Exploring the influence of soil and climatic factors on the growth response of radiata pine to nitrogenous fertiliser

Authors:
Simeon Smaill and Graham Coker

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EXECUTIVE SUMMARY

The application of nitrogenous fertiliser has the capacity to improve the productivity and sustainability of the New Zealand radiata pine estate. However, uncertainty regarding the extent of productivity gains has reduced confidence in the cost-effectiveness of investment in nitrogen fertilisers. Foliage sampling and analysis can reduce this level of uncertainty, but to date this has not proven sufficiently reliable due to the influence of other contributing factors (e.g. other nutrient limitations) to support large scale nitrogen application programmes.

The establishment of significantly increased productivity targets for the forestry sector has placed a renewed focus on identifying opportunities to increase forest growth. Although numerous factors are involved in attaining this target, it is apparent that the sector will need an improved capability to understand fertiliser response and to improve the precision of nitrogen applications. To support this effort the Forest Growers Levy Trust has provided funding to the Growing Confidence in Forestry's Future (GCFF) research programme to further investigate and improve predictions of nitrogenous fertiliser growth response in radiata pine.

This project, conducted under Research Aim 1.2 "Enhancing productivity of older stands" of the GCFF programme, examined data collected from a paired-plot study tracking the response of radiata pine to the addition of 200 kg ha^{-1} of nitrogen across ten diverse sites. The radiata pine stands were between 7 and 9 years old when treated, and measured for five years post-treatment. Various foliar, soil and climatic metrics were also collected, then analysed to determine the best predictors of growth response. This research identified a number of new results, including substantial changes in the relative predictive power of the various metrics with elapsed time since nitrogen application. When considering only nutritional predictors of growth response, initial total soil nitrogen was the best predictor, explaining 51% of the difference in the presence of fertiliser application. However, the episodic nature of the growth responses indicated climate may be a factor, and a second series of analyses were performed with climatic data in combination with nutritional data. This determined that initial soil Bray phosphorous and mean monthly rainfall over the full measured period were the best predictors of the relative response to nitrogen fertiliser use, explaining 78% of the observed growth differences. It is likely that the effects of weed competition and stocking rates accounted for the remaining variation. However, the relatively limited number of fertiliser response measurements available to this study and the post-hoc nature of the nutritional data collected require these findings to be treated with circumspection until further evidence is gathered, despite the relatively conclusive nature of the results to date.

Despite the limitations on this post-hoc study, it is apparent that soil sampling and improved knowledge of soil properties will have a significant role in improving the precision of nitrogenous fertiliser use, and efforts to increase forest productivity. It is therefore suggested that further work should be conducted, using the results of this study as a starting point. If the results presented here are found to hold true in a trial specifically designed to test the contribution of soil and climatic factors, this will enable relevant soil and climate data to be incorporated with foliage sampling as a comprehensive platform that systematically increases confidence in the predicted growth response to nitrogenous fertiliser application at any given site.

INTRODUCTION

The New Zealand Forest Owners Association has set a goal of becoming this country's leading export industry and a top five global supplier of wood fibre by 2025 (NZFOA, 2016). To stimulate the additional forest growth required to meet this target, and to replace the nutrients lost in the harvest of forests, it is readily apparent that the sector will need to undertake a programme of significant manipulation of site nutrition, with a particular focus on nitrogen (Payn et al, 1998). Much research has been conducted to understand the impact of nitrogenous fertiliser applications on nitrogen pools and uptake in radiata pine forests, and the consequences for growth (e.g. Davis et al., 2015; Mead et al., 1984; West, 1998; Will, 1985). However, this research has produced various conflicting results, leaving many issues and uncertainties about the likely growth response to nitrogenous fertiliser use at a given site that are yet to be satisfactorily resolved. Furthermore, increasing fertiliser costs are driving a need for greater levels of confidence in the predicted growth response to nitrogen fertiliser to justify the investment in these products.

The collection and analysis of foliage samples has been the dominant protocol to assess radiata pine nutrition and the likely growth response to fertiliser for several decade. Scion has supported this practice through a monitoring system maintained with industry partners, providing recommendations to correct potential deficiencies (Payn et al., 2013). However, relying solely on foliar material does not fully account for the longer term interaction with climatic fluctuations that determines the ability of soil to supply nutrients (Payn & Clinton, 2005), as it only captures information about nutrient availability at a certain point in time. The potential for confounding factors (e.g. the availability of other nutrients) to reduce the accuracy of foliage-based fertiliser response predictions has led to a renewed interest in assessing soil properties directly as indicators of potential fertiliser response (Smethurst, 2010).

This report describes the results of a study that determined and compared the relative accuracy of foliar, soil and climatic parameters as predictors of the growth response of ten stands of radiata pine located around New Zealand. While it is known that nitrogen fertiliser application can impact on wood density (Beets et al., 2001), assessments of wood properties were considered outside of scope for this project and were not investigated.

METHODS

Study sites

Ten trial sites spanning a 10º latitude range and a 650 m elevation range were included in the study (Table 1). The trial sites were from a group of Long Term Site Productivity trial sites initially established to identify soil indicators influencing forest productivity (Watt et al., 2005, 2008), at a subset of which an additional plot was established to receive a single application of nitrogen in the form of urea at a rate of 200 kg nitrogen ha^{-1} (Davis et al., 2014). The treated plots were established in nearby locations that matched the original plot in terms of initial soil properties, slope and aspects closely as possible to reduce confounding effects. Full descriptions of the original sites and their general properties are provided in Watt et al., 2005; 2008).

Table 1: Site locations

Site	Latitude (decimal degrees)	Longitude (deceimal degrees)	Altitude (m)
Mahurangi	36.345	174.610	160
Riverhead	36.674	174.555	90
Woodhill	36.777	174.424	55
Kaingaroa	38.268	176.667	450
Waimarino	39.450	175.116	559
Karioi	39.470	175.557	690
Hochstetter	42.544	171.651	291
Eyrewell	43.430	172.297	150
Longwood	46.163	167.950	368
Catlins	46.420	169.457	256

Data collection

Growth data were collected immediately prior to the application of nitrogenous fertiliser from both the existing and the new plot that was designated to receive the fertiliser. Following application, growth data were collected approximately annually for the first three years, then after five years. To assess the relative impact on growth, the sum of the volume increment over the different measurement windows was calculated, and the effect of the application of nitrogen on volume increments was determined by subtraction. This approach was favoured as it accounted for any variations in stocking between the treated and untreated plots that developed over time.

To enable relevant comparisons between sites, the nitrogen induced difference in volume increment was divided by the number of days elapsed, as this differed considerably between some sites for particular measurement windows. This data is presented in Table 2.

Table 2: Growth data

Site	Measurement Window	Days Elapsed	Δ Volume Increment [1] (m^3)	Δ Daily Volume Increment [1] (m^3)
Mahurangi	1	358	5.33	0.015
	2	762	-1.81	-0.002
	3	1089	0.45	0.000
	4	1898	-8.32	-0.004
Riverhead	1	357	1.56	0.004
	2	760	6.75	0.009
	3	1088	10.21	0.009
	4	1939	-2.59	-0.001
Woodhill	1	245	6.83	0.028
	2	649	25.39	0.039
	3	976	39.48	0.040
	4	1828	91.28	0.050
Kaingaroa	1	322	19.41	0.060
	2	687	45.98	0.067
	3	1171	77.53	0.066
	4	1953	124.23	0.064
Waimarino	1	344	5.61	0.016
	2	707	16.16	0.023
	3	1186	-11.48	-0.010
	4	1952	-10.92	-0.006
Karioi	1	318	-4.17	-0.013
	2	708	-18.60	-0.026
	3	1176	-37.26	-0.032
	4	1953	-54.54	-0.028
Hochstetter	1	366	5.25	0.014
	2	730	16.07	0.022
	3	1100	27.90	0.025
	4	1884	44.09	0.023
Eyrewell	1	400	0.32	0.001
	2	741	3.40	0.005
	3	1164	7.81	0.007
	4	1868	18.46	0.010
Longwood	1	355	-6.13	-0.017
	2	732	-15.61	-0.021
	3	1139	-26.04	-0.023
	4	1821	-80.81	-0.044
Catlins	1	354	13.91	0.039
	2	732	36.70	0.050
	3	1140	53.37	0.047
	4	1821	105.47	0.058

[1] Indicates the relative effect of nitrogenous fertiliser on volume increment; positive values indicate increased volume increments following fertiliser application, negative values (highlighted in red) indicate decreased volume increments following fertiliser application.

While this growth data is limited to ten data points per measurement window (one per site), the numerical spread of the growth response (Fig. 1) in any given window was relatively large. This suggested that an analysis using a regression based approach would be an appropriate technique to assess the relative importance of forest and environmental factors to fertiliser response. The identification of several negative responses to nitrogenous fertiliser application indicated that volume increments had apparently been reduced by fertiliser application, which is not commonly found, although the overall variability in response agreed relatively well with past research (Davis et al., 2015). It is considered likely that the negative impact of nitrogen application may have be related to a stimulation of weed growth that increased competition for other resources, negatively impacting on the growth of the radiata pine.

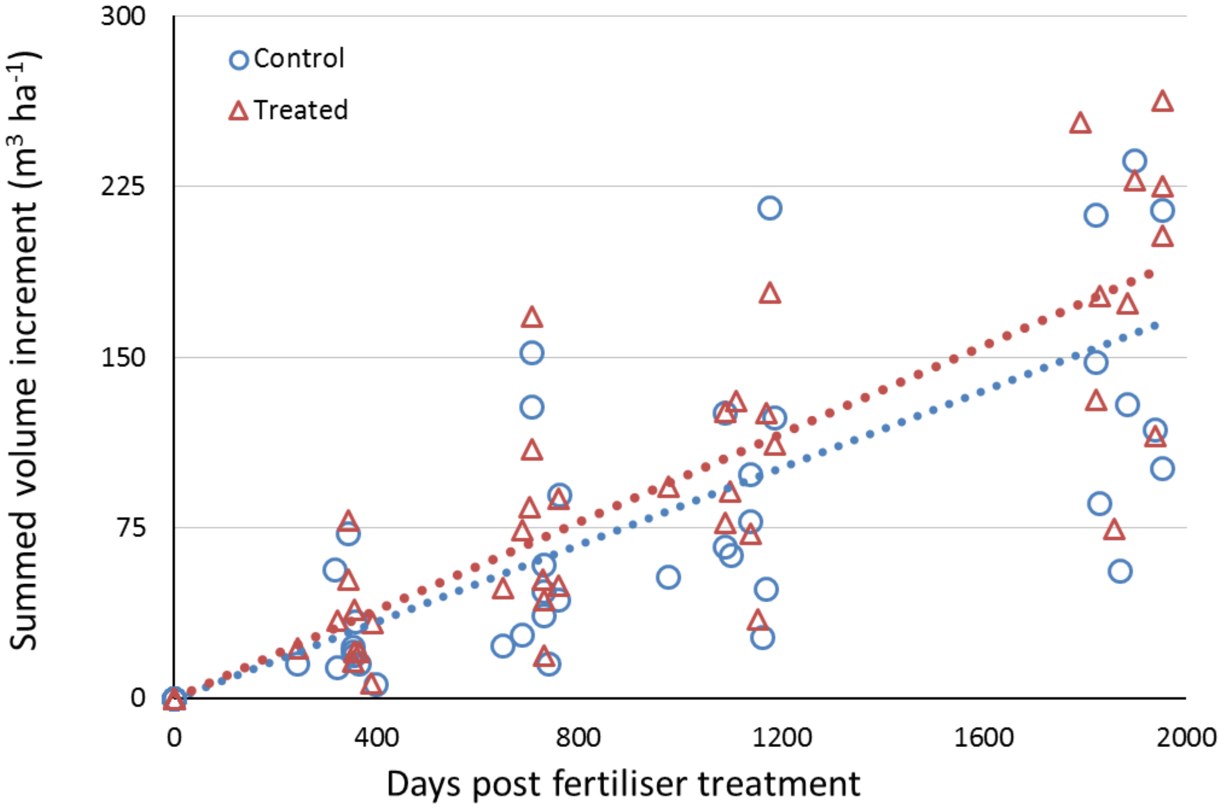

Figure 1: The effect of nitrogenous fertiliser application on summed volume increment through time. Significant overlap between the treated and control plots is evident, but the overall trend indicates a separation in the relative trajectories of the control (blue dotted line) and treated (red dotted line) plots.

Foliar and soil data were collected from the plots that did not receive fertiliser at the end of this five year period; this data as acted as a proxy for the nutritional status of the plot that was to receive fertiliser before the nitrogen was applied. Soil sampling was conducted to 100 mm following the paired-plot methodology described in Davis et al. (2004). Foliage sampling was conducted using established sampling protocols ensuring needles of comparative age and condition were collected from all sites. All nutrient analysis was conducted using standardised analytical techniques (Veritec Laboratories, Scion). Comparisons of recent trends in climatic factors and long term climatic data previously acquired for the sites indicated historic average values properties would not be not suitable, so updated relevant climate data was obtained from the NIWA virtual weather station network. This data was compiled on a daily basis for the five year period for all ten sites. The list of parameters captured for the analysis of the growth data is presented in Table 3. Rainfall and evapotranspiration data was summed to monthly figures that were then used to provide mean values; temperature data was averaged first by month, then across the measured timeframe.

Table 3: Site and forest property data

Foliar	Soil	Climatic
Al (%)	pH	Mean monthly rainfall (mm)
B (%)	Total C (%)	Mean monthly maximum temperature (^oC)
C (%)	Total N (%)	Mean monthly minimum temperature (^oC)
Ca (%)	C : N	Mean monthly Penman potential evapotranspiration (mm)
Cu (%)	Olsen P (%)	
Fe (%)	Bray P (%)	
K (%)	Total P (%)	
Mg (%)	Soluble P (%)	
Mn (%)	Organic P (%)	
N (%)	Ca (%)	
Na (%)	Mg (%)	
P (%)	K (%)	
S (%)	Na (%)	
Zn (%)	Sum of Bases (meq 100 g^{-1})	
N : P (ratio)	Cation Exchange Capacity (meq 100 g^{-1})	
C : N (ratio)	Base Saturation (%)	
K : Mg (ratio)	Bulk Density (g cm^{-3})	

Single and multiple regression models were then used to determine the site and forest property data that acted as the best predictors of the change in the daily volume increment value. This was performed with the R statistical package, using Pearson's product moment correlation coefficient. Given the low number of response points, model construction was highly parsimonious to avoid over parameterisation, and a full error checking protocol was used to identify any potential bias or undue points of leverage in the regressions.

RESULTS

Examination of volume increment response

Across all sites the use of fertiliser numerically increased the daily volume increment in every measurement window, but in no case was the extent of the increment statistically significant. In fact, as time progressed, the variations in fertiliser response between sites increased, and the effect became further from statistical significance (Table 4). This agrees well with results from previous growth analysis at some of these sites, using a slightly different metric to assess the significance of nitrogenous fertiliser response after 19 months (Davis et al. 2012).

Table 4: Analysis (Student's t-test) of the volume increment response to nitrogen application

Measurement Window	Mean Δ Daily Volume Increment [1] (m^3)	P-value
1	0.015	0.08
2	0.017	0.11
3	0.013	0.23
4	0.012	0.32

[1] Mean effect of nitrogenous fertiliser on volume increment across all sites

Regression analysis was then conducted to determine if any sites factors where significantly correlated to the observed variations, and why the variability of the response to fertiliser use was increasing over time.

Correlations between volume increment response and site factors

Initial analysis

The initial exploration of the data focussed solely on the correlations between volume increment response and nutritional properties of the foliage and soil samples. Single regressions were conducted initially due to the limitations imposed on model construction by the small number of responses. Following the selection of a number of likely predictors, multiple regressions were used to examine the improvements derived from different combinations of predictors. The explanatory power associated with a relevant selection of these regressions is presented in Table 5.

Table 5: Variation in volume increment response to explained by soil and foliage properties

Predictor	Measurement Window			
	1	2	3	4
Soil Total N (%)	31%	34%	43% ✶	51% ✶
Soil C : N ratio	9%	5%	2%	9%
Soil Bray P (%)	24%	27%	39%	44% ✶
Soil Total P (%)	0%	1%	3%	0%
Soil Cation Exchange Capacity (meq 100 g^{-1})	30%	30%	39%	48% ✶
Foliar N (%)	3%	0%	1%	1%
Foliar C: N ratio	8%	21%	37%	33%
Foliar P (%)	8%	5%	6%	3%

✶ indicates a significant correlation at $\alpha = 0.05$

The most effective single nutrient based predictor of fertiliser response over the measured time period was total soil nitrogen concentration, but this only became a relatively effective predictor of volume increment response after several years had elapsed. This was also the case for soil Bray phosphorus and soil cation exchange capacity (Table 5). Properties of the foliage where not found to be significantly related to fertiliser response over any time period. All attempts to generate an adequate multiple regression model that combined one or more nutrient based predictors were unsuccessful, as none were more accurate than total soil nitrogen alone.

Inclusion of climatic data

Further examination of the data as plotted in Fig.1 raised a new issue. Given that fertiliser response at most sites were staggered through time (i.e. evident in window one, absent in window 2, evident again in window 3, etc.), it was considered that climatic conditions may be acting as a gatekeeper that influences the manifestation of volume increment changes in response to fertiliser addition. This was explored by introducing climatic data into the regressions. A critical element of this work was establishing appropriate timeframes linking climatic data with growth data due to the need to include a lag factor. This aspect was aided by the use of existing modules developed previously to assess the impacts of nitrogen addition on biomass and nutrient allocation in native beech forests (Smaill et al., 2011).

A range of single regressions were then run with the climatic data, but no significant correlations were evident. Inclusion of the climatic factors with soil factors as multiple regression produced very different results, however, producing models with substantially greater explanatory power than achieved previously. This new analysis indicated that the combination of soil Bray phosphorus and mean monthly rainfall over the measured period were most closely correlated with volume increment response to nitrogen application. The extent of the explanatory power increased over time (Fig. 2), and appears to have stabilised at just under 80%.

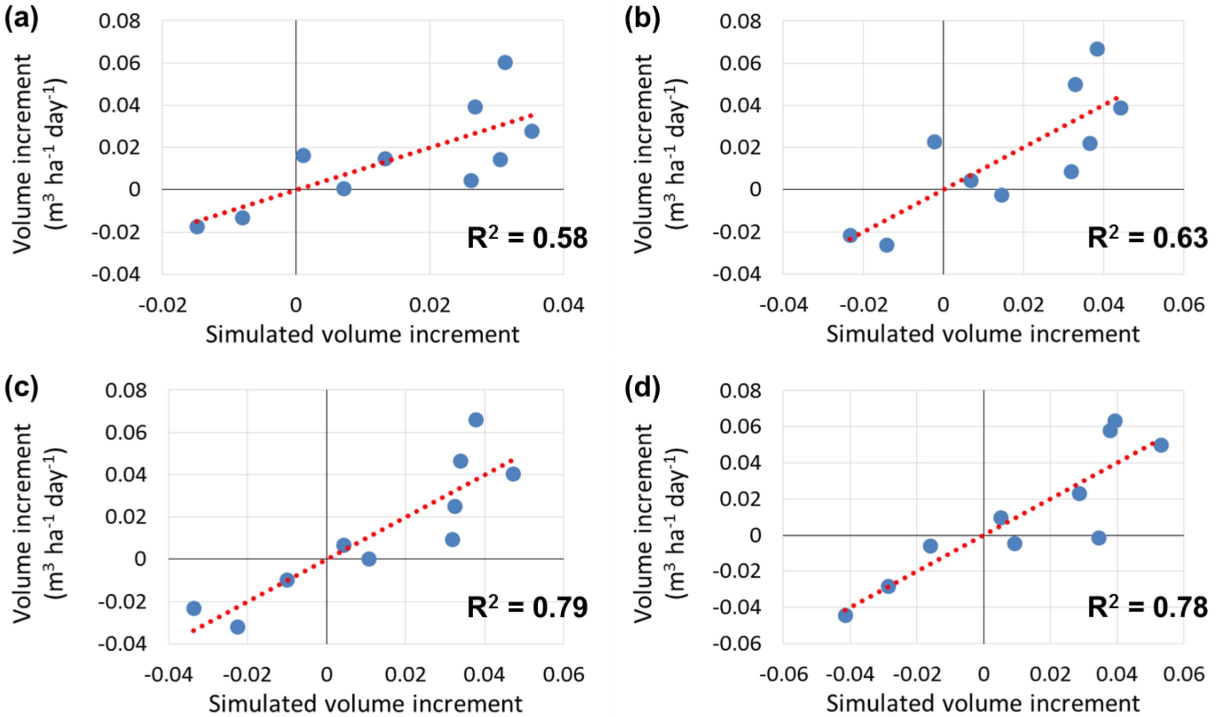

Figure 2: Changes in the degree of variation in volume increment following fertiliser use explained by soil Bray phosphorus and mean monthly rainfall. Measurement windows 1 – 4 are represented in plots (a) – (d), respectively. A 1:1 reference line is included (red dotted line) in all plots.

Comparisons of the individual degree of explanatory power associated with each predictor clearly identified a strong synergistic effect between the two predictors (Table 6). It was also noted that this was the only combination of predictors significantly correlated with observed volume increments over all measurement windows. In comparison, an adequate multiple regression model containing total soil nitrogen (still the best sole predictor of volume increment response to nitrogen addition) and any climatic parameters was not able to be generated.

Table 6: Variation in volume increment response as explained by soil Bray phosphorus and mean annual rainfall for each measurement window

Predictor	**Measurement Window**			
	1	**2**	**3**	**4**
Soil Bray P (%)	24%	27%	39%	44% ✶
Mean Annual Monthly Rainfall (mm)	11%	11%	10%	7%
Combined model	58% ✶	63% ✶	79% ✶✶	78% ✶✶

✶ indicates a significant correlation at $\alpha = 0.05$; ✶✶ indicates a significant correlation at $\alpha = 0.01$

Further exploration of the model determined there was no interactions between the components of the model, allowing a simple linear surface to represent the projected relative importance of soil Bray P and mean monthly rainfall to volume increments (Fig. 3). This exploration of the data indicates that at low Bray P values, high rainfall is required to produce post-fertiliser gains in volume increment, whereas at high Bray P values even relatively low rainfall values are sufficient to induce additional growth, although this is clearly optimised by higher rainfall values.

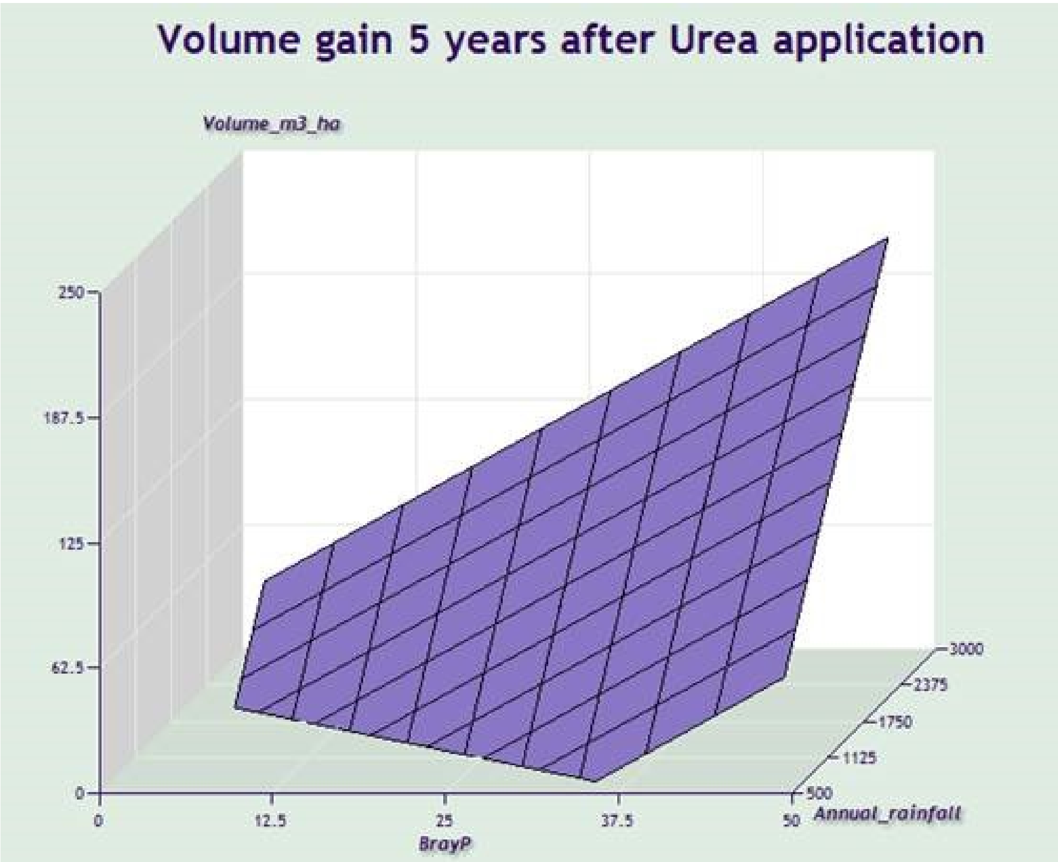

Figure 3: Surface illustrating the relationship between soil Bray phosphorus, rainfall and volume gains five years after the application of 200 kg nitrogen ha^{-1}.

CONCLUSION

The identification of rainfall and soil Bray phosphorous as key drivers of nitrogenous fertiliser response is important, as it provides new avenues to increase the precision of fertiliser use. This outcome is reasonable, as the application of theories around resource co-limitation to this case suggests that if phosphorous and water are not limiting, then any increase in nitrogen availability will produce a gain in growth that is proportional to the extent of the balance of limitations between all resources, regardless of the initial soil nitrogen status. This explains why total soil nitrogen was an important predictor at an individual level, but was no longer important when the next two most critical factors where combined. Various studies of shifts and balances in nutrient limitations have been performed across the primary sectors, and have found similar effects at broader levels (e.g. Harpole et al., 2011; Bracken et al., 2015).

As well as this support, the limitations to this research must also be acknowledged. The trials from which the data was collected were not designed to support this work, and as a consequence only one data point is provided per site per measurement window, eliminating any opportunity to assess within site variability. Secondly, and perhaps most crucially, the foliar and nutritional data used here was not collected from the sites prior to the application of fertiliser – it was obtained from the paired plots that did not have fertiliser added, but five years after the application had taken place. Therefore, there is some degree of uncertainty to these findings based on the potential for natural changes in soil and foliar nutrient stocks over time. That said, past research does indicate that the stock changes are likely to be small if they occur at all, and in all likelihood these results could be used to guide improved fertiliser response. However, it is questionable if they provide any meaningful increase in the confidence around the fertiliser use predictions at this stage.

Another caveat to this work is that the effects of competition for resources by weed and understory plant species across the sites were not considered, nor was the influence of restrictions on the space available to each tree for growth, which is driven by stocking rates. It is likely that these factors could explain some of the uncertainty left unresolved by the optimum fertiliser response model identified here.

Despite these limitations, this research has indicated the additional predictive power that can be derived from the use of soil and climatic data as predictors of fertiliser response. Further research using trials designed specifically for this purpose are strongly encouraged, using the parameters identified here as starting points for hypothesis formation and experimental manipulations to determine the extent to which phosphorous ability and rainfall determine the extent to which nitrogen promotes volume production, and how changes to phosphorus availability can enable a greater response to added nitrogen.

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