trophic state varied from microtrophic to hypertrophic (see Burns *et*  
261 *al.* 2000 for definitions), with concomitant wide variations in the trophic status parameters  
262 TN (44.5 – 4247.5 mg m<sup>-3</sup>), TP (1.5 – 440.0 mg m<sup>-3</sup>) and chl *a* (0.3 – 149.0 mg m<sup>-3</sup>) (Table  
263 3). The land use composition of the lake catchments was broadly representative of the  
264 overall land use composition of New Zealand (Table 4).

265         Significant (p < 0.05) Pearson's correlation coefficients (Table 5) show that as  
266 expected, the parameters TN, TP and chl *a* were highly positively inter-correlated. Total  
267 nitrogen provided a better predictor of chl *a* (r = 0.85, p < 0.001) than TP (r = 0.80, p <  
268 0.001). Comparison of correlations between catchment land use and lake eutrophication  
269 parameters showed that TN was positively correlated with % high prod. grass (r = 0.62, p  
270 ≤ 0.001) and weakly positively correlated with % built up area (r = 0.20, p < 0.05). Total  
271 phosphorus was positively correlated with % high prod. grass (r = 0.57, p < 0.001) and %  
272 exotic forest (r = 0.32, p ≤ 0.001). There was a significant (p ≤ 0.05) negative correlation  
273 between % low prod. grass and both TN (r = -0.43) and TP (r = -0.55) and % native also  
274 correlated negatively with both TN (r = -0.36) and TP (r = -0.31). Chlorophyll *a* was  
275 positively correlated with % high prod. grass (r = 0.60) and % built up area (r = 0.20),  
276 while it correlated negatively with % low prod. grass (-0.46) and % native (r = -0.20).  
277 Catchment soil P correlated negatively with in-lake TP (r = -0.52) and also TN (r = -0.48).  
278 Chlorophyll *a* declined both with increasing lake altitude (r = -0.60) and maximum depth  
279 ( $Z_{\max}$ , r = -0.57), both of which were positively correlated (r = 0.66).

280         The results of PCA (Figure 4) helped to characterise the inter-relations between  
281 lake and catchment variables. The Eigenvalues of the two principal components were 3.86  
282 and 2.17 respectively and cumulatively they accounted for 40.2 % of the variance in the

283 lake and catchment variables that were analysed. The first component, represented on the  
284 horizontal axis of the ordination diagram, is most strongly loaded with the variables of  
285 slope (-0.42), soil P (-0.39),  $z_{\max}$  (-0.35), lake order (-0.34) and % high prod. grass (0.29).  
286 The second component is represented on the vertical axis and is most strongly loaded with  
287 the variables mean annual rainfall (0.45),  $A_c:A_l$  (-0.44), % native (0.38) and % low prod.  
288 grass (-0.34). Different lake types are relatively evenly distributed along both axes,  
289 however glacial lakes are predominantly in the negative sector of the horizontal axis  
290 whereas dune lakes are predominantly in the positive sector of the horizontal axis.

291

### 292 *Quantifying land use effects*

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

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

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

306

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

309 To address our second question (is the relationship between land use and in-lake nutrient  
310 concentrations influenced by other catchment and lake characteristics?), we focused on the  
311 catchments comprising high prod. grass as the dominant land use, i.e. catchments where  
312 the proportion of high prod. grass in the non-lake area of the catchment was greater than  
313 the proportion of any of the other 40 LCDB2 land use types present in our sample.  
314 Accordingly, a sub-sample of 43 lakes was identified with catchments comprising 28.7 % -  
315 99.8 % high prod. grass. These lakes were distributed throughout New Zealand with North  
316 Island lakes (69.8 % of the sub-sample) being marginally better represented than in the  
317 whole sample (65.2 %).

318 Regression of TN on % high prod. grass yielded a significant function ( $p < 0.001$ ,  
319  $r^2 = 0.27$ ,  $SE = 0.31$ ). This regression model was significantly improved by the addition of  
320 interaction terms that included the product of % high prod. grass and  $A_c:A_1$  and  $z_{max}$  (Table  
321 7). The addition of an interaction term to represent the influence of  $z_{max}$  yielded the  
322 greatest improvement to the predictive power of the model ( $r^2 = 0.43$ ) and the standardised  
323 regression coefficient for this term had a negative value, while the coefficient for the  
324 interaction term to represent the influence of  $A_c:A_1$  was positive.

325 Regression of TP on % high prod. grass also yielded a significant function ( $p <$   
326  $0.01$ ,  $r^2 = 0.16$ ,  $SE = 0.43$ ). Like TN, this regression model was significantly improved by  
327 the addition of interaction terms to represent the influence of  $A_c:A_1$  and  $z_{max}$  with the terms  
328 having a positive and a negative coefficient respectively (Table 7). The addition of an  
329 interaction term to represent the influence of lake order also significantly improved the  
330 regression model and this term had a positive coefficient.

331

## 332 **Discussion**

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

351

### 352 *Land use effects at the national scale*

353 A positive relationship between pastoral agriculture and nutrient concentrations in  
354 freshwaters has generally been established in New Zealand (McCull 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



380 is required if productivity is to be decoupled from nutrient loss. The contrast in nutrient  
381 losses between low and high productivity grassland is further emphasised by the fact that  
382 even though low intensity pasture and mean catchment soil P content were positively  
383 correlated (see Figure 4 and Table 5), both correlated negatively with in-lake P due to the  
384 opposing influence of high producing grassland. Although our estimates of mean acid-  
385 soluble P content for catchment soils are derived from relatively broad categories, we had  
386 expected to find a positive relationship between soil P and in-lake TP concentrations,  
387 especially given the range in the soil P values ( $4.0 - 47.1 \text{ mg (100 g)}^{-1}$ ) and the fact that  
388 unusually high concentrations of P in igneous rocks in New Zealand have been shown to  
389 be associated with elevated P concentrations in freshwaters at a regional scale (Timperley  
390 1983) and a local scale (Quinn and Stroud 2002). The fact that our results are contrary to  
391 this expectation indicates that, at the national scale, anthropogenic sources of P exert a  
392 greater influence on in-lake TP concentrations than naturally occurring edaphic sources.

393         The magnitude of variance (18.8 %) in in-lake TP explained by the proportion of  
394 exotic forestry in a catchment was appreciably high. Exotic forests in New Zealand  
395 comprise 90% radiata pine (*Pinus radiata* Dons) (Fahey *et al.* 2004) and, while it has been  
396 noted that pine plantations have the potential to export P at a greater rate than native  
397 forests in New Zealand (Hamilton 2005), a knowledge gap exists regarding nutrient export  
398 from plantation forests (Drewry 2006). Intriguingly, export coefficients used to estimate P  
399 loss from exotic forests in New Zealand can be less than those for native forests (Ministry  
400 for the Environment 2002), however, these are based on a limited number of studies.  
401 Cooper and Thomsen (1988) estimated TP export from pine-forested catchments at  $9.5 \text{ kg}$   
402  $\text{km}^{-2} \text{ yr}^{-1}$ ; lower than their estimate for either native forest ( $12 \text{ kg km}^{-2} \text{ yr}^{-1}$ ) or pasture ( $167$   
403  $\text{kg km}^{-2} \text{ yr}^{-1}$ ). Similarly, Quinn and Stroud (2002) compared a stream draining pine forest  
404 with two streams draining native forest and found that average dissolved reactive P

405 concentrations were significantly lower in the stream draining pine forest. Analysis of land  
406 use effects in the previously cited study was based, however, on monthly sampling; a  
407 frequency that may not be sufficient to derive precise estimates of P export due a failure to  
408 obtain accurate data for P loss during high-flow events (Johnes 2007). Studies have shown  
409 that TP exported from plantation forest catchments predominantly comprises particulate  
410 phosphorus (PP) (Zhang *et al.* 2007; Luz Rodriguez-Blanco *et al.* 2009) which can be  
411 higher in storm flow than in base flow by a factor of ten (Ellison and Brett 2006). The  
412 export of PP from sources in exotic forests such as exposed soil in clear-felled areas and  
413 logging roads may therefore be underestimated due to the spatial heterogeneity of such  
414 critical source areas and the temporally variable nature of losses from these sources.  
415 Although PP that enters streams draining exotic forest may not be immediately available  
416 for plant uptake (and thus would appear not to promote eutrophication), for example due to  
417 pH constraints (McDowell *et al.* 2004), PP which enters downstream lentic receiving  
418 systems may become available following early diagenesis processes at the sediment-water  
419 boundary (Pacini and Gachter 1999; Sondergaard *et al.* 2003). Sediment flux (but not  
420 necessarily P export) has been shown to be greatest following initial native forest clearance  
421 and to then steadily diminish following afforestation (Kasai *et al.* 2005). It is therefore  
422 possible that P in lakes that have catchments containing substantial proportions of exotic  
423 forest is in part a legacy of PP export during historic land clearance and not associated *per*  
424 *se* with ongoing forestry operations. Clearly, our finding that a substantial proportion of  
425 the variance in in-lake TP can be attributed to the extent of exotic forest in a catchment  
426 elicits the need for further research to quantify P export from this source, and, underlines  
427 the importance of considering the potential for P loss when making decisions regarding  
428 aspects of forestry management such as felling regimes and the maintenance of riparian  
429 buffers within the forested hydrological landscape (Quinn 2005).

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

437

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

439 Our finding that lake and catchment morphology variables mediate the relationship  
440 between pastoral land use and in-lake nutrients is consistent with other studies. Deeper  
441 lakes have greater volume relative to their area than shallow lakes and, therefore, lake  
442 depth has been shown to have a buffering effect on nutrient inputs (Nixdorf and Deneke  
443 1997; Nõges 2009; Liu *et al.* 2010). Furthermore, both wind driven resuspension of  
444 sediment (Hamilton and Mitchell 1997) and internal loading of P (Sondergaard *et al.* 2003)  
445 are more prevalent in shallow lakes than in deep lakes, thereby providing mechanisms for  
446 nutrients in lake sediments that originate from agricultural sources to be recycled in the  
447 water column. The positive interactive effect of the catchment to lake area ratio is in  
448 accord with empirical analysis undertaken by Håkanson (2005) which showed that TP was  
449 significantly related to this variable. This result reflects the fact that external N and P loads  
450 to lakes will typically be greater in a lake with a relatively large catchment compared to a  
451 lake with a relatively small catchment but the same proportion of land use (Nõges 2009).

452           Although intuitive, there is limited precedent in the literature for our finding that a  
453 variable (lake order) related to hydrologic connectivity in catchments mediates the

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

471

#### 472 *Implications for lake water quality policy*

473 It is reasonable to conclude that our results provide an approximation of the relative  
474 contribution made by major land uses to explaining variation in nutrients in New Zealand  
475 lakes, given the range of lake types and the representative land use composition of the  
476 catchments included in our study (Table 4). Also, our sample size would seem appropriate  
477 for a national scale study; Liu *et al.* (2010) analysed 103 lakes to characterise relationships

478 amongst lake and catchment variables at the national scale in China and Van Sickle (2003)  
479 notes that watershed studies rarely have a sample size exceeding 50 and a sample of 20 -  
480 30 is common. Our findings therefore provide an evidence base to guide water quality  
481 policy at the national level. On this basis, our results indicate that actions are required to  
482 reduce nutrient pollution from intensive pastoral farms to mitigate lake eutrophication in  
483 New Zealand. Furthermore, by highlighting the potential for significant interactive effects,  
484 our study emphasises the importance of considering individual lake and catchment  
485 characteristics when assessing the likely vulnerability of lake ecosystems to land use  
486 change.

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

502 and catchment connectivity need to be considered when strategically assessing and  
503 planning for the potential impact of land use on lake water quality.

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

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

541

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Figure 1 Conceptual diagram showing hypothetical relationships between sources of nitrogen (N) and phosphorus (P) in a lake catchment (rectangles) and factors that may mediate the relationship between sources and nutrient loading (circles). Sources and factors shaded grey were not examined in this study.

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Figure 3 Conceptual diagram outlining analytical methods used to address research questions. Detailed descriptions of individual analytical methods are given in the text.

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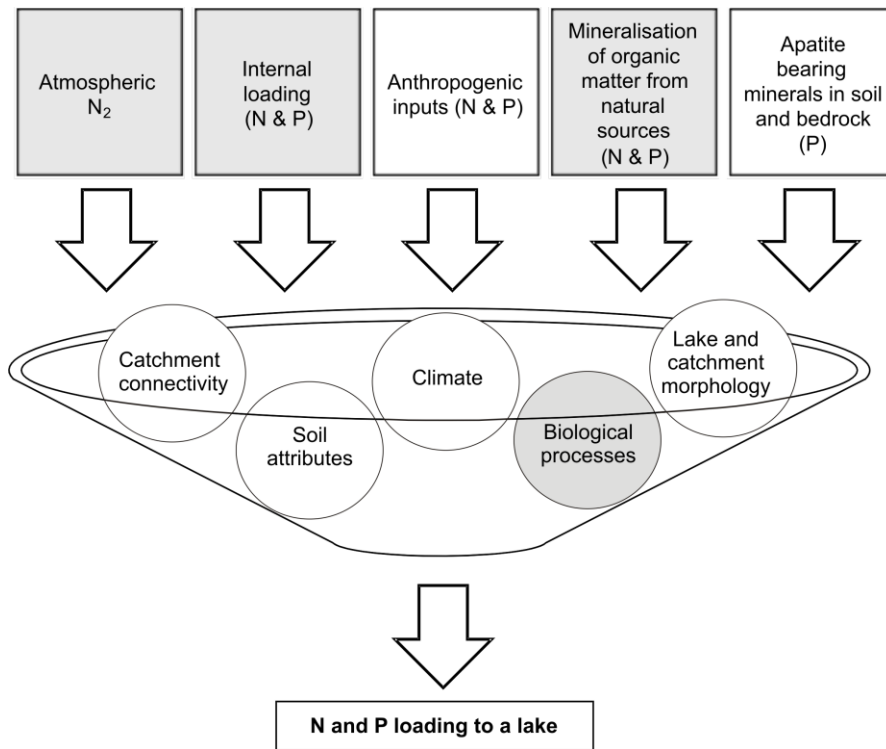


Figure 1

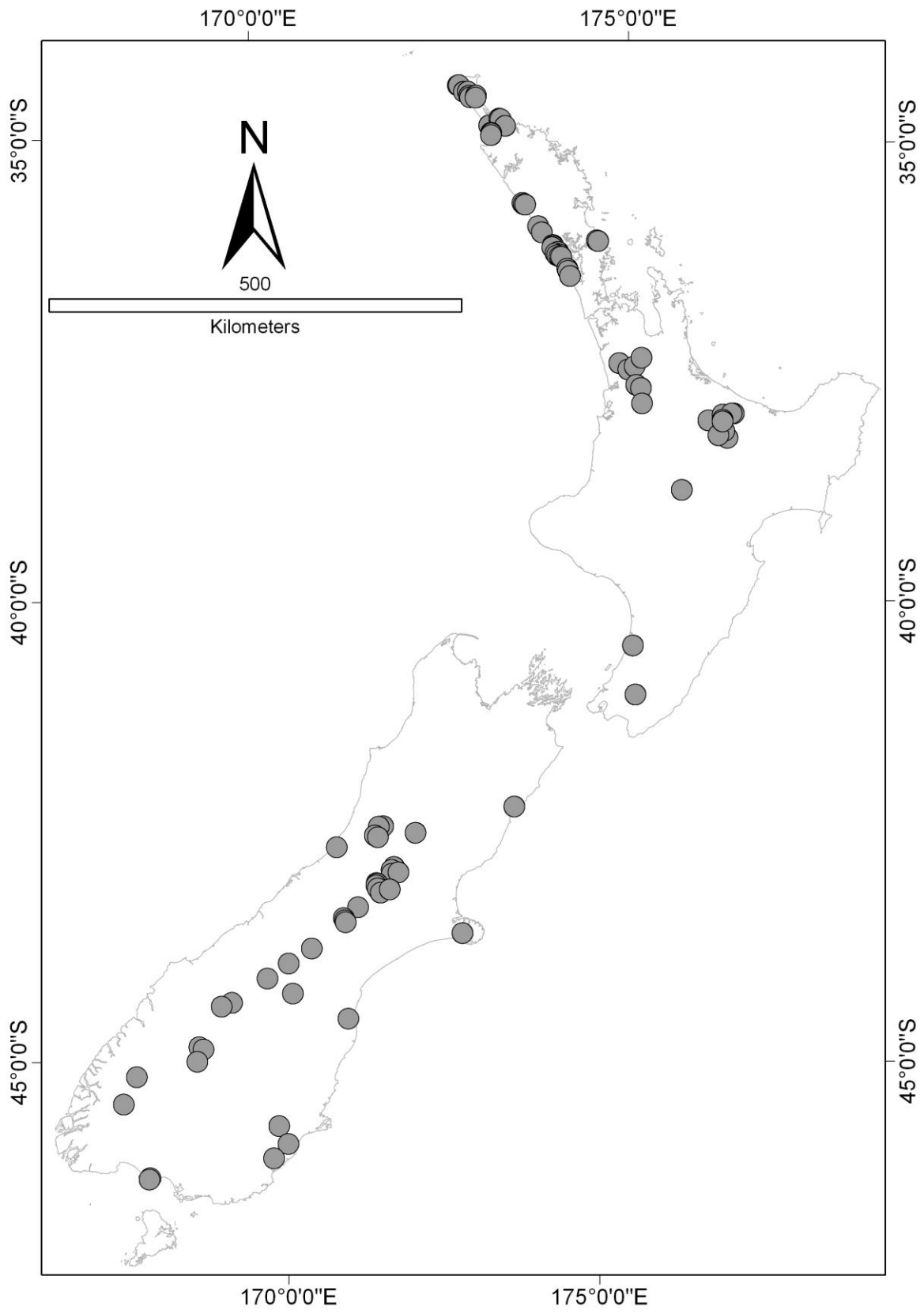


Figure 2

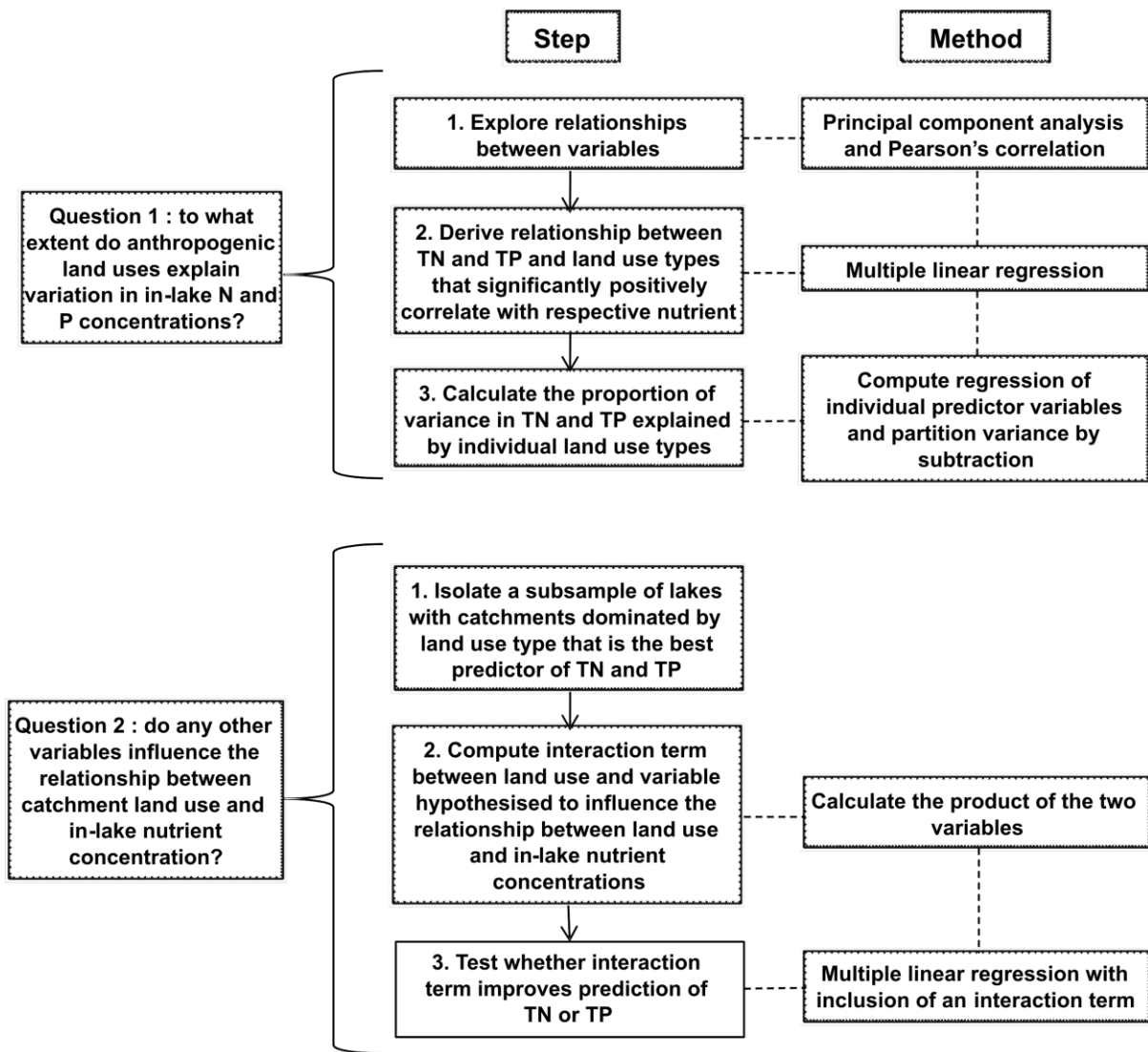


Figure 3

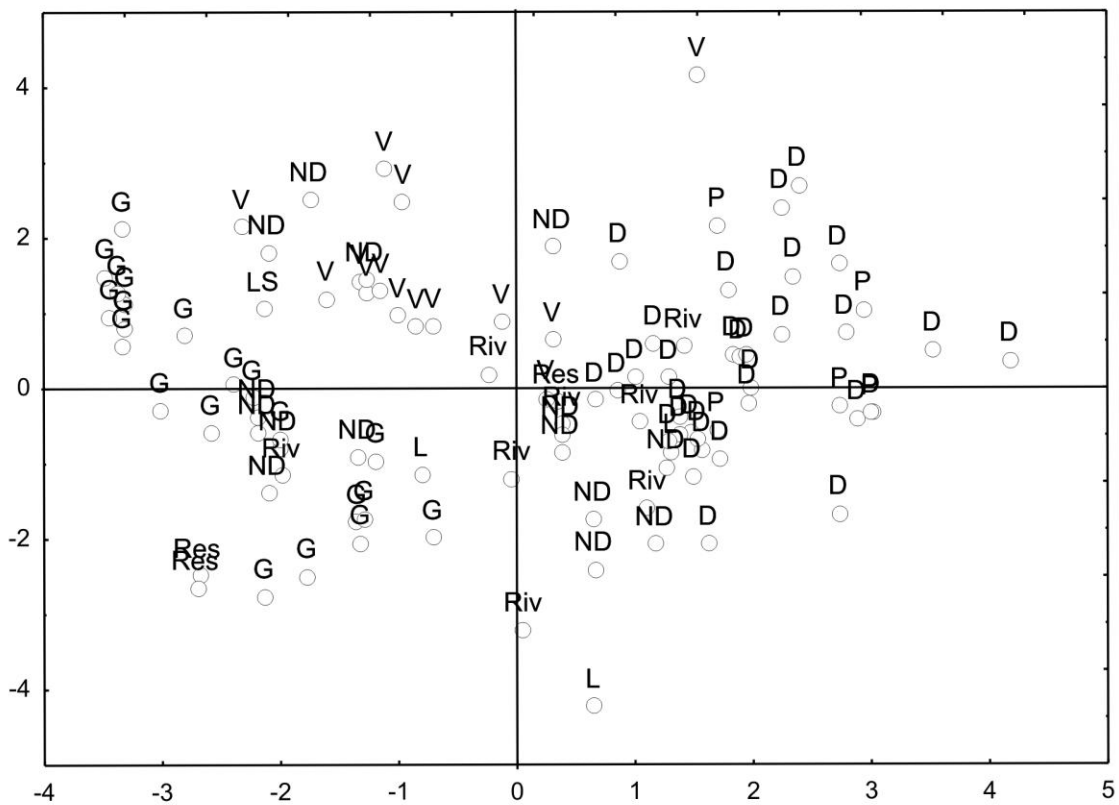
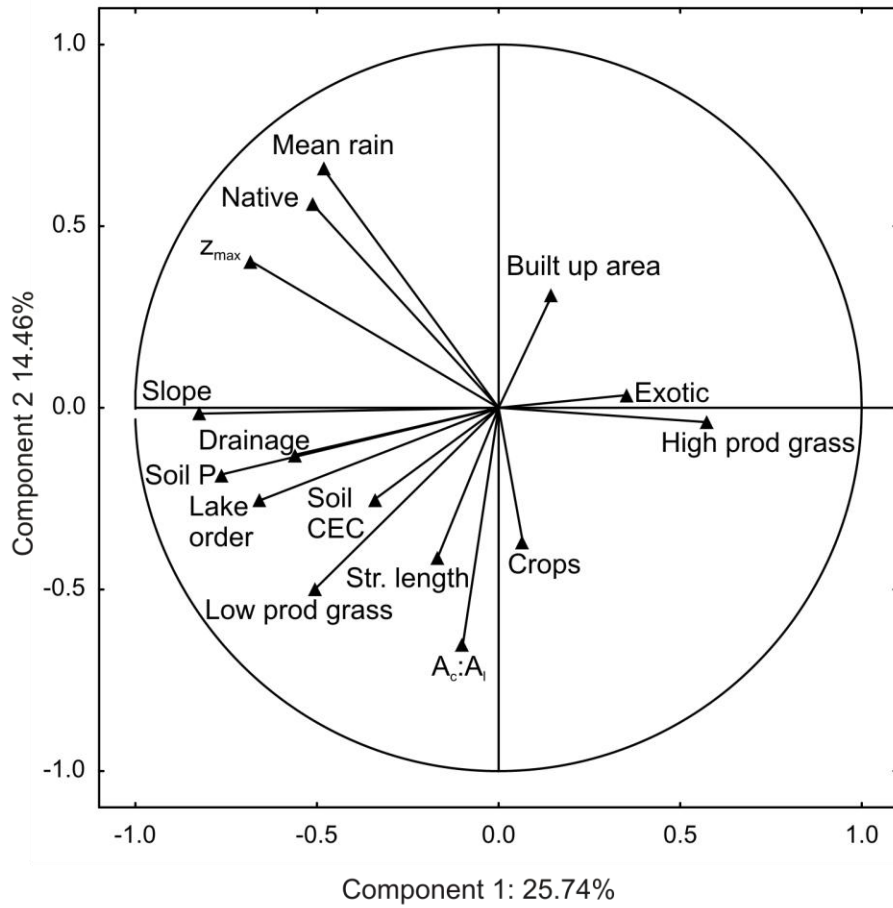


Figure 4



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Table 2 Summary of the hypothesised interactions of catchment characteristics on the relationship between anthropogenic land use and in-lake nutrient concentrations.

Table 3 Descriptive statistics for lake and catchment variables

Table 4 Mean proportion of Land Cover Database (LCDB) version 2 land use classes in the 101 lake catchments included in the study compared to the overall proportions for New Zealand (Ministry for the Environment 2009). Note that we use ‘arable cultivation’ to refer to the sum of ‘short rotation cropland’, ‘vineyard’ and ‘orchard and other perennial crops’.

Table 5 Pearson correlation matrix of lake and catchment variables. Significant correlations are shown in bold ( $p < 0.05$ ). Data have been transformed prior to analysis.

Table 6 Summary of linear regression analyses. All data were standardised and nutrient data were  $\log_{10}$  transformed and land use data were arcsine square-root transformed prior to analysis. The variance column denotes the proportion of variance in the dependent variable explained by each land use type after a correction has been made to account for covariation between predictor variables.

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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;  $\epsilon$  = error;  $\beta_1$  and  $\beta_2$  are regression coefficients. Model statistics are only reported in cases where the interaction term ( $\beta_2$ ) 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) <sup>-1</sup>	Class	mg (100 g) <sup>-1</sup>
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	<b>Positive</b>	High catchment to lake ratio will yield a high nutrient load per unit of lake area.
	Maximum lake depth	<b>Negative</b>	Shallow lakes less able to buffer nutrient inputs than deep lakes.
	Average catchment slope	<b>Positive</b>	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 <sup>2</sup> catchment	<b>Positive</b>	More hydrologically connected catchments have greater capacity to transport nutrients.
	Lake order	<b>Positive</b>	More hydrologically connected catchments have greater capacity to transport nutrients.
Soil attributes	Cation exchange capacity (CEC)	<b>Negative</b>	Greater mobility of mineral nutrients with decreasing soil CEC.
	Drainage	<b>Positive</b>	Rate of nutrient flux associated with hydrological flows will be higher in well drained catchments.
Climate	Mean rainfall	<b>Positive</b>	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 <sup>-3</sup>	TN	44.5 – 4247.5	687.1
	Total phosphorus	101	mg m <sup>-3</sup>	TP	1.5 – 440.0	64.3
	Chlorophyll <i>a</i>	101	mg m <sup>-3</sup>	Chl <i>a</i>	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 <sup>2</sup>	$A_l$	0.02 - 612.6	26.2
	Catchment area (m <sup>2</sup> ) to lake area (m <sup>2</sup> ) 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 <sup>2</sup> of catchment	101	m	Str. length	225.6 – 3015.0	1245.3
Catchment soil attributes	Cation exchange capacity	99	meq (100 g) <sup>-1</sup>	Soil CEC	4.9 – 40.0	15.1
	Acid soluble phosphorus content of the soil	101	mg (100 g) <sup>-1</sup>	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 6

Dependent variable	Predictor variable	$\beta$	$r^2$	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 ( $\beta_2$ )	$\beta_2$ (standardised)	$r^2$
TN	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{mean rain}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * A_c:A_1) + \varepsilon$	< <b>0.05</b>	0.41	0.38
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * z_{\max}) + \varepsilon$	< <b>0.01</b>	- 0.41	0.43
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{slope}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{CEC}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{drainage}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{stream length}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{LO}) + \varepsilon$	> 0.05	-	-
TP	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{mean rain}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * A_c:A_1) + \varepsilon$	< <b>0.01</b>	0.49	0.31
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * z_{\max}) + \varepsilon$	< <b>0.05</b>	- 0.36	0.28
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{slope}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{CEC}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{drainage}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{stream length}) + \varepsilon$	> 0.05	-	-
	$a + \beta_1 * \% \text{ high prod. grass} + \beta_2 * (\% \text{ high prod. grass} * \text{LO}) + \varepsilon$	< <b>0.01</b>	0.39	0.30