

# Phosphorus and nitrogen loading restraints are essential for successful eutrophication control of Lake Rotorua, New Zealand

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## Abstract

Anthropogenic activity has greatly enhanced the inputs of nitrogen (N) and phosphorus (P) to lakes, causing widespread eutrophication. Algal or cyanobacterial blooms are among the most severe consequences of eutrophication, impacting aquatic food webs and humans that rely on lakes for ecosystem services. In New Zealand, recent debate on the relative importance of N versus P control for limiting occurrences of algal blooms has centered on the iconic Lake Rotorua (North Island). Water quality in Lake Rotorua has declined since the late 1800s following catchment vegetation clearing and subsequent land-use intensification, as well as from sewage inputs. A multimillion dollar restoration programme began in the early 2000s, with key mitigation actions including nutrient load targets for the entire catchment and alum dosing in 2 tributaries. In this manuscript we analyse 2 water quality datasets (>10 yr) from Lake Rotorua and compare these with a global lake dataset. Generalised additive models predicted highly significant ( $p < 0.001$ ) declines in total phosphorus (TP), total nitrogen (TN) and chlorophyll *a* (Chl-*a*) in surface waters between 2001 and 2015. Alum dosing had a negative (i.e., reducing) and highly significant effect on TP and Chl-*a* ( $p < 0.001$ ). Correlations of Chl-*a* on TP and TN were highly significant, but the difference between the 2 correlation coefficients was not, indicating a need to control both nutrients to reduce algal productivity. This conclusion is reinforced by recent bioassay studies which show co-limitation by N and P. Collectively, our data and previous studies provide strong support for the current strategy of limiting both N and P loads to Lake Rotorua for effective eutrophication control.

**Key words:** alum dosing, chlorophyll *a*, cyanobacteria, nutrient bioassays, Trophic Level Index

## Introduction

Increased anthropogenic eutrophication is one of the greatest challenges facing surface water quality globally (Conley et al. 2009, Smith and Schindler 2009). A major consequence of over-enrichment in phosphorus (P) and nitrogen (N) is enhanced primary productivity. Although the critical role of N and P in enhancing phytoplankton growth is well described, the relative importance of these remains a key subject in eutrophication science and a critical consideration for water managers. After more than

half a century of lake eutrophication research, P remains a primary target for eutrophication control (OECD 1982, Carpenter 2008, Schindler et al. 2008), but increasingly there is a dual nutrient limitation paradigm to achieve both N and P limitation of phytoplankton growth (Elser et al. 2007, Lewis et al. 2011, Paerl et al. 2014).

Analysis of a 121-lake dataset and a review of experimental limitation studies led Abell et al. (2010) to recommend dual control of both N and P for ongoing management of lakes in New Zealand. The authors emphasise a greater need to reduce P inputs. Although the

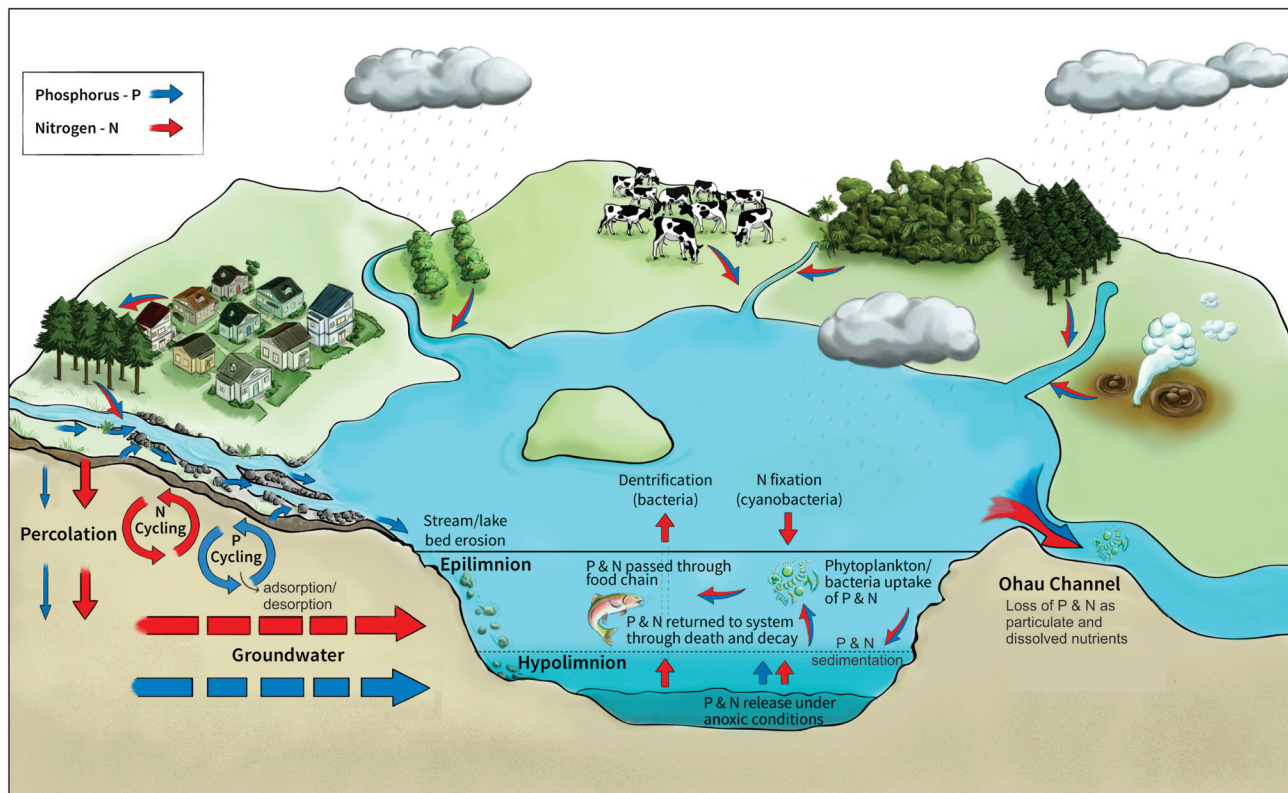
dual control strategy is becoming internationally accepted, some scientists and managers continue to advocate for a single nutrient control approach (e.g., Wang and Wang 2009). In New Zealand, the debate was recently resurrected following publication of Morgenstern et al. (2015). They used a unique set of high-quality tritium data covering >4 decades to determine the detailed age distribution of the groundwater discharging into Lake Rotorua. Their hydrogeochemical study effectively demonstrates how the isotopic and chemical signatures of groundwater can be used to help determine the sources and the dynamics of both groundwater flows and their dissolved contaminants, allowing a more complete understanding of groundwater processes at the catchment scale and making a valuable contribution to the understanding of groundwater-based processes in the Lake Rotorua catchment. Morgenstern et al. (2015), however, asserted that for Lake Rotorua, managers should focus only on restricting external N loads, stating that “the only effective way to limit algae blooms and improve lake water quality in such environments is by limiting the nitrate load.” Morgenstern (2015) also notes that “while in-lake P removal is a well-established technique to improve lake water quality over the short-term, and may be applicable in lakes that do not have a natural high P load such as Lake Rotorua, this strategy will be

compromised and unlikely to result in long-term benefits in Lake Rotorua.”

Abell et al. (2015) and Smith (2015) provide conclusive responses to the above propositions. Here we focus on the above 2 assertions and build on the evidence provided in Abell et al. (2015) and Smith (2015). Through the analysis of 2 long-term (>10 year) water quality datasets from Lake Rotorua and a comparison with a global lake dataset, we provide empirical evidence to support the current strategy of limiting both N and P loads to Lake Rotorua for effective eutrophication control.

## Lake Rotorua, New Zealand

Lake Rotorua is the largest (area 80 km<sup>2</sup>, mean depth 10 m) of the Te Arawa lakes in the Central Volcanic Plateau, North Island, New Zealand. Prior to European settlement, the catchment was predominantly temperate rainforest (Clarkson et al. 1991). Land around the lake was cleared, and farming began in the 1880s and has been associated with pastoral conversion and land use intensification. Treated wastewater from the adjacent city of Rotorua was pumped directly into Lake Rotorua from 1973 until 1991, when a new sewage treatment system involving a tertiary-treatment land application process was implemented. The initial response (1993–1995) to the wastewater treatment



**Fig. 1.** Conceptual diagram showing key pathways of N and P transport into and out of Lake Rotorua, including recycling. Detailed nutrient budgets for Lake Rotorua are given in Hamilton et al. (2015) and Tempero et al. (2015).

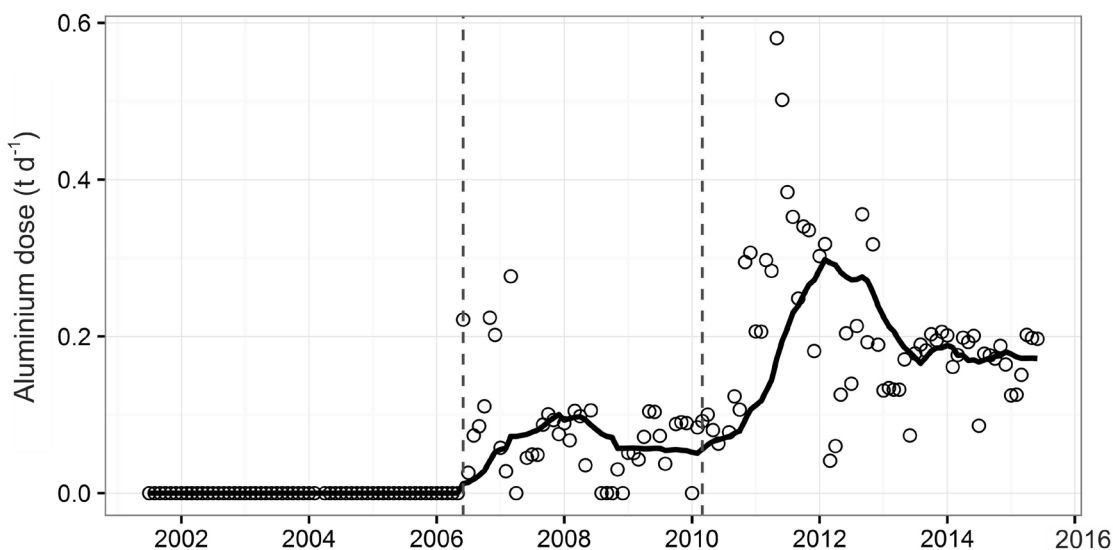
upgrade was improved water clarity (Rutherford et al. 1996), but water quality continued to degrade through the 2000s (Burger et al. 2008). This continued decline has been attributed to land use intensification in the catchment, increases in nitrate in the aquifers draining agricultural land (Rutherford et al. 2011; Fig. 1), and releases of nutrients to the lake water column from bottom sediments enriched in N and P (Burger et al. 2008, Trolle et al. 2008; Fig. 1). External nutrient loads to the lake are now dominated by inputs from agricultural land use (~45% of the catchment area and an estimated 75% of the N load and 45% of the P load; Parliamentary Commissioner for the Environment 2006; Fig. 1). Runoff from urban areas, plantation forestry, native vegetation, and geothermal sources are other important contributors to the total nutrient load (Fig. 1).

In 2004, a rule was implemented by the regional environmental management authority, Bay of Plenty Regional Council (BoPRC), to prevent land use change or intensification (e.g., increased stock density) activities that would increase nutrient losses from land within the lake catchment (Rule 11; BoPRC 2008). The BoPRC has also set a target for water quality in the lake using a trophic level index (TLI), which averages log transformed values of 4 constituents in surface waters: total nitrogen (TN), total phosphorus (TP), chlorophyll *a* (Chl-*a*), and Secchi disk depth (Burns et al. 1999). The target TLI for Lake Rotorua is 4.2, a value considerably lower than that of the early 2000s (i.e., requiring re-oligotrophication) but considered representative of trophic state in the 1960s before widespread public concern about the state of the lake (Mueller et al. 2015). Recent studies have indicated that the target TLI of 4.2 can be attained with TN and TP

loads of <math><435\text{ t y}^{-1}</math> (Rutherford et al. 2011) and <math><37\text{ t y}^{-1}</math> (Hamilton et al. 2012), respectively, which represent a major reduction of loads currently received by the lake. The BoPRC seeks to meet the required load reductions through voluntary land use change and mitigation strategies as well as financial incentives, with up to \$40 million to support land use change (BoPRC 2015a).

While policies and plans for land use change and nutrient mitigation are being developed for the catchment of Lake Rotorua, alum (aluminium sulphate) dosing has been used to reduce TLI. Alum dosing began in the Utuhina Stream inflow in 2006, followed by Puarenga Stream in 2010. Between 2006 and 17 June 2015, 496 t of aluminium (Al) was added to these tributaries as alum, although dosing rates have been variable, peaking in July 2011 (Fig. 2). The main aim of inflow alum dosing is to reduce external P loads by binding P entering the lake. Evidence shows, however, subsidiary benefits from adsorption of P in the lake water column and the settling of the resulting alum floc onto the lake bottom sediments, which may reduce sediment release of P to the overlying water column (Özkundakci et al. 2013).

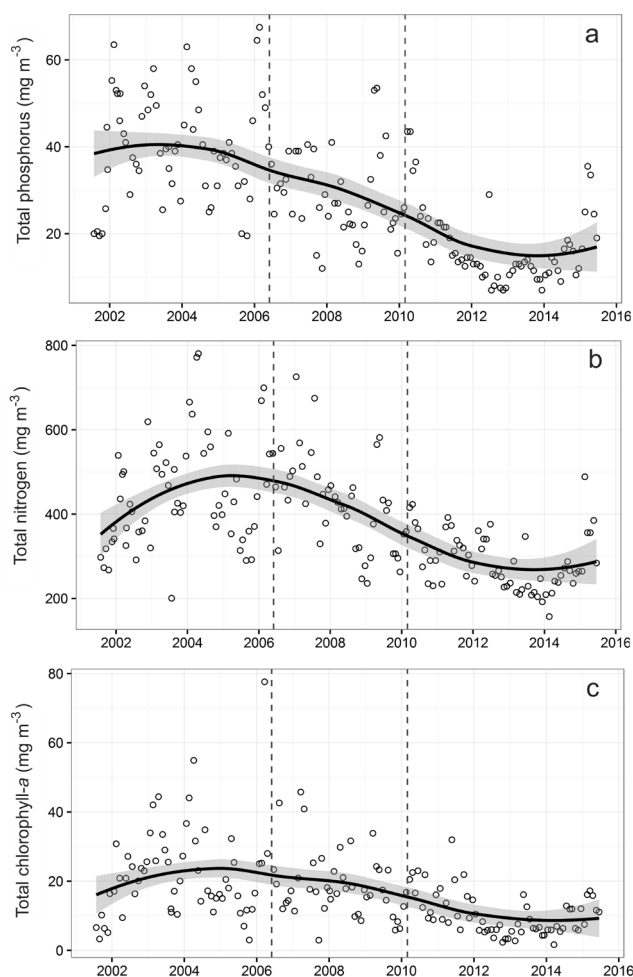
Water quality has improved following tributary alum dosing, and in 2012 the target TLI was attained (Hamilton et al. 2015, Mueller et al. 2015). The current strategy for continued water quality improvement in Lake Rotorua water quality is based on dual control of N and P (BoPRC 2009, Burns et al. 2009), a strategy supported by a multi-million dollar restoration programme, with statutory instruments in place to help achieve load reduction targets (Parliamentary Commissioner for the Environment 2006, Burns et al. 2009).



**Fig. 2.** Alum dosing rates (as  $\text{t d}^{-1}$  of Al) in 2 tributaries of Lake Rotorua. Left and right vertical dashed lines represent initiation of dosing in Utuhina Stream and Puarenga Stream, respectively. Solid line shows moving average calculated over the prior 18-month period. These data were used in the generalised additive models (Fig. 4).

## Assertion 1: Water quality in Lake Rotorua has steadily declined during the past 50 years despite mitigation efforts

We analysed a 14-year (2001–2015) dataset of surface water samples from Lake Rotorua (data are monthly averages from Station 2 and 5; BoPRC 2015b). A significant ( $p < 0.001$ ) downward trend was found in TN, TP, and Chl-*a* (Fig. 3) and a consistent decrease in TP from 2001 until 2014, with a steeper decline during 2006–2014 (Fig. 3a). An upward trend in TN was observed from 2001 until 2005/2006, when a monotonic decline in TN was recorded until 2014. Both TP and TN increased markedly during 2015 (Fig. 3a and b). Chl-*a* peaked in 2004 and has been in a reasonably consistent decline since 2006 (Fig. 3c).



**Fig. 3.** (a) Total phosphorus, (b) total nitrogen, and (c) chlorophyll *a* in the surface water of Lake Rotorua (data are averages from sampling sites 2 and 5) between 2001 and 2015. The black line is a loess-smoothed local polynomial regression, and grey shading represents pointwise 95% confidence interval of the fitted values. Left and right vertical dashed lines represent initiation of dosing in Utuhina Stream and Paurenga Stream, respectively.

Generalised additive models (GAMs; Hastie and Tibshirani 1990) were used to model nonlinear trends for total TN, TP, and Chl-*a* data through the time series and to examine seasonal variation and the effect of alum dosing. A rolling mean over the previous 18 month period (the estimated residence time of Lake Rotorua; Burger et al. 2008) was used for the alum dosing data. The models assumed normally distributed errors with zero mean and equal variance. For the seasonally smoothed functions, a cyclic cubic spline with a maximum of 12 knots was used to allow continuity between January and December. For the long-term trend smoothing functions, a cubic spline was used, and the number of knots was selected using generalised cross-validation. To account for the temporal autocorrelation in the time series data, models were fitted using an autoregressive moving-average correlation structure. To account for heteroscedasticity patterns in residuals detected in all models, different variances were allowed for each year (Pinheiro and Bates 2000). Candidate models were selected via a generalised likelihood ratio test and Akaike information criteria values and were validated by inspecting the deviance residuals. All analyses were conducted in the “*gamm*” package (Wood 2004) with the software R (R Development Core Team 2014).

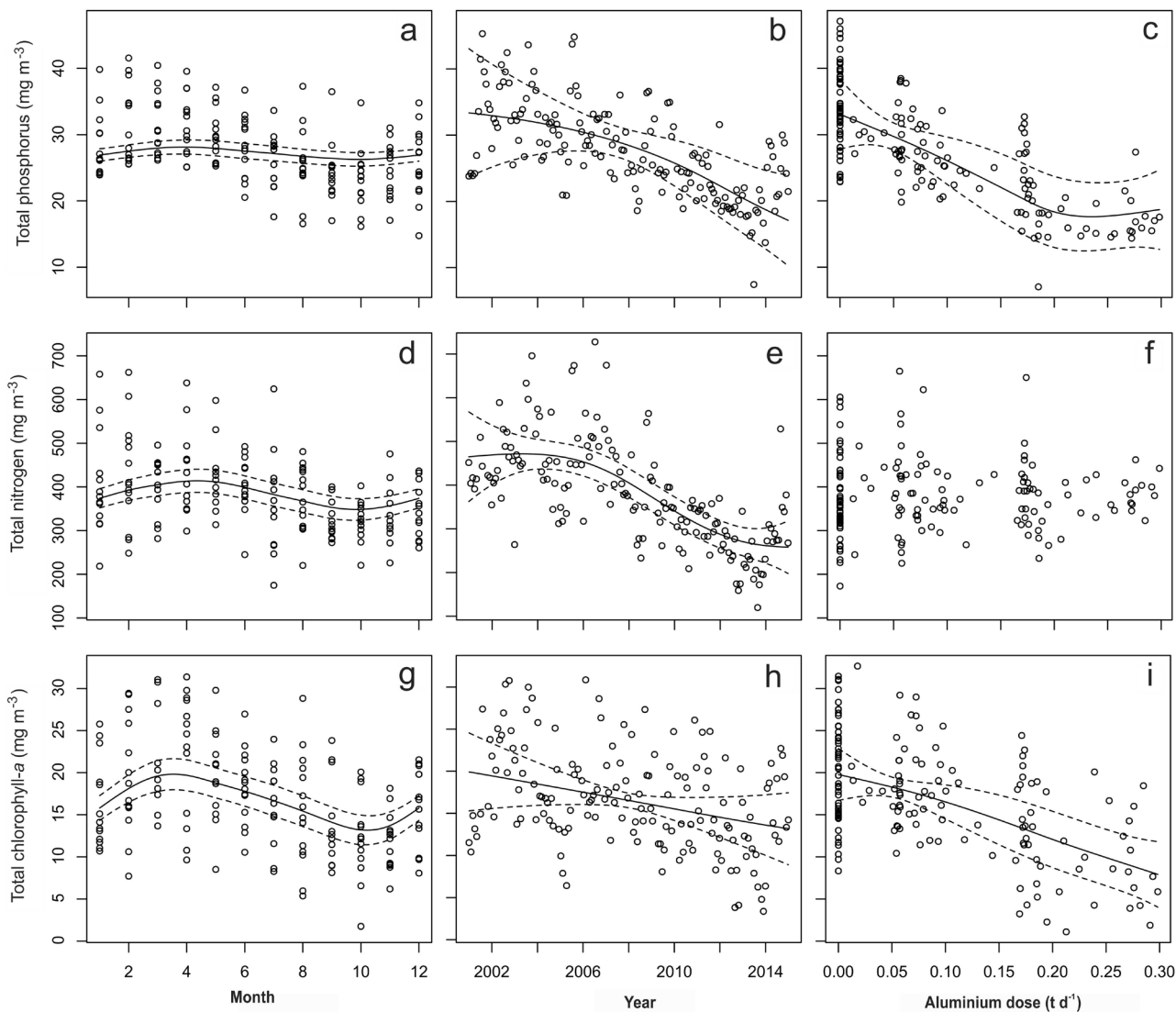
The GAM models explained 71.4% of the total variance of TP, 51.8% of TN, and 55.8% of Chl-*a*. Seasonal effects were generally weak but significant (Fig. 4;  $p < 0.001$ ), with the exception of TP (Fig. 4a;  $p = 0.07$ ). The seasonal model showed a slight discrepancy in the month when the maximum of each variable occurred. Concentrations of TP were predicted to peak between February and March and lowest levels to occur in September (Fig. 4a); TN to peak between January and February, with the lowest concentrations predicted around October (Fig. 4d); and Chl-*a* to peak in April, with lowest levels in October (Fig. 4g).

Long-term decreases in concentration were highly significant for all 3 response variables (Fig. 4;  $p < 0.001$ ). A predicted monotonic decline was observed for TP from 2001 until 2015. Maximum TP levels ( $\sim 60 \text{ mg m}^{-3}$ ) were recorded in 2006 before alum treatment was initiated in June 2006 (Fig. 4b). The model showed a steeper decline post-2006 until 2015, when minimum levels of  $\sim 15 \text{ mg m}^{-3}$  were predicted (Fig. 4d). TN was relatively stable from 2001 until 2006, when highest predicted values were  $400\text{--}600 \text{ mg m}^{-3}$ . Post-2006, a monotonic decline was observed in TN until 2014, when minimum levels of  $\sim 250 \text{ mg m}^{-3}$  were predicted. In 2015, however, TN concentrations increased, with maximum values reaching  $500 \text{ mg m}^{-3}$  (Fig. 4e). Chl-*a* showed a weaker long-term trend, but the model predicted a significant downward trend, albeit with considerable variability.

Alum dosing was associated with a negative and highly significant effect on TP and Chl-*a* (Fig. 4c and i;  $p < 0.001$ ) but not on TN (Fig. 4f;  $p > 0.5$ ). The model indicated a linear decrease in TP from ~35 to 15 mg m<sup>-3</sup> as alum dosing increased up to 0.2 t d<sup>-1</sup> of Al. Doses exceeding this value did not result in further reductions in TP (Fig. 4c). The effect of alum dose on Chl-*a* was close to linear, with nearly 4-fold reductions in Chl-*a* at the maximum dose of 0.3 t d<sup>-1</sup> of Al (Fig. 4i).

Alum dosing was included in the GAMs as a rolling mean over the previous 18 months (see earlier reasoning), allowing us to test whether the inflow dosing and possible subsidiary lake water column effects accounted for the trends over time in TP, TN, and Chl-*a*. Özkundakci et al. (2013) noted higher rates of in-stream alum dosing

associated with increasing proportions of unbound Al entering the lake, potentially reducing in-lake water column P concentrations. The GAMs predict that a significant proportion of the decline in TP and Chl-*a* may be attributed to alum dosing. The effect of year (time) was still significant, however, suggesting other variables not accounted for in the model may have also contributed to improvements in TP and Chl-*a* after 2006. We advocate in the short-term (1–2 decades) for the continued use of flow-adjusted alum dosing in the 2 streams, albeit at modest levels relative to those used in some years (e.g., 2010). Our suggested time scale for continuation of alum dosing is predicated on successful implementation of land use change and mitigation of nutrient runoff in the catchment, aligned with improvements to agricultural



**Fig. 4.** Partial plots of (a, d, and g) seasonal and (b, e, and h) long-term trends, and (c, f, and i) alum dose as Al for (a–c) total phosphorus, (d–f) total nitrogen, and (g–i) chlorophyll *a* in the surface water of Lake Rotorua (data are monthly averages from sampling sites 2 and 5) between 2001 and 2015. The solid lines ( $\pm 2$  SE, dashed lines) are a cubic spline fitted using the generalised additive model.

practices, urban storm water systems, wastewater treatment, and forestry operations (Abell et al. 2013, Tempero et al. 2015), and partially accounting for groundwater delivery lags that impact the timing of N delivery to the lake (Morgenstern et al. 2015). Little information exists on long-term, low-level alum dosing on aquatic biota (Tempero et al. 2015), and there has been significant opposition from tangata whenua (indigenous Māori tribes) around the lake with regard to the sustainability of alum dosing. We therefore do not advocate alum dosing in perpetuity, and any need to do so would likely reflect a failure to achieve the level of catchment land use change and mitigation practices outlined by the BoPRC and necessary to achieve a 4.2 TLI for the lake.

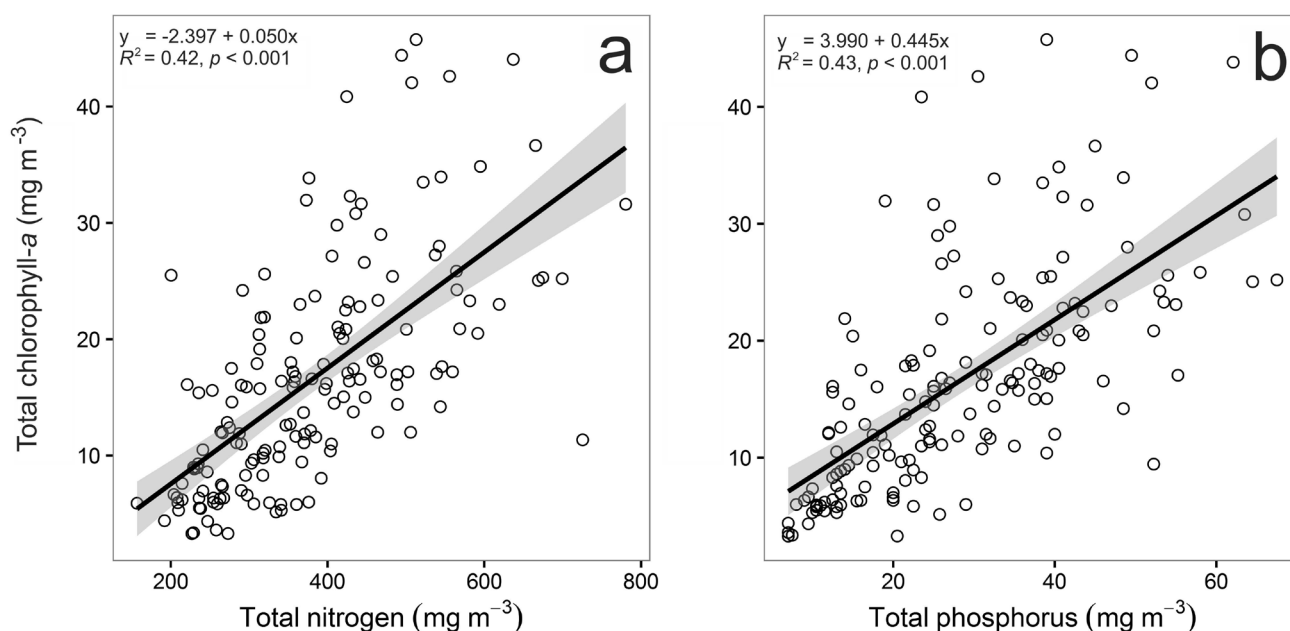
In summary, the observed data (Fig. 3) and the GAMs (Fig. 4) indicate a significant improvement in Lake Rotorua water quality since ca. 2006, clearly refuting the proposition that water quality in Lake Rotorua has declined despite mitigation efforts.

## Assertion 2. The only effective way to limit algae blooms and improve lake water quality in environments such as Lake Rotorua is by limiting the nitrate load

This proposition is firmly contradicted by Smith (figure 1 in Smith 2015), by data presented in the present paper, and by decades of eutrophication research performed worldwide. The results of Smith et al. (1987), Smith (1985, 2015), and the monthly data on relationships

among Chl-*a*, TN, and TP in the surface water of Lake Rotorua between 2001 and 2015 (Fig. 5) all indicate that a failure to control external P and N inputs to Lake Rotorua will result in an undesirable increase in the intensity and frequency of algal/cyanobacterial blooms.

Linear regression analysis shows a positive and significant relationship between Chl-*a* and both TN and TP. The difference between the 2 correlation coefficients was not significant using Fisher's *z*-transformation of *R* ( $z = 0.11$ ,  $p = 0.9$ ). These data corroborate the findings of Abell et al. (2010) who found no significant difference between TP and TN to Chl-*a* Pearson's correlation coefficients in their analysis of a dataset from 121 New Zealand lakes. Although Schindler (2012) urges caution when using correlations between TN or TP with Chl-*a* to infer which nutrient is more likely to be limiting and supports whole-lake manipulation studies for this purpose, the consistency of co-limitation found in recent bioassays in Lake Rotorua also indicates the importance of both N and P for enhancing phytoplankton growth rates (Table 1). These studies include laboratory bioassays, *in situ* mesocosms of different scales, and model simulations. The studies by Burger et al. (2007) and Abell and Hamilton (2014) are noteworthy because they demonstrate the potential for co-limitation. Burger et al. (2007) found using *in situ* mesocosms that individual species responded differently to N and P additions, suggesting co-limitation within the phytoplankton species assemblage. Abell and Hamilton (2015) used a dynamic 3-dimensional water quality model, validated with field measurements and nutrient bioassays from the laboratory, to show a high



**Fig. 5.** Relationship between chlorophyll *a* and (a) total nitrogen and (b) total phosphorus in the surface water of Lake Rotorua using monthly data (averages from sampling sites 2 and 5) between 2001 and 2015.

**Table 1.** Summary of results from nutrient bioassay and model studies conducted for Lake Rotorua. Volumes of laboratory bioassays of White et al. (1985) were not specified. Laboratory bioassays of Abell and Hamilton (2015) are for 3 separate occasions within 5 d under different hydrological (streamflow) conditions: laboratory bioassays (1) is the littoral zone (all 3 periods), and laboratory bioassays (2), (3), and (4) are pelagic zone for the 3 conditions. These samples were subjected to identical treatments. Relative response compares strength of nutrient addition responses when both nutrients individually stimulated phytoplankton growth. Co-limitation response similarly compares strength of dual nutrient addition to individual additions. Observed and relative responses for the model simulations refer to output from a simulated phytoplankton limitation factor for each nutrient. For co-limitation, strength of relative response and co-limitation response is denoted qualitatively by  $\approx$ ,  $>$ , and  $\gg$ .

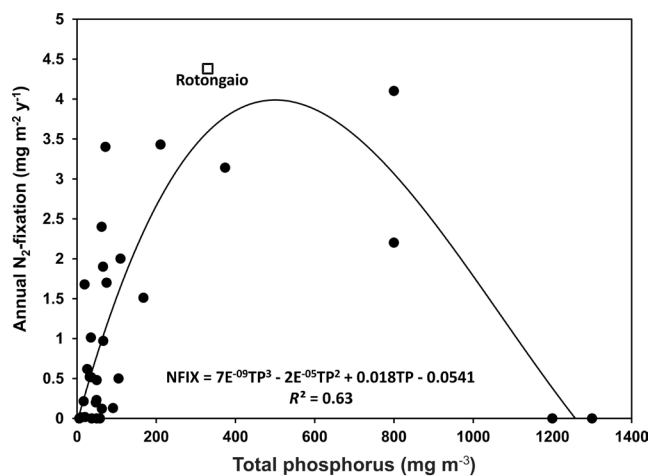
Experiment organisation level	Observed response		Relative response	Co-limit. response	Incubation/simulation duration	Study
	+N	+P				
Lab bioassays (0.25 L)	Yes	No			5 d	White and Payne (1978)
Lab bioassays	Yes	No		$>N$	2 h, 24 h	White et al. (1985)
In situ mesocosm (3 L)	Yes	Yes	$P>N$	$>N, >P$	4 d, 6 d	Burger et al. (2007)
In situ mesocosm (1 m <sup>3</sup> )	Yes	No		$\gg N$	1-9 d	Meads (unpub. data 2009)
Lab bioassays (1)	No	No		No	1 d	Abell and Hamilton (2015)
Lab bioassays (2)	Yes	No		$\approx N$	1 d	Abell and Hamilton (2015)
Lab bioassays (3)	No	Yes		No	1 d	Abell and Hamilton (2015)
Lab bioassays (4)	Yes	Yes	$N\approx P$	$\approx N, \approx P$	1 d	Abell and Hamilton (2015)
Model simulations	Yes	Yes	$N\gg P$	$>N, \gg P$	5 d	Abell and Hamilton (2015)

degree of spatial (littoral vs. pelagic) and temporal (at time scales  $<5$  d) variation in the limiting nutrient (i.e., N vs. P). The analysis in Abell and Hamilton (2015), in concert with previous work (Table 1) and the low probability of diatoms being limited due to silica concentrations  $\sim 10$  mg L<sup>-1</sup> (Pearson et al. 2016), clearly show a need for dual control of N and P to reduce cultural eutrophication and limit phytoplankton growth in Lake Rotorua.

Morgenstern (2015) and Morgenstern et al. (2015) focused only on groundwater nitrate inputs into Lake Rotorua. This narrow focus on nitrate as a growth-limiting nutrient is misleading because phytoplankton can obtain N from a variety of both inorganic and organic sources (Tandeau de Marsac and Houmard 1993, Vrede et al. 2009). Moreover, numerous species of bloom-forming cyanobacteria can meet their N requirements for growth by fixing dissolved atmospheric dinitrogen (N<sub>2</sub>) into cellular inorganic N (Smith et al. 1995, Wood et al. 2010a, Oliver et al. 2012).

Many decades of extensive experimental evidence have demonstrated that the eutrophication of freshwater lakes cannot be controlled by reducing N inputs alone (e.g., Schindler et al. 2008). Although Chl-*a* is a sensitive and internationally agreed-upon measure of eutrophication-related water quality used for more than 75 years in the assessment of eutrophication in lakes worldwide, the public is especially sensitive to occurrences of harmful cyanobacterial blooms (CyanoHABs; Paerl and Otten 2013). CyanoHAB events can result in the closure of lakes for recreational activities or as drinking water

supplies, the development of nuisance taste and odor problems, and the occurrence of high concentrations of cyanobacterial toxins in lake water (Chorus and Bartram 1999, Wood et al. 2010b). Nutrient management policies that advocate reductions only in N loading are likely to lead to sharp and highly predictable declines in the water quality by stimulating the development of CyanoHABs dominated by heterocystous N<sub>2</sub>-fixing genera such as *Dolichospermum* (basonym *Anabaena*) and *Aphanizomenon*. Peak summer bloom concentrations of both genera have been shown to be highly correlated with water column TP concentrations (Smith et al. 1987). This



**Fig. 6.** Relationship between annual rates of nitrogen fixation (NFIX) and lake water concentrations of total phosphorus (TP) in 20 North Temperate lakes and Lake Rotongaio, New Zealand.

vitaly important finding was made with reference to Lake Rotorua more than 25 years ago by Rutherford et al. (1989), who cautioned that “Removal of nitrogen alone may reduce phytoplankton growth, in the short term (say 5–10 yr), but [it] is not recommended because the algal community may become dominated by heterocystous blue-green algae, which can meet their nitrogen requirements by fixing dissolved molecular nitrogen and form dense unsightly assemblages.” Annual rates of planktonic N fixation are strongly dependent on TP concentrations in both North Temperate and New Zealand lakes (Fig. 6).

Cyanobacterial enumeration has been conducted at 4 shoreline sites in Lake Rotorua since 1997 as part of a monitoring programme aimed at protecting the health of recreational users. The trend in declining Chl-*a* (discussed earlier) is also evident in the cyanobacterial biovolume data (Fig. 7). Consistent with the proposition that reducing P is a requirement to remove N<sub>2</sub> fixing species, a marked decline has occurred in the percent of biomass containing heterocystous species since 2009 (Fig. 7). In the late 1990s and early 2000s, CyanoHABs dominated by large buoyant *Dolichospermum* species including *circinale*, *lemmermannii*, and *planctonicum*, and *Aphanizomenon gracile*

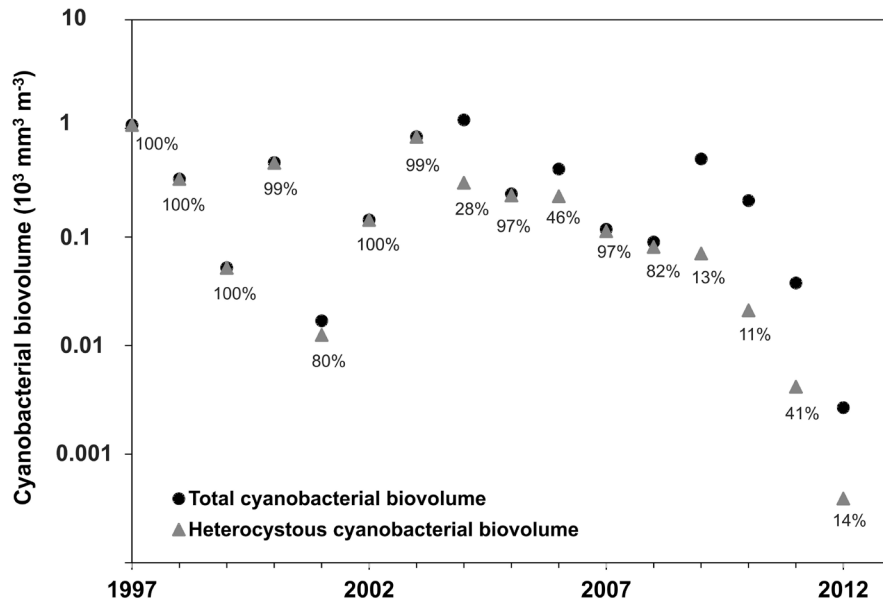


Fig. 7. Total cyanobacterial biovolumes and total heterocytous cyanobacterial biovolumes. Percentages show proportion of heterocytous cyanobacteria in each sample. Data are averages from 4 sites around the edge of Lake Rotorua (Hamurana, Holdens Bay, Ngongotaha, and Ohau Channel Bay).

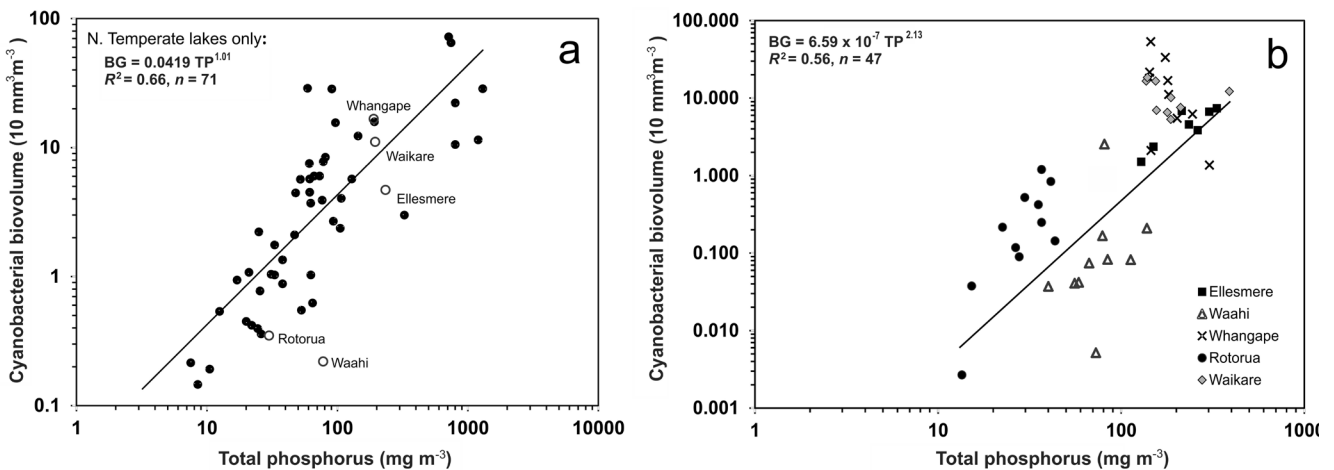


Fig. 8. (a) Relationship between summer mean concentrations of cyanobacterial biovolume (BG) and total phosphorus (TP) in 71 North Temperate (N. Temperate) lakes and 4 New Zealand lakes. North Temperate lakes data from Smith (1985) and V.H. Smith (unpubl.). (b) Relationship between summer mean concentrations of cyanobacterial biovolume (BG) and total phosphorus (TP) in Whangape, Waikare, Ellesmere, and Waahi for all available lake-years of data (data from Wood et al. 2014; Environment Canterbury unpubl.).



species regularly dominated the phytoplankton assemblage during summer. Blooms have now become less frequent, and small non-N<sub>2</sub> fixing, nonbloom forming, nontoxic genera such as *Pseudanabaena* and *Aphanocapsa* are the most abundant cyanobacteria (data not shown).

Smith (2015) reported a strong power function between average cyanobacterial biovolume and concentrations of TP in 71 North Temperate lakes. We have added long-term average data from 5 New Zealand lakes (Ellesmere, Rotorua, Whangape, Waikare, and Waahi) to his dataset to confirm that cyanobacteria in New Zealand lakes behave in a manner consistent with the global temperate lake relationship (Fig. 8a). Moreover, a highly significant regression model was obtained when the data from all available lake-years of the study were analysed (Fig. 8b).

## Conclusion and future perspectives

The data presented here and results and analysis of previous studies on Lake Rotorua (e.g., Burns et al. 2009, Abell et al. 2015, Hamilton et al. 2015, Tempero et al. 2015) clearly support the current strategy of controlling both N and P loads to the lake. This strategy corroborates international studies such as those of Schindler et al. (2008) that demonstrate a focus on N control only would have detrimental consequences for lakes, leading to increased eutrophication, and Paerl and Otten (2013) that relate some mono-specific blooms of cyanobacteria to excess N loads. Alum dosing of Puarenga and Utuhina streams has been effective at reducing P loads to Lake Rotorua and resulted in decreases in algal biomass. Increased alum dosing is unlikely to be a viable long-term strategy, however, because of potential concerns over toxicity to aquatic organisms (Tempero 2015). To achieve the desired trophic state commensurate with an acceptable level of restoration of the lake (i.e., a TLI of 4.2), further mitigation efforts will be required. A major challenge is the duration of major reductions in both external and internal loads from catchment restoration efforts. Baseflow in the major stream inflows is mostly supported by aquifers with groundwater residence times of decades to more than a century (Morgenstern et al. 2015). Concentrations of nitrate in the baseflow of most streams are therefore rising from the dual effects of historical land use change and intensification of pastoral agriculture (Rutherford et al. 2011) and will continue to rise until the effects of contemporary N management strategies become evident. Similarly, stores of “legacy P” (*sensu* Jarvie et al. 2013) in highly fertilised agricultural soils and streambed sediments may take time to deplete (Peryer-Fursdon et al. 2015). A specific management focus should be to reduce the loss of soil from productive landscapes because these

sediments are enriched in P (Abell et al. 2013). These sediments are also highly manageable compared with the dissolved P of geological origin, and their sorption–desorption kinetics mean that they may liberate P in periods of high biological demand (Abell and Hamilton 2013) as well as in deeper areas of the lake where sediments are exposed for periods (days to weeks) of stratification-driven anoxia due to the eutrophic, polymictic nature of Lake Rotorua (Burger et al. 2008). Nutrient mitigation will be judged successful if alum dosing can be progressively reduced, and ultimately removed, while maintaining a TLI  $\leq 4.2$ .

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