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Assessing the impacts of experimental mid-rotation forest fertiliser treatments on water quality

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Abstract

Background: Planted forests face on-going challenges to increase productivity while remaining within sustainable limits. Forest management activities that potentially impact on water quality are under increasing public scrutiny and regulatory controls. New Zealand's forest industry is experimenting with aerially applied, mid-rotation fertiliser treatments as a sustainable option to increase productivity from planted forests. However, the effect of such applications on water quality requires investigation.

Methods: Field trials were established to assess the effects of two conventional fertiliser applications (either granular di-ammonium phosphate (DAP) or granular urea) and a new-to-forestry liquid foliar fertiliser blend, on nitrogen and phosphorus concentrations in stream water of three planted forest sites representing a range of New Zealand climatic and soil environments.

Results: Overall, the liquid foliar fertiliser treatment had the least impact on water quality compared with the two conventional fertiliser treatments. On the day of fertiliser application, when compared with pre-treatment in-stream concentrations, the urea treatments resulted in short-term increases in total nitrogen. The DAP treatment increased total phosphorus and dissolved reactive phosphorus concentrations with peak concentrations declining within hours. In the post-application period, any increases in nutrient concentrations in stream water were mainly associated with rainfall events within six months of application and at one site, the resumption of stream flow following a dry spell. Riparian 'no-spray' buffers of varying widths assisted in mediating the impacts of fertiliser applications.

Conclusions: Initial evidence from these trials indicates that mid-rotation fertiliser treatments have the potential to provide an alternate management option to increase forest productivity or disease resilience with minimal or only short-term effects to water quality. However, further research on their environmental effects would support the development of guidelines specific to mid-rotation fertiliser applications, particularly if mid-rotation fertiliser applications become standard management practice in the forest industry.

Keywords: fertiliser; mid-rotation; New Zealand; nitrogen; nutrients; phosphorus; planted forest; water quality

Introduction

Fertilisers are a practical option for improving forest productivity and can provide significant productivity benefits from applications at tree establishment until mid-rotation (Ingerslev et al. 2001; Fox et al. 2007). Nevertheless, in some regions the use of fertiliser has declined over time amid concerns of escalating fertiliser costs, treatments not achieving the desired outcomes, impacts on wood properties, potential impact on biodiversity and the risk of leaching and contamination of waterbodies. Improved forest nutrition management is another likely contributor to the decline in the amount of fertiliser applied to planted forests (Ingerslev et al. 2001; Smaill & Clinton 2016).

In the past, fertiliser use has concentrated on addressing nutrient deficiencies (Albaugh et al. 2007). In New Zealand's planted forests fertiliser use is very low and it is mainly applied to young trees to address key nutrient deficiencies, primarily nitrogen, phosphorus and boron (Davis et al. 2015; Scion 2019). Increasingly research is focusing on the targeted delivery of site-specific fertiliser treatments for improved productivity outcomes and reduced environmental risk. This approach aims to match soil and site nutrient supply with crop demand. This is a more effective approach than addressing nutrient deficiencies in isolation, and reflects the use of balanced fertiliser blends as part of a wider management strategy to improve site capacity (Smaill & Clinton 2016; Rubilar et al. 2018).

The New Zealand forest industry strategy to 2050 includes the goal of doubling tree growth and forest production efficiency (Forest Owners Association 2019). To assist in meeting this ambitious goal current research is investigating opportunities to improve the precision of fertiliser applications to meet specific site conditions and maximize site productivity (Clinton 2018). More efficient sampling strategies for soil and foliar analyses and on-going advances in modelling techniques to apply these results to forest areas containing similar geospatial characteristics, are providing an improved basis to underpin precision nutrition research. These outcomes may encourage wider use of fertilisers in New Zealand's planted forests in the future. However, where nutrient inputs exceed tree crop demand and soil nutrient retention capacities, there is a risk of nutrient leaching into waterbodies with potential negative impacts on the aquatic environment (Davis et al. 2012). Globally (United Nations Environment Programme 2016), and across New Zealand (Ministry for the Environment & Statistics New Zealand 2019), water quality is a critical issue. Interventions that improve productivity of planted forests need to also comply with international, national, and regional water quality regulatory guidelines and forest certification standards.

Research on the effects of fertiliser use on water quality in New Zealand's planted forests is dated (Leonard 1977; Neary et al. 1978). The purpose of this project was to assess the impact of conventional fertiliser treatments (DAP at one site and granular urea at two sites), along with a new experimental fertiliser treatment applied to mid-rotation stands, on water quality at three 'case study' sites across New Zealand. It was hypothesised that targeting the canopy of the crop more precisely with applications of liquid foliar fertiliser would have lower impacts on water quality on the day of application and in the post-treatment period, compared with conventional granular forestry fertiliser applications.

Methods

Study sites

Nine trial sites were established across New Zealand's planted forests to assess the effects of a range of mid-rotation fertiliser applications on productivity, economics, timber quality and soil characteristics (Coker & Palmer 2019). Three of these sites (Fig. 1) were selected to assess the impacts of experimental mid-rotation fertiliser applications on water quality in streams. These sites covered a range of geographical, geological, climatic and hydrological conditions (Table 1 and described below). Site 1 was in Tairua Forest on the Coromandel Peninsula, North Island of New Zealand; Site 2 was in Tarawera Forest in the central North Island region and Site 3 was in Berwick Forest in the Otago region of the South Island (Fig. 1). Site selection was influenced by the proximity of perennial streams to the mid-rotation fertiliser trial sites. Two of the water quality trials (Tairua and Berwick) were within the same catchment or within two kilometres of the mid-rotation fertiliser trials. The Tarawera water quality trial was approximately 25 kms from the associated mid-rotation fertiliser trial, but on the same volcanic plateau and site characteristics were similar. All sites were mid-rotation stands of *Pinus radiata* D.Don, in their second rotation of trees and had recently been thinned (Table 1).

The Coromandel Peninsula (Tairua site) has a warm (median annual temperature 12- 14° C), sunny (>2100 median annual sunshine hours) climate with relatively high rainfall (annual average 1840 mm) and is susceptible to extreme weather events that bring high winds, rainfall and flooding to the area (Chappell 2014). The volcanic plateau of the Bay of Plenty Region (Tarawera site) has a cooler but moderately sunny (2050-2100 median annual sunshine hours) climate with a median annual temperature of 11- 13° C and frosts are common in the cooler months. Annual rainfall averages 1353 mm (Chappell 2013). The South Island Otago region (Berwick site) has a cool, windy climate

FIGURE 1: Location of the mid-rotation water quality trial sites.

TABLE 1: Characteristics of the three study sites.

Site characteristics	**Planted Forest**		
	Tairua	**Tarawera**	**Berwick**
Geology[1]	Rhyolite	Rhyolite and Basalt	Schist and Loess
Predominant soils[1]	Ortstein Pan Podzols, Acidic Orthic Brown Soils	Buried-pumice, Tephric Recent Soils, Immature Orthic Pumice Soils	Orthic Brown Soils
Topography[1]	Rolling to strongly-rolling hill country	Rolling to steep hill country	Rolling hill country
Stand characteristics			
Site index[2] (m)	27.0-30.0	33.5-38.6	22.4-24.1
Age	14-15 years	9-11 years	12 years
Stocking after thinning	436-494 stems ha^{-1}	520-550 stems ha^{-1}	494-534 stems ha^{-1}

[1] Hewitt 2010; Manaaki Whenua - Landcare Research 2019

[2] An index of site quality and potential productivity defined as the mean top height (average height of the 100 largest diameter stems within a hectare) at 20 years of age.

where frosts and snow are common. This region is also susceptible to extreme weather events with high rainfall, flooding and contrasting dry spells. Annual rainfall averages 700-800 mm, the median annual temperature ranges from 8- 9° C with median annual sunshine hours ranging from 1650-1700 (Macara 2015).

At each site, three headwater catchments were selected for the fertiliser treatment comparisons. Table 2 outlines the catchment characteristics. The streams in Tairua had a stony substrate (visual assessment), were dominated by an overland flow hydrology, and responded rapidly during significant rainfall events. In Tarawera there was no surface flow upstream of the water monitoring point, a reflection of the high drainage capacity of the soils and sandy substrate at this site. However, flows in these streams also responded to changes in rainfall. The gullies at the Berwick site were poorly drained and contained wetlands with intermittently defined stream channels. Stream substrate composition had a fine silty-clay texture and stream flow likewise responded to rainfall.

Fertiliser treatments

At each site, the following fertiliser treatments were aerially applied (Table 3) to the three catchments:

Treatment 1 – control catchment, no fertiliser applied;

Treatment 2 – liquid foliar fertiliser (5.1 kg ha^{-1} nitrogen (N) as Urea @ 11kg ha^{-1}; 0.49 kg ha^{-1} of phosphorus (P) as Phospot @ 4.45 L ha^{-1}), application rate 100 L ha^{-1};

Treatment 3 – granular fertiliser: di-ammonium phosphate (DAP) at 375 kg ha^{-1} (66 kg N ha^{-1}; 75 kg P ha^{-1}) (Tairua) or urea 450 kg ha^{-1} (207 kg ha^{-1} N) (Tarawera and Berwick).

TABLE 2: Catchments characteristics within each study site.

***Site*/Fertiliser treatment**	**Catchment area (ha)**	**Average stream width (m) (sample size)**	**Average stream flow (l s^{-1}) (sample size)**
Tairua			
Control	7.0	0.56 (14)	4.31 (14)
Liquid foliar	7.3	0.55 (14)	3.97 (14)
Granular DAP	6.4	0.39 (14)	2.22 (14)
Tarawera			
Control	11.2	0.17 (18)	0.45 (18)
Liquid foliar	18.7	0.50 (11)	2.74 (11)
Granular urea	5.8	0.17 (6)	0.38 (6)
Berwick			
Control	13.9	0.15 (10)	1.34 (10)
Liquid foliar	12.8	0.23 (10)	1.40 (10)
Granular urea	11.5	0.23 (10)	1.21 (10)

TABLE 3: Fertiliser aerial application specifications.

Specification	**Planted forest**		
	Tairua	**Tarawera**	**Berwick**
Application date	14/11/2016	granular 31/10/2017; foliar 21/3/2018	6/10/2018
Liquid foliar fertiliser			
Helicopter	MD500	AS350 B3	Bell 206 B
Nozzle configuration	Accu-Flow 0.28-64, 22 nozzles	D6 with 46 swirl plate, 64 nozzles	T Jet 008, 56 nozzles
Droplet size (VMD, micron)	≈ 450	≈ 450	400-500
Boom length (m)	6.9	8.5	9
Swath width (m)	16	24	12
Spray release height above trees (m)	10	6-8	5-6
Average ground speed (knots)	45	60	45
Granular fertiliser			
Helicopter type	MD500	AS350 B3	Bell 206 L4
Bucket specifications	IMS 650L	Heli Resources Top Dressing bucket	HeliOtago Stainless Steel
Flight line separation (m)	15	20	16
Fertiliser release height (m)	35	15 – 18	25
Average ground speed (knots)	45	50	40

A 10-m buffer width was retained either side of the stream for Treatment 2 and 20 m buffer either side of the stream for Treatment 3 (excluding Tarawera – no surface water flow above the water sampling point, therefore no buffer was retained).

Fertiliser treatments were aerially applied by helicopter (Table 3) in spring at all three sites except for the liquid foliar fertiliser treatment at Tarawera, which was applied in autumn (Table 3). This was due to an accidental application of a granular fertiliser in spring, requiring re-establishment of a liquid foliar fertiliser catchment and allowing sufficient time to collect a set of pre-treatment water quality data.

Data collection

At each of the three sites a Campbell Scientific Inc. data logger (model CR1000) meteorological station was installed at approximately 2.5 m above the ground and programmed to record air temperature (° C), relative humidity (RH) (%), wind speed (m s^{-1}) and direction (degrees), and rainfall (mm) at 15-minute intervals. The data provided information on weather conditions on the day of fertiliser application and rainfall patterns over the trial duration.

Water monitoring points were established at the downstream end of each of the nine catchments. Part way through the trial, the monitoring site in the urea catchment at Berwick was moved upstream, due to potential contamination from a nearby wild pig carcass. Three to four water samples were collected over a period of several months prior to fertiliser application to establish background rates of nitrogen (N) and phosphorus (P).

On the day of fertiliser application, at the Tairua and Berwick sites, water samples were collected at 15-minute intervals in the two fertiliser treatment catchments for the first hour after application. Thereafter, four water samples were taken at 15-minute intervals and combined to produce an hourly composite water sample for a further three hours. Because there was no upstream flow at the Tarawera site the more intensive sampling undertaken in the first hour at Tairua and Berwick was not required. Instead, composite samples were collected over a three-hour period in the two fertiliser treatment catchments. On the day of application a single water sample was also taken at the control catchment at all three sites.

The day after fertiliser application, water samples were collected from all three catchments at the three sites. Several water samples were collected within the first month following fertiliser application with a focus on sampling immediately after rainfall events. Thereafter, water sampling continued at approximately monthly intervals for four to six months after application. The post-application monitoring period was extended to nine months at the urea-treated catchment at Tarawera as stream flow was intermittent during the summer period, providing an opportunity to measure nutrient response under these hydrological conditions. In addition, a single water sample was taken from each catchment at low-flow conditions and analysed for a range of parameters (see Analysis section) to provide an indication of water quality characteristics. We did attempt to install an auto-water sampler at one site, but logistical difficulties precluded its use. In accordance with laboratory guidelines, all water samples were labelled and couriered to the laboratory in insulated chilled containers, accompanied by a chain-of-custody form. Water flow measurements were taken using a Hach FH950 portable velocity meter each time water samples were collected.

Laboratory analyses

The water samples were analysed by RJ Hills Laboratory (RJ Hill Laboratories, Hamilton, New Zealand; http://www.hill-laboratories.com/). This Laboratory is accredited by International Accreditation New Zealand (IANZ). Water samples collected for nutrient analysis were analysed for TKN (Total Kjeldahl N) (Detection limit (DL) 0.05 g m^{-3}), Nitrate-N (DL 0.001 g m^{-3}), Nitrite-N (DL 0.002 g m^{-3}), ammoniacal N (DL 0.010 g m^{-3}), total nitrogen (TN) (TKN + Nitrate-N + Nitrite-N DL = 0.05 g m^{-3}), dissolved reactive phosphorus (DRP) (DL 0.004 g m^{-3}) and total phosphorus (TP) (DL 0.004 g m^{-3}). The water samples collected for water quality characterisation were analysed for the same nutrient parameters above along with the following water quality indicators; pH (DL 0.1 pH Units), electrical conductivity (EC) (DL 0.1 mS m^{-1}), total suspended solids (TSS) (DL 3 g m^{-3}) and dissolved organic carbon (DOC) (DL 0.5 g m^{-3}).

Statistical analyses

To analyse temporal changes in nutrient concentration at each site, the water quality data for the treatment catchments was divided into four sampling time periods: pre-fertiliser application, the day of application, within a month of application, and > 2 months after application (range: up to 136 to 253 days after treatment (DAT)). For the control catchments, similar sampling time periods were applied using fertiliser application dates for each site. As a result, the Tarawera control catchment data was arranged into two separate sets of sampling time periods to align with the two fertiliser treatments that were applied on two different dates at this site. For controls, as only one sample was collected on the day of application, the day of application period was merged with the within a month of application period. For each measured nutrient (Total N, Nitrate N, Total P, DRP) and N/P ratio, and for each fertiliser type (treatment), the mean of each site and period combination was estimated using a Bayesian regression linear model.

For each fertiliser treatment *T*, denoting *y* as the response variable (nutrient concentration), *i* as the index for an observation, S as the vector of sites (factor, fixed effect) and P as the vector of periods (factor, fixed effect), a lognormal regression was performed, following the model:

$$y_i \sim Normal\,(\mu_i, \sigma^2)$$

$$log(\mu_i) = c_{S[i]:P[i]}$$

with prior distributions

$$(c_1 \ldots c_{nS*P}) \sim Normal(\alpha, 2)$$

$$\sigma \sim Normal^{+}(0,1)$$

where $C = (c_1 \ldots c_{nS*P})$ is the vector of effects for each site and period combination and represents the overall observed mean of the log-transformed response. The log-transformation has been chosen because the responses can only take positive values. The prior for lognormal means has been chosen to be weakly informative with a large enough standard deviation to cover all possible log-transformed values of the response.

Performing the analysis under the Bayesian paradigm allows the computation of a posterior distribution of uncertainty for parameters of interests (here, concentration means within period-site categories) and further derived quantities of interest. In this study, the uncertainty carried by concentration means posterior distributions could naturally be propagated to ratios between post- and pre-treatment values, allowing to quantify medians (50th percentile) and uncertainties (95% credible intervals) for the change in concentration between pre- and post-fertiliser application. Parallel modelling of concentration means for control catchments across the same time periods indicated if observed changes in treatment catchments were caused by the fertiliser application process. All analyses were performed using the brms package (Bürkner 2017) in R (R Core Team 2021).

Results

Water quality characteristics

Low-flow water quality at the streams in all three sites was characterised by circumneutral pH (range 6.4-7.5), low ion concentrations as indicated by the EC values (range 4.7-11.3 mS m^{-1}) and low TSS concentrations (range 3-7 g m^{-3}). Dissolved organic carbon concentrations were also low at the Tairua and Tarawera sites (range 0.3-0.9 g m^{-3}) but higher at Berwick (range 4.0-5.6 g m^{-3}), attributed to organic matter leaching into the streams from the wetlands upstream.

Nitrogen composition in the stream water of the Tairua and Tarawera sites predominantly consisted of nitrate-N and TKN (Table 4). TKN comprised a higher proportion of TN composition in stream water at the Berwick site compared with Tairua and Tarawera and was almost entirely composed of organic-N. Ammoniacal-N concentrations were low at all three sites (Table 4) and frequently below detection limits, indicating that the organic-N comprised a large component of TKN. TP concentrations in the stream water of the Tairua and Tarawera sites were mainly comprised of DRP, whereas DRP comprised a smaller component of TP at the Berwick site (Table 4).

Tairua

On the day of fertiliser application, the air temperature averaged 12.3° C, RH averaged 81%, wind speed averaged 0.3 m s^{-1} and wind direction ranged from 187-357° (≈ southerly through to a north-westerly).

This trial site experienced a series of high rainfall events in the latter part of the monitoring period (Fig. 2a), and we were unable to collect samples during the high rainfall

TABLE 4: Median[1] nitrogen (N) and phosphorus (P) concentrations (g m^{-3}).

***Site*/Fertiliser treatment**	**Fertiliser composition**					
	TKN	**Nitrate-N**	**Ammoniacal-N**	**Total N**	**DRP**	**Total P**
Tairua						
Control	0.04	0.06	0.005	0.12	0.009	0.010
Liquid foliar	0.03	0.06	0.005	0.10	0.054	0.057
Granular DAP	0.06	0.15	0.005	0.22	0.003	0.006
Tarawera						
Control	0.10	0.40	0.010	0.50	0.002	0.005
Liquid foliar	0.07	0.26	0.010	0.33	0.002	0.006
Granular urea	0.10	0.23	0.005	0.47	0.002	0.002
Berwick						
Control	0.27	0.24	0.005	0.51	0.003	0.027
Liquid foliar	0.30	0.22	0.005	0.51	0.002	0.026
Granular urea	0.35	0.34	0.005	0.61	0.006	0.029

[1] median values calculated using half the detection limit when concentrations were below the detection limit
TKN - Total Kjeldahl Nitrogen
DRP - Dissolved Reactive Phosphorus

event (381 mm) 114 DAT due to widespread flooding in the area. Variation in stream flow in all three catchments was closely aligned with rainfall (Fig. 2a & b).

On the day of fertiliser application, in both the granular DAP and liquid foliar catchments, there was no discernible response in TN (Fig. 2c, Fig. 3a) and nitrate-N (Fig. 3b) concentrations in stream water. However, there was an increase in TP (Fig. 2d, Fig. 3c) and DRP (Fig. 3d) associated with the DAP application that was about five times that of pre-treatment concentrations. In the liquid foliar treatment, there was no obvious increase in TN and TP concentrations on the day of application in the graphical results (Fig. 2c & d). However, further analysis showed a TP and DRP increase associated with this treatment (Fig. 3c & d) that was approximately three times that of pre-treatment concentrations (but noting the higher background concentrations of TP in this catchment). No change was detected in TP and DRP in the associated control catchment (Fig. 3c & d).

Beyond the day of fertiliser application, elevated nutrient concentrations in the stream water in the three catchments were mainly associated with the first rainfall event sampled after fertiliser application (95 DAT) (Fig. 2c & d). The highest nitrate-N, TKN and TN concentrations (0.35 g m^{-3}, 0.32 g m^{-3}, 0.67 g m^{-3}, respectively) were recorded in the DAP catchment during this rainfall event. Peak DRP and TP concentrations (0.076 g m^{-3} and 0.068 g m^{-3}, respectively) were recorded in the foliar fertiliser catchment 65 DAT but were difficult to differentiate from the high background TP concentrations (Fig. 2d). Analysis of nutrient concentrations in stream water in the first month after application, and 2 months onward, showed no discernible long-term treatment effects of both the DAP and liquid foliar treatments on TN and nitrate-N (Fig 3a & b). While TP and DRP concentrations in the post-application period were higher than the control (Fig. 3c & d), the data was insufficient to confidently detect any treatment effects from both the DAP and liquid foliar fertilisers.

Tarawera

At the Tarawera site, weather conditions on the days that the urea and liquid foliar fertiliser were applied (spring and autumn, respectively) were similar. The air temperature average 12.3° C and 12.7° C, and RH average 94% and 97%, respectively. Wind speed average 0.11 m s^{-1} and 0.10 m s^{-1}, respectively with wind direction predominantly from the north for the urea catchment and ranging between north-west to south-west for the liquid foliar catchment. Rainfall was regular throughout most of the trial period (Fig. 4a), and flow response in all catchments was influenced by rainfall (Fig. 4a & b). However, in the urea catchment, flow ceased for several months during a period of low summer rainfall (Fig. 4b).

The highest TN concentrations were detected in stream water at the urea catchment on the day of fertiliser application, reaching a peak concentration 1.74 g m^{-3} but declined thereafter (Fig. 4c). TN concentrations were approximately three times higher than pre-treatment concentrations on the day of application (Fig 3a). There was no corresponding increase in nitrate-N (Fig. 3b) as TKN comprised a large proportion of TN in the samples taken on the day of application (data not shown). There were also no discernible increases in TP and DRP in the urea catchment both on the day of application and in the post-treatment period (Fig. 3c & d). However, one high TN concentration data point, dominated by nitrate-N, was detected in stream water 189 DAT (Fig 4c), after a 160 mm rainfall event, when stream flow resumed after approximately five months of minimal or no flows in this catchment. This data point influenced the high ratios of both TN and nitrate-N in the 2-month onward period (Fig. 3a & b).

No increases in TN, nitrate-N and DRP were detected,

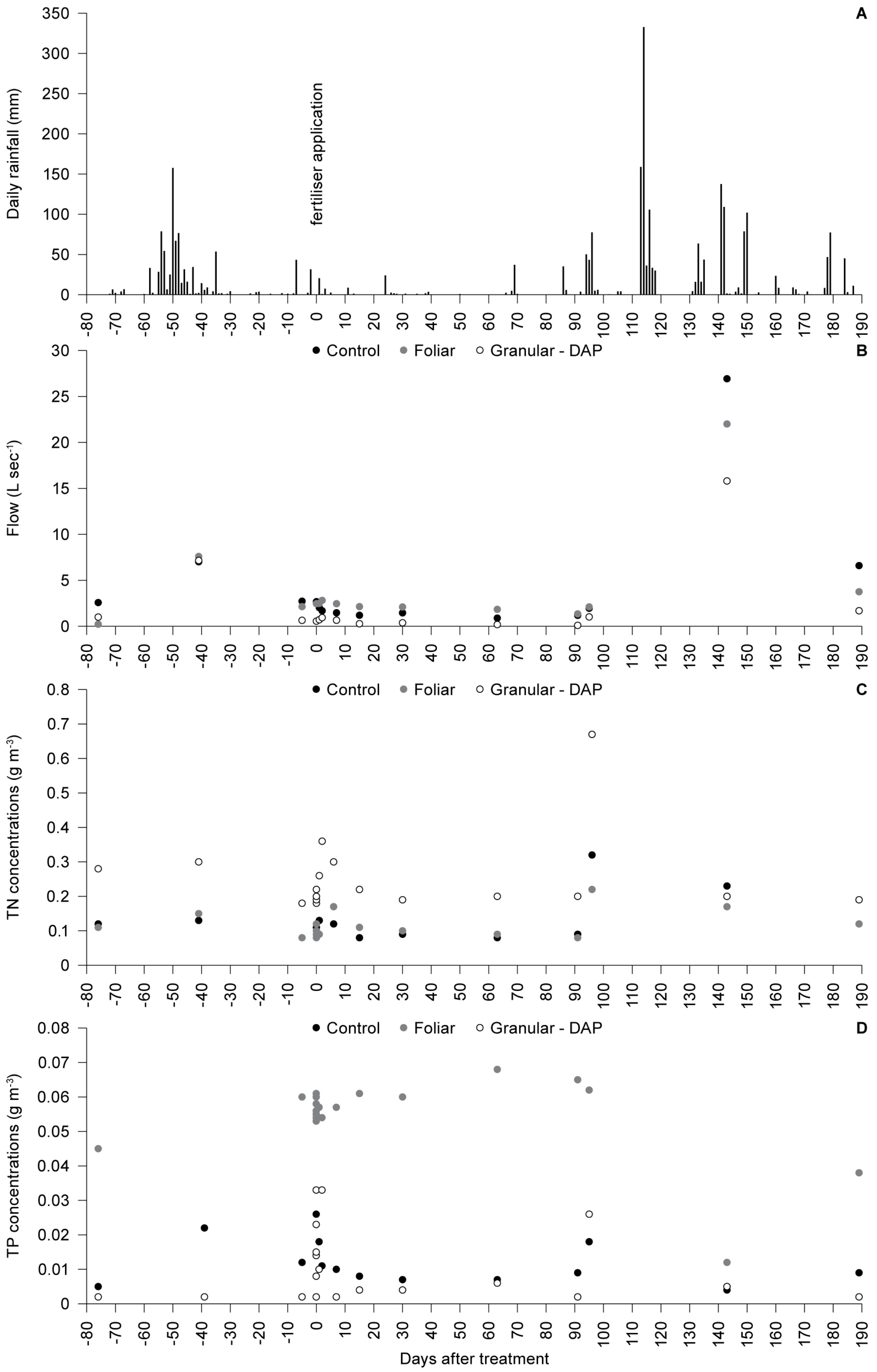

FIGURE 2: Tairua site: (a) daily rainfall; (b) flow; (c) total nitrogen concentrations in the three treatment catchments; (d) total phosphorus concentrations in the three treatment catchments.

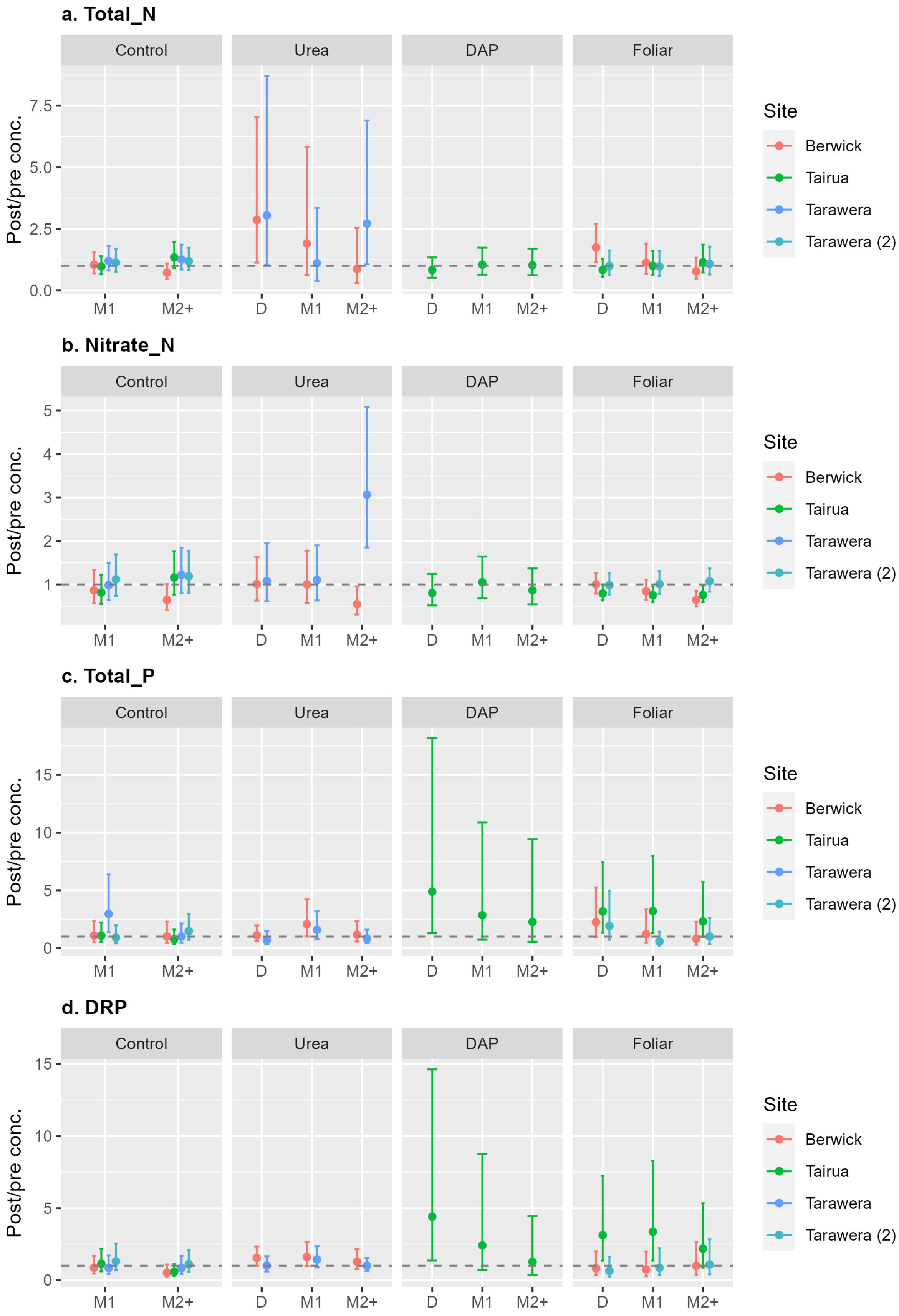

FIGURE 3. Post- to pre-treatment concentration ratios for: (a) total nitrogen; (b) nitrate; (c) total phosphorus; and (d)dissolved reactive phosphorus on the day of fertiliser application (D), within the first month of treatment (M1), and two months onward (M2+), for the control and fertiliser treatments at each of the three study sites. Points represent estimated posterior medians and error bars represent 95% credible intervals.

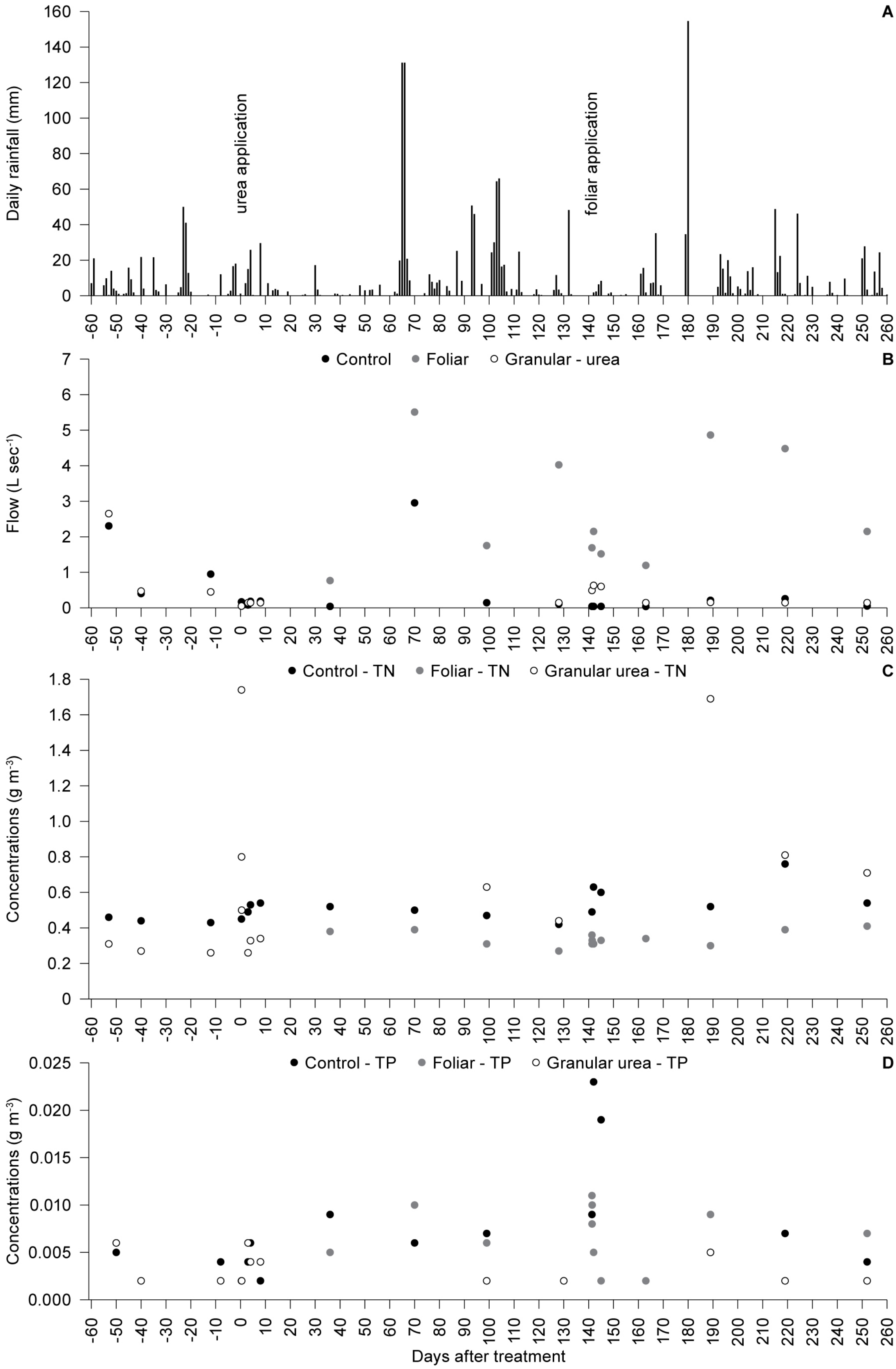

FIGURE 4: Tarawera site: (a) daily rainfall; (b) flow; (c) total nitrogen concentrations in the three treatment catchments; (d) total phosphorus concentrations in the three treatment catchments.

neither on the day of applying the liquid foliar treatment, nor in the post-treatment period (Fig. 4c, Fig 3a, b & d). The increase in TP concentrations on the day of application (peak concentration 0.011 g m^{-3}) (Fig. 4d) was approximately twice that of pre-treatment concentrations, but no long-term increases were detected (Fig. 3c). Except for TP in the first month after treatment, no changes were detected at the control site for any of the water quality parameters measured over the trial period (Fig 3a-d).

Berwick

On the day of fertiliser application at the Berwick site, the air temperature averaged 5.7° C and wind speed averaged 1.4 m s^{-1}. Wind direction was predominantly northerly at the beginning of fertiliser application before shifting to the south-west. Rainfall throughout the trial period was lower than the two other sites and the maximum daily rainfall recorded was 59.8 mm (Fig. 5a). Flows were highest in the spring and earlier summer period but declined toward the end of the monitoring period in the late summer and autumn (Fig. 5b).

On the day of fertiliser application, highest TN concentrations in stream water were recorded in the urea catchment (peak concentration 5.7 g m^{-3}) with a smaller increase in TN concentrations recorded at the liquid foliar fertiliser site (Fig. 5c), resulting in TN concentrations of approximately three and 1.5 times that of pre-treatment concentrations (Fig. 3a). No similar response was detected for nitrate-N (Fig. 3b) for both the urea and liquid foliar treatments, most likely a result of TKN comprising a large portion of TN in some (but not all) samples collected on the day of application (data not shown). In the post-application period, TN concentrations increased at one and four DAT at the urea site (Fig. 5c), in response to the rainfall during that time (Fig. 5a). However, the data was not sufficient to confidently detect treatment effects on TN and nitrate-N concentrations in the post-application period for both the urea and liquid foliar treatments (Fig. 3a & b).

On the day of fertiliser application, there was one elevated TP data point in the urea catchment (Fig. 5d), but this was insufficient to result in a treatment effect (Fig 3c). However, in the first month after application, TP concentrations were approximately double the pre-treatment concentrations. This result was influenced by one data point 4 DAT of 0.105 g m^{-3} (Fig. 5d). However, this figure is suspect as it is an unusually high concentration for TP and the highest recorded across all sites during the trial period, especially given that the urea treatment did not contain any phosphorus. TP concentrations were elevated in liquid foliar catchment on the day of treatment (Fig. 5d) and were approximately double the pre-treatment concentrations (Fig. 3c), but there were no discernible increases in DRP, nor were any discernible long-term treatment effects detected for TP and DRP (Fig. 3c & d). No changes were detected at the control catchment for any of the water quality parameters measured over the trial period (Fig. 3a-d).

TN:TP ratios

The urea treatment had the greatest impact on TN:TP ratios (Fig. 6), influenced by the increase in in-stream TN on the day of application at the Tarawera and Berwick sites and by the high concentration of TN measured at the Tarawera site when the stream resumed flowing after a dry spell (Fig. 4c & 5c). On the day of application, TN:TP ratios increased by approximately four times compared with pre-treatment TN:TP ratios at the Tarawera site and around two times at the Berwick site, and were around three times that of pre-treatment TN:TP rations at the Tarawera site in the 2-month and onward post-application period (Fig. 6). No discernible effects of fertiliser treatments on TN:TP ratios were detected for the DAP and liquid foliar treatments (Fig. 6).

Discussion

Effects of experimental fertiliser treatments on water quality

The hypothesis that the liquid foliar fertiliser would have lower impacts on water quality on the day of application and in the post-treatment period, compared with conventional granular urea and DAP fertiliser applications, was mainly upheld by these results. The exception was the treatment effect of the liquid foliar fertiliser on TP and DRP at the Tairua site. This was unexpected given the smaller quantities of phosphorus applied in the liquid foliar treatment (0.49 kg ha^{-1}) compared with the DAP (75 kg ha^{-1}). A possible explanation is that the liquid foliar catchment had high background TP and DRP concentrations throughout the monitoring period, except for one pre-treatment sample that was below detection limits for both TP and DRP. As there were only three pre-treatment water samples taken, this data point would have lowered the pre-treatment average used in the analysis to assess treatment effects on the day of application and in the post-application period.

Otherwise, treatment effects on water quality were associated with the conventional DAP fertiliser treatment at Tairua on the day of application (elevating TP concentrations) and the urea fertiliser applications at the Tarawera and Berwick sites. At both these sites there was some direct input of urea into the stream channel. As a result, there was a short-term (several hours) increase in TN in the stream water on the day of application influencing the increase in TN:TP ratios. At the Tarawera site, there was no surface flow upstream of the water monitoring point so the entire upstream catchment area was treated, although there was a buffer between the edge of the treatment area and the water sampling point. At the Berwick site, an experimental 20-m buffer was retained along the stream edges in the treatment catchments. These buffers were effective in reducing, but not eliminating, urea from the stream channel.

At the urea catchment in Tarawera, the flushing of nitrate (a component of TN that is highly soluble in water)

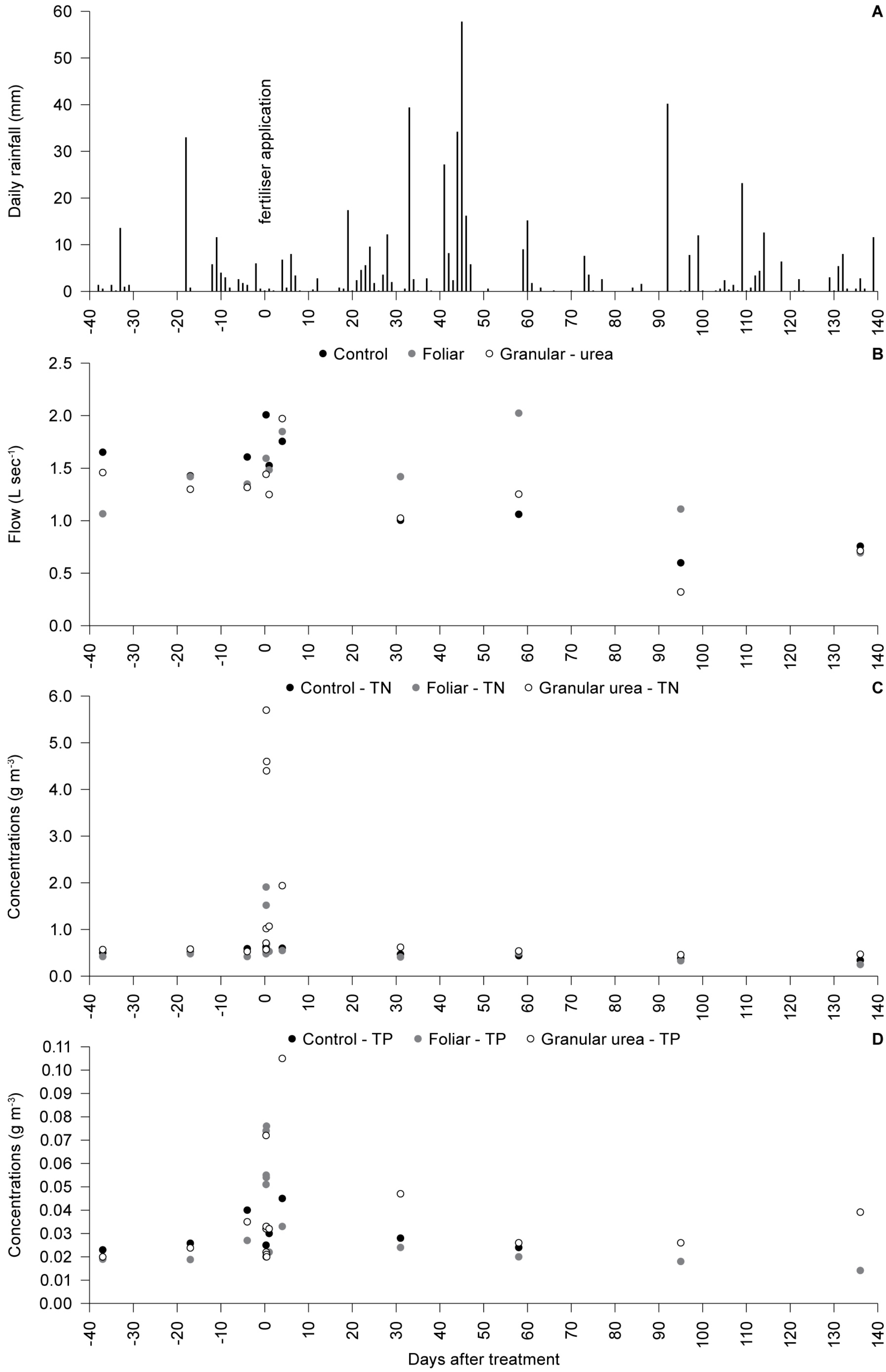

FIGURE 5: Berwick site: (a) daily rainfall; (b) flow; (c) total nitrogen concentrations in the three treatment catchments; (d) total phosphorus concentrations in the three treatment catchments.

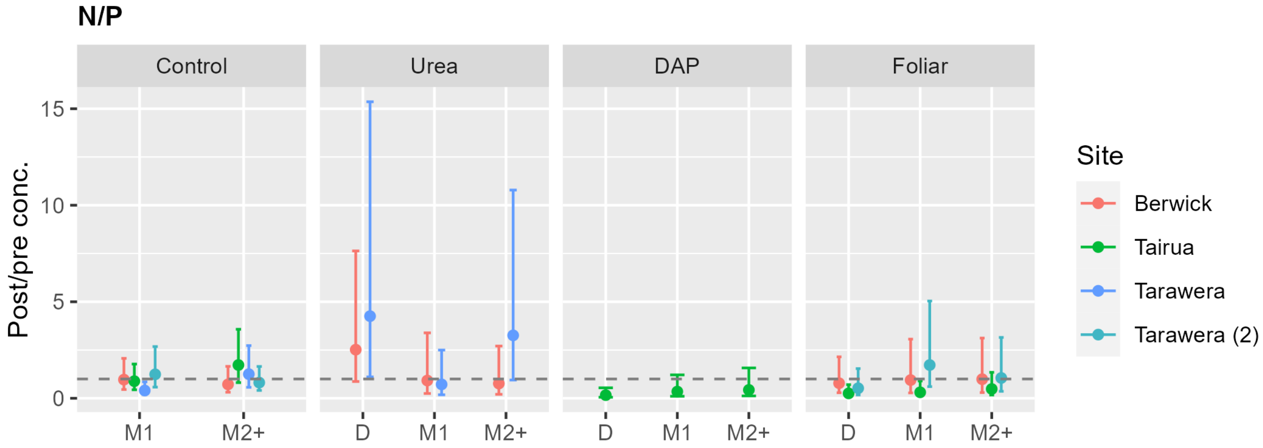

FIGURE 6. Post- to pre-treatment concentration ratios for N:P ratios, on the day of fertiliser application (D), within the first month of treatment (M1), and two months onward (M2+), for the control and fertiliser treatments at each of the three study sites. Points represent estimated posterior medians and error bars represent 95% credible intervals.

when stream flow resumed after a period of intermittent or no flows, generated nitrate-N concentrations similar to that on the day of urea application. This is an example of how other background factors can influence nutrient concentration variation in stream water.

Peak TN concentrations in the urea treatments at the Tarawera and Berwick sites were considerably lower than in a historic mid-rotation urea fertiliser trial (trees 17-19 years of age) in the central North Island of New Zealand (estimated TN 9-10 g m^{-3}, 2-3 DAT; maximum 16.0 g m^{-3} in a 19 mm rainfall event 7 DAT) (Leonard 1977). While the urea application rate in Leonards (1977) trial was slightly higher (500 kg urea ha^{-1} (230 kg N ha^{-1})), the most likely reason for the higher stream water concentrations was the deliberate (experimental) lack of riparian buffers along the stream edge. Similarly, in a further series of fertiliser application trials across New Zealand (Neary et al. 1978) where either super-phosphate or urea were applied with no stream buffers, peak concentrations of both nitrogen and phosphorus were (with the occasional exception) higher than those measured in our trial. The more precise fertiliser aerial application techniques currently used in New Zealand, lower application rates (particularly for liquid foliar fertiliser), and the retention of experimental buffer widths probably all contributed to the lower nitrogen and phosphorus concentrations detected in stream water, compared with the earlier New Zealand studies.

The findings from this study are similar to those reported in forest fertiliser trials in the overseas literature. Peak nitrogen and phosphorus concentrations were usually associated with the day of fertiliser application, particularly where no streamside buffers were retained, and during rainfall events shortly thereafter, with a subsequent decline to background concentrations within several months (Binkley et al. 1999; Anderson 2002; Hopmans & Bren 2007; Beltran et al. 2010; Shah & Nisbet 2019). In an example in older-aged stands (Beltran et al. 2010), urea was applied to 8-year-old and 31-year-old *Pinus taeda* L. stands in North Carolina USA (118kg ha^{-1} and 175 kg ha^{-1}, respectively), with a 15 m buffer retained along the drains. The high concentrations of N and P in stream water were attributed to three storm events occurring within 49 days of fertiliser application. These events flushed the majority of fertiliser from the site before uptake into the forest system and concentrations returned to pre-application levels within three months. The authors also measured seasonal increases in nitrogen exported from the control site, attributed to natural leaching processes that occurred during these storm events. This example highlights the value of having control sites as part of the fertiliser trial design to assist in determining whether other environmental factors are influencing the variation in nutrients concentrations in stream water.

Nitrogen and phosphorus in stream water

Following fertiliser application in forests, the three main forms of N measured in stream water include nitrate-N, TKN (organic-N and ammonium) and ammoniacal-N (Bisson et al. 1992). In this study, the first two forms of N dominated TN composition at all three sites. Bisson et al. (1992) observed that elevated TKN concentrations following fertiliser application typically lasted a few days. While elevated TKN concentrations were measured at Tarawera and Berwick in the urea catchments following fertiliser application (data not shown), the high contribution of TKN to TN composition across all sites indicated that organic-N was a natural component of these forested streams. In Berwick, organic matter from the wetlands may have contributed to these results. Nitrate-N concentrations in forested streams are typically below 1 g m^{-3} (Binkley et al. 1999). Nitrate-N concentrations were below this threshold at all sites in this trial, except for one measurement in the Tarawera urea treatment catchment.

Background TN concentrations were higher in Tarawera and Berwick compared with Tairua. Possible explanations for these results could be historical nutrient legacies from previous land-use, particularly agriculture. All sites in this trial had been recently thinned and tree thinning operations may also contribute nitrogen to waterways as biomass decomposes. In a North Island study, thinning operations in first rotation stands increased both nitrate-N and total nitrogen in stream water (Hughes & Quinn 2019). The authors suggested that reduced nitrogen uptake by the remaining trees elevated nutrient outputs, exacerbated by the existing high background rates from past agriculture land-use. Further research is needed to confirm thinning influences and assess whether these changes in water quality characteristics are affecting freshwater biological communities. These results also highlight the value of routine water quality monitoring to identify background nutrient concentrations in streams when considering fertiliser applications in planted forests.

Similar to nitrogen, phosphorus is naturally present in stream water, and it is the DRP component of phosphorus that is readily available for uptake by aquatic plants. Few studies have assessed the effects of fertiliser applications in forests on in-stream phosphorus concentrations. These studies have reported a several-fold increase in peak phosphorus concentrations following fertiliser application (Binkley et al. 1999). The magnitude of peak phosphorus concentrations was much lower in this study, likely influenced by the riparian 'no spray' buffers and in the case of the liquid foliar fertiliser, much lower application rates.

Elevated concentrations of both nitrogen and phosphorus, and changes in TN:TP ratios, have the potential to increase the risk the risk of excessive plant growth in a stream system and the type of algal blooms that may occur. For example, New Zealand's stream usually have low concentrations of phosphorus so a small increase in phosphorus in proportion to the existing nitrogen concentrations may be sufficient to trigger an algal bloom. However, other factors such as sunlight, water temperatures, flow regimes, suitable substrate, and soil nutrient losses, also influence algal production in streams (Biggs 2000; McDowell et al. 2009; Liu et al. 2023). In this study, given the short-term influence of fertiliser treatments on nitrogen and phosphorus concentrations and TN:TP ratios, along with the high levels of shade associated with most mid-rotation stands, the risk to in-stream primary production is likely to be low. Also, the median nitrate-N, Ammoniacal-N and DRP concentrations (Table 4) were below the threshold considered detrimental to river ecosystem health in New Zealand (Ministry for the Environment 2020) (excluding the high background DRP concentrations in the Tairua liquid foliar fertiliser catchment). However, this is indicative only given the small dataset.

Of all the different components of nitrogen and phosphorus, it is the nitrate-N component of TN that poses the greatest risk to human health if concentrations exceed guidelines (Land Air Water Aotearoa 2023). The nitrate-N concentrations in this study were well below New Zealand's drinking water standards (Water Services (Drinking Water Standards for New Zealand) Regulations 2022).

However, further research is needed on the effects of fertiliser application on freshwater biological communities other than algal and plant growth. While the review by Binkley et al. (1999) found no evidence of fertiliser applications in forests impacting on stream communities, the authors noted the need for more detailed studies in this area.

Buffer strips

Leaving un-treated buffers along stream margins is an effective management practice in reducing risk of fertiliser contamination to aquatic environment (Bisson et al. 1992; Binkley et al. 1999; Anderson 2002). In a mid-rotation *P. radiata* catchment in south-eastern Australia, the retention of a minimum 30-m buffer was effective in minimising increases in N and P concentrations in stream water following aerial treatment with a phosphate and nitrogen fertiliser (Hopmans & Bren 2007). The 10- and 20-m buffer widths tested in our trials were effective in mitigating the risks to water quality associated with liquid foliar fertiliser and granular DAP treatments, particularly on the day of application, but were less effective for the granular urea treatment. In steep catchments with dense drainage systems, maintaining effective buffer widths during aerial applications of chemicals can be logistically challenging. Flight lines often run perpendicular rather than parallel to stream channels so there is some forward spray drift even when buffer widths are maintained, and headwater channels are frequently obscured by vegetation making it difficult to determine whether they are flowing or not (Baillie et al. 2017; Baillie et al. 2015).

Future development

Liquid foliar fertilisers are a relatively new product for New Zealand's planted forests. If proven effective in improving forest productivity, they could provide a cost-effective alternative to other more traditional fertiliser products, and as these trials demonstrate they pose a low environmental risk to water quality in streams.

Should mid-rotation fertiliser application prove to be a viable forest management option to increase productivity, the information in this trial provides an initial start-point for the development of operational guidelines that minimise impacts on water quality. However, it is necessary to undertake further research on application methods and different buffer widths to assist in the development of these guidelines. Mid-rotation fertiliser applications are applied at a greater height than fertiliser applications to newly established trees, hence best management practices used to apply fertiliser to young trees may not be appropriate for mid-rotation fertiliser applications, particularly when the risk of direct entry into water ways may be higher.

International studies on the effects of mid-rotation fertiliser applications on water quality are limited. Risks to waterways from mid-rotation aerial fertiliser applications will vary with climate, soil type, geology, hydrology, historical land use and fertiliser type and quantity. This highlights the need to repeat this research across a range of national and international sites, or to develop a mechanistic understanding that will allow research findings to be generalised over varying sites, application methods and fertiliser types.

On-going development and availability of in-situ sensors that provide continuous monitoring of TN and TP and their key components, would provide more robust data on the effects of fertiliser on water quality than the spot sampling undertaken in this study, particularly during high rainfall events that induce drainage and flush nutrients from the system. Rigorous study design involving continuous data collection and the use of controls would also improve the ability to separate background nutrient concentration variation from the effects of fertiliser treatments. Accompanying ecological studies to assess impacts of mid-rotation fertiliser treatments on biological communities would provide a more robust assessment of the sustainability of this practice.

Conclusions

These initial experimental mid-rotation fertiliser trials, including the new liquid foliar fertiliser treatment, showed effects on water quality from short term (nitrogen) to longer term (phosphorus). Should the use of mid-rotation fertiliser applications gain traction as a standard management practice in New Zealand's planted forests, this information would provide additional supporting evidence on their environmental performance regarding stream water quality and assist in the development of mid-rotation fertiliser management guidelines. However further research on this topic is needed to cover a wider range of freshwater environmental indicators and forest site conditions, test recent advances in application methods and to take advantage of more sophisticated water quality monitoring technologies to better differentiate treatment effects from natural background variation and further reduce the environmental impact of these practices.

Competing interests

The author(s) declare that they have no competing interests.

Authors' contributions

BB was the primary author. BB and GC created the trial design and methodology. BB and others (see Acknowledgements) collected the data. JE undertook the statistical analyses. BB lead the writing with contributions from GC and JE. All authors have read and agreed to the published version of the manuscript.

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