

# Nutrient limitation of algal biomass in the Waikato River

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*Prepared for the Technical Leaders Group of the  
Waikato – Waipa Healthy Rivers Wai Ora Project*

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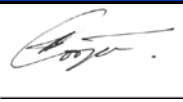


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## Executive summary

This study, commissioned by the Technical Leaders Group (TLG) of the Healthy Rivers/Wai Ora project, aims to improve understanding of the relationships between algal biomass and nutrients in the Waikato River, by an in-depth analysis of the water quality data collected monthly by Waikato Regional Council (WRC) at 10 sites along the river's length. The main goal of such an analysis was to reveal useful insights of what potentially limits phytoplankton growth in the Waikato River. The results will inform the structure of the scenario model that seeks to determine the extent of nutrient load reduction required to meet phytoplankton targets (as measured by chlorophyll *a*) determined by the Collaborative Stakeholder Group taking into account the needs of both the National Policy Statement for Freshwater Management and the Vision and Strategy for the awa.

There was no evidence that algal biomass in the Waikato River is currently limited by the flushing rate in the hydro-dams. Algal biomass appears to be able to adapt to increasing nutrient concentrations along the length of the river with ratios of chlorophyll *a* : nutrients similar to that observed in lakes. Instead of being limited by the flushing rate, average algal biomass in the Waikato River is nutrient limited. High algal biomass resulted in the drawdown of dissolved inorganic nutrients.

There is abundant evidence that algal biomass in the Waikato River is primarily limited by phosphorus (P), and not by nitrogen (N), as shown by regressions of chlorophyll *a* against total nitrogen (TN) and total phosphorus (TP) (section 3.1), the long term trends showing TP and chlorophyll *a* to have decreased while TN increased ( section 3.4), frequency distributions of low values of dissolved inorganic nitrogen (DIN) (section 3.6), the ratios of DIN/algal N and dissolved inorganic P (DRP)/algal P (section 3.9), and the proportions of DIN/TN and DRP/TP (section 3.9). In addition, the proportion of TP that is algal P was greater than the proportion of TN that is algal N at all stations (section 3.9), in agreement with greater limitation by P.

Reduced P concentrations in the Waikato River in the past two decades appear to have been responsible for the trend of reducing average algal biomass in the river. The decrease in algal biomass was achieved without reducing N. Potentially N limiting conditions are more likely to occur in summer, when dissolved nitrogen concentrations were lower on average and algal biomass higher, than in winter. However, during summer the slopes of the relationships between algal biomass and TN were negative at most stations (as they were for annual means or medians as well), suggesting decreasing algal biomass as TN increased, while the slopes were positive for the relationships between algal biomass and TP. The findings suggest that P reduction is of primary importance to further reduce annual average algal biomass, including during summer.

Irrespective of the method used (means, medians, maxima, different periods), in all cases the regressions of chlorophyll *a* against TP had positive slopes for each site plotted separately, and the regressions of chlorophyll *a* against TN at individual sites were generally negative. The explanation for the unexpected negative relationships between TN and chlorophyll *a* and positive relationships for TP over the past 25 years, is that chlorophyll and TP concentrations decreased at almost all sites along the river and TN concentrations increased at almost all sites. As a result, TN:TP increased, at all sites. In spite of strong covariation between TN and TP *across* sites, the TN data are less useful for predicting chlorophyll *a* and not useful when considered by site separately. This indicates that annual average chlorophyll *a* in the Waikato River is controlled by the amount of P.

Frequency distributions of low DIN values suggest that N limitation becomes less likely in the downstream direction. The increase in the DIN:DRP ratio at all sites except at Taupo Gates since 1990, as a result of increasing DIN and decreasing DRP, could be viewed as evidence that P limitation may have increased in importance. However, the slopes of regressions of chlorophyll *a* against TN were negative at most stations in 1990-1995, while the slopes of regressions against TP were positive, as they were in any other period in the examined data since 1990. This indicates that annual average chlorophyll *a* in the Waikato River was controlled by the amount of P throughout the examined period (1990 to 2014). DIN may have become more available as the demand for DIN has decreased as a result of decreased algal biomass because of lower availability of P.

## 1 Introduction

The Waikato and Waipa Healthy Rivers/Wai Ora Plan Change project is currently using a collaborative stakeholder group (CSG) process to implement the National Policy Statement for Freshwater Management and be consistent with the Vision and Strategy for the awa. This process is supported by a Technical Leaders Group (TLG). This study, commissioned by the TLG, aims to improve understanding of the relationships between the key attributes of algal biomass and nutrient concentrations in the Waikato River, by detailed analysis of the water quality data collected monthly by Waikato Regional Council (WRC) at 10 river sites. The main goal of this analysis was to reveal useful insights into what limits phytoplankton growth in the Waikato River. This report presents a record of the data analysis supplemented by commentaries on the key implications. The key findings form part of the synopsis report of a range of studies and expert input that the TLG has provided to the Collaborative Stakeholder Group.

## 2 Methods and data limitations

Data were obtained from the Waikato Regional Council, courtesy of Mr Bill Vant who freely contributed his knowledge of the dataset and its limitations.

Data were examined for the period January 1990 to December 2014. Data collected before 1990 were less reliable. Whakamaru chlorophyll *a* data were not useful after approximately the year 2000 because, after a change in the sampling location, chlorophyll *a* data became much more variable and higher on average than it was before the change in sample location. This was probably the result of high amounts of filamentous algal matter and other organic material, other than phytoplankton, being included in the water samples. Data at Huntly are affected by being just below the confluence with the Waipa River which carries high loads of sediment and nutrients but as a result is low in chlorophyll *a*. Therefore, chlorophyll *a* at Huntly appears relatively diluted. For these reasons, Whakamaru and Huntly data were not included in certain parts of the data analysis (where this was the case this is indicated in the figures).

Dissolved reactive phosphorus (DRP) is less reliable before 2006. Near the end of 2005 a step change occurred in recorded DRP concentrations as a result of a change in analytical procedures. This particularly affected sites where DRP was low. Therefore, for data analysis involving DRP or comparisons with DRP data before 2006 must be regarded with caution. Lastly, it has been estimated that about 27% of the chlorophyll *a* recorded at Mercer is derived from Waikare and Whangape, two lakes that have outflows entering the Waikato River below Huntly. The percentage of chlorophyll *a* (and nutrients as well presumably) in the lower Waikato River derived from these two lakes was probably much less in the 1990's because the lakes were much less eutrophic then.

Total nitrogen (TN) data were not measured but calculated from  $\text{NO}_3 + \text{NO}_2$  (indicated as NNN in the data file and in a number of the figures in this report) + total Kjeldahl nitrogen (TKN). This method produced nearly 30% more TN data than the sum of  $\text{NO}_3 + \text{TKN}$  (which was therefore not used; in addition  $\text{NO}_2$  ought to be included in TN, although its concentration is typically negligible). Dissolved inorganic nitrogen (DIN) was calculated as the sum of NNN and  $\text{NH}_4$ . Because NNN was mostly  $\text{NO}_3$  (about 97%, Table 1) NNN is indicated as  $\text{NO}_3$  in the remainder of this report. A number of issues with total phosphorus (TP) data in the provided data set were corrected before the analysis. Previously uncorrected TP data were adjusted for this report for the effect of arsenic on the analysis of TP, following methods given by Bill Vant. All nutrient ratios given in this report are weight ratios, not molar ratios.

Particulate organic carbon (PC or POC) was calculated as the difference of total organic carbon (TOC) and dissolved organic carbon (DOC) as  $\text{PC} = \text{TOC} - \text{DOC}$ .

In the data set of 2006-2014, 100% of chlorophyll *a* data of Taupo Gates, 100% of chlorophyll *a* data of Ohaaki and 37% of chlorophyll *a* data of Ohakuri were below the detection limit of  $0.003 \text{ mg L}^{-1}$ . In the data analysis half the value of the detection limit was used when chlorophyll *a* data were below detection. However, in sites with a large proportion of below detection data the analysis of relationships between chlorophyll *a* and nutrient concentrations will be less reliable and clearly impossible at sites where no above detection data are available. Therefore, in certain parts of the report Taupo Gates and Ohaaki data were not included in the analysis (where this was the case this is indicated in the figures).

After removing 20 stations with too few chlorophyll *a* or nutrient data, 10 stations remained. These were, in order from upstream to downstream: Taupo Control Gates, Ohaaki Bridge, Ohakuri Tailrace, Waipapa Tailrace, Whakamaru Tailrace, The Narrows, Horotiu Bridge, Huntly-Tainui Bridge, Mercer Bridge, Tuakau Bridge. Data from the Narrows Boat Ramp and Narrows Bridge were combined as one sampling station (a changeover between the two stations occurred in 2005 with several months overlap). A summary of the data, including the total number of data available are given in Table 1.

Table 1. Summary of available data. Statistics are for 1990-2014, and counts are included for 2006-2014 ( $\text{mg L}^{-1}$ ).

Variable	count	count	min	max	mean	median
	1990-2014	2006-2014				
CHLA	2987	1493	0.0001	0.1480	0.0091	0.0054
DOC	2274	1314	0.1500	19.0000	1.5011	1.2600
DRP	2958	1461	0.0015	0.0590	0.0144	0.0130
NH4-N	2941	1448	0.0050	0.2100	0.0171	0.0100
NNN	2930	1435	0.0010	2.2600	0.1923	0.1230
NO3-N	2487	1429	0.0010	1.7000	0.1864	0.1180
Temp	3051	1552	9.0000	25.3000	16.1466	16.0000
TOC	2273	1315	0.2500	15.8000	2.1234	1.7000
TP	3039	1542	0.0008	0.4800	0.0369	0.0310
TN	2894	1415	0.0260	2.6100	0.3972	0.3310
DIN	2928	1435	0.0060	2.2900	0.2091	0.1400
Black Disk	1960	1096	0.1100	9.0100	1.9807	1.6000

For the analysis of the relationships between concentrations of chlorophyll *a* and nutrients either annual data (i.e., all data of a given period) were processed or growing season data (October - March), and either means or medians were calculated, and in addition, maxima for chlorophyll *a*. The overall maximum chlorophyll *a* concentration of each station was calculated as the mean of the annual maxima for each year.

Systat was used to determine multiple regression statistics.

## 3 Results and Discussion

### 3.1 Relationships between chlorophyll *a* and TN and TP

In regressions of chlorophyll *a* against TP or TN (Appendix A), using annual means, annual medians, annual maxima (the latter only for chlorophyll *a*), growing season means or growing season medians, Whakamaru and Huntly-Tainui plot away from the regression line for reasons explained in section 2. Whakamaru plots consistently above the regression line (high chlorophyll *a* relative to the nutrient concentrations) and Huntly consistently below the line (low chlorophyll *a* relative to the nutrient concentrations). For the data of all other stations, the regressions of chlorophyll *a* against TP by year and station resulted in  $R^2$ 's around 0.8 and by station only ( $n = 8$ ) typically in high  $R^2$ 's of about 0.97 – 0.98. Plots of chlorophyll *a* against TN resulted in almost all examined cases (different time periods, differences in processing the variables; Figs. A1-A35) in lower  $R^2$ 's than the regressions against TP, in particular for data by year and station. The proportion of the variability in chlorophyll *a* explained by TN was less than that explained by TP. Nevertheless, the agreement with chlorophyll *a* was fairly similar for TP and TN. The similarity in the proportion of the variability in chlorophyll *a* explained by TN and by TP is mostly a result of the high covariation between TP and TN (Appendix L).

The figures of chlorophyll *a* against nutrients by year and by station, with regressions separate by station (Figs. A2, AS4, A6, A8, A10, A12, A15, A18, A22, A24, A26, A28, A30, A30, A34 and A 36) show generally positive slopes for regressions of chlorophyll *a* against TP, as expected, and much more variable and often negative slopes for chlorophyll *a* vs TN. In the most relevant graphs, for annual medians of 1990-2014 (Figs. A26 and A28), and annual maxima of 1990-2014 (Figs. A30 and A32; annual medians and annual maxima [the latter only for chlorophyll *a*] are the required metrics of the NOF Attribute States) *all* regressions against TP had positive slopes while *all* regressions against TN were negative. The same was the case for annual means of 1990-2014 (Figs. A22 and A24). The explanation for the positive regressions of chlorophyll *a* against TP and the negative regressions against TN is that TP and chlorophyll *a* concentrations have both decreased in the Waikato River while TN increased since 1990 (Appendix D). Also the summary plots (Fig. A19a) show that in recent years TP and chlorophyll *a* have decreased relative to the 1990's and slopes have decreased as well, while TN did not decrease (Fig. A20a).

While the TN concentrations increased at individual stations, they did not increase sufficiently to upset the positive regressions between chlorophyll *a* and TN across stations (for instance, Fig A27; compare with Fig. A28), because the differences between the stations in nutrient and chlorophyll *a* concentrations are larger than the changes in concentrations within stations.

Plots with regressions for each individual station of chlorophyll *a* against nutrients are shown for growing season means of four different periods. The recent data of 2006-2014, the full period with data deemed reliable (1990-2014), 1990-1999 to include and compare Whakamaru chlorophyll *a* data in the period before it became erratic, and 1990-1995 because in those years dissolved nitrogen showed a more consistent seasonal pattern than in later years (Bill Vant, WRC, pers. comm.) and to examine the possibility that nitrogen more frequently limited chlorophyll *a* in those years than it does now. In each of these four cases the patterns are similar as the results described above, with mostly positive slopes against TP and negative slopes against TN, even in the earliest period of 1990-1995. In 1990-1999 the only regression slope for chlorophyll *a* against TP that was not positive was for Whakamaru, for which only 5 years of data were available (since 1995) and which was not included in the regressions beyond 1999.

Much larger slopes were evident for regressions of growing season data compared with annual data. The slopes for regressions of chlorophyll *a* against TP were about 40% higher and the slopes of regressions against TN were about 70% higher for growing season data. This is explained by the annual data including winter time data. During the winter months algae in the Waikato River do not respond to nutrients, and in addition, nutrient concentrations are higher (Appendix C).

The graphs and regressions in Appendix A supply an argument in favour of using TP as the predictor of chlorophyll *a* in the Waikato River while the TN data are not useful for predicting chlorophyll *a*. Evidence from the data indicates that annual average algal biomass in the Waikato River is controlled by the amount of available P. When chlorophyll *a* and TP both decrease while TN does not, the most parsimonious explanation for the decrease in chlorophyll *a* is the decrease in TP, unless convincing contrary evidence is available. There is no such evidence. There is no good case for the idea that simultaneous, and therefore correlating decreases in TP and chlorophyll *a* might not be the result of a causal relationship but might be accidental, for instance as a result of a simultaneous change in grazing pressure. The idea that a change in grazing intensity, perhaps as a result of a change in zooplankton species community by invading zooplankters, would explain the changes in chlorophyll *a* also would have to assume that these grazing changes occurred in the same way at all stations between years. However, no marked ecosystem or food web community changes occurred in the Waikato River system during 2006-2014 to my knowledge. Moreover, the known invasive zooplankters were well established in the Waikato River system before or by the early 2000's (Duggan et al. 2006). In particular, the invading zooplankton species *Daphnia galeata*, a ferocious grazer compared with native zooplankton species, could in theory be responsible for a decrease in chlorophyll *a*. However, *D. galeata* was already observed in 1997-1998 in Lake Maraetai (Duggan et al. 2006, which misidentified *D. galeata* as *Daphnia dentifera*), was present in many Waikato peat lakes in 1997-1998 (Duggan et al. 2006), was observed in Taupo in January 2000 when zooplankton sampling first began in that lake (Verburg unpublished data), and therefore was likely present elsewhere in the Waikato River apart from Lake Maraetai from at least the mid 1990's. Therefore, their establishment is not recent. Results elsewhere in New Zealand show that the effect of invasive *Daphnia*'s on chlorophyll *a* and water clarity is greatest in the first 1 or 2 years (unpublished data). Nevertheless, the more recent period of 2006-2014 shows the same positive relationship between chlorophyll *a* and TP, as both decreased, and the negative relationship with TN, as does the longer period described above (Figs. A2, A4, A34, A36). Therefore, the decrease in chlorophyll *a* is not likely a result of invasive zooplankton species.

The inter-annual variability of either TP or TN may enhance the correlation with chlorophyll *a*. The relative standard deviation (standard deviation divided by the mean) was larger for TP compared with TN, at all stations in 2006-2014 (Fig. A37; this figure shows inter-annual variability and not inter-sample or inter-seasonal variability). This might contribute to the stronger correlation found between TP and chlorophyll *a* compared with the correlation between TN and chlorophyll *a*. However, in 1990-2014 the relative standard deviation was larger for TN than for TP at four of the stations (Fig. A37). Moreover, the overall relative standard deviation was similar for TP (0.61) and TN (0.56) in 2006-2014, and for TP (0.61) and TN (0.59) in 1990-2014. Therefore, the range and variability of either TP or TN did not affect which variable correlated better with chlorophyll *a*.

The more detailed figures (Appendix A) that include data by year and station (as opposed to overall station means or medians) make clear that chlorophyll *a* data of Ohaaki and Taupo Gates are not very useful to infer relationships with nutrient concentrations because their chlorophyll *a* concentrations were typically below the detection limits of the method used for the analysis (3 mg m<sup>-3</sup>).

<sup>3</sup>). Removing Taupo Gates and Ohaaki from the analysis would be practical because levels of TP were not sufficient to find chlorophyll *a* concentrations above detection limits until Ohakuri. However, as the summary Figures A19b and A20b show, after removing these stations the slopes and the R<sup>2</sup>'s were similar.

While the regressions of chlorophyll *a* against nutrients were strong across stations, it is clear from the figures that within stations the proportion of the variation in chlorophyll *a* explained by nutrient concentrations was low.

### 3.2 Station comparisons

There was a steady increase in TN and TP along the river, except that after Mercer both plateaued (Appendix B). Chlorophyll *a* increased along the river as well, except the obvious bump at Whakamaru because of the doubtful values since 2000. Chlorophyll *a* still increased after Mercer, in contrast to nutrient concentrations. The TN:TP ratios dropped after the Taupo Gates and then remained steady at about 10 apart from a minor bump at the Narrows.

Comparisons between stations along the river from up to downstream (Appendix B), show that DRP increases until Huntly and then drops off. NH<sub>4</sub> increases until Horotiu and then drops off to values similar to Taupo Gates. NO<sub>3</sub> increases until Huntly and then drops off. DIN increases until Huntly and then drops off. The PC : Chlorophyll *a* ratio decreases after Ohaaki and then remains similar at about 60. DIN:TP reaches its maximum between the Narrows and Huntly. DIN:DRP increases steadily all the way with a minor drop at Horotiu. Temperature plateaus after Ohaaki and increases again after Huntly. Spatial variation in temperature probably mostly depends on hydrodynamics and depth of the measuring site. DOC, TOC and PC (= POC) increase all the way downstream starting after Ohaaki. Black Disk decreases all the way downstream.

### 3.3 Seasonality

Figures in Appendix C show the seasonality in variables of interest. Those on average highest in summer are: temperature, chlorophyll *a* and Black Disk (upstream stations only). Those highest in winter are: TN, DOC (downstream stations), TOC (at a number of the stations), DRP, NO<sub>3</sub>, DIN, Black Disk (reservoirs), TN:TP ratio, DIN:DRP ratio, DIN:TP ratio, PC:chlorophyll *a* ratio (downstream stations). The TN:TP ratio becomes gradually more seasonal downstream, from non-seasonal at Taupo Gates to pronounced seasonality at Mercer and Tuakau. Those variables that appear without seasonality are: TP, NH<sub>4</sub>, DOC (upstream stations), TOC (remaining stations), PC, Black Disk (downstream stations), PC:chlorophyll *a* ratio (upstream stations). None of the various forms of nutrients peaked in summer when chlorophyll *a* peaks.

### 3.4 Long-term trends

Over the past 25 years, chlorophyll *a* and TP have decreased at almost all stations and TN has increased almost everywhere (Appendix D). As a result, TN:TP increased, at all stations. DRP decreased in most places, especially below Hamilton. NH<sub>4</sub> decreased everywhere along the river, NO<sub>3</sub> increased everywhere except at the Taupo Gates, temperatures increased, DIN increased somewhat at most places (but strong decline at Taupo Gates), Black disk showed both small increasing and declining trends, DOC showed recent increases, there were no clear trends in TOC, an increase in PC was followed by decrease with a similar pattern across stations, and there were no clear trends in the PC:chlorophyll *a* ratio. The DIN:TP and DIN:DRP ratios increased at all stations except Taupo Gates and the DIN:DRP ratio increased everywhere as well except at Taupo Gates.



### 3.5 Upstream nutrients versus downstream chlorophyll *a*, and flushing effects on chlorophyll *a*

If understood correctly, an argument of the reviewers of previous WRC and Dairy NZ studies of Waikato River nutrient limitation, against interpreting chlorophyll *a* versus nutrient relationships using data collected at the same site, was that chlorophyll *a* derives from algae that grew upstream and that recorded algal biomass therefore is not causally linked to nutrients recorded at the same station as chlorophyll *a*. It may be counter argued that, naturally, the locally measured chlorophyll *a* comes from upstream but so does the locally measured TP. Upstream nutrients flow downstream just like algal cells. The algae have been grown from TP assimilated upstream, both move downstream, and the relationships between TP and chlorophyll *a* in the Waikato River are therefore as valid as they are in lakes. There is no need for the suggested complex data manipulations to take into account river travel time by linking local chlorophyll *a* to TP measured upstream. Nevertheless, a correlation of upstream nutrients with downstream chlorophyll *a* was performed. Appendix E shows plots of chlorophyll *a* for each station against nutrient concentrations of the next upstream station. The data are medians for 1990-2014. When correlating downstream chlorophyll *a* with upstream nutrients the data set is reduced because there is no upstream station above Taupo Gates. That means Tuakau nutrients and Taupo Gates chlorophyll *a* cannot be used in this type of analysis. The correlations were similar (Appendix E) as they were for the correlations of chlorophyll *a* and nutrients of the same station (Appendix A). The results (illustrated in Appendix E) do not prove or disprove anything and are not helpful. The main difference is in the intercepts which become more positive, in other words more different from zero, compared with the analysis results in Appendix A. That does not seem realistic, as one would expect zero chlorophyll *a* when nutrients concentrations are zero. However, that particular disadvantage disappears if log-log scales are used and the data fitted with a power curve (as is often done with nutrient-chlorophyll *a* relationships in the literature) instead of a linear regression (Fig. E5).

As a variant of the suggestion examined above, it may be argued that algal biomass in the Waikato River is likely to be “flushing limited” instead of nutrient limited (Bill Vant, WRC. pers. comm.). This scenario would suggest that algae would not have sufficient time to adjust their biomass to the inputs of nutrients along the length of the river. In this scenario the chlorophyll *a* : nutrient ratio and the slopes of the regressions of chlorophyll *a* against nutrient concentrations would be lower than in lakes. Therefore, regressions of mean and medians of chlorophyll *a* against nutrient concentrations were compared between the Waikato River stations (excluding Whakamaru and Huntly) and lakes that were monitored by Regional Councils in 2005-2009 (Verburg et al. 2010). A selection of lakes was made such that the range in nutrients in the lakes was the same as for the stations in the Waikato River (including one lake higher and one lake lower in either nutrient). While the regression coefficients (i.e., the slopes) for the Waikato River stations were smaller against TP (Fig. E6, Table 2), it is clear that the variance of the chlorophyll *a*: TP ratio in lakes is large and the 95% confidence limits of the slope for lakes and the slope for the Waikato River overlapped. When the chlorophyll *a* and TP data were log transformed (Fig. E6), as is typically done (OECD 1982), the overlap between the 95% confidence limits (CL) of the slopes was greater (lakes: slope 1.21, 95% CL 0.99 - 1.43; Waikato River: slope 1.05, 95% CL 0.75 - 1.36). The 95% confidence limits of the slopes of medians for chlorophyll *a* against TP overlapped as well (Table 2; Fig. E6). Two high chlorophyll *a* values for lakes were outside the range shown in the figures. These outliers were included in the analysis. Although the differences in slopes between lakes and the Waikato River were not significant, the two outliers had a relatively strong effect on the slopes. Without the two outliers the slope was 0.27 for

lake chlorophyll *a* against TP using means, and 0.29 using medians. These slopes were much closer to those in the Waikato River.

The slope of the regression of chlorophyll *a* against TN (Fig. E7) was greater for the Waikato River than for lakes, in contrast to the regressions against TP (both for means and medians). While not significantly different (Table 3), the higher slope against TN for the Waikato River is strong evidence to reject the theory that algal biomass in the river is primarily flushing limited rather than nutrient limited. The chlorophyll *a* : TN ratios were on average about 40% larger in the Waikato River than in lakes, while the chlorophyll *a* : TP ratios were about 25% lower in the Waikato River. However, the differences between the River and lakes in chlorophyll *a* : nutrient ratios were not significant.

Table 2. Comparisons of slopes of regressions of chlorophyll *a* against nutrients, between the Waikato River stations (without Whakamaru and Huntly) and lakes. The lower and upper 95% confidence limits of the slopes are given. The chlorophyll *a* (CHLA) : nutrient ratios are given as well, for lakes and for the Waikato River, for TN and TP, and for means and medians. The *p* value is given for a *t*-test (assuming equal variances) comparing the chlorophyll *a* : nutrient ratios between the Waikato River and lakes.

	Lakes			Waikato River					<i>p</i>
	slope	lower 95%	upper 95%	CHLA: nutrient	slope	lower 95%	upper 95%	CHLA: nutrient	
CHLA vs TP means	0.40	0.24	0.56	0.32	0.26	0.22	0.29	0.24	0.47
CHLA vs TP medians	0.44	0.28	0.60	0.31	0.26	0.22	0.29	0.22	0.48
CHLA vs TN means	0.015	0.007	0.023	0.015	0.026	0.022	0.029	0.021	0.18
CHLA vs TN medians	0.018	0.007	0.030	0.014	0.025	0.022	0.028	0.020	0.34

The residence times of the seven Waikato River hydro lakes range from 1 to 8 days (Brown 2005). The weighted average flushing time in the seven lakes was 0.2 d<sup>-1</sup> (calculated from data in Brown 2005), amounting to an average retention time of about 5 days. Schallenberg and Burns (1997) observed that phytoplankton biomass and productivity were only depressed at the shortest observed hydraulic residence times (< 3 days). This is less than the average in the Waikato lakes, perhaps explaining why there was no evidence for a difference between the river and lakes in the chlorophyll *a* : nutrient relationship. Thompson (1992) concluded that rapid flushing did not necessarily reduce planktonic biomass and that short term retention time was not useful for the prediction and management of planktonic biomass in seven impoundments on the St. Lawrence and Ottawa Rivers. Thompson (1992) found a higher slope of chlorophyll *a* against TP in 62 reservoirs, compared with 55 lakes (although the difference was not significant, as in our results).

Pridmore and McBride (1984) “assumed that impoundments of short hydraulic retention time rarely achieve their phytoplankton carrying capacity” and developed a theoretical model that predicted chlorophyll *a* concentrations in reservoirs based on measurements of phytoplankton concentrations in the inflows, the maximum specific growth rate of phytoplankton, and the growing season mean TP concentration.

Pridmore and McBride (1984) argued that in rapidly flushed impoundments and rivers, flushing disallows use of the chlorophyll *a*-nutrient relationship established in lakes with long retention times (OECD 1982) if phytoplankton are removed from the system before the standing crop reaches the level determined by the concentration of the limiting nutrient. In other words, chlorophyll *a* build-up may be limited not by nutrients but by flushing (Pridmore and McBride 1984).

However, the relationships that, as Pridmore and McBride (1984) write, "...are not generally applicable to impoundments of short (< 2 weeks) hydraulic retention time (..... OECD, 1982)" were those that are used to predict nutrient and chlorophyll concentrations "from a combination of geomorphological, hydraulic and nutrient loading data". That does not apply here because in this report nutrient and chlorophyll *a* concentrations are not predicted from those variables. Chlorophyll *a* concentrations are predicted directly from concentrations that were measured, not predicted. These relationships are therefore real.

The argument that our capability of predicting chlorophyll in the Waikato River, using a single model across all stations is compromised by algal biomass limitation by rapid flushing (Pridmore and McBride 1984) can be addressed as follows: (1) The argument of flushing limitation of algal biomass is irrelevant in our case because we determined our own relationships under potentially flushing limited conditions instead of using those from literature in lakes with long residence times. In other words, it does not matter whether or not chlorophyll *a* is flushing limited. (2) If there is a flushing effect, then there does not seem to be a difference in this effect between stations. As indicated by the high  $R^2$  of about 0.98, all stations are virtually on a straight line (note that the fit is much better than the  $R^2$  of about 0.8 used in lake eutrophication management and derived from slower flushed lakes: OECD 1982). The high correlation allows reliable prediction of chlorophyll *a*. A potential flushing effect would not appear to affect the ability to predict chlorophyll *a* from P concentrations. Moreover, chlorophyll *a* : TP and chlorophyll *a* : TN ratios (Figs. I2, I5-I6) were similar between stations (if Whakamaru, Huntly, Taupo Gates and Ohaaki are excluded, for reasons given in the method section). Therefore, it is appropriate to use across station regressions instead of within station regressions. (3) There does not actually seem to be evidence for a flushing effect on the chlorophyll *a* concentrations or on the relationship between TP and chlorophyll *a* concentrations, because the slope and chlorophyll *a* : nutrient ratios are not significantly different from those in lakes with much longer residence times.

It appears reasonable to expect that algae can grow especially efficiently in the hydro lakes during stratification in summer. In other words, algae might grow more cell biomass per unit nutrient in the hydro lakes in the river, compared with the faster flowing unaltered riverine sections of the river, and a substantial part of the chlorophyll *a* downstream of the hydro lakes might be explained by growth in these hydro lakes. However, there is no clear evidence in the data of chlorophyll *a* to nutrient ratios. The graphs in Appendix H show chlorophyll *a* : nutrient ratios by station in four periods: 1990-1995, 1990-1999, 2000-2014, 2010-2014, and both annual means and growing season means. The chlorophyll *a* : TP ratio was fairly stable between stations. In 1990-1999 the ratio was on the high side in Whakamaru, Waipapa and the Narrows (which assumedly is affected by chlorophyll *a* from Karapiro), then dropped substantially after the high sediment and low chlorophyll *a* input from the Waipa River. The river receives a lot of nutrients from the Waipa as shown by the jump in TP between Horotiu and Huntly which was the largest increase in TP between all stations (Appendix B) – Huntly representing the one site where the algae indeed have had insufficient time to respond to the upstream nutrient input and is thus an 'outlier' in chlorophyll to nutrient plots. By the time the river flow gets to Mercer the chlorophyll *a* : TP ratio is similar again to that in the hydrolakes. It is true that after 2000 that effect can in part be explained by the high chlorophyll *a* and high nutrient inputs from lakes Whangape and Waikare. But before 2000 these inputs were much lower (Bill Vant, WRC, pers. comm.). Therefore, certainly in 1990-1999 and in 1990-1995, it means that the large amount of nutrients stemming from the Waipa River have been utilized as well by the time the river flow gets to Mercer, to the same extent as the nutrients are utilized in the hydro lakes. After 2000 the chlorophyll

$\alpha$  : TN ratios at Tuakau were even above those in the hydro lakes and the Narrows. Figures I5 and I6 illustrate the variability in chlorophyll  $\alpha$  : nutrient ratios between samples.

### 3.6 Frequency distributions of potential growth limiting conditions

It would be of interest, if possible, to determine whether and when bioavailable, dissolved nutrient (DIN and DRP) concentrations drop to levels at which limitation of algal growth rates might be expected. Furthermore, it would be of interest to determine which nutrient this occurs for most frequently, at different sites along the river. A first attempt can be based on half saturation values for DIN and DRP given in the literature. Therefore, eight papers on nutrient half-saturation constants were examined (Table 3). While the literature search was certainly not exhaustive it appeared that literature on half saturation values for NO<sub>3</sub>-N were relatively numerous while those for DRP were harder to find. The various estimates of the half saturation constant for NO<sub>3</sub>-N for various algal species (Table 3) ranged across more than an order of magnitude (0.0014-0.1442 mg L<sup>-1</sup> NO<sub>3</sub>-N), mostly above the detection limit (0.002 mg L<sup>-1</sup>), while the single estimate of the half saturation constant for DRP was well below the detection limit in the data set of WRC (0.004 mg L<sup>-1</sup>).

Table 3. Half saturation constants for dissolved nutrients and TP from the literature.

Half saturation constants (mg L <sup>-1</sup> )				
	NO <sub>3</sub> -N	NH <sub>4</sub> -N	DRP	TP
Eppley et al. 1969a	0.0014-0.1442	0.0014-0.1302		
Eppley et al. 1969b	0.0028-0.021			
Auer et al. 1986			0.00091	0.0085
Falkowski 1975	0.0014-0.0196			
Toetz et al. 1973	0.0161-0.0425			
Reynolds 1992				0.0217
Halterman and Toetz 1984	0.0035-0.0972			
Eppley and Rogers 1970	0.0084			

From the various half-saturation constants given in the publications with multiple estimates (Eppley et al. 1969a, Eppley et al. 1969b, Auer et al. 1986, Falkowski 1975, Toetz et al. 1973, Reynolds 1992, Halterman and Toetz 1984) it appears that the more common values are in the range of 0.02 to 0.04 mg L<sup>-1</sup> NO<sub>3</sub>-N. I have selected an arbitrary value within this range, 0.03 mg L<sup>-1</sup> NO<sub>3</sub>-N, as the “average” half-saturation constant for NO<sub>3</sub>-N for algal assemblages in the Waikato River. Because the growth rate is half of the maximum when nutrient concentrations are at the value of the half saturation constant it was multiplied by three to give a cutoff value above which the algal growth rate was assumed unaffected by nutrient availability, while recognizing the asymptotic nature of the curve. The frequency at which NO<sub>3</sub>-N <0.09 mg L<sup>-1</sup> occurs at different stations and in different months was examined (Appendix N). This is well above the detection limit for NO<sub>3</sub>-N (0.002 mg L<sup>-1</sup>).

For DRP the lowest value observed at each station was always below detection. Because of the dearth of literature about half saturation constants of DRP for algal growth, to examine how often DRP concentrations were below where algal growth rate may be affected by nutrient availability it was assumed that the cutoff value for DRP would have the same proportion relative to that for NO<sub>3</sub>-N as the average stoichiometric ratio in algae (N:P = 7.2). The frequency at which DRP <0.012 mg L<sup>-1</sup> occurs at different stations and in different months was examined (Appendix N). NH<sub>4</sub> seems relatively unimportant compared with NO<sub>3</sub>, with generally much lower concentrations, and NH<sub>4</sub> was often below detection. NH<sub>4</sub> is therefore not considered in Appendix N.

In the most recent data (2006-2014) the frequency of  $\text{NO}_3\text{-N}$  below  $0.09 \text{ mg L}^{-1}$  decreases from about 100% of the data at Taupo Gates to nearly zero % from Waipapa onwards. However, in 1990-1995 the frequency of  $\text{NO}_3\text{-N} < 0.09 \text{ mg L}^{-1}$  decreased more linearly from Taupo gates until Huntly where it was less than 3%. The frequency of low values of DRP appears to have been more similar between the periods of 1990-1999 and 2006-2014 at all stations, except perhaps somewhat higher percentages at Mercer and Tuakau in 2006-2014. However it must be kept in mind that DRP data before 2006, in particular low concentrations that are examined here, must be regarded with caution because of analytical issues (see Methods section). The ratio of frequencies at which low values of  $\text{NO}_3\text{-N}$  and DRP occurred may have decreased since the early 1990's, with the greater decrease the further downstream (Fig. N2E). The ratio dropped in 2006-2014 from about 1 at Taupo Gates (meaning both  $\text{NO}_3\text{-N}$  and DRP were almost always, i.e., nearly 100%, below their selected cutoff values) to near zero at the Narrows, while there was no obvious drop downstream in the 1990's.

$\text{NO}_3\text{-N}$  values  $< 0.09 \text{ mg L}^{-1}$  occurred most frequently during the growing season. From these results it would appear that in recent years dissolved nitrogen does not limit algal growth most of the time from Waipapa onwards, but may at times limit algal growth up to Whakamaru, in particular during the growing season. Low values of DRP were also most frequent during the growing season but occurred during the winter time as well.

Naturally, conclusions derived from the observed frequency of occurrence of values below the selected half-saturation constant for  $\text{NO}_3\text{-N}$  must be regarded with caution. In the literature, half-saturation constants for  $\text{NO}_3\text{-N}$  range across several orders of magnitude (Table 3) and they depend on the algal species that were tested in each study and especially on their cell size. In the literature studies typically individual species were tested, not species assemblages. Species with larger cells have larger half-saturation constants. Because of a smaller surface area to volume algal species with larger cells need higher nutrient concentrations to be able to absorb sufficient amounts of nutrient to allow growth. It is not possible to say what a correct half-saturation constant for  $\text{NO}_3\text{-N}$  for the Waikato River would be because the average half-saturation constant will differ by time and by place, and will depend on the species composition and diversity in the algal assemblage. Appropriate half-saturation constants for each station in the Waikato River can only be determined by carrying out experiments with the actual species assemblage present at each station and the results would be expected to change with season and between years. Moreover, DIN and DRP are not highly reliable indicators of nutrient deficiency because, while their concentrations are known, the rates at which nutrient cycling takes place is not. Therefore, availability of dissolved nutrients may be able to keep up with the needs of algae.

Data with  $\text{TN:TP} > 17$  (indicating strong relative P limitation of algal growth) occurred in 7 to 55% of the data at each station (Appendix N), with no clear pattern from upstream to downstream.  $\text{TN:TP} < 10$  (indicating potential N limitation) occurred in 12 to 46% of the data at each station, again with no clear spatial pattern. When  $\text{TN:TP} > 17$  occurred, it occurred most frequently in winter, especially at the downstream stations (Appendix N).  $\text{TN:TP} < 10$  occurred most frequently in summer (again, when it occurred). It must be noted that data of  $\text{TN:TP}$  ratios alone are insufficient to determine nutrient deficiency.  $\text{TN:TP}$  ratios only indicate N or P deficiencies when concentrations are sufficiently low. Therefore typically other indicators are used for N or P deficiency. As mentioned, the results described above for the frequency of occurrence of values below the half-saturation constant for  $\text{NO}_3\text{-N}$  would indicate that N deficiency is rare below Whakamaru.

### 3.7 Nutrient conditions when chlorophyll *a* is high

Dissolved nutrients decrease with increasing chlorophyll *a*, as expected (Appendix I) (due to uptake into algal cells), at all stations. Algal biomass affects dissolved nutrient concentrations, not vice versa. Algae, when abundant, draw down dissolved nutrient concentrations. The plots in Appendix I use individual data, not means or medians, in order to better examine relationships between chlorophyll *a* and dissolved nutrient concentrations at their extremes, which would be masked if averages were used. Correlations with chlorophyll *a* were usually similar for DRP and DIN. Analysis of what the concentrations of various nutrients are when chlorophyll *a* is high are in Appendix M. When chlorophyll *a* was above the 95<sup>th</sup> percentile TN:TP ratios were lower than the average, at all stations, indicating sufficient TP is needed to allow chlorophyll *a* to grow to maxima. DRP as a fraction of the mean or median was typically similar to DIN when chlorophyll *a* was above the 95<sup>th</sup> percentile.

### 3.8 Nutrient and chlorophyll *a* concentrations and relationships under different TN:TP conditions

As expected, DRP usually decreases with increasing TN:TP and dissolved nitrogen increases with TN:TP (Appendix J). DRP versus TN:TP had more error around the regression (less variance explained by the regression) than DIN or NO<sub>3</sub> versus TN:TP. This can simply be explained by the fact that the values of DRP were much closer to the detection limit than the values of dissolved nitrogen, and therefore the DRP values contained a larger error.

Correlations between dissolved P and chlorophyll *a* (always negative) are stronger when TN:TP>17, compared with TN:TP<10, as expected, except at Tuakau and Waipapa (Appendix K; all individual data were used, not means or medians, in order to better examine chlorophyll *a* and dissolved nutrient concentrations at their extremes). At four out of six stations with good chlorophyll *a* data, correlations between dissolved N and chlorophyll *a* (always negative) were stronger as well when TN:TP>17, compared with TN:TP<10. Correlations between dissolved P and chlorophyll *a* were stronger than for dissolved N and chlorophyll *a* when TN:TP>17 as would be expected, except at Tuakau and Waipapa.

There was a large difference between seasons in the relationships between concentrations of chlorophyll *a* and nutrients in the Waikato River. Algal concentrations were low in winter and high in summer. That was not driven by nutrients but by temperature and perhaps light. Nutrient concentrations were higher in winter than in summer (Appendix C) but algae do not respond to nutrients during the winter time (Appendices A, C).

The correlations of DIN:DRP versus TN:TP ratios were low (appendix F). Histograms showing the frequency distribution of the DIN:DRP ratio, for three different TN:TP brackets (Appendix G) indicate that the most frequent DIN:DRP values are lower when TN:TP<10 compared with 10<TN:TP<17, as expected. However, DIN:DRP ratios were frequently low as well when TN:TP>17 (Fig. G1). As mentioned, available nutrient ratio data alone are insufficient to determine nutrient deficiency. Nutrient ratios only indicate N or P deficiencies when concentrations are sufficiently low. Moreover, DIN, DRP, and the DIN:DRP ratio are not reliable indicators of nutrient deficiency because, while concentrations are known, the rates at which nutrient cycling takes place is not. Furthermore, ratios, in particular DIN:DRP, become highly variable when either one or both of the nutrient variables become low. Naturally, when values are low the measurement error becomes proportionally more important.

### 3.9 Proportions of dissolved inorganic nutrients and particulate nutrients

The proportion of DRP in TP (Figs. P1-2) was highest at upstream stations. It decreased downstream of Horotiu. The proportion of DIN in TN (Figs. P1-2) increased downstream until Waipapa. DIN:TN remained similar downstream from Waipapa except a peak at Huntly, possibly because of the lower amount of algal biomass relative to total nutrients, and therefore a higher proportion of dissolved nutrients, following the confluence with the Waipa River. Below Ohakuri the proportion of DIN was greater than the proportion of DRP, with the difference progressively increasing downstream (Fig. O1, bottom panel). In agreement with the findings in Appendix N, N limitation becomes less likely the further downstream. DIN as a proportion of TN increased since about 2000 in the stations downstream from Ohaaki (Fig. O2).

The assumption that particulate carbon was mostly algal carbon was supported by a significant correlation ( $R^2 = 0.39$ ,  $p < 0.000000$ ) between median annual data of PC and chlorophyll *a* across stations, although agreement within stations was not good. Moreover, the median ratio of PC : chlorophyll *a* was 73, the middle of the range of 50 to 100 for algal cells with moderate N or moderate P deficiency (weight ratios; Healy and Hendzel 1979). Concentrations of nutrients contained in algal cells were estimated assuming PC = 100% algal carbon, particulate C:N = 10, particulate C:P = 75 (based on the middle of the range for where moderate deficiency of N and P, respectively, is expected; Healy and Hendzel 1979). Algal N and algal P steadily increased downstream until Mercer (Figs. P3-4), naturally reflecting the PC data (Fig. B22 shows PC by station for the 1990-2014 data).

Since 2002 there was a decrease in algal N and algal P at all stations, independently confirming the decrease in algal biomass as indicated by the decrease in chlorophyll *a* (Fig. O4). Algal N as a proportion of TN was similar from Ohakuri onwards, ranging from 10 to 15%. Algal P as a proportion of TP was similar from Ohakuri to Huntly (15-18%), increasing thereafter to 22-23%. The proportion of algal P of TP was greater than the proportion of algal N of TN at all stations, in agreement with greater limitation by P. The ratio of algal P as a proportion of TP and algal N as a proportion of TN was similar from Whakamaru to Tuakau ( $1.6 \pm 0.1$ ). Algal N as a proportion of TN and algal P as a proportion of TP were high in 1996-97 and were unreliable at the upstream stations. A minimum occurred in both variables in 1998-2000 and both decreased since 2002. Data of the two stations furthest upstream, in particular Taupo Gates, were unreliable throughout as a result of dividing by two low numbers, especially for P.

Excluding the data of the three upstream stations because of their low nutrient concentrations, the mean proportion of algal N in TN was  $11 \pm 4\%$  ( $\pm$ standard deviation) in 2006-2014, the mean proportion of algal P in TP was  $19 \pm 5\%$ , the mean proportion of algal N in organic N was  $28 \pm 8\%$ , and the mean proportion of algal P in organic P was  $32 \pm 9\%$ .

Algal N as a proportion of organic N (the latter calculated by TN – DIN) increased steadily from Whakamaru at 20% to Tuakau at 34%. Algal P as a proportion of organic P (the latter calculated by TP – DRP) was similar throughout from Ohakuri to Tuakau, ranging from 30 to 33%. Data from the two stations furthest upstream were unreliable as a result of dividing two low numbers with DRP and TP often below detection.

There was about 4 to 7 times as much nitrogen present as inorganic N compared with algal N, at all stations after Taupo Gates. There was 3 to 4 times more inorganic P compared with algal P from Ohakuri to Horotiu, decreasing thereafter until inorganic P compared with algal P were about the same at Tuakau. The amount of DIN per algal N showed a peak in 1999, and increased at all stations

in recent years. Also the amount of DRP available per algal P appeared to have increased in the most recent two years (Appendix O). The relative amount of DIN available per algal N was greater than the amount of DRP available per algal P at all stations below Ohaaki, supplying more evidence for the pervasiveness of P limitation of algal growth in the Waikato River (the values at Taupo Gates and Ohaaki were, as mentioned, less reliable than those further downstream). This is shown by the ratio of both ratios, DIN/algal N : DRP/algal P, which increased progressively downstream (Fig. O5), with only a minor decrease at Horotiu relative to the next upstream station. DIN/algal N : DRP/algal P has been increasing since 2006 (the start of reliable DRP data) at the four stations furthest downstream.

### 3.10 National Objectives Framework Numeric Attribute States and relationships between chlorophyll *a* and nutrients in the Waikato River

Boundaries of National Objective Framework (NOF) Attribute States A, B, C and D (NPS 2014) for chlorophyll *a* did not always correspond well with boundaries of the Attribute States for TN or TP, as illustrated by superimposition on the regressions of chlorophyll *a* against TP and TN (Appendix P). The Attribute State boundaries appeared more stringent for TP than for chlorophyll *a*. For instance, annual median TP at some of the stations in the Waikato River (the NOF proposed to use annual medians to demarcate water quality Attribute State boundaries) could classify water quality as Attribute State C while chlorophyll *a* would classify it as B (Fig. P1). The opposite was the case for TN. TN appeared to suggest a better water quality Attribute State than chlorophyll *a*. This was the case especially for the lower water quality Attribute States (C and D). The difference between NOF Attribute States suggested by either chlorophyll *a* or TN was greater when only growing season mean data were considered (Fig. P2), as expected because TN was lower during summer while chlorophyll *a* was higher (Appendix C). Two of the stations classified in Attribute State C according to their mean TN during the growing seasons, while mean chlorophyll *a* was in Attribute State D. None of the stations were classified as in Attribute State D according to TN in the growing season. These NOF Attribute States refer to seasonally stratified lakes. The NOF does not mention numeric Attribute States for chlorophyll *a*, TN or TP for rivers. The NOF does mention numeric Attribute States for chlorophyll *a*, TN and TP for polymictic lakes. These are the same for chlorophyll *a* and TP as for seasonally stratified lakes. However, the numeric Attribute States for TN are higher for polymictic lakes compared with seasonally stratified lakes (OECD 1982). As a result, correspondence between the boundaries of the Attribute States for TN for polymictic lakes, and the boundaries of the Attribute States for chlorophyll *a* was worse compared with the boundaries of the Attribute States for seasonally stratified lakes, with TN values suggesting a better water quality than chlorophyll *a* (Fig. P3). Half of the eight stations in the Waikato River were classified in a better water quality class ("Attribute State") when using TN in polymictic lakes as an Attribute compared to using chlorophyll *a* as an Attribute (annual medians, 2006-2014 data).

Therefore, if algal biomass were N limited, N concentrations in the Waikato River would need to be reduced to higher water quality Attribute States than chlorophyll *a*, in order to comply with the required concentration of chlorophyll *a* to fit in the desired Attribute State. However, in view of the fact that N appears to have little effect on average algal biomass in the Waikato River this is probably of little concern.



### 3.11 Predicting chlorophyll *a* from TP and TN

The across station regressions using the station overall median chlorophyll *a* vs station overall median nutrient concentrations, under all TN:TP conditions (2006-2014, without Whakamaru and Huntly-Tainui), were (Figs. A33 and A35):

$$\text{chlorophyll } a = 0.2150 \text{ TP} - 0.0006, R^2 = 0.97$$

$$\text{chlorophyll } a = 0.0191 \text{ TN} - 0.0009, R^2 = 0.97$$

and the same across all separate station years (Figs. A33 and A35):

$$\text{chlorophyll } a = 0.2060 \text{ TP} - 0.0003, R^2 = 0.83$$

$$\text{chlorophyll } a = 0.0187 \text{ TN} - 0.0007, R^2 = 0.80$$

$R^2$ 's were similar between TP and TN, which is explained by the strong co-variation between TP and TN. Little of the variance in chlorophyll *a* was explained by TP regressions by station, compared with the across station regression which had a very high  $R^2$  of 0.97, leaving only 3% of the variance in chlorophyll *a* unexplained.  $R^2$ 's of the regressions by station of chlorophyll *a* against TP concentrations (Fig. A34) ranged only from 0.11 to 0.47 (mean  $R^2 = 0.30$ ) after Waipapa.  $R^2$ 's of the regressions by station of chlorophyll *a* against TN concentrations (Fig. A34) were between 0.00 and 0.08 (mean  $R^2 = 0.04$ ). Moreover, regressions by station of chlorophyll *a* against TN concentrations had mostly negative slopes in 2006-2014, unlike against TP. Slopes against TN for the annual median or mean data of 1990-2014 (Fig. A24 and Fig. A28, respectively) were negative for all stations, demonstrating that TN is not useful in predicting chlorophyll *a* at individual sites. Moreover, regressions separate by station would only apply to the relative short ranges in the existing data of nutrients within each station and cannot be used to predict effects outside those ranges. At individual sites TN or TP have little predictive value to estimate changes in chlorophyll *a*, leaving high unexplained variability in chlorophyll *a*. The negative relationships between chlorophyll *a* and TN within stations underline the absence of a direct causative relationship. Negative relationships with TN occurred as a result of the decrease in TP and chlorophyll *a*, while TN increased, suggesting algal biomass in the Waikato River is mainly P limited. Negative relationships with TN on within station basis while not on across station basis are explained by the fact that the changes in TN within station between years were much less than the differences that exist between stations, explained by the large distances between the stations with nutrients being added along the length of the river. Chlorophyll *a* is best predicted from nutrients using across station data, in other words with data of all stations included, instead of separate for individual stations. In the management of lake eutrophication relationships are applied between chlorophyll *a* and nutrient concentrations that are derived from data across lakes, not within lakes, to predict the effects on algal biomass of changes in nutrient loads to individual systems (OECD 1982). From there the effects of a change in chlorophyll *a* on water clarity in the Waikato River are easily estimated by the equation derived by Vant 2015.

Even if algal biomass in the Waikato River would be flushing limited to some extent (Pridmore and McBride 1984) the strong correlation between chlorophyll *a* and TP was similar to that in among slow flushed lakes ( $R^2 \sim 0.8$ ; OECD 1982). The strong correlation shows that algal biomass in the Waikato River is nutrient limited and allows reliable prediction of chlorophyll *a* from concentrations of TP.

A multivariate approach can be used which allows both TP and TN to be used simultaneously as predictors of chlorophyll *a*. Such an approach could be particularly attractive here if shifts in N and P inputs were to occur in the future. While growth of an algal cell can be limited by either N or P, at a system scale it is important not to think about nutrient limitation in black and white terms. Entire algal assemblages in rivers or lakes are not limited by either N or by P. Both N limitation and P limitation of algal growth can occur all the time, everywhere, in rivers and lakes. When N becomes less available relative to P (decreasing N:P) N limitation becomes more frequent and vice versa. Therefore, one needs to think of nutrient limitation as a “sliding scale”. There is no sudden transition from P limitation to N limitation at some point suggested by a particular TN:TP ratio. The reason for this is that there are many differences between the algal cells present in a system, differences in species, cell size, life stage (ranging from just formed to becoming senescent), environmental conditions such as light availability, differences that affect their individual nutrient requirements and all of these conditions change all the time and differ between locations in a system. As a result, ratios of C:N in algal cell matter of algae that are not N limited is typically considered < 7.1, for those with moderate N deficiency C:N is between 7.1 and 12.5, and for algae with extreme N deficiency C:N > 12.5 (Healy and Hendzel 1979). Even these useful but merely indicative boundaries must be considered stricter than what occurs in reality. There is no single boundary for N limitation but a sliding scale. The same is the case for P limitation.

A multiple least squares regression of chlorophyll *a* as dependent variable against TN and TP (annual medians of each station year, 2006-2014, all ten stations, using Systat), resulted in the equation (Fig. Q1):

$$\text{Chlorophyll } a = -0.001 + 0.140 * \text{TP} + 0.006 * \text{TN} \quad \text{Eq. 1}$$

, with  $R^2 = 0.84$  (adjusted  $R^2 = 0.83$ ), standard error of the estimate:  $0.002 \text{ mg L}^{-1}$ . This standard error of the estimate is below the detection limit of chlorophyll *a* (of  $0.003 \text{ mg L}^{-1}$ ). The constant was not significantly different from zero but the coefficients for TP and TN were both significant ( $p = 0.000$  and  $p = 0.040$  respectively) in spite of the strong covariation between TN and TP ( $R^2 = 0.88$  for the linear relationship between TN and TP, Fig. L1). The standardized coefficient for TP was twice as high as for TN, illustrating the greater effect of variation in TP on chlorophyll *a* concentrations, compared with variability in TN, as can also be seen in the figure (Fig. Q1). The multiple regression, including both TP and TN as predictors, explained only about 1% more in the variance of chlorophyll *a* than the single regression against TP (Fig. A33, bottom right panel). As a result of the strong covariation between TN and TP the data do not cover most of the plane in the figure but are more or less in a straight line (Fig. Q1). However, annual medians were used for this analysis (the required metric by the NOF to determine Attribute States), while in reality a much wider range of TN:TP conditions would be expected to occur if the regression was applied to all unprocessed data. Much less of the variability in chlorophyll *a* would be explained by a regression against TP and TN on the basis of the individual data because such an analysis would include winter time data when algae do not respond to nutrients.

Three tests for normality, the K-S Test (Lilliefors) ( $p < 0.002$ ), Shapiro-Wilk Test ( $p < 0.000$ ), and the Anderson-Darling Test ( $p < 0.012$ ), showed the residual data to be consistent with a normal distribution. Log transformed variables did not result in a normal distribution. Removing Taupo Gates and Ohaaki from the data set, because their annual medians of chlorophyll *a* were always below the detection limit (half detection limits were used in the analysis) which was responsible for the peculiar linear pattern on the left hand side in the residual plot (Fig. Q2), did not improve the multiple regression. It resulted in a lower adjusted  $R^2$  (0.76) and the contribution of TN to the variation in

chlorophyll *a* was not significant ( $p = 0.051$ ). The predicted chlorophyll *a* values agreed well with the measured chlorophyll *a* (Fig. Q3).

The lower  $p$  value for the coefficient of TP in the multiple regression equation and the larger standardized coefficient for TP compared with TN suggest at least a tighter coupling between TP and algal biomass than is the case for TN, as followed from the single linear regressions (Appendix A).

## 4 Acknowledgements

I thank the Waikato Regional Council, in particular Jonathan Cowie, Ian Buchanan and Asaeli Tulagi, for supplying the data set which was analysed for this report. Bill Vant provided extensive assistance by explaining peculiarities of the data set and by providing background information on the Waikato River. Bill Vant, Sandy Elliott, John Quinn and Bryce Cooper provided helpful feedback and review comments on an earlier version of this report.

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## Appendix A Relationships between Chlorophyll a and nutrient concentrations

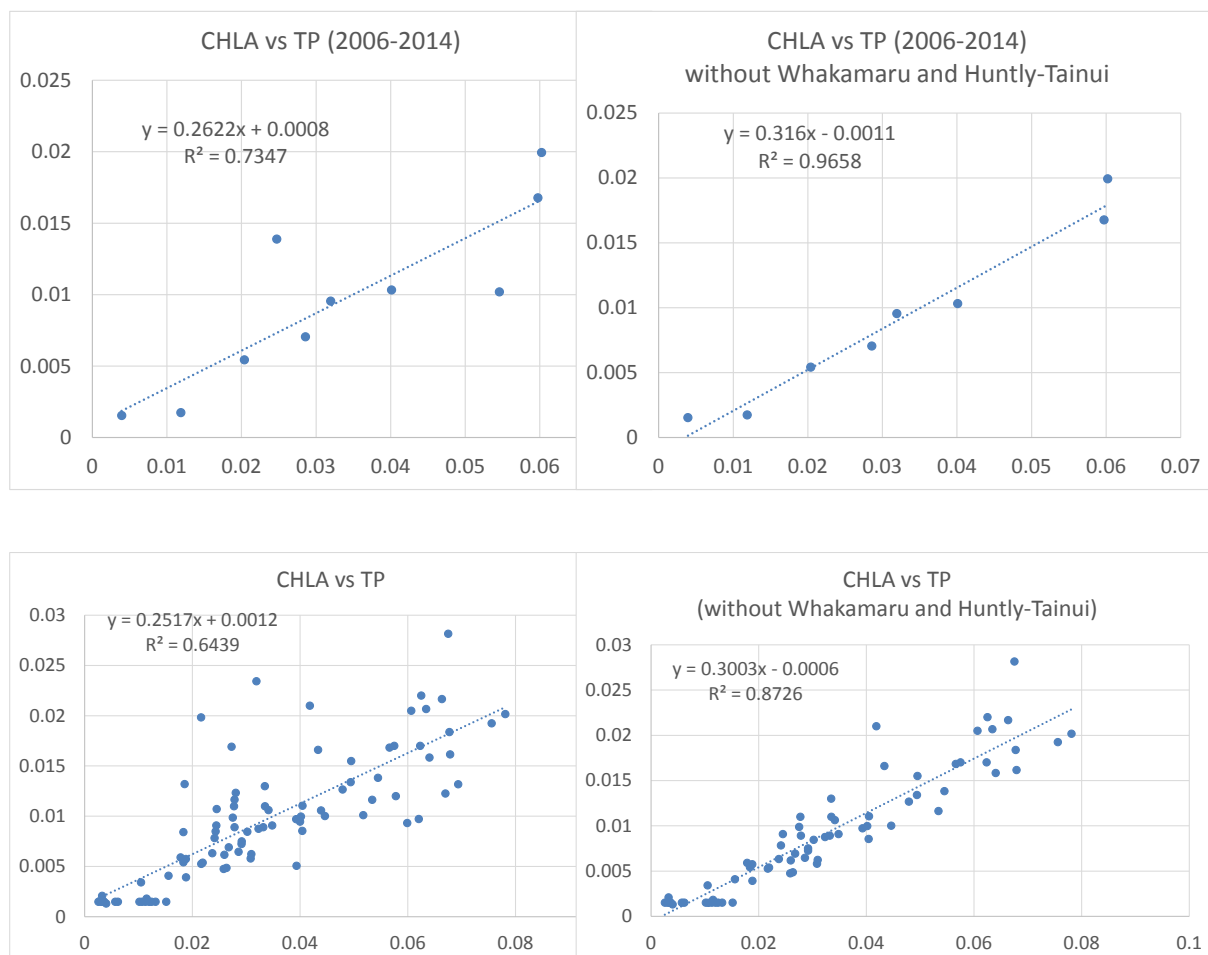


Fig. A1. Chlorophyll *a* plotted against TP. Shown are mean data, with and without Whakamaru and Huntly, of growing seasons (Oct-Mar) in 2006-2014. Top: station means. Bottom: means of each year (growing season months only) with more than 4 data points for each station. All data are in mg/L.

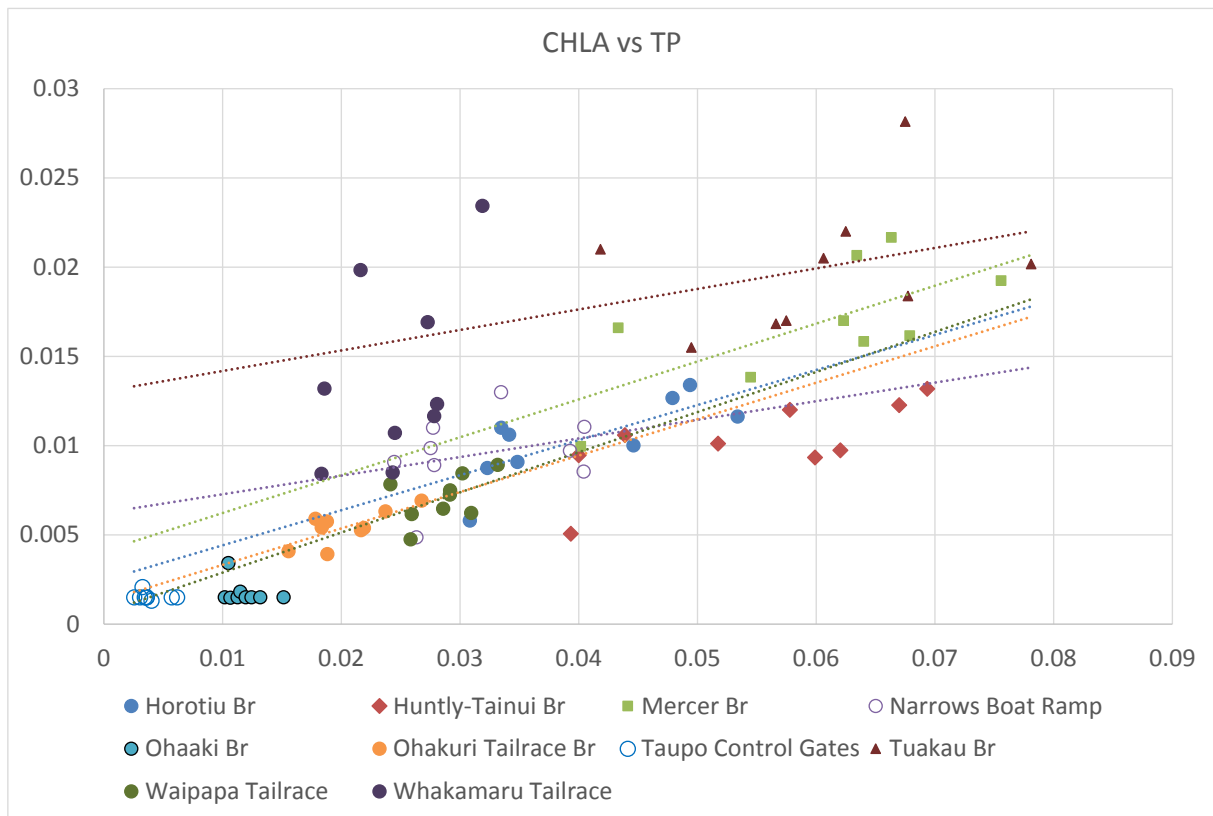


Fig. A2. Chlorophyll *a* plotted against TP. Growing season means in 2006-2014. Regression lines shown for each station except Whakamaru, Huntly, Ohaaki, Taupo Gates.



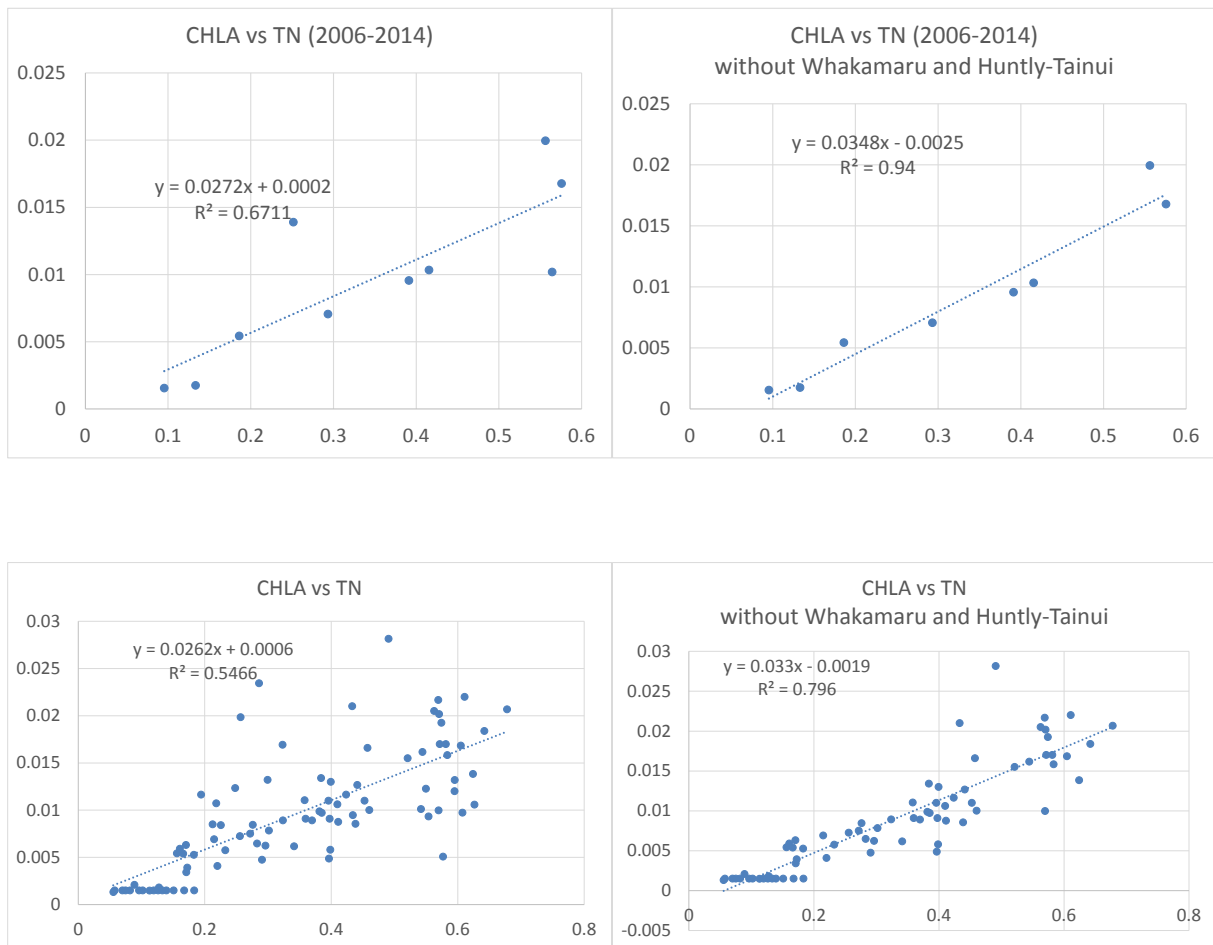


Fig. A3. Chlorophyll *a* plotted against TN. Shown are mean data, with and without Whakamaru and Huntly, of growing seasons (Oct-Mar) in 2006-2014. Top: station means. Bottom: means of each year (growing season months only) with more than 4 data points for each station.

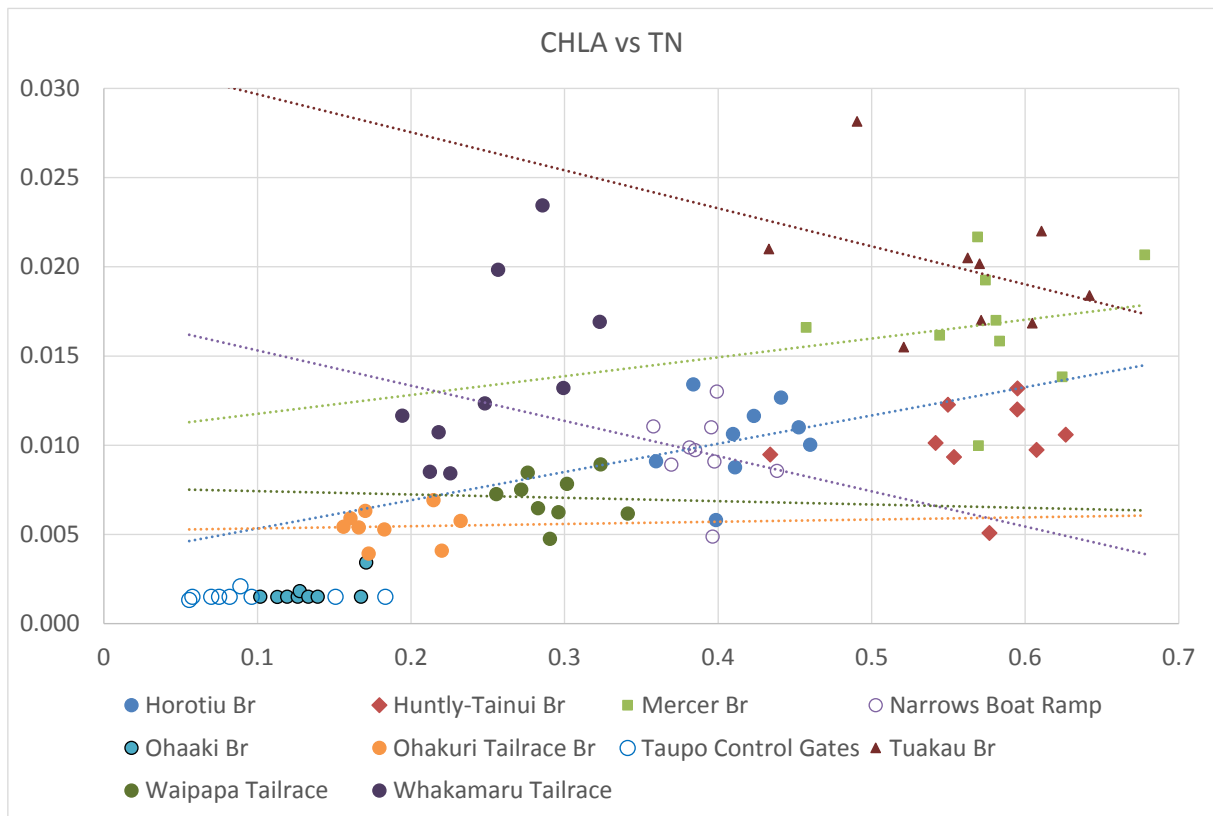


Fig. A4. Chlorophyll *a* plotted against TN. Growing season means in 2006-2014. Regression lines shown for each station except Whakamaru, Huntly, Ohaaki, Taupo Gates.

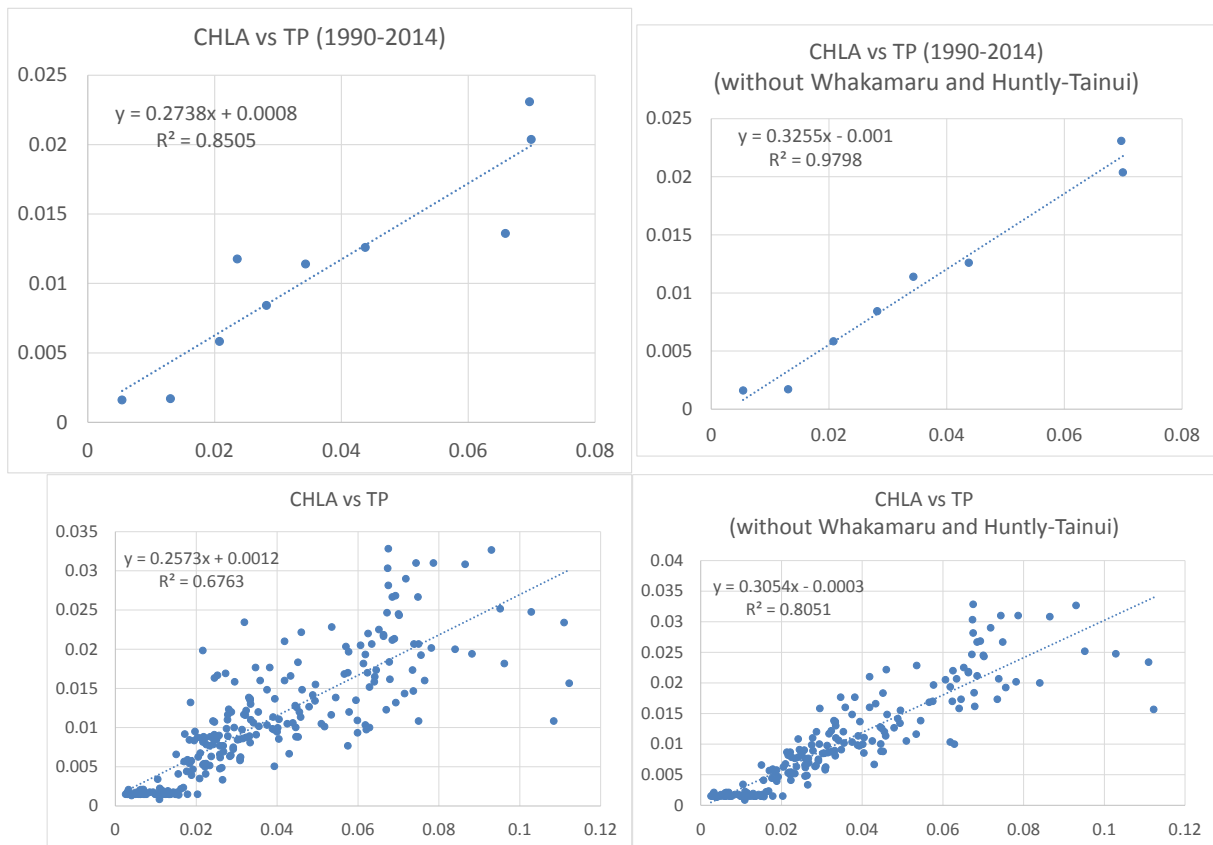


Fig. A5. Chlorophyll *a* plotted against TP. Shown are mean data, with and without Whakamaru and Huntly, of growing seasons (Oct-Mar) in 1990-2014 (Tuakau and Whakamaru from 1995). Top: station means. Bottom: means of each year (growing season months only) with more than 4 data points for each station.

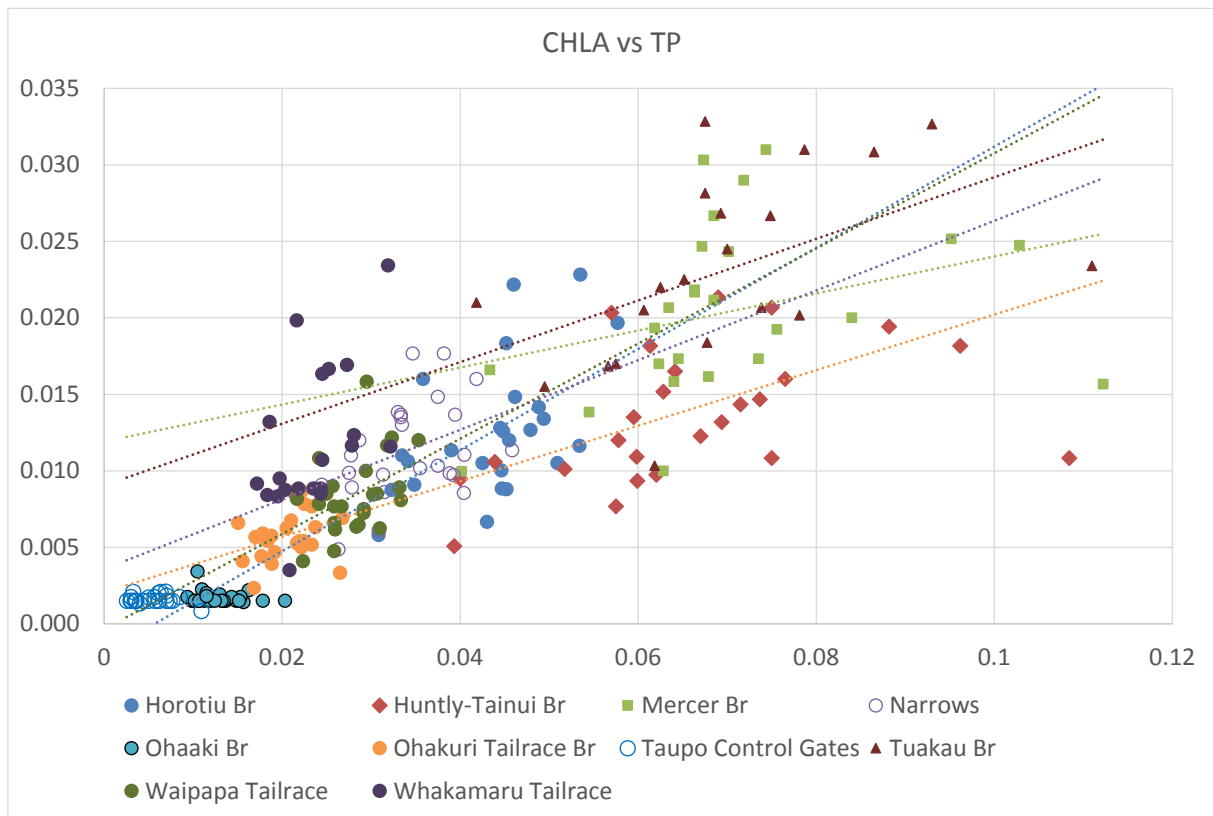


Fig. A6. Chlorophyll *a* plotted against TP. Growing season means in 1990-2014 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Whakamaru, Huntly, Ohaaki, Taupo Gates.

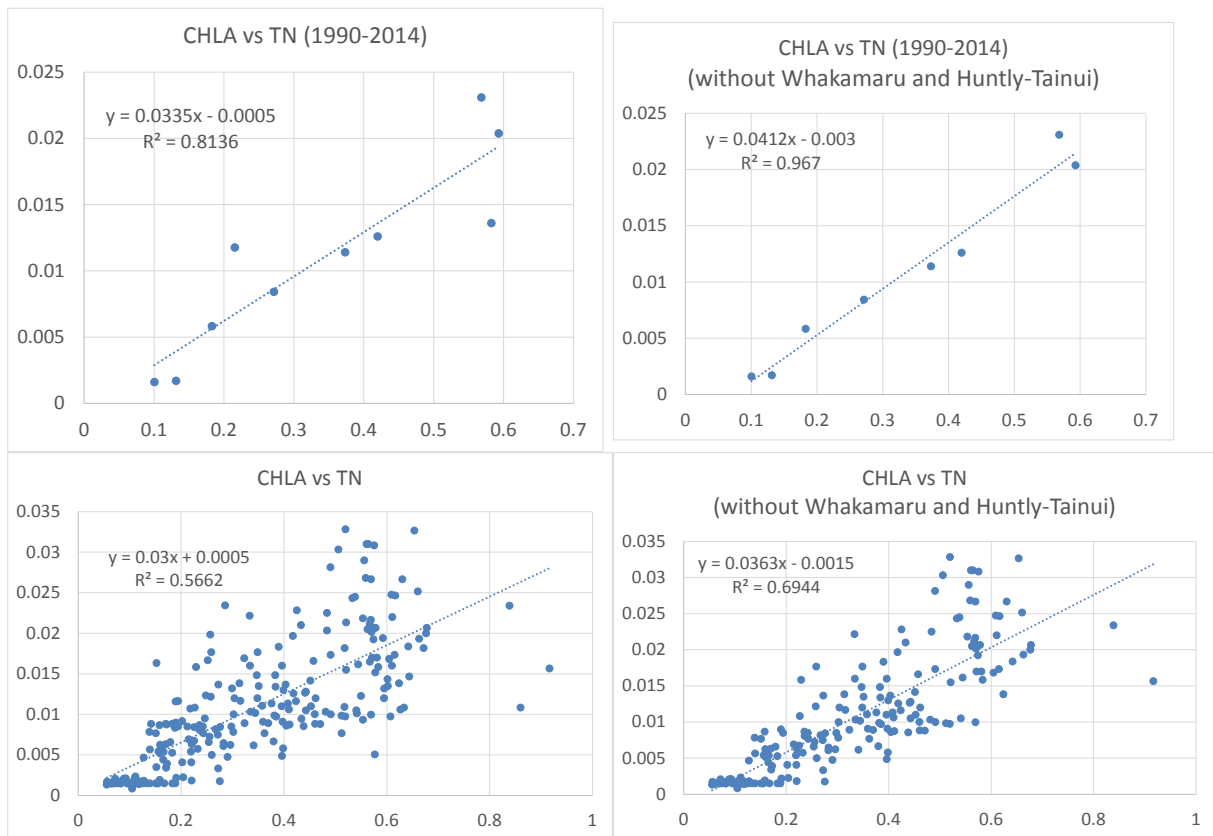


Fig. A7. Chlorophyll *a* plotted against TN. Shown are mean data, with and without Whakamaru and Huntly, of growing seasons (Oct-Mar) in 1990-2014 (Tuakau and Whakamaru from 1995). Top: station means. Bottom: means of each year (growing season months only) with more than 4 data points for each station.

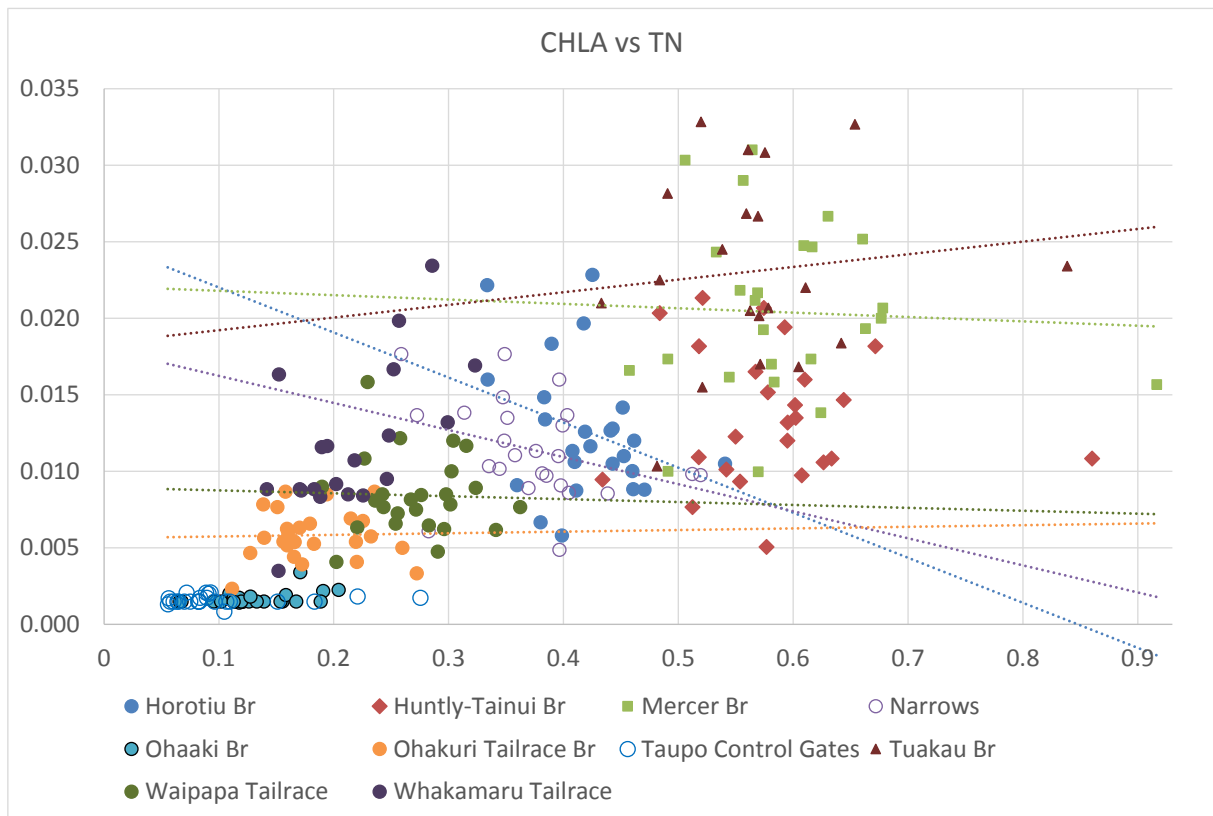


Fig. A8. Chlorophyll *a* plotted against TN. Growing season means in 1990-2014 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Whakamaru, Huntly, Ohaaki, Taupo Gates.

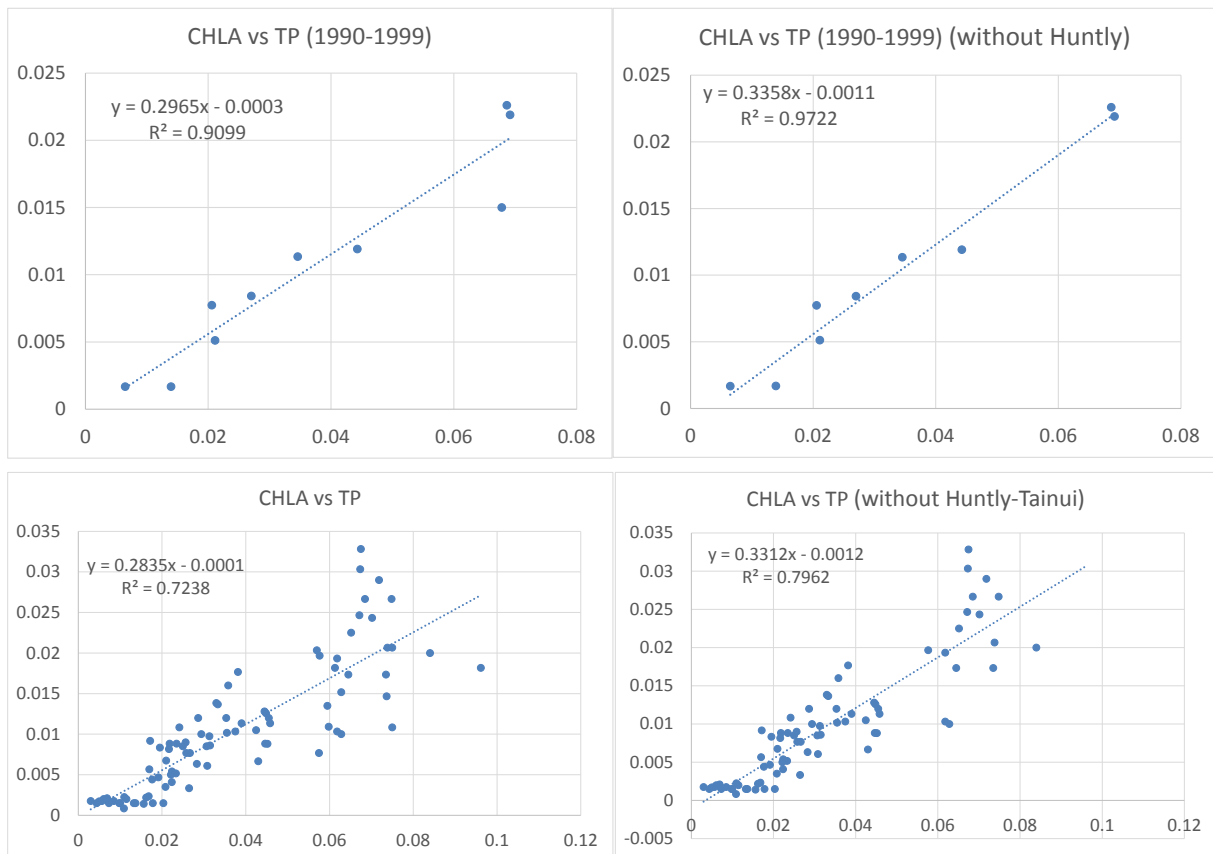


Fig. A9. Chlorophyll *a* plotted against TP. Shown are mean data, with and without Huntly, of growing seasons (Oct-Mar) in 1990-1999 (Tuakau and Whakamaru from 1995). Top: station means. Bottom: means of each year (growing season months only) with more than 4 data points for each station.

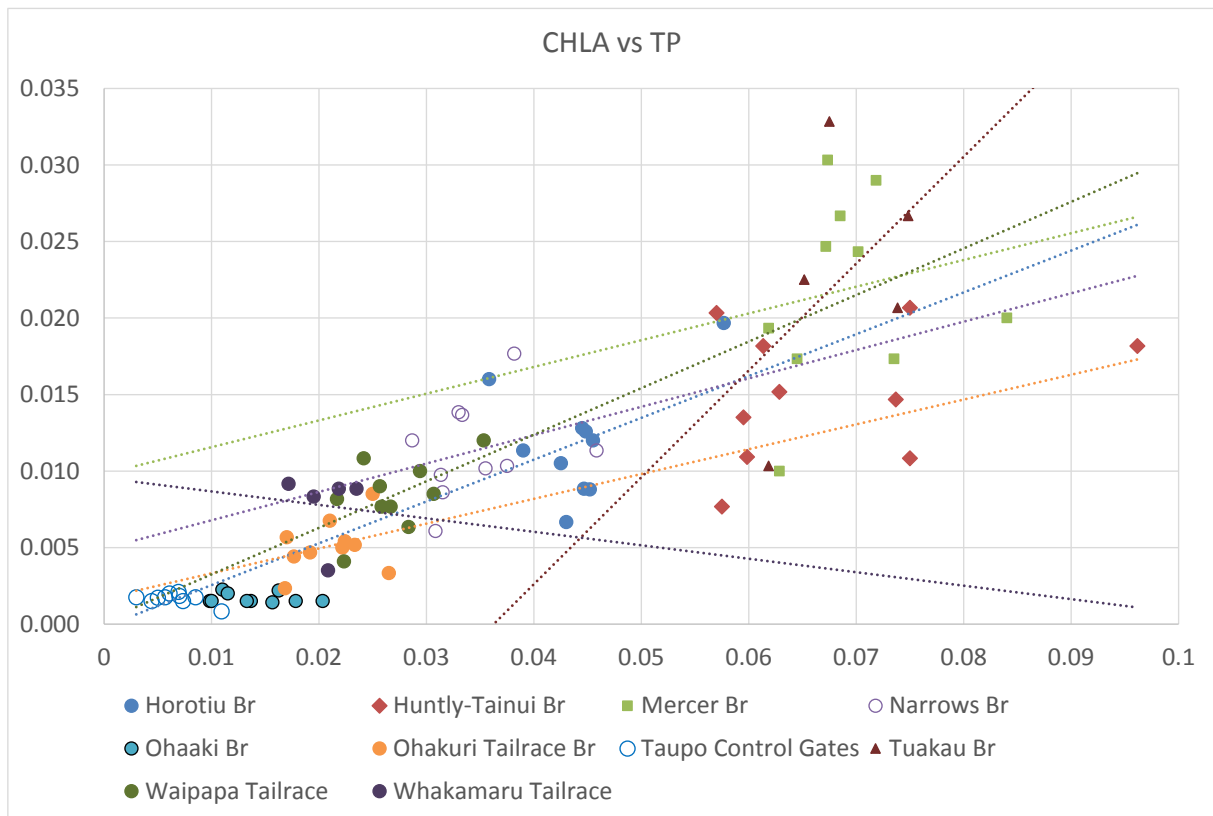


Fig. A10. Chlorophyll *a* plotted against TP. Growing season means in 1990-1999 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Huntly, Ohaaki, Taupo Gates.



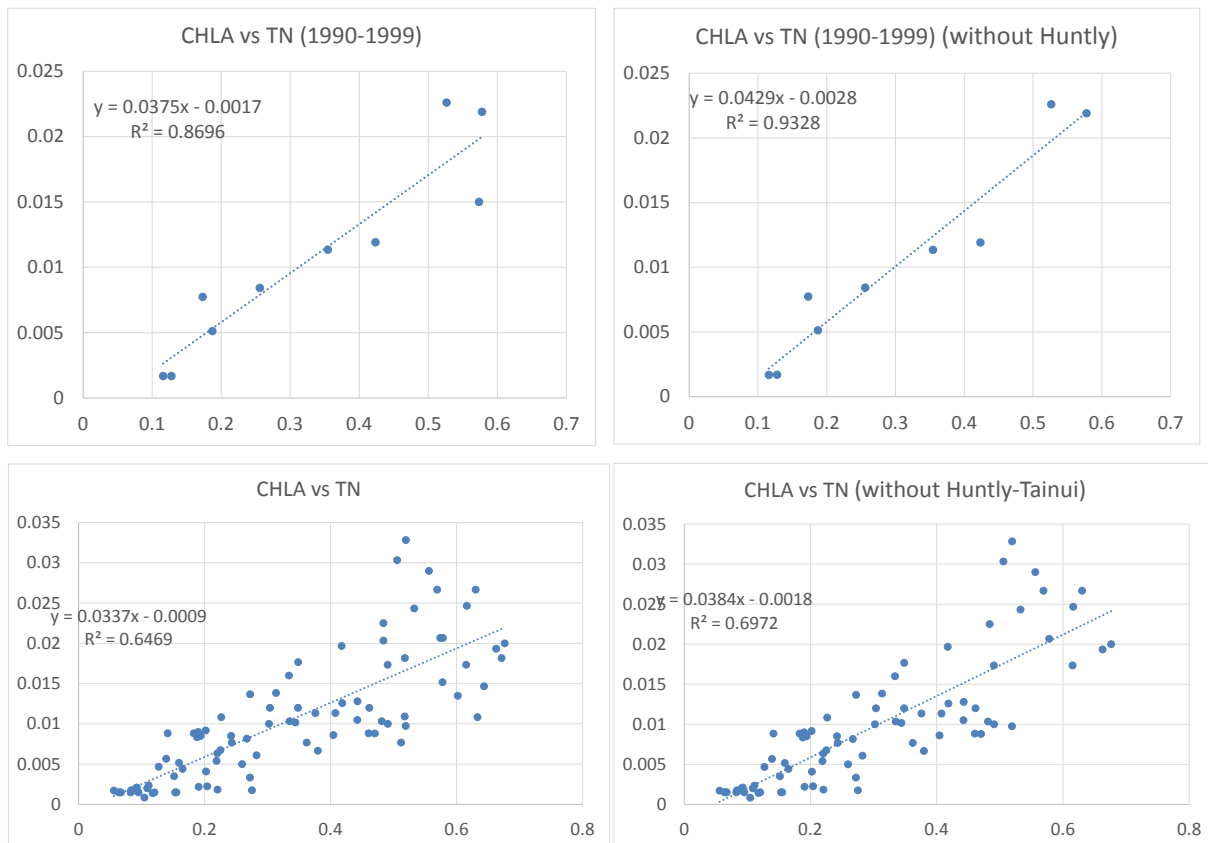


Fig. A11. Chlorophyll *a* plotted against TN. Shown are mean data, with and without Huntly, of growing seasons (Oct-Mar) in 1990-1999 (Tuakau and Whakamaru from 1995). Top: station means. Bottom: means of each year (growing season months only) with more than 4 data points for each station.

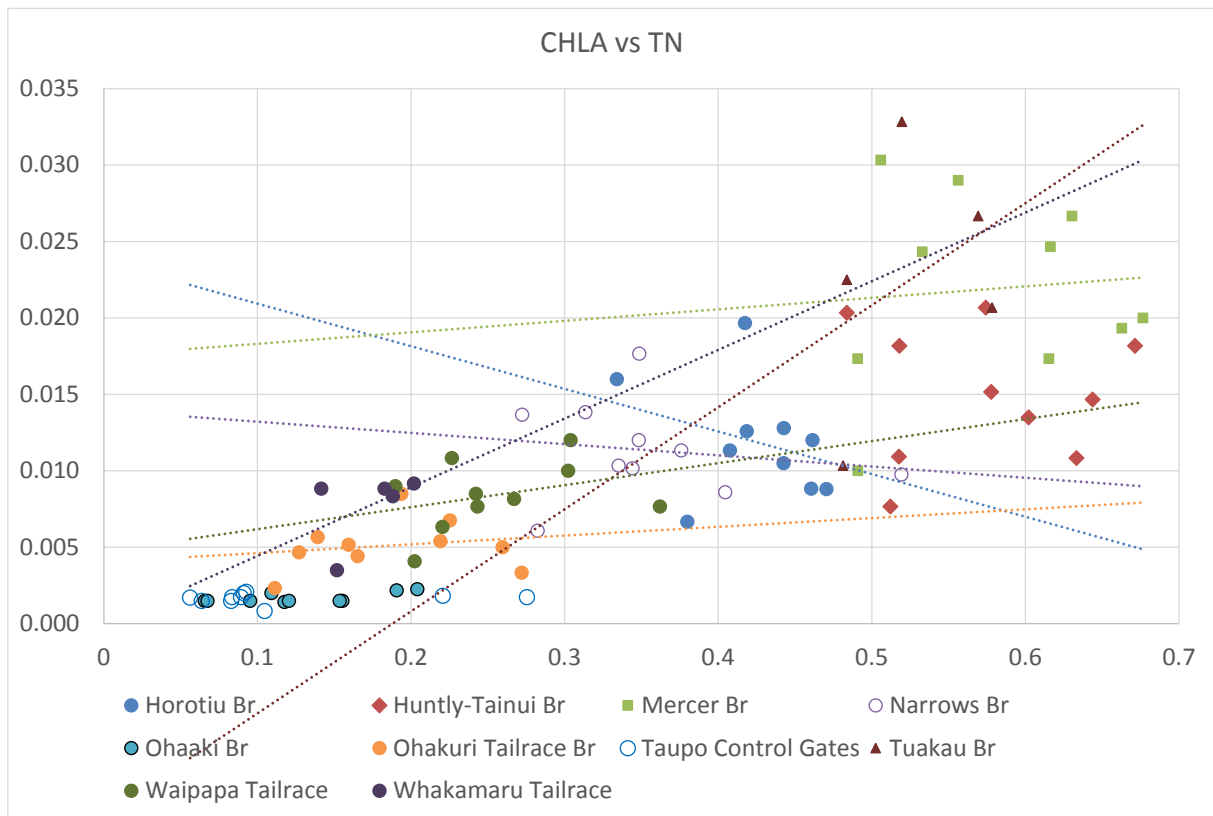


Fig. A12. Chlorophyll *a* plotted against TN. Growing season means in 1990-1999 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Huntly, Ohaaki, Taupo Gates.

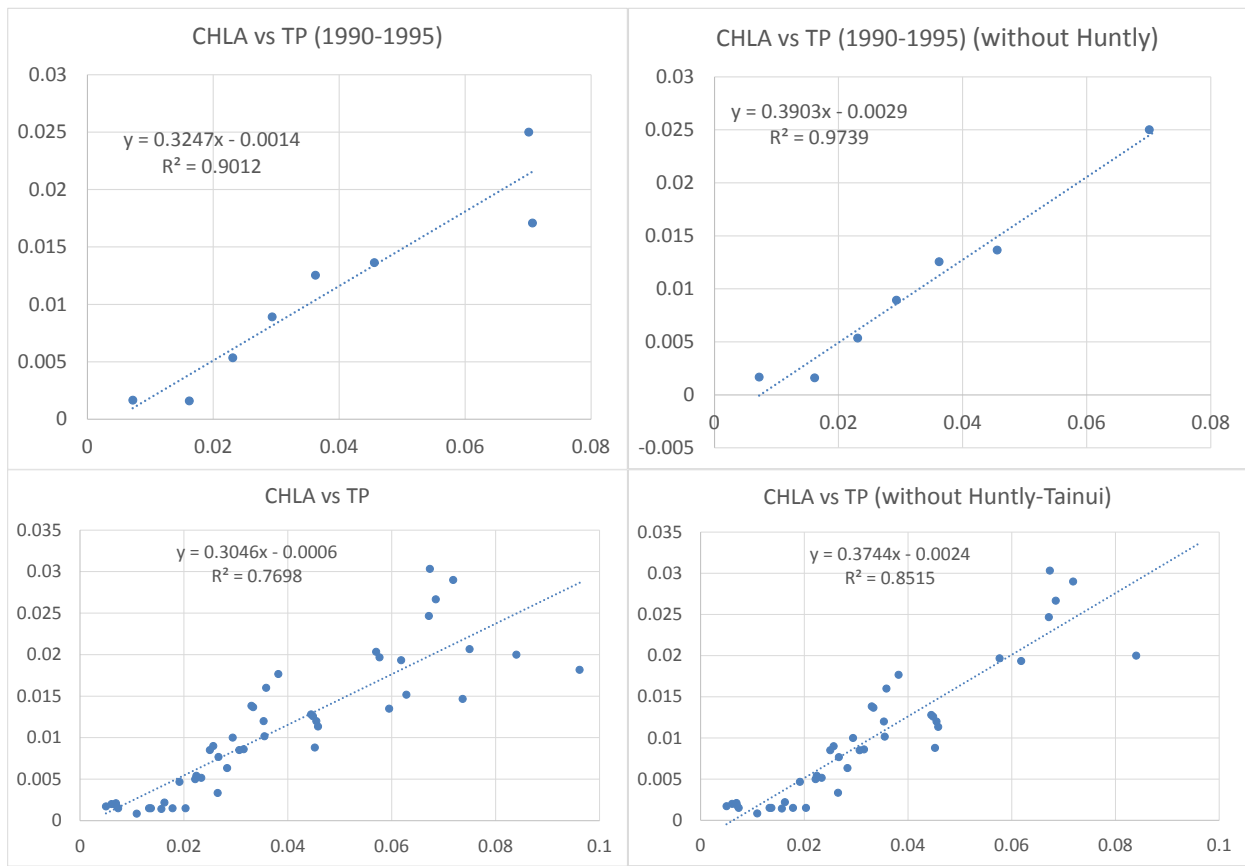


Fig. A13. Chlorophyll *a* plotted against TP. Shown are mean data, with and without Huntly, of growing seasons (Oct-Mar) in 1990-1995 (no data for Tuakau and Whakamaru). Top: station means. Bottom: means of each year (growing season months only) with more than 4 data points for each station.

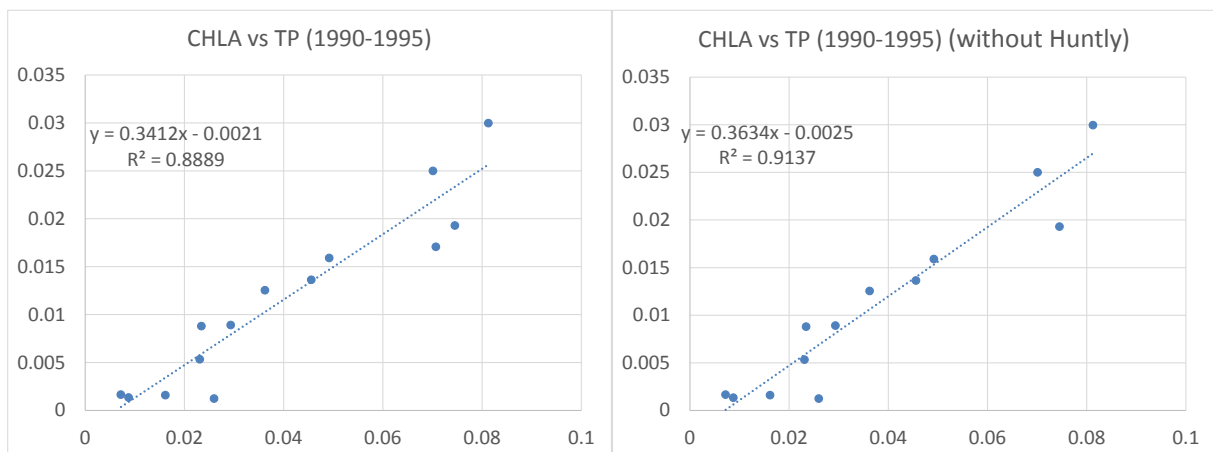


Fig. A14. Same as Fig A13, but this includes six additional stations with too few samples for the annual means shown in the bottom panels of Fig A13 (note four stations have all their chlorophyll *a* values below the detection limit).

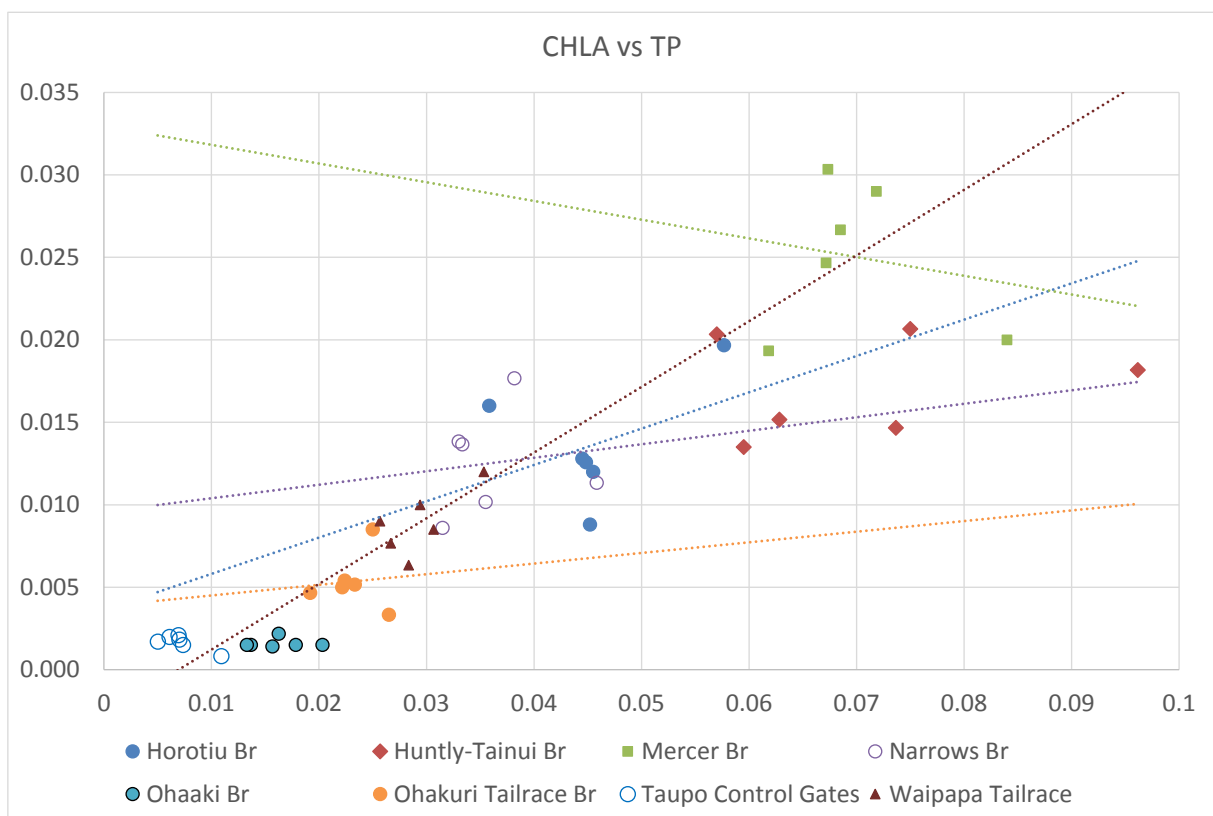


Fig. A15. Chlorophyll *a* plotted against TP. Growing season means in 1990-1995 (no data for Tuakau and Whakamaru). Regression lines shown for each station except Huntly, Ohaaki, Taupo Gates.

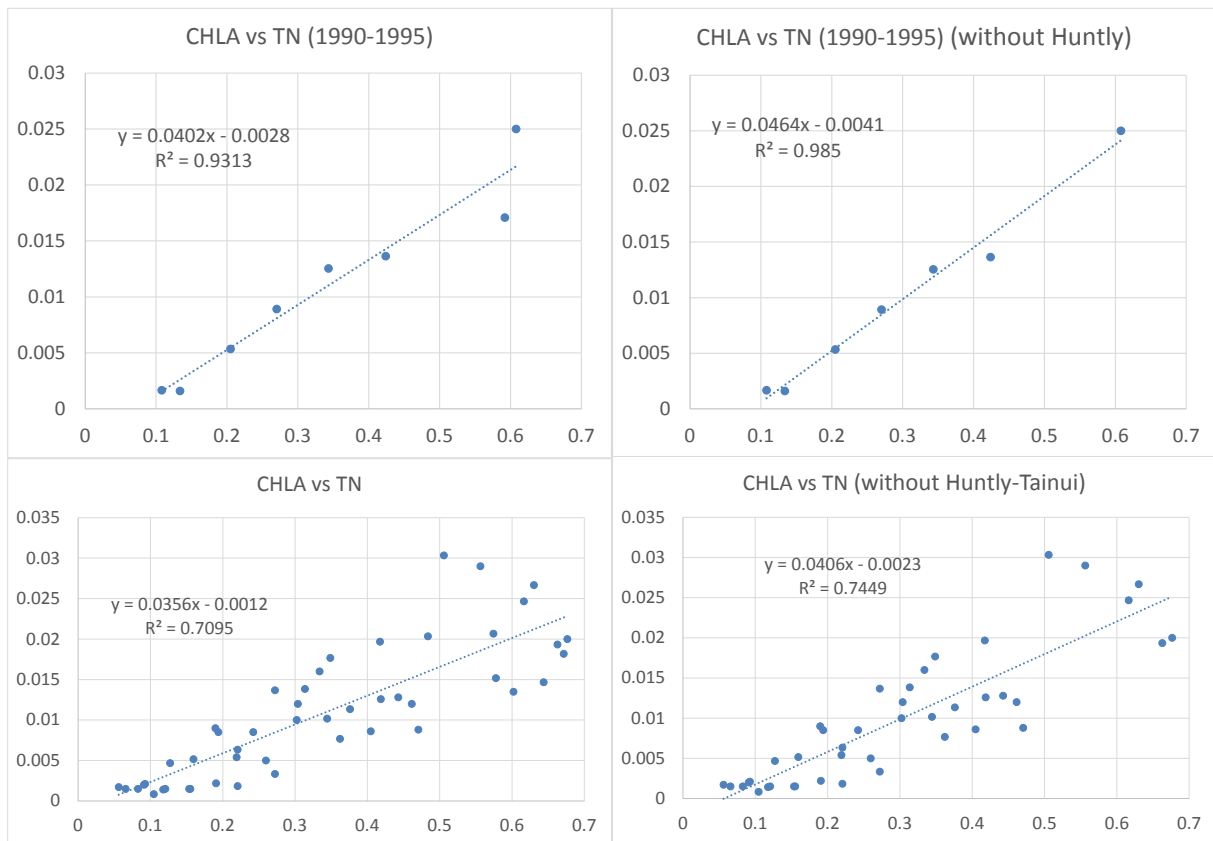


Fig. A16. Chlorophyll *a* plotted against TN. Shown are mean data, with and without Huntly, of growing seasons (Oct-Mar) in 1990-1995 (no data for Tuakau and Whakamaru). Top: station means. Bottom: means of each year (growing season months only) with more than 4 data points for each station.

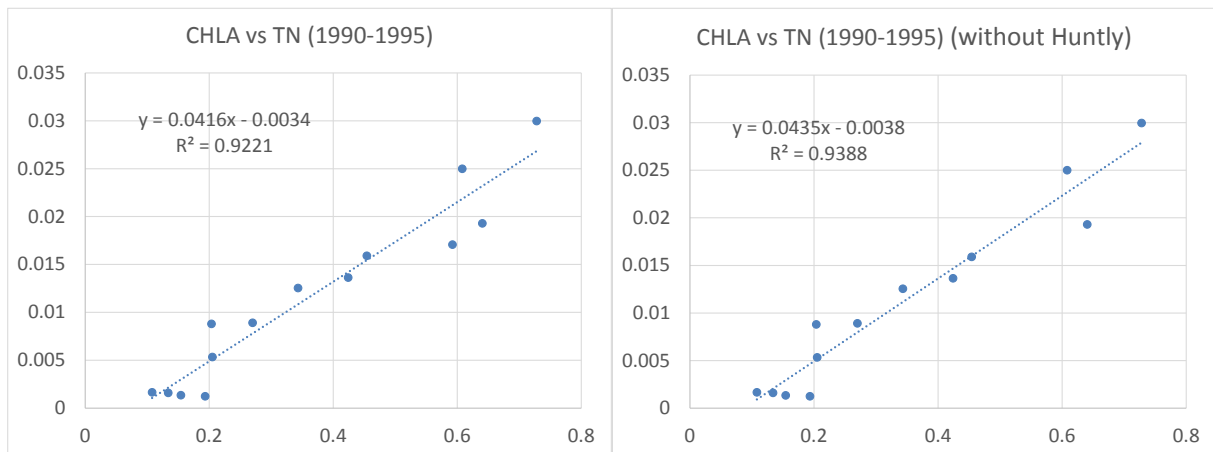


Fig. A17. Same as Fig A16, but this includes six additional stations with too few samples for the annual means shown in the bottom panels of Fig A16 (note four stations have all their chlorophyll  $a$  values below the detection limit).

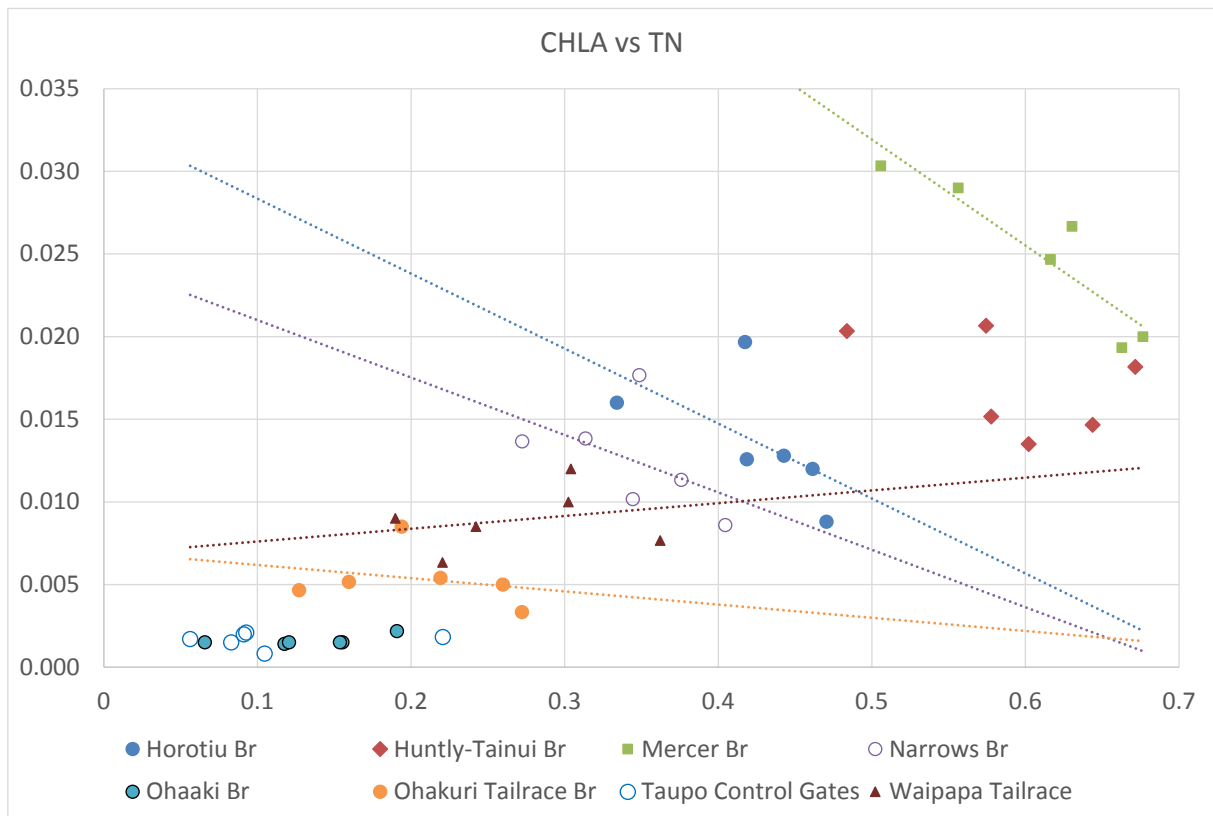
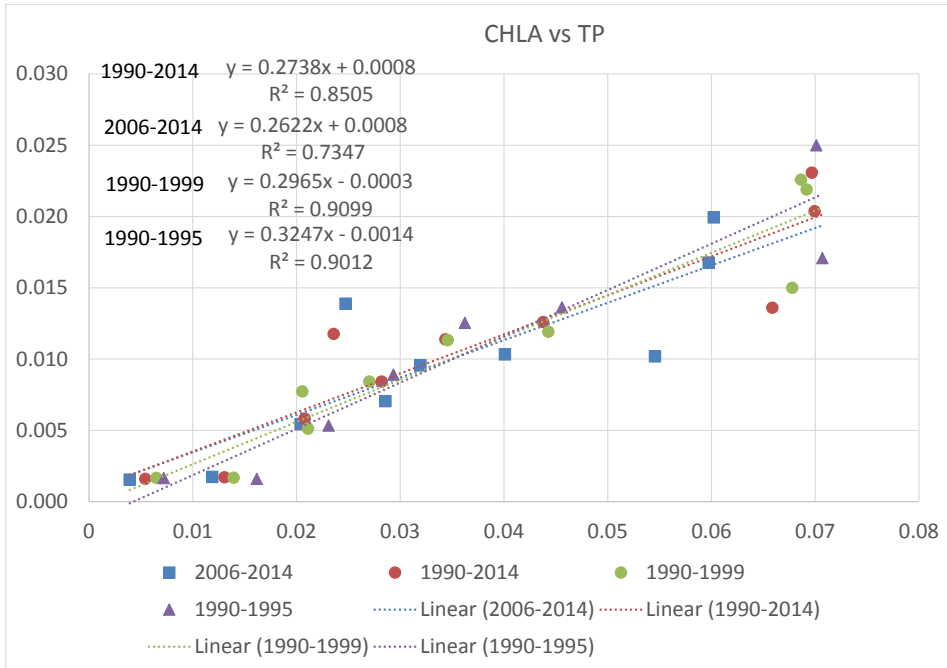


Fig. A18. Chlorophyll  $a$  plotted against TN. Growing season means in 1990-1995 (no data for Tuakau and Whakamaru). Regression lines shown for each station except Huntly, Ohaaki, Taupo Gates.

## All stations



## Not including Huntly, Whakamaru

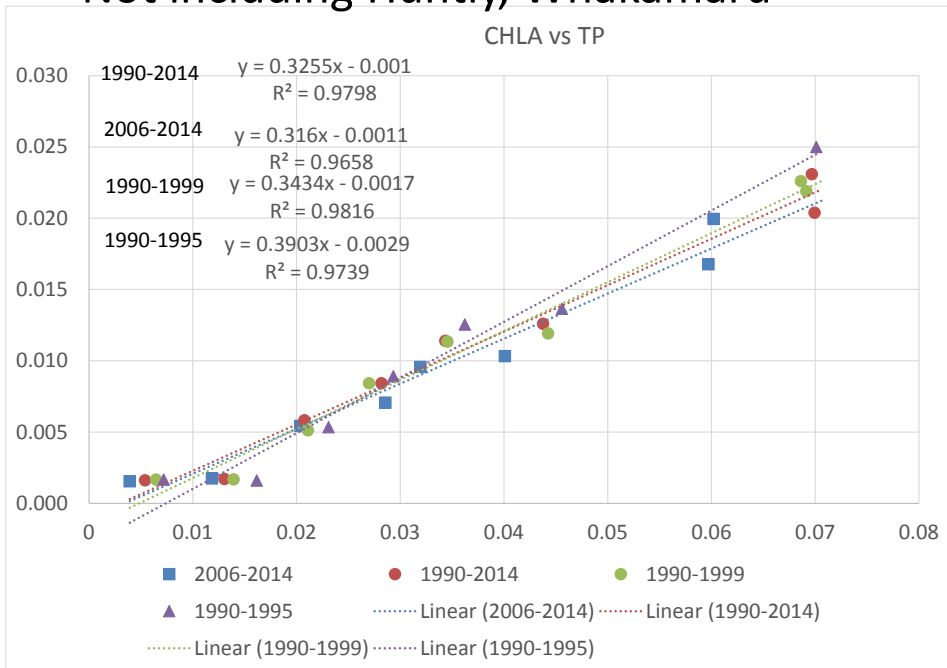


Fig. A19a. Summary plots with regression equations comparing results for each of the four periods shown in the plots of Chlorophyll *a* against TP of Figs A1-A18. Shown are mean data of growing seasons (Oct-Mar). Top: all stations. Bottom: Huntly and Whakamaru excluded.

## Not including Huntly, Whakamaru, Taupo gates, Ohakuri

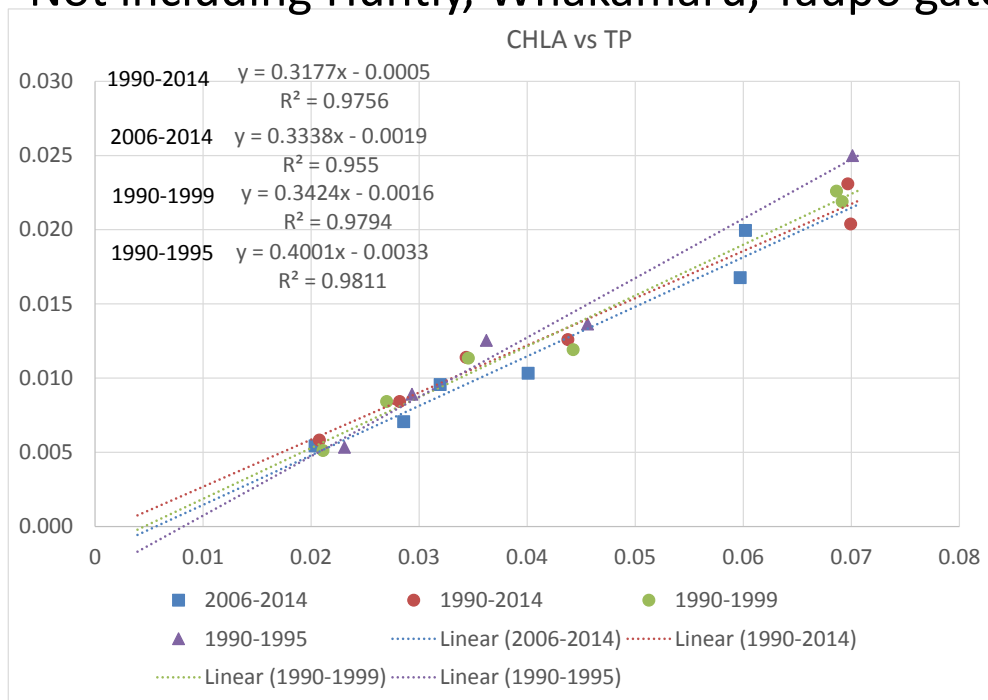
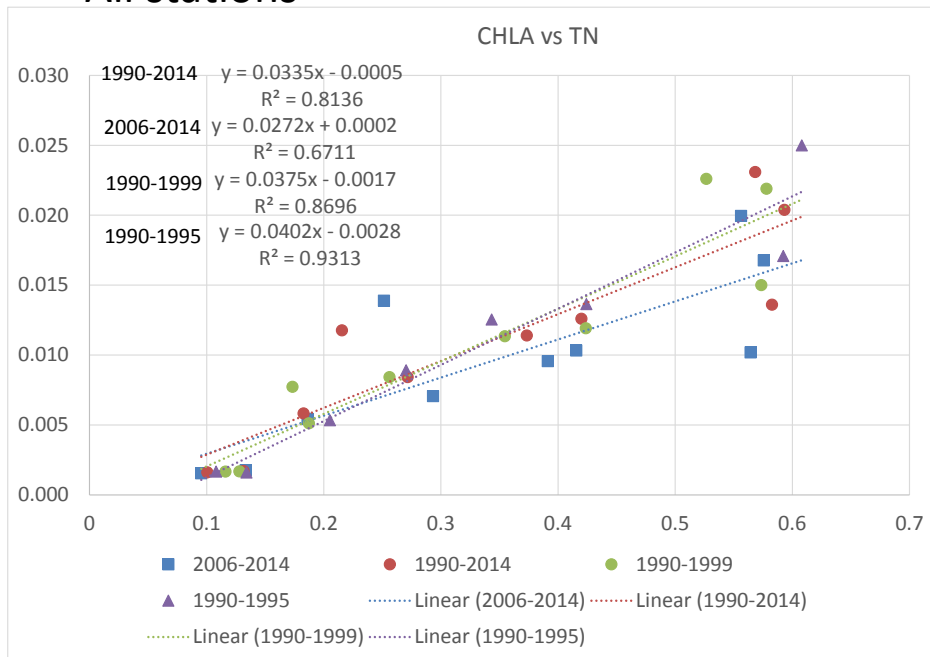


Fig. A19b. Same as Fig. A19a but with Huntly, Whakamaru, Taupo Gates and Ohakuri data excluded.



## All stations



## Not including Huntly, Whakamaru

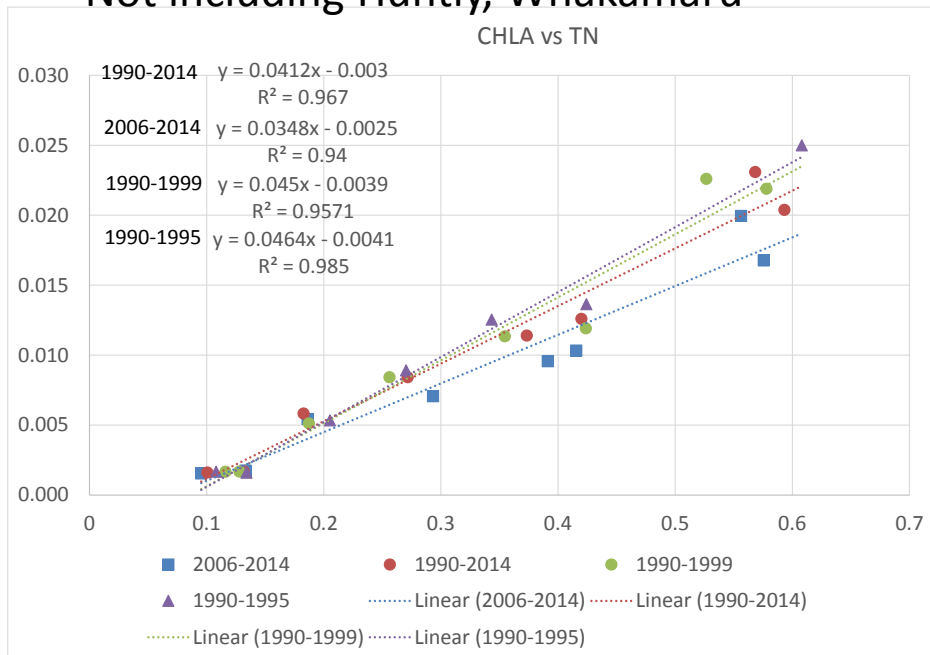


Fig. A20a. Summary plots with regression equations comparing results for each of the four periods shown in the plots of Chlorophyll *a* against TN of Figs A1-A18. Shown are mean data of growing seasons (Oct-Mar). Top: all stations. Bottom: Huntly and Whakamaru excluded.

## Not including Huntly, Whakamaru, Taupo gates, Ohakuri

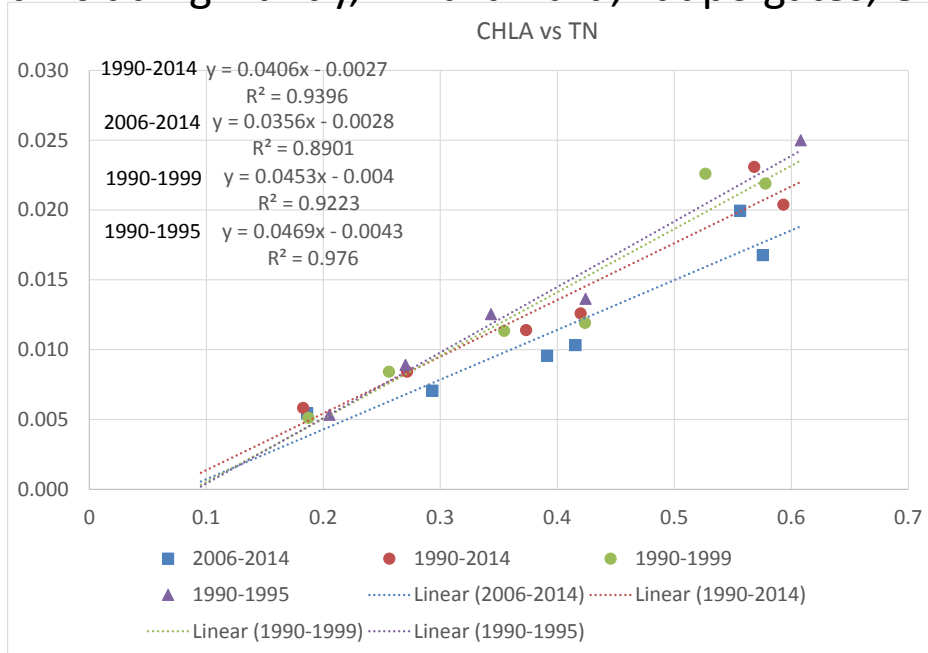


Fig. A20b. Same as Fig. A20a but with Huntly, Whakamaru, Taupo Gates and Ohakuri data excluded.

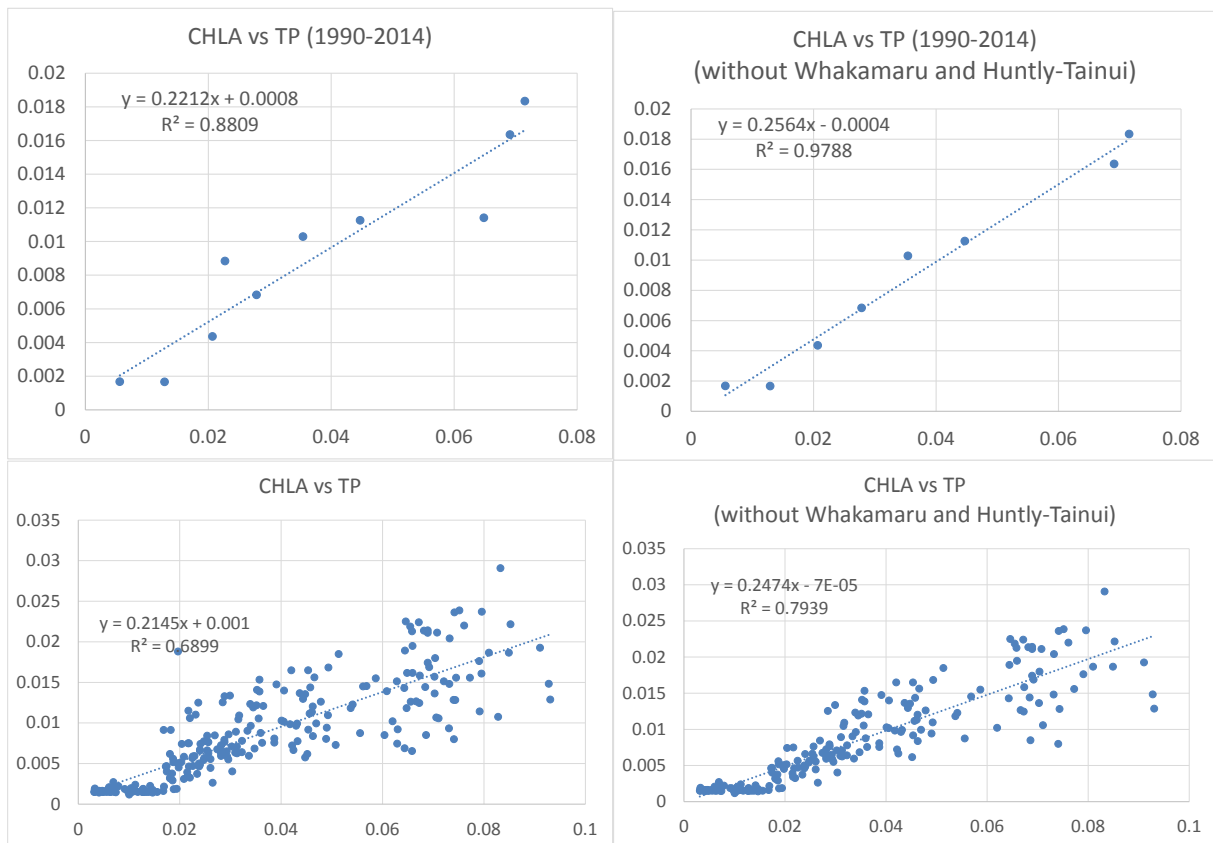


Fig. A21. Chlorophyll *a* plotted against TP. Shown are annual mean data, with and without Whakamaru and Huntly, of 1990-2014 (Tuakau and Whakamaru from 1995). Top: station means. Bottom: means of each year for each station.

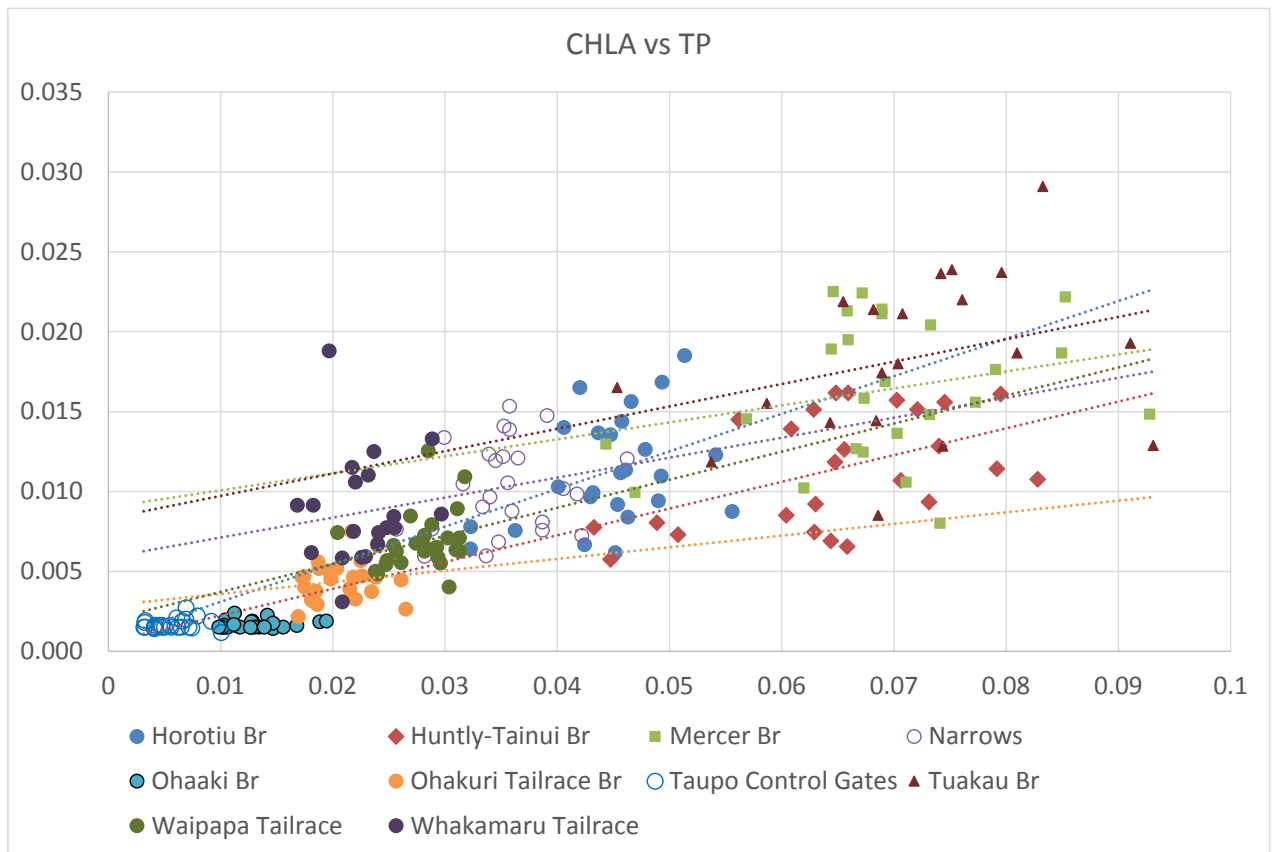


Fig. A22. Chlorophyll *a* plotted against TP. Annual means in 1990-2014 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Whakamaru, Ohaaki, Taupo Gates.

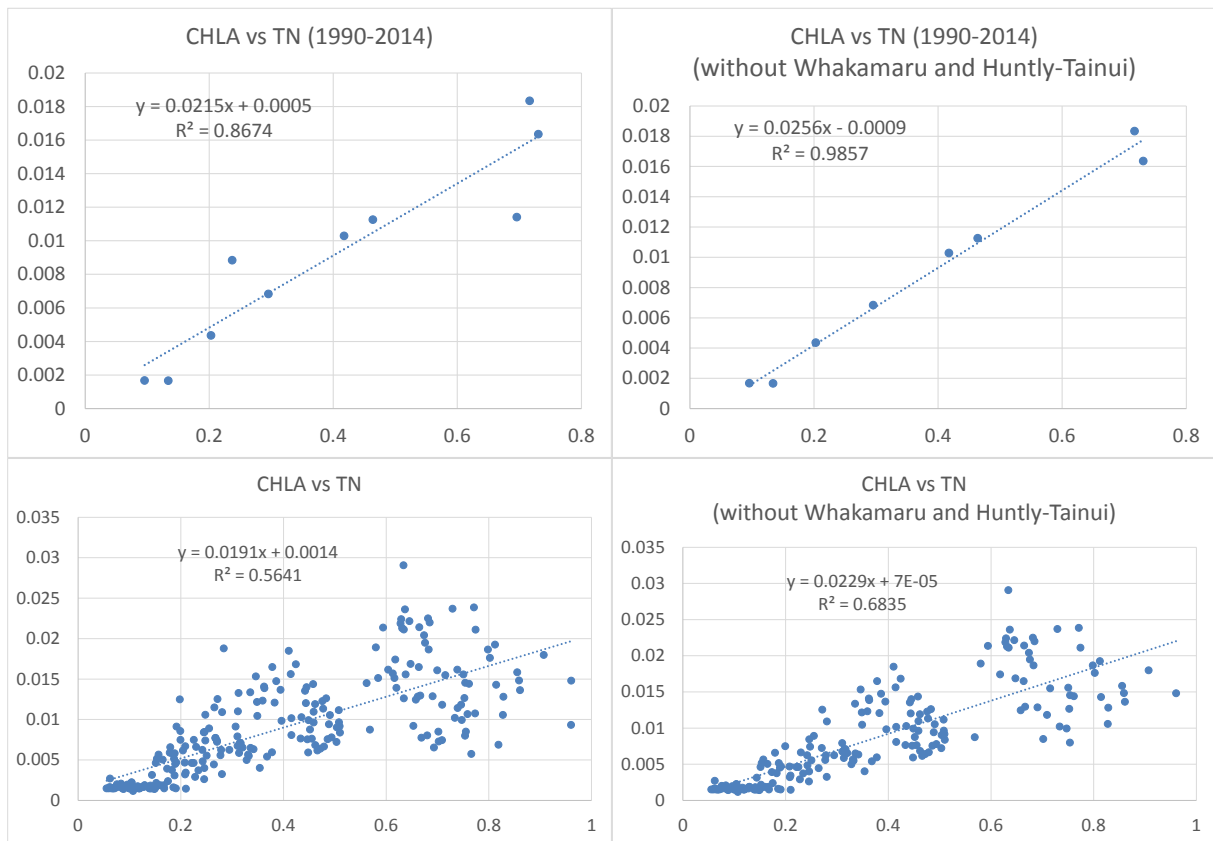


Fig. A23. Chlorophyll *a* plotted against TN. Shown are annual mean data, with and without Whakamaru and Huntly, of 1990-2014 (Tuakau and Whakamaru from 1995). Top: station means. Bottom: means of each year for each station.

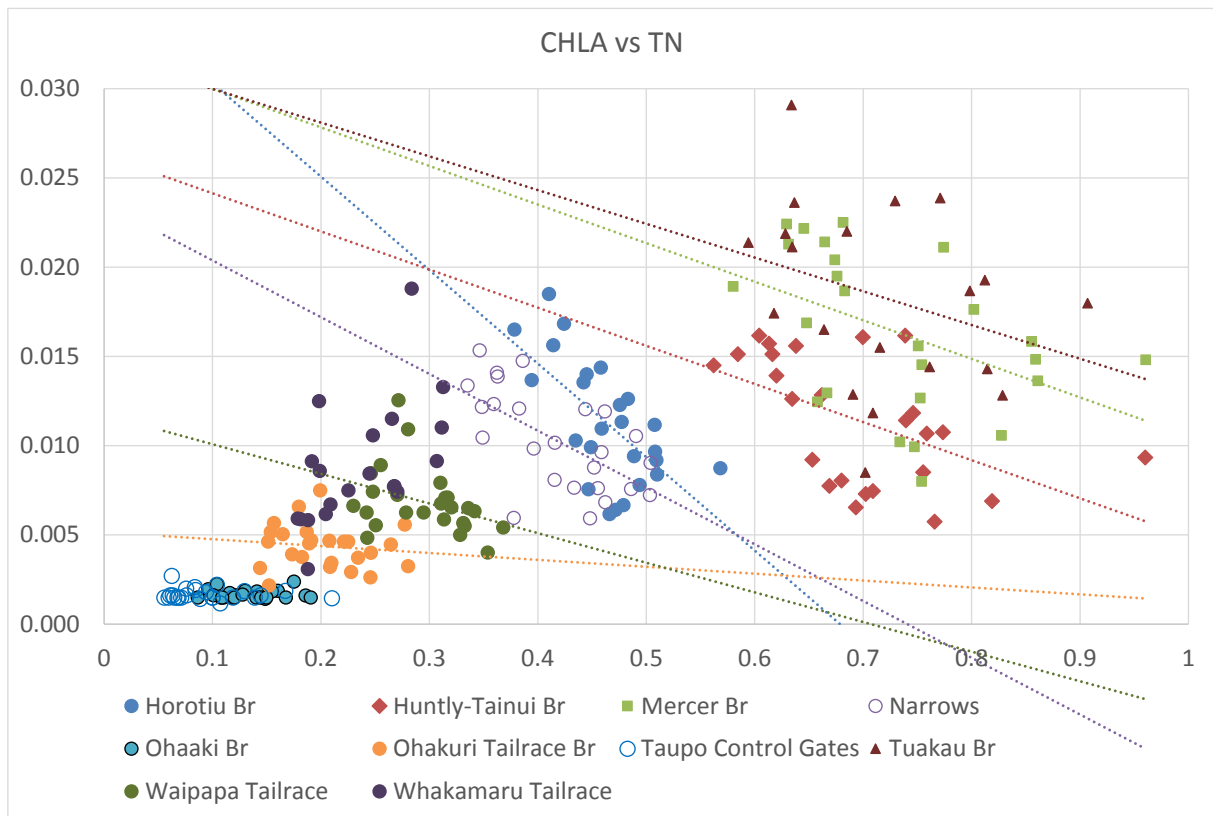


Fig. A24. Chlorophyll *a* plotted against TN. Annual means in 1990-2014 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Whakamaru, Ohaaki, Taupo Gates.

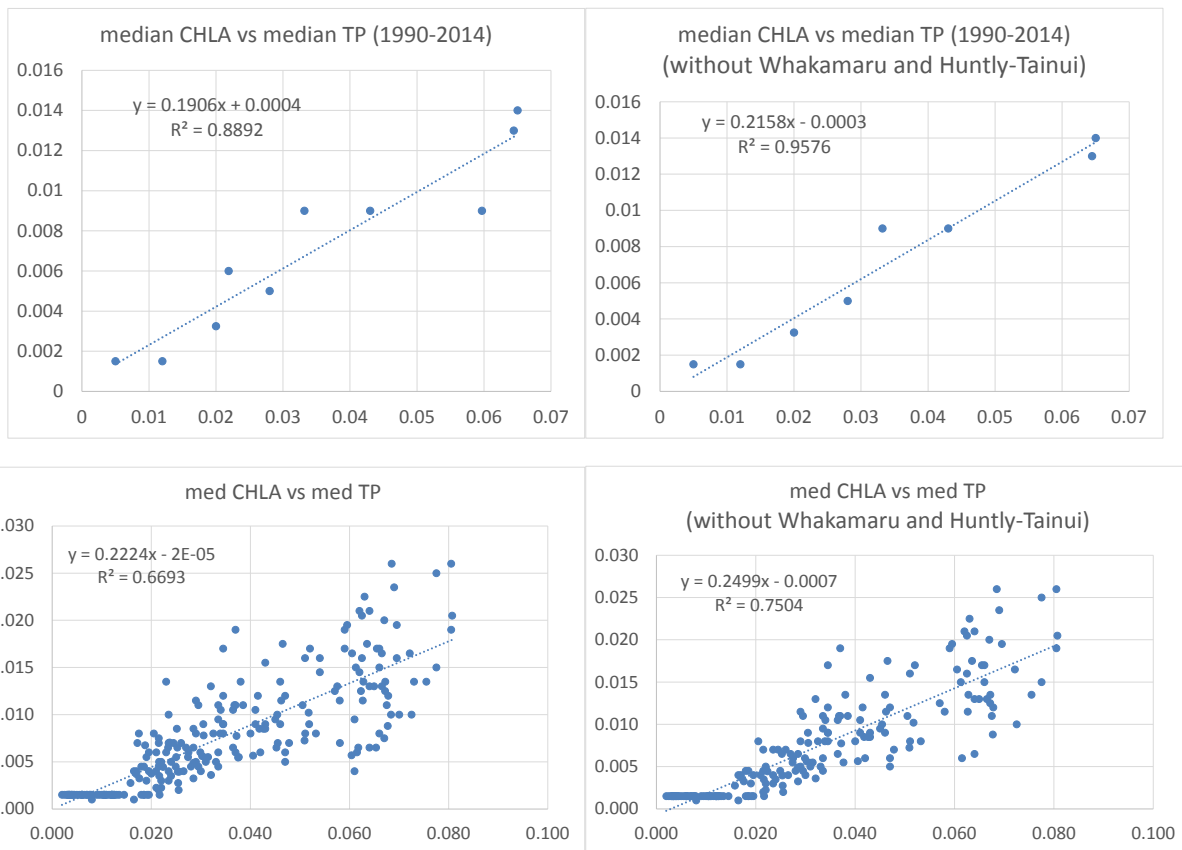


Fig. A25. Chlorophyll *a* plotted against TP. Shown are annual medians, with and without Whakamaru and Huntly, of 1990-2014 (Tuakau and Whakamaru from 1995). Top: station means. Bottom: medians of each year for each station.

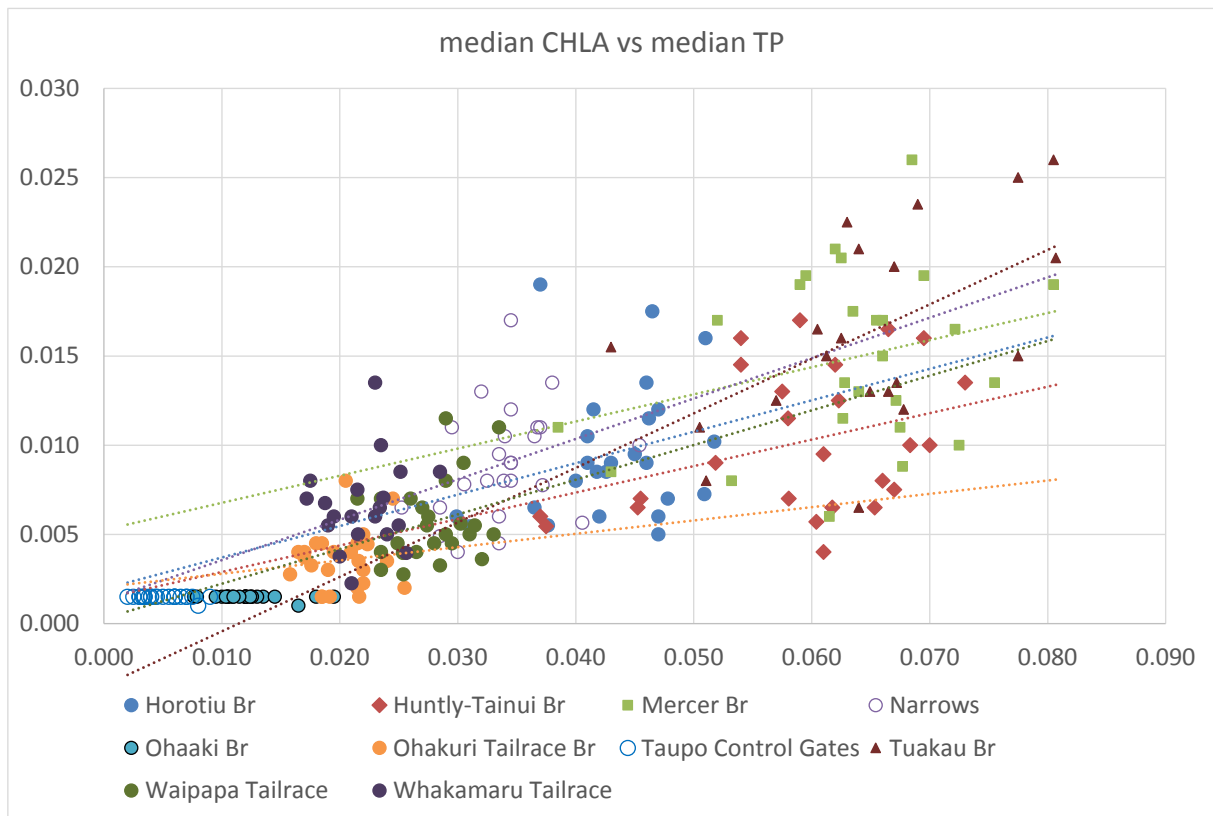


Fig. A26. Chlorophyll *a* plotted against TP. Annual medians in 1990-2014 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Whakamaru, Ohaaki, Taupo Gates.



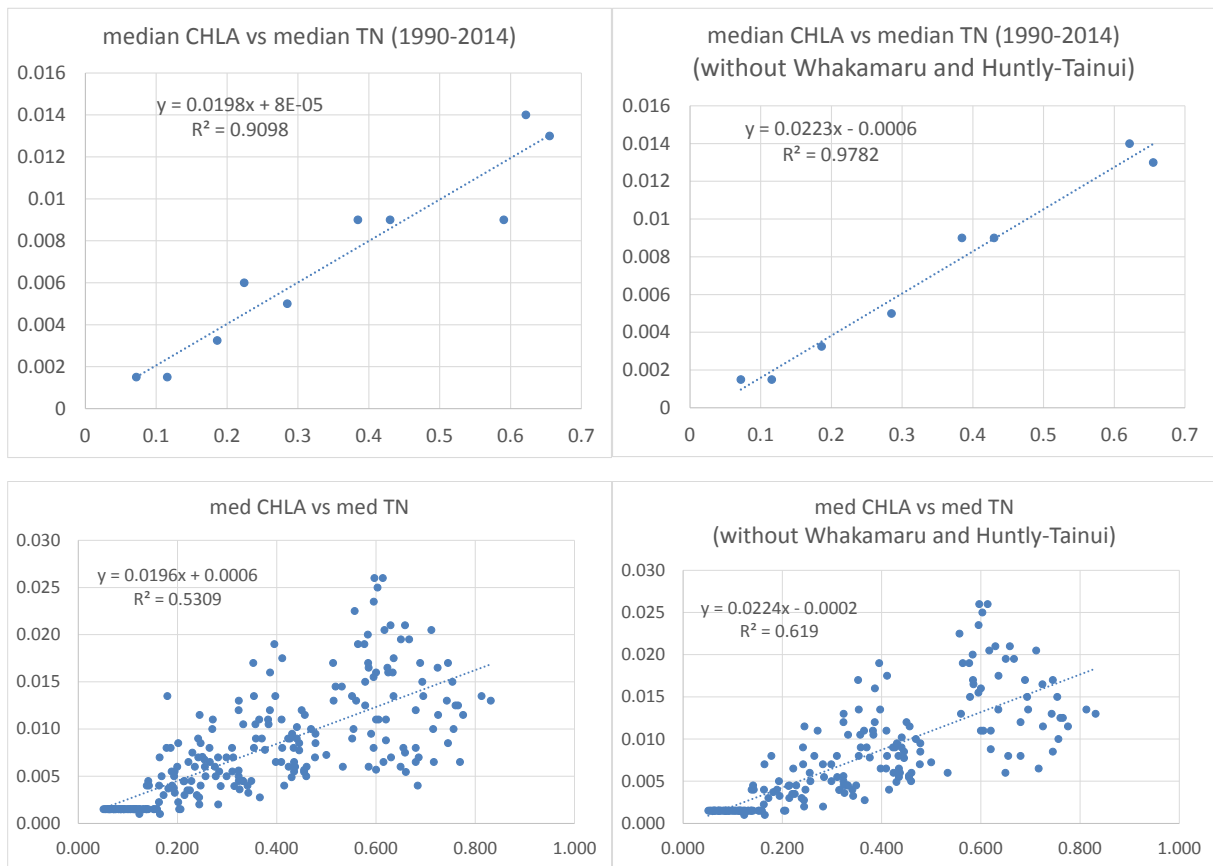


Fig. A27. Chlorophyll *a* plotted against TN. Shown are annual medians, with and without Whakamaru and Huntly, of 1990-2014 (Tuakau and Whakamaru from 1995). Top: station means. Bottom: medians of each year for each station.

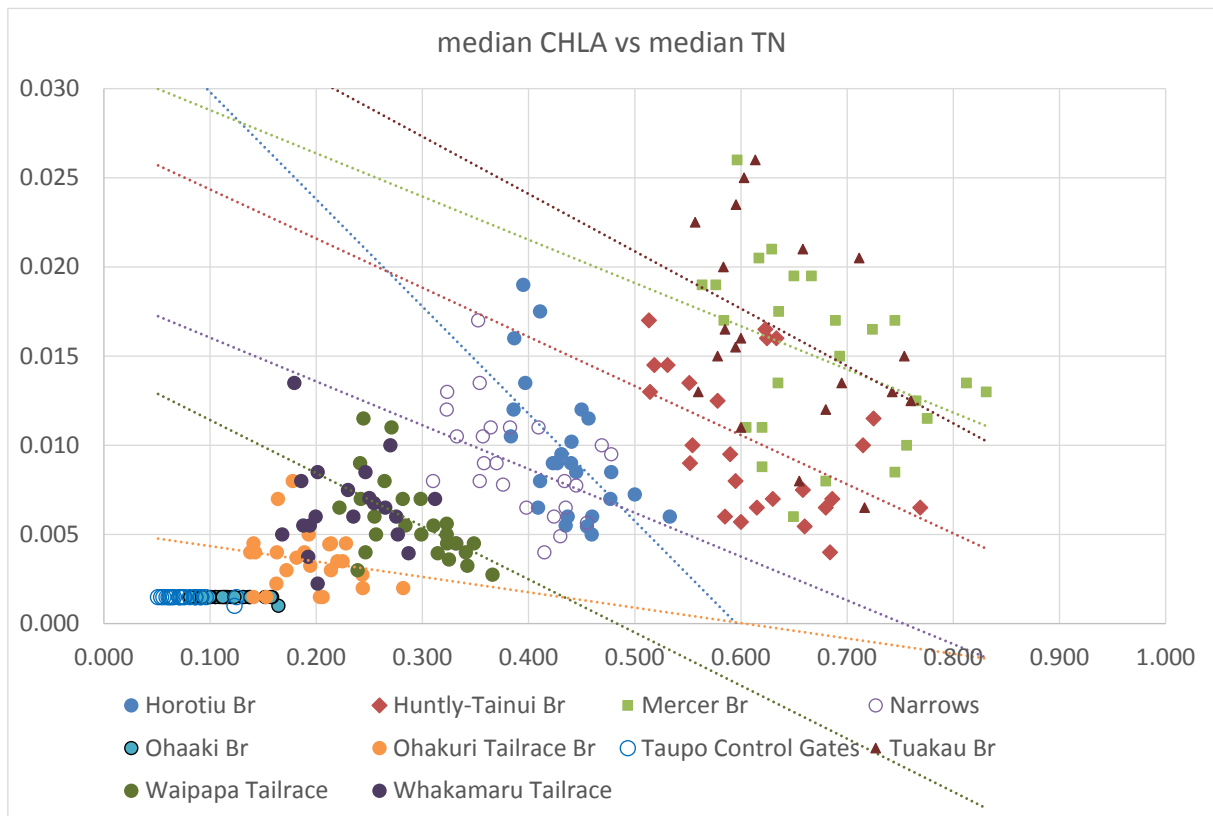


Fig. A28. Chlorophyll *a* plotted against TN. Annual medians in 1990-2014 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Whakamaru, Ohaaki, Taupo Gates.

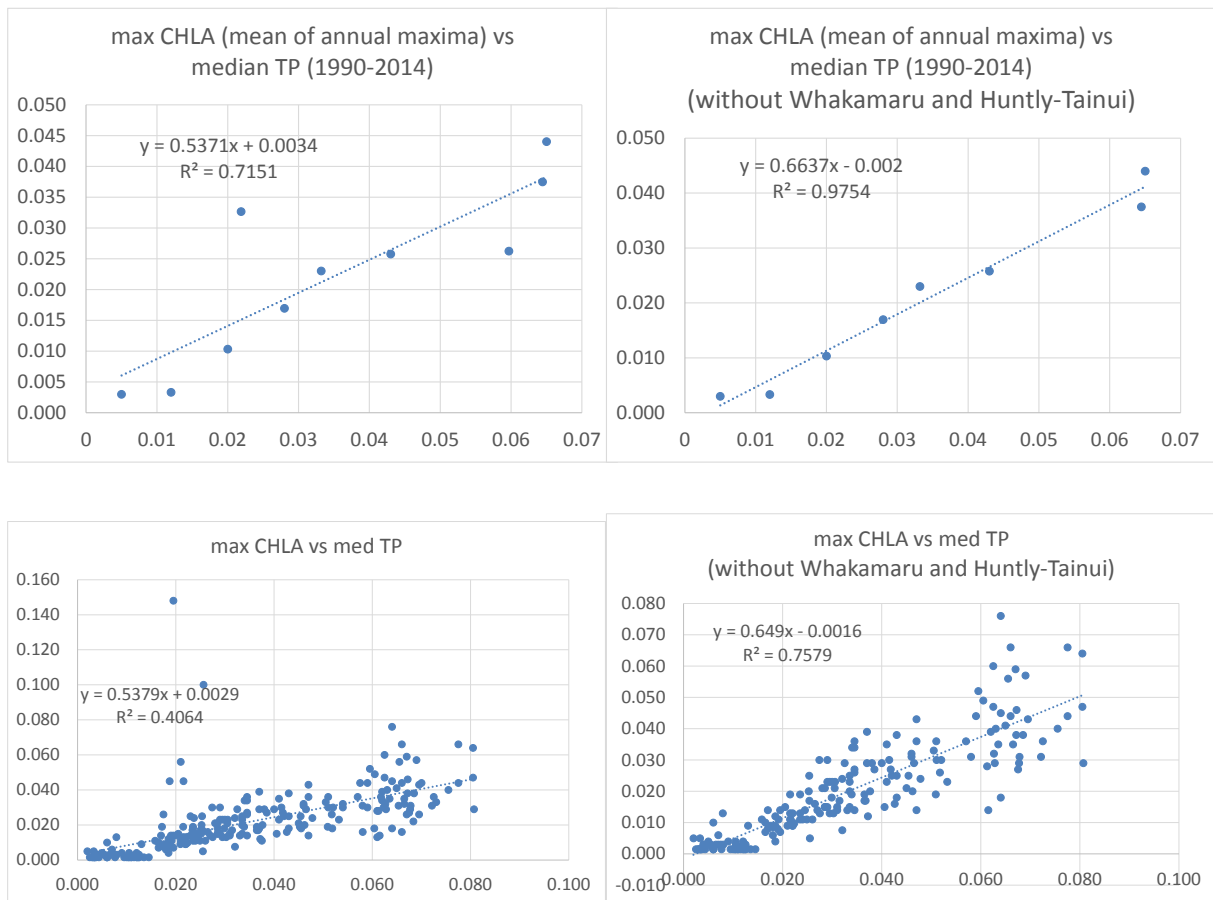


Fig. A29. Chlorophyll *a* plotted against TP. Shown are annual maxima of chlorophyll *a* against median TP, with and without Whakamaru and Huntly, of 1990-2014 (Tuakau and Whakamaru from 1995). Top: station values. Maximum chlorophyll *a* was calculated as the mean of annual maxima for each year. Bottom: values for each year for each station.

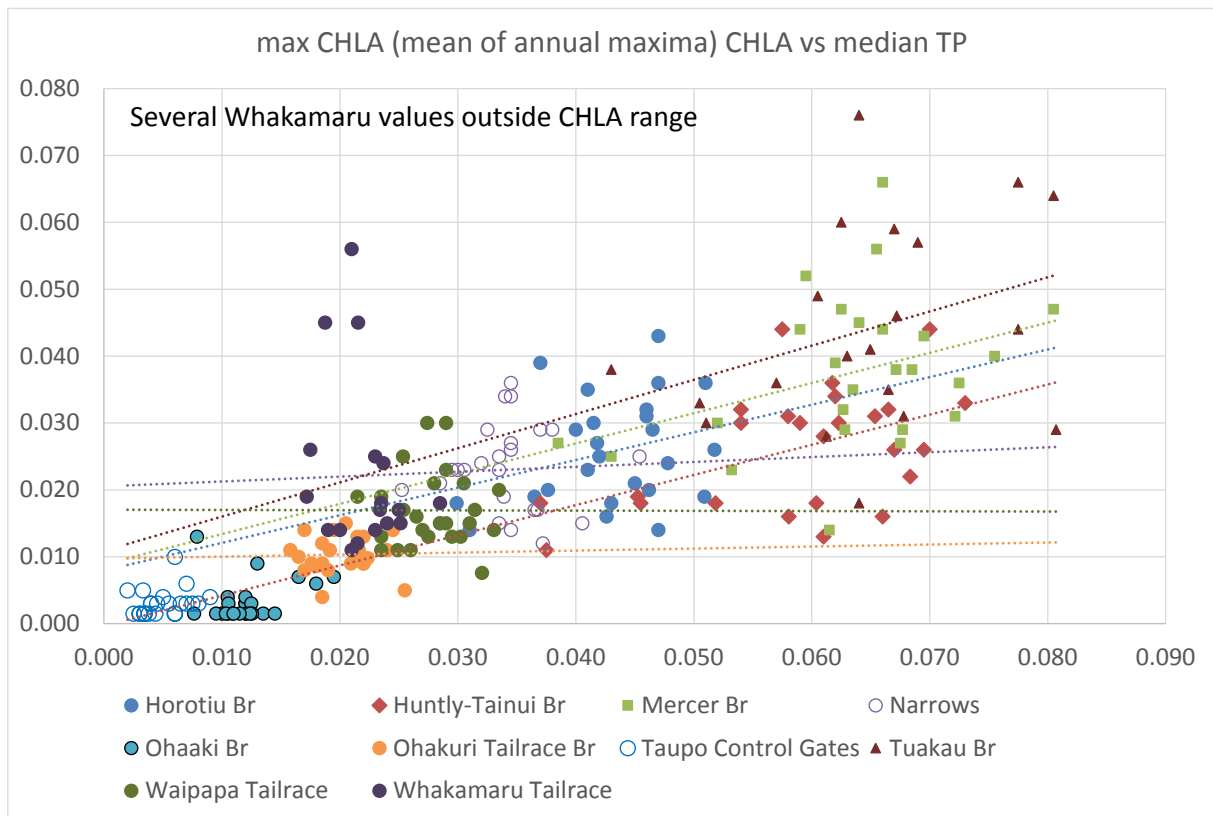


Fig. A30. Chlorophyll *a* plotted against TP. Annual maxima of chlorophyll *a* against median TP in 1990-2014 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Whakamaru, Ohaaki, Taupo Gates.

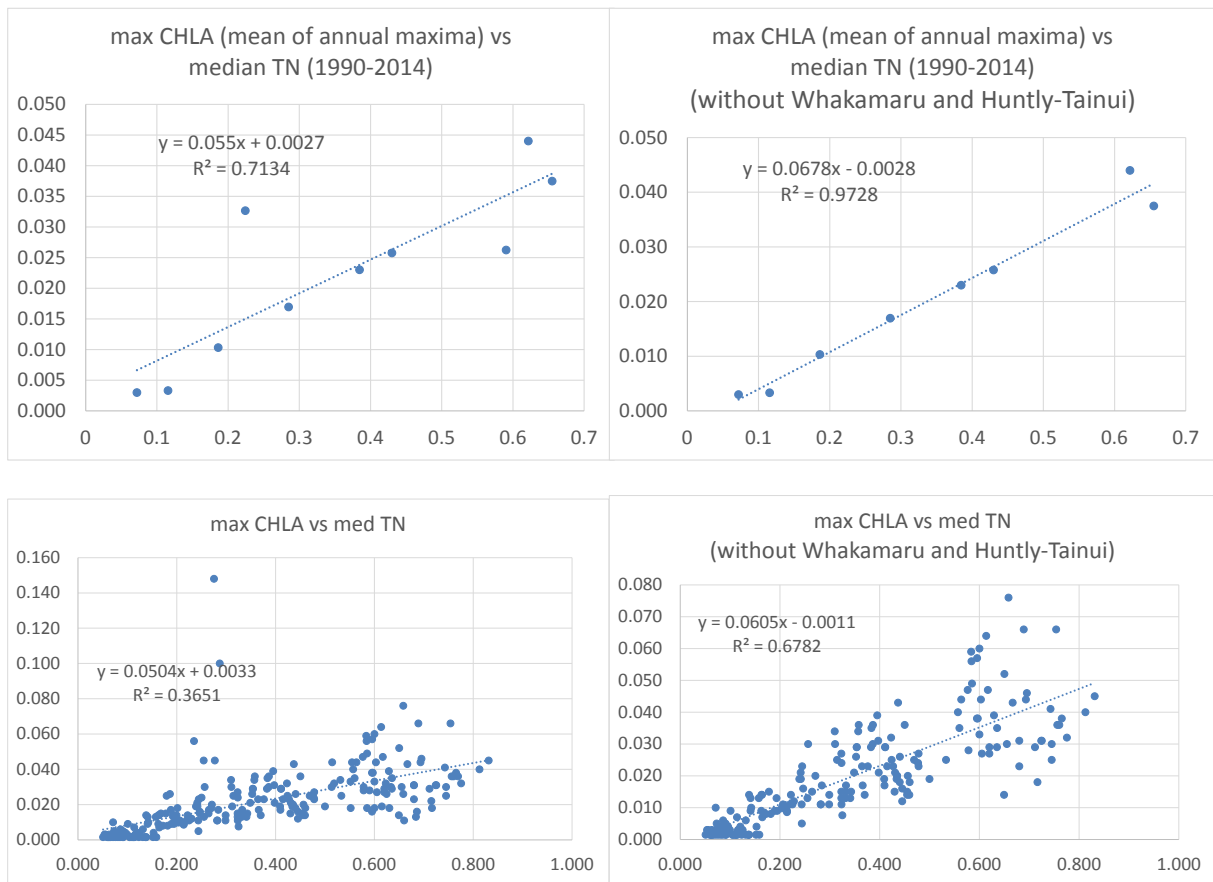


Fig. A31. Chlorophyll *a* plotted against TN. Shown are annual maxima of chlorophyll *a* against median TN, with and without Whakamaru and Huntly, of 1990-2014 (Tuakau and Whakamaru from 1995). Top: station values. Maximum chlorophyll *a* was calculated as the mean of annual maxima for each year. Bottom: values for each year for each station.

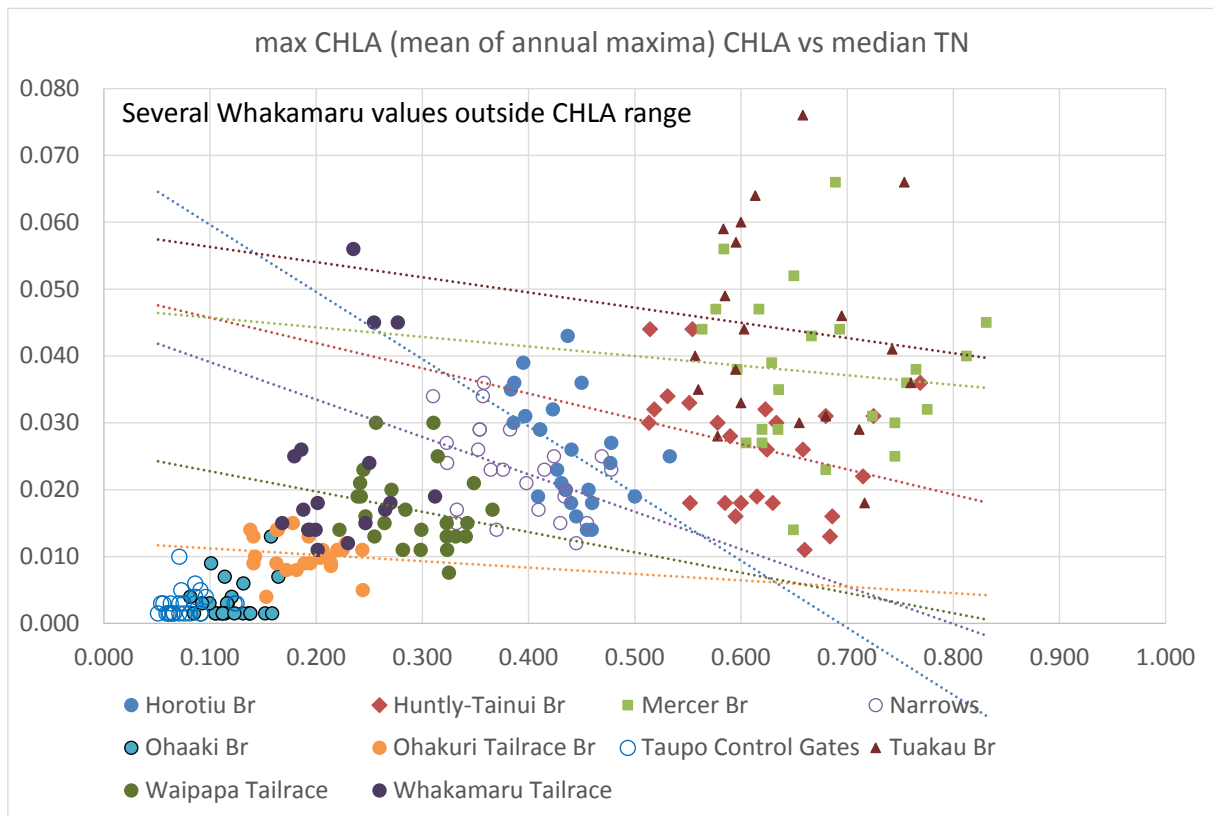


Fig. A32. Chlorophyll *a* plotted against TN. Annual maxima of chlorophyll *a* against median TN in 1990-2014 (Tuakau and Whakamaru from 1995). Regression lines shown for each station except Whakamaru, Ohaaki, Taupo Gates.

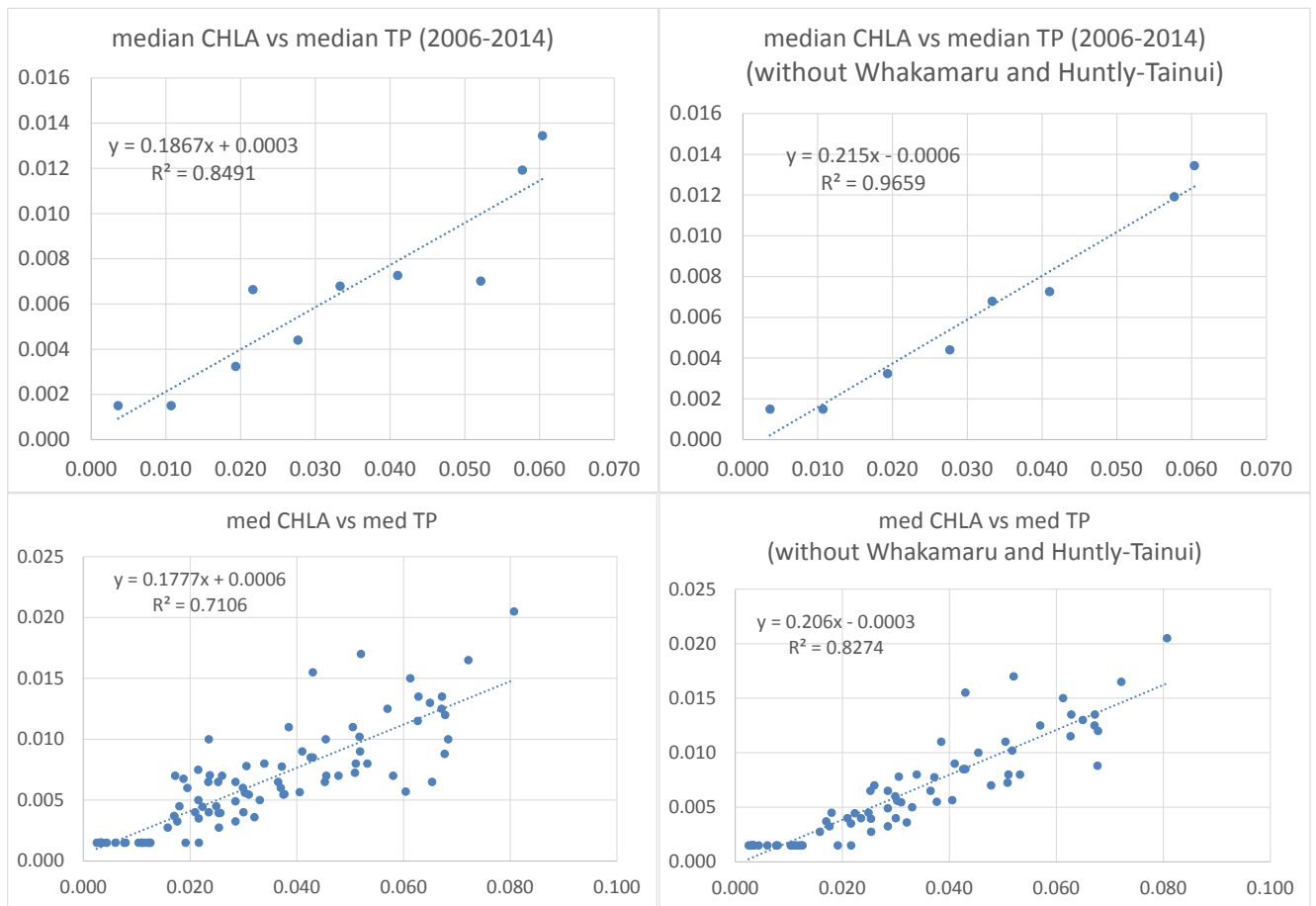


Fig. A33. Chlorophyll *a* plotted against TP. Shown are annual median data, with and without Whakamaru and Huntly, of 2006-2014. Top: station medians. Bottom: medians of each year for each station.

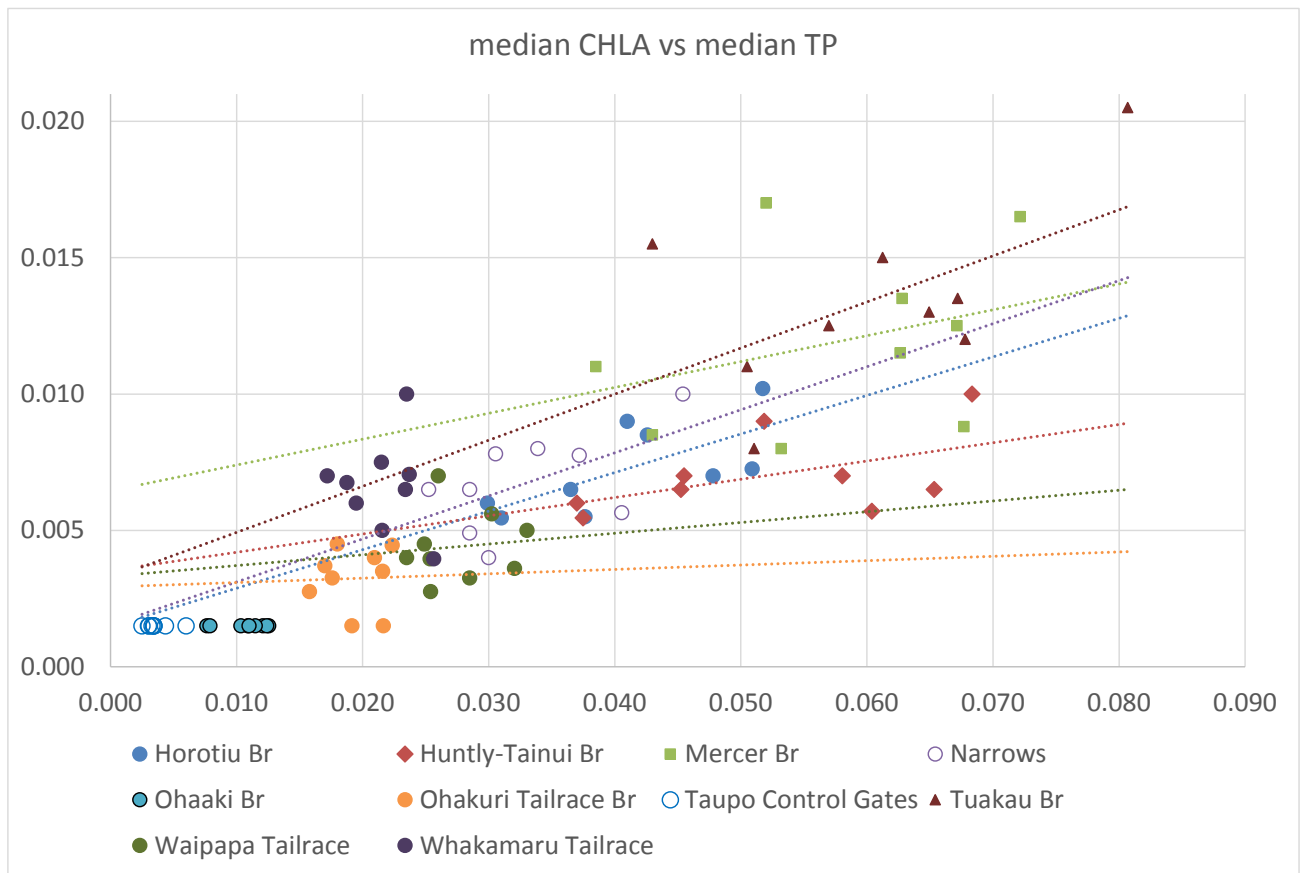


Fig. A34. Chlorophyll *a* plotted against TP. Annual medians in 2006-2014. Regression lines shown for each station except Whakamaru, Ohaaki, Taupo Gates.



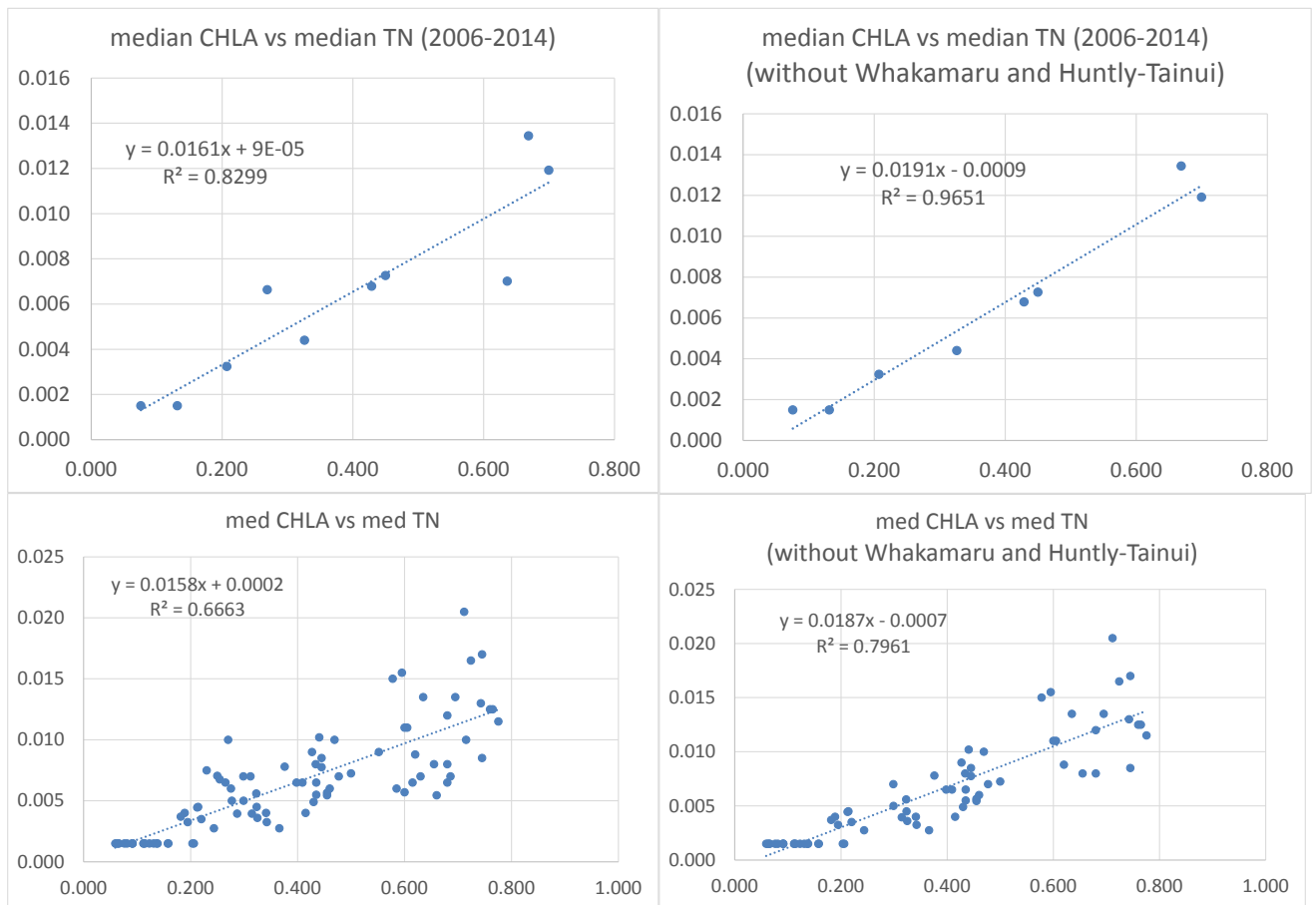


Fig. A35. Chlorophyll *a* plotted against TN. Shown are annual median data, with and without Whakamaru and Huntly, of 2006-2014. Top: station medians. Bottom: medians of each year for each station.

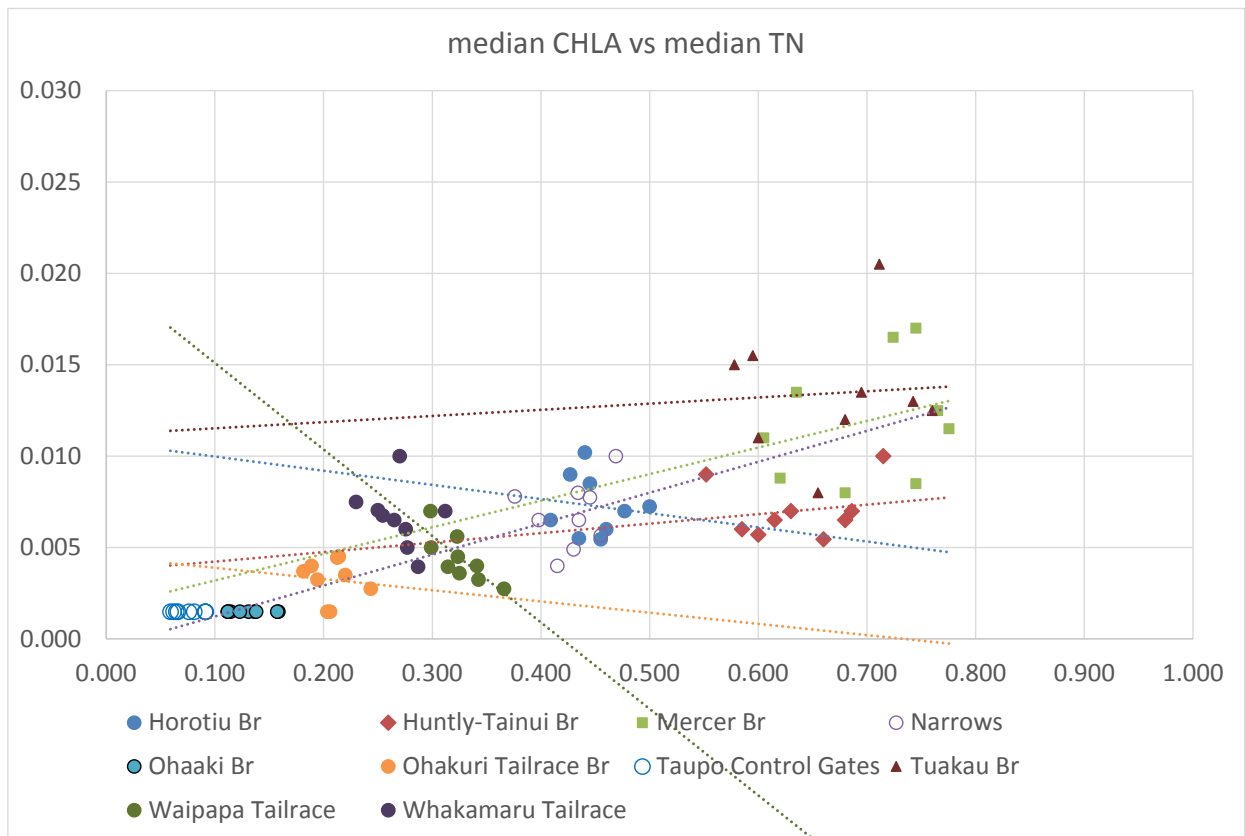


Fig. A36. Chlorophyll  $a$  plotted against TN. Annual medians in 2006-2014. Regression lines shown for each station except Whakamaru, Ohaaki, Taupo Gates.

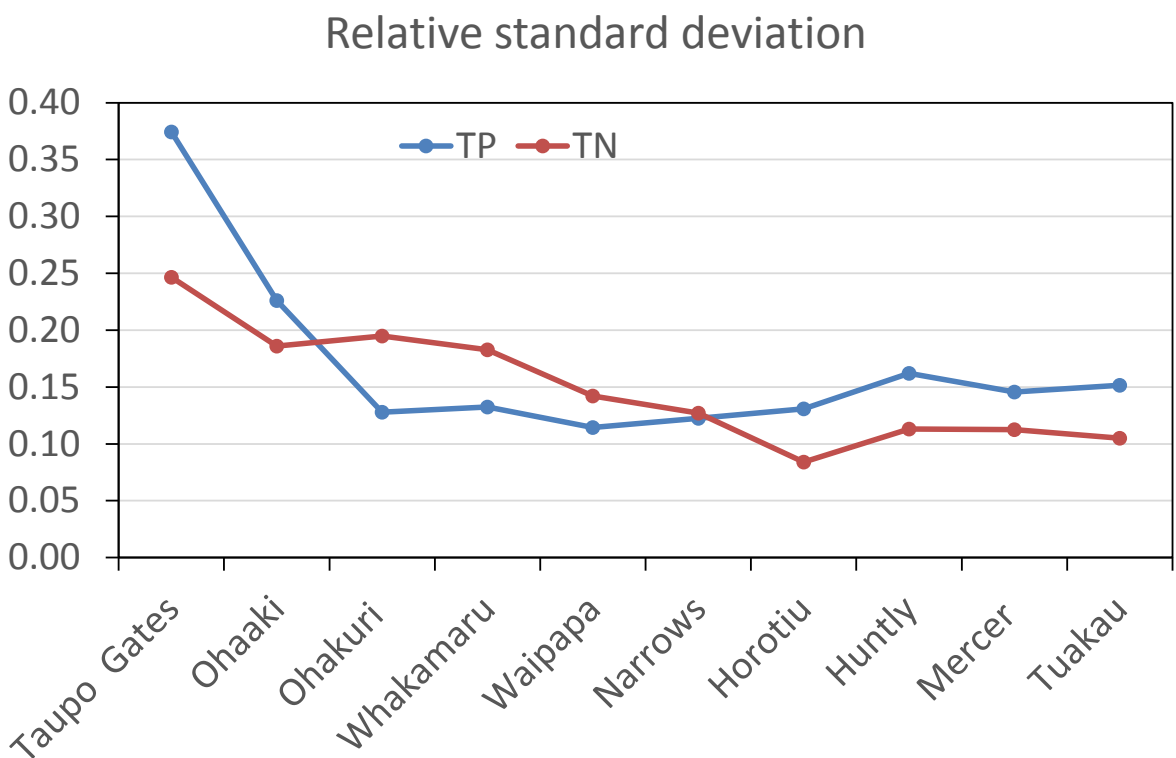
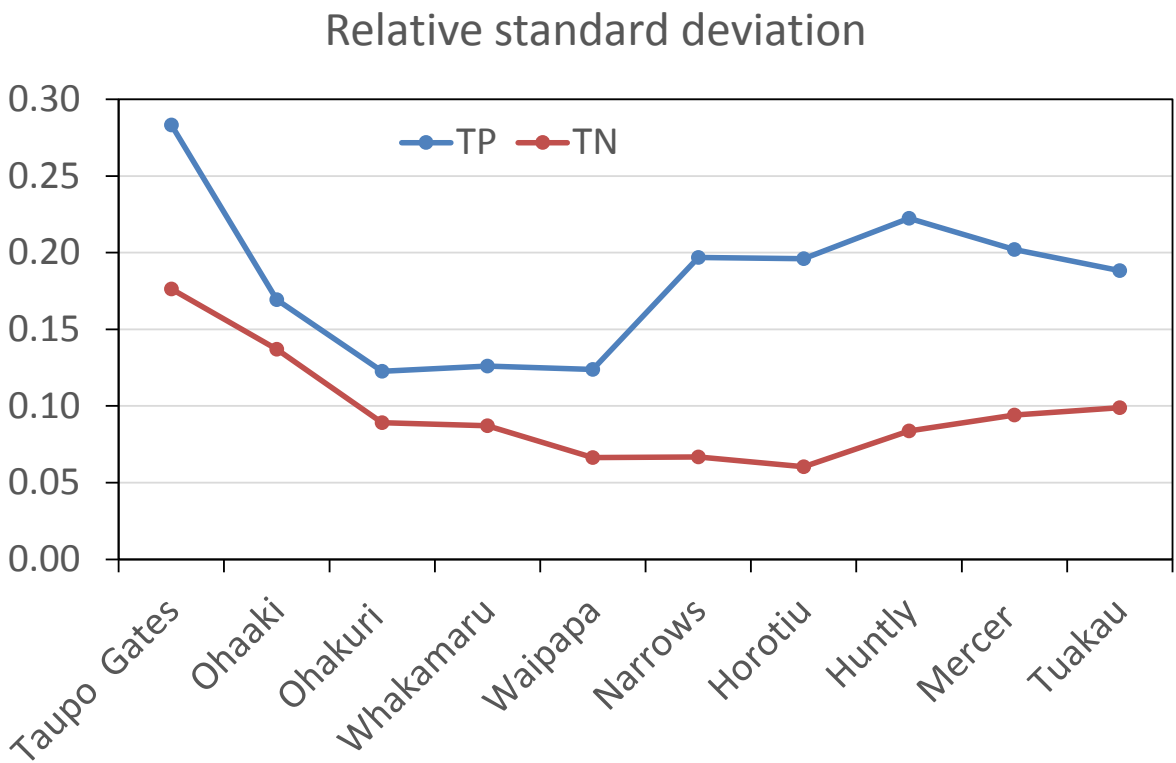


Fig. A37. Relative standard deviations (standard deviation divided by the mean) of annual medians of TP and TN for each station, in 2006-2014 (top) and 1990-2014 (bottom).

## Appendix B Station comparisons

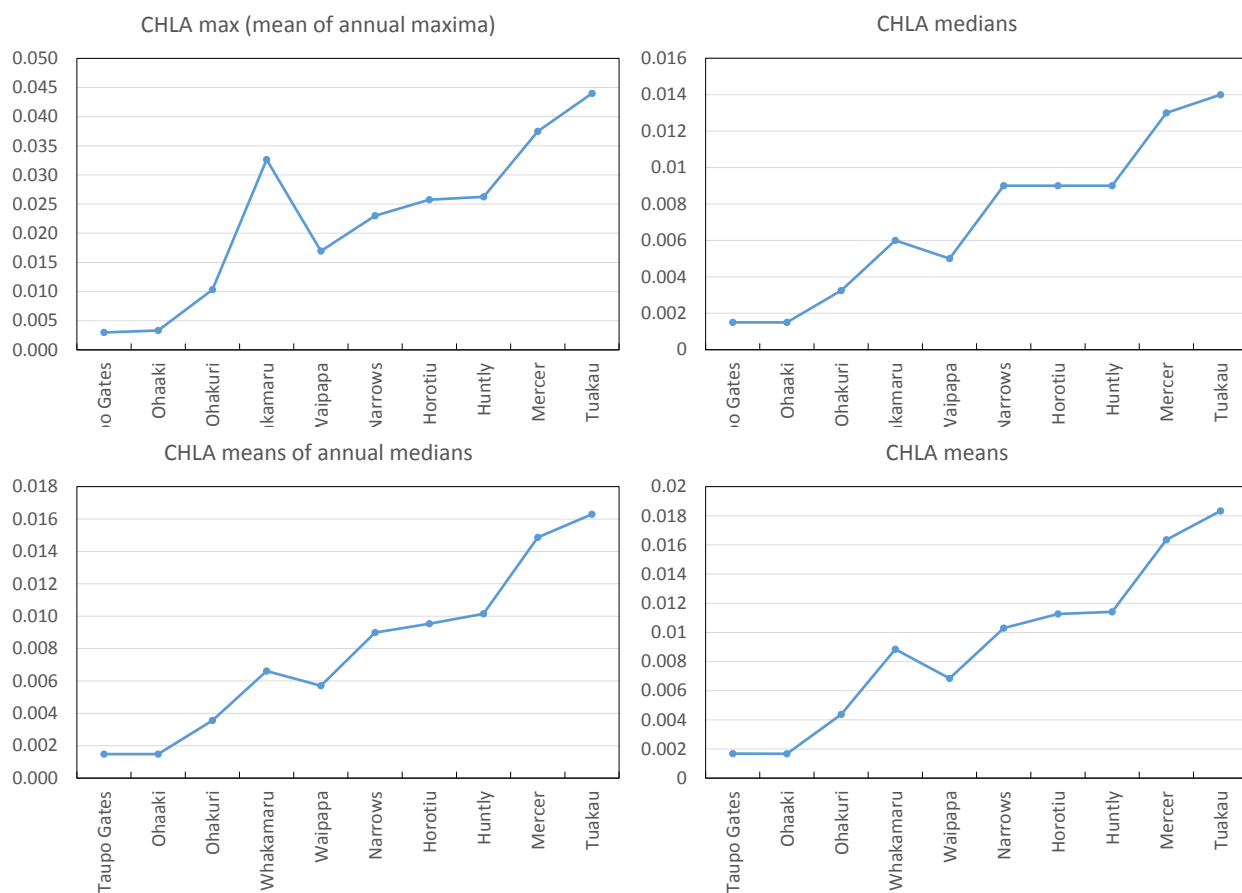


Fig. B1. Station comparisons, in order from Taupo on the left to downstream on the right, of chlorophyll *a*, means of annual maxima, overall medians, overall means, and means of annual medians. Data of 1990-2014 (Tuakau and Whakamaru from 1995).

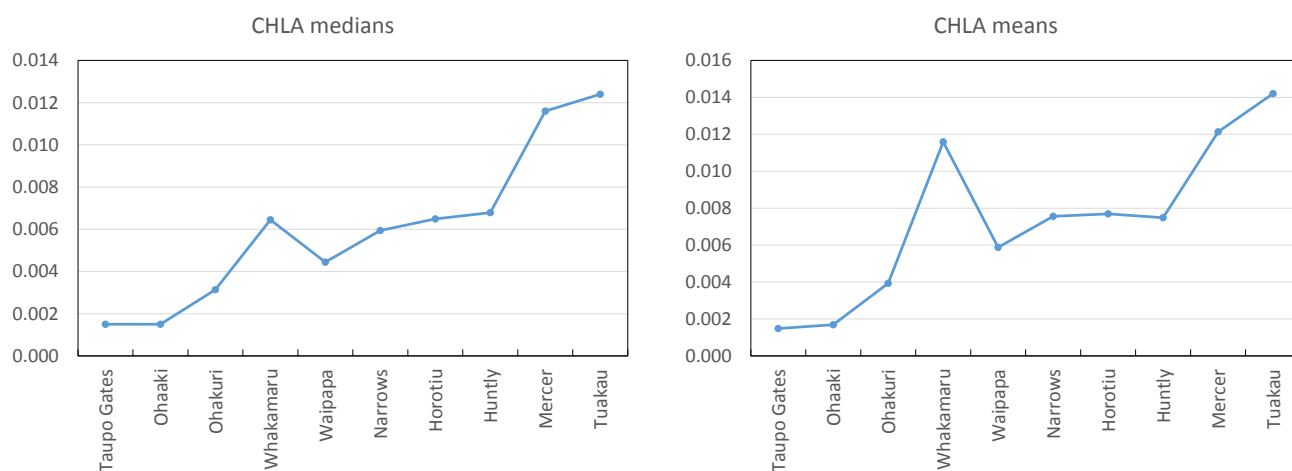


Fig. B2. Station comparisons, in order from Taupo, of chlorophyll *a*, means of annual medians and overall means. Data of 2010-2014.

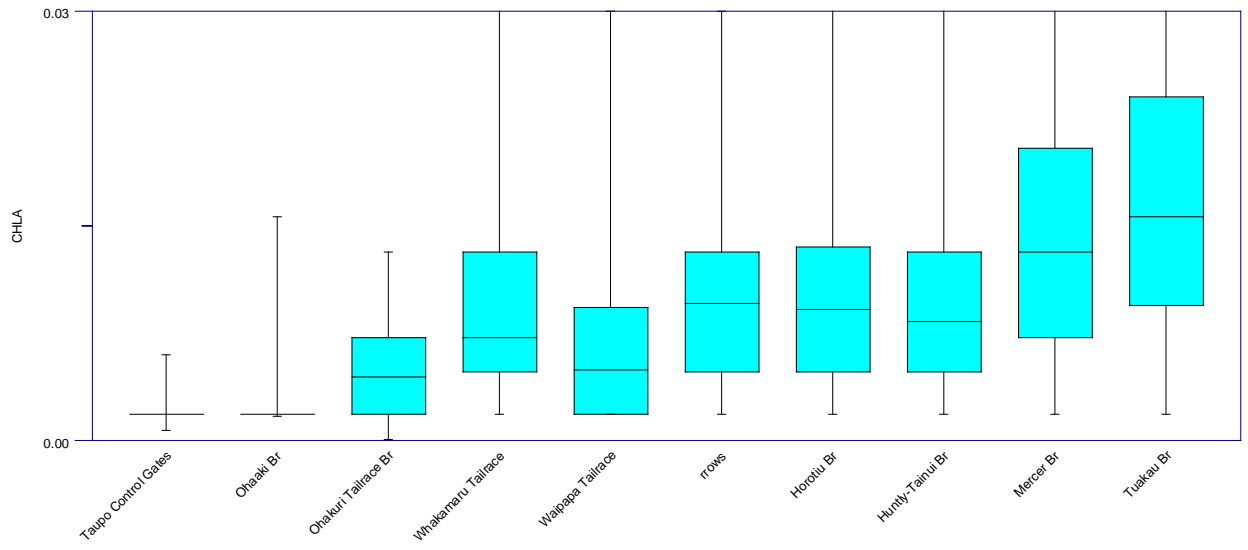


Fig. B3. Boxplots of chlorophyll *a* by station, in order from Taupo. Data of 2010-2014.

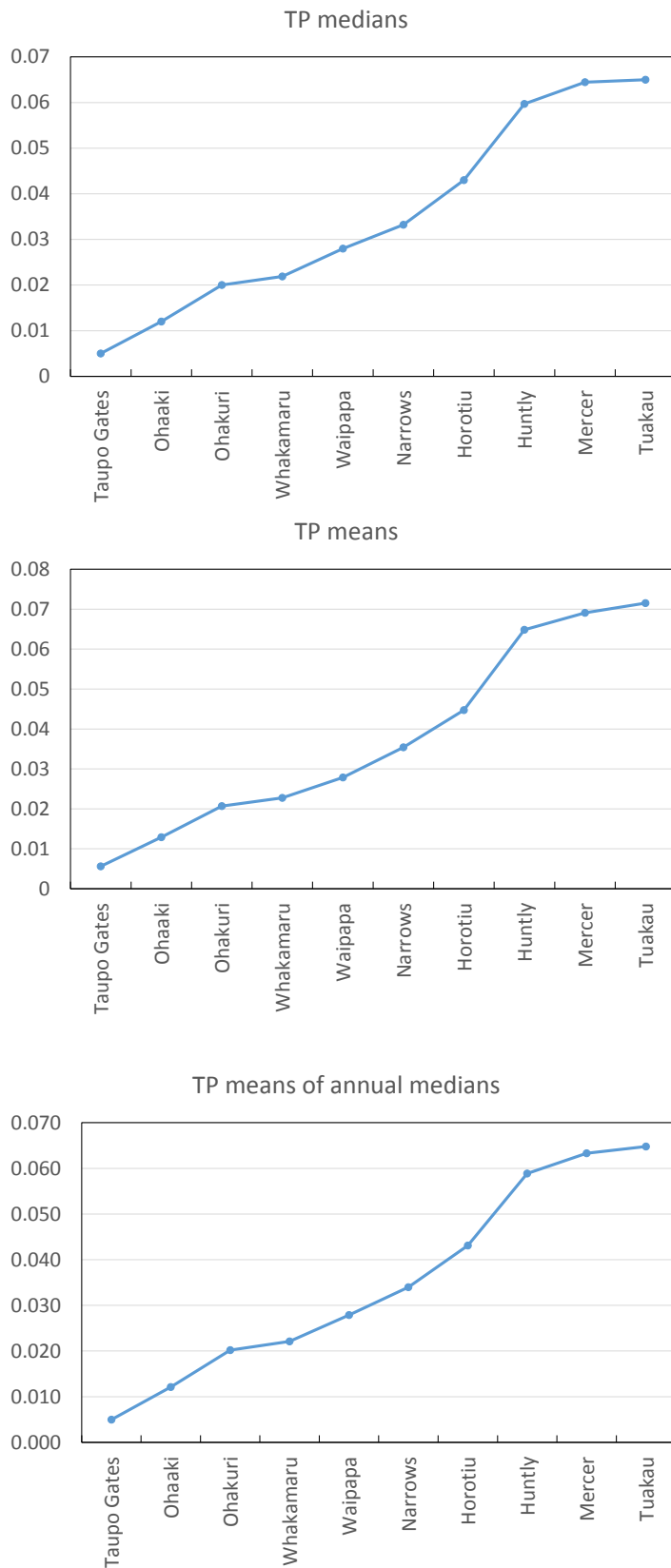


Fig. B4. Station comparisons, in order from Taupo on the left to downstream on the right, of TP, overall medians, overall means, and means of annual medians. Data of 1990-2014 (Tuakau and Whakamaru from 1995).

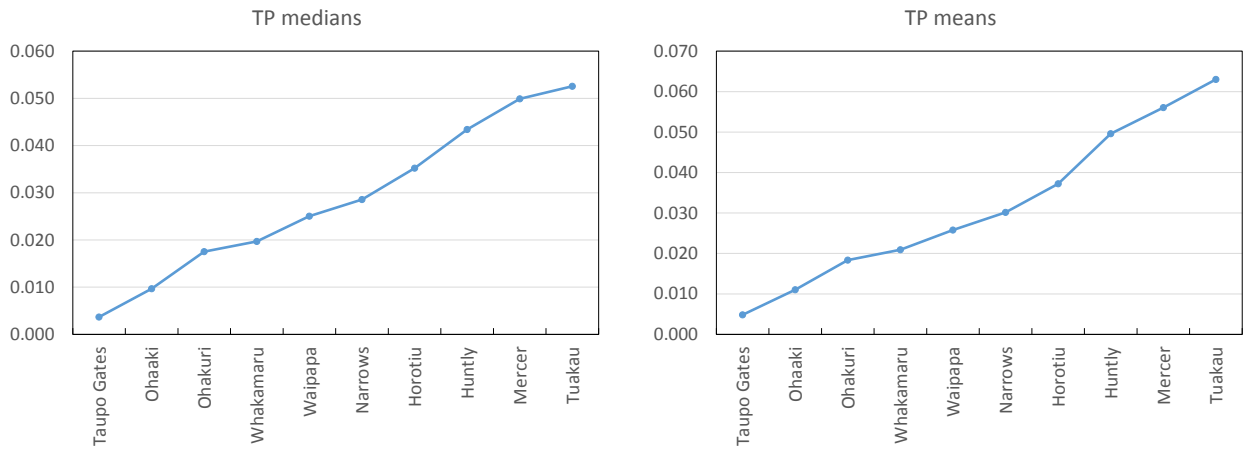


Fig. B5. Station comparisons, in order from Taupo, of TP, means of annual medians, and overall means. Data of 2010-2014.

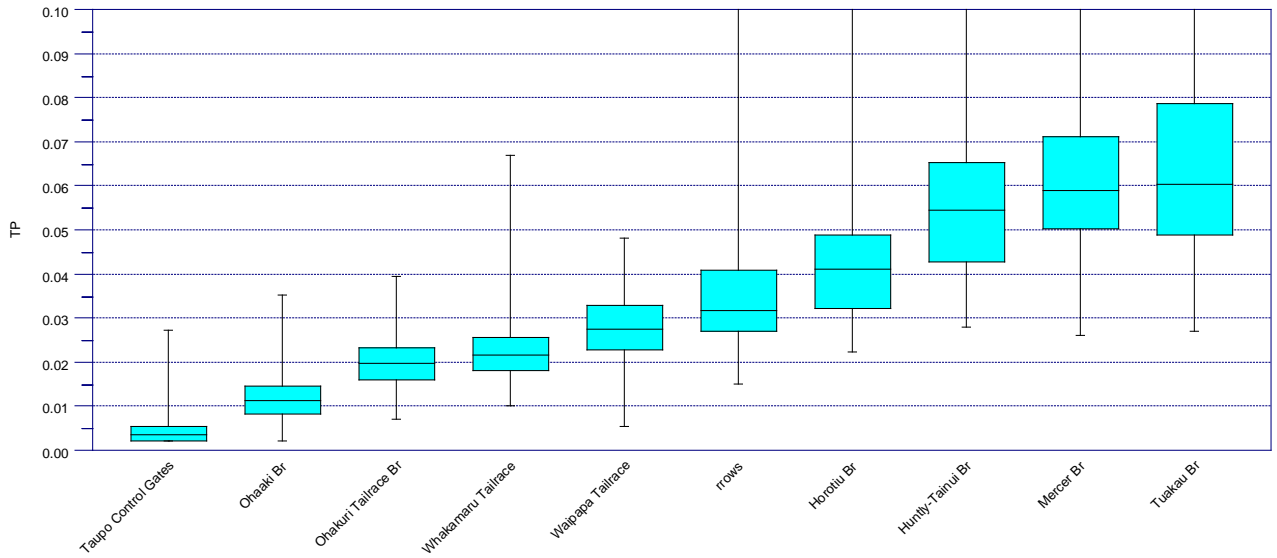


Fig. B6. Boxplots of TP by station, in order from Taupo. Data of 2010-2014.

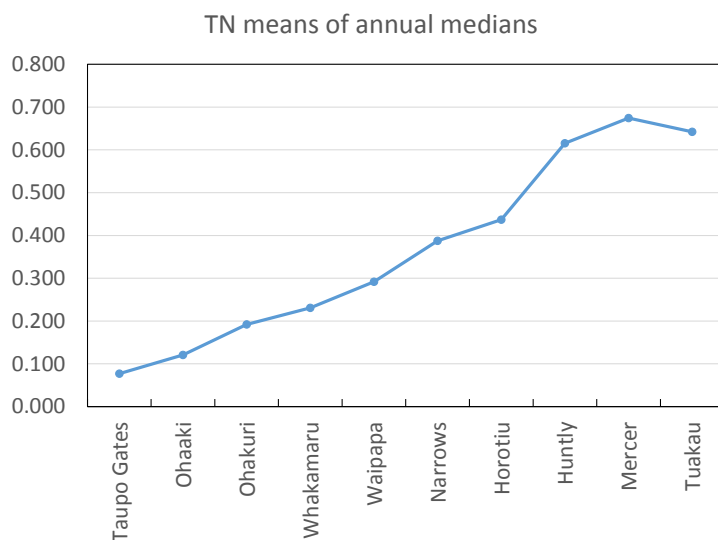
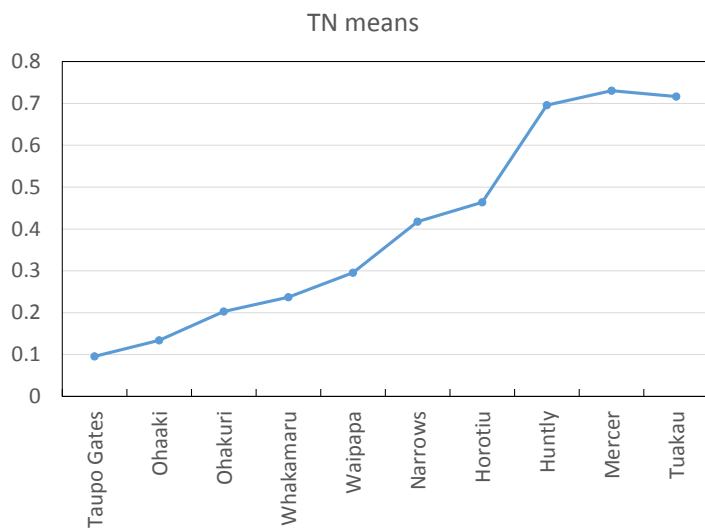
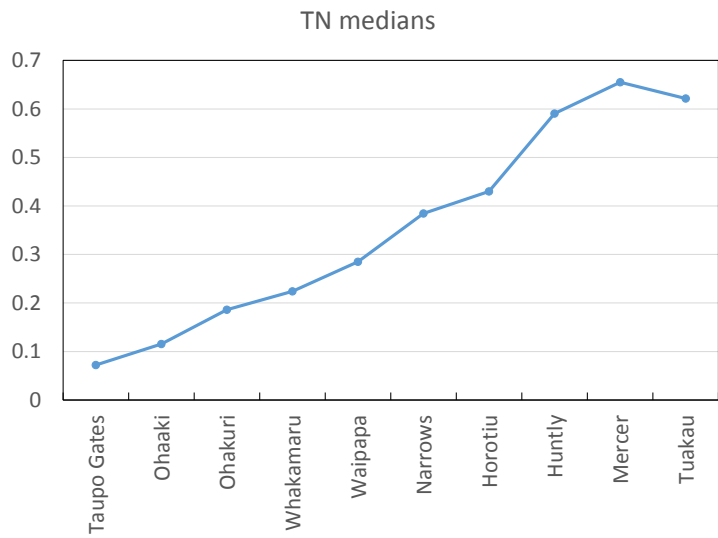


Fig. B7. Station comparisons, in order from Taupo on the left to downstream on the right, of TN, overall medians, overall means, and means of annual medians. Data of 1990-2014 (Tuakau and Whakamaru from 1995).



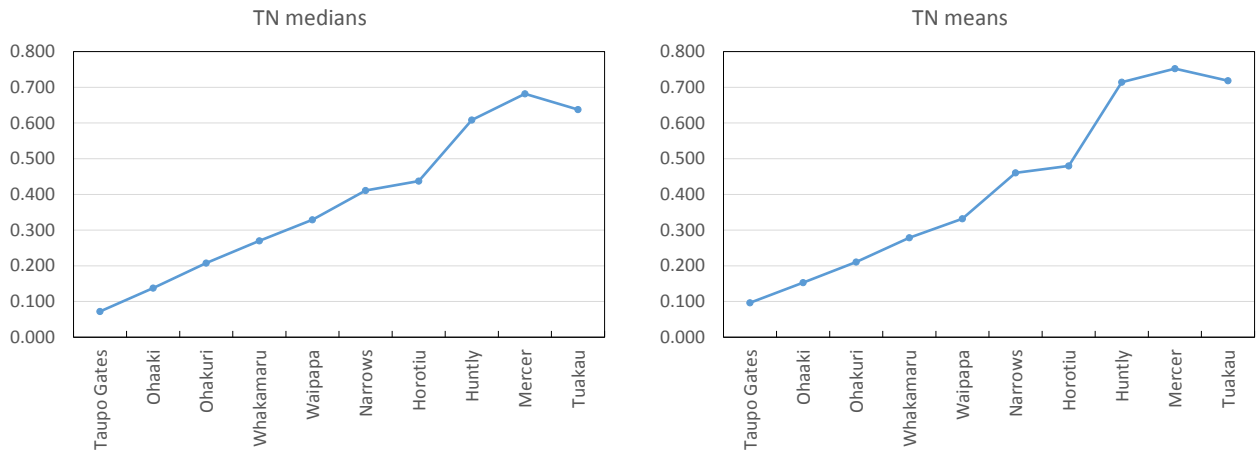


Fig. B8. Station comparisons, in order from Taupo, of TN, means of annual medians, and overall means. Data of 2010-2014.

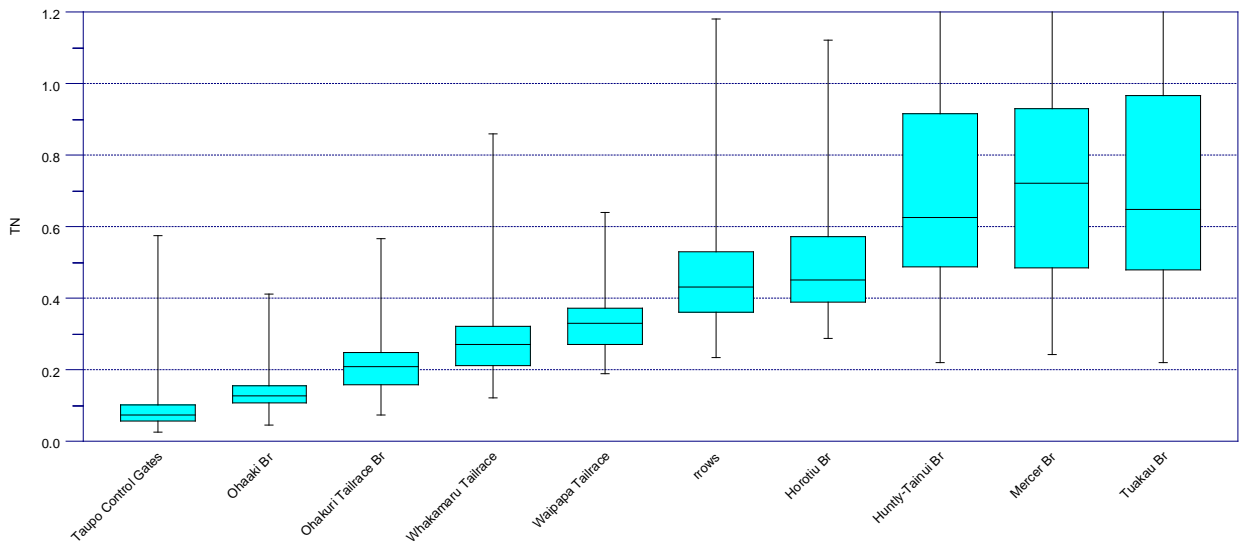


Fig. B9. Boxplots of TN by station, in order from Taupo. Data of 2010-2014.

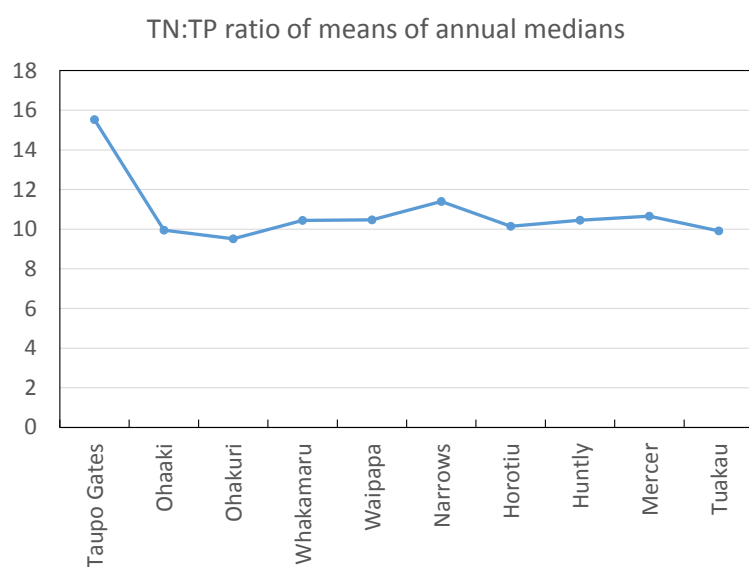
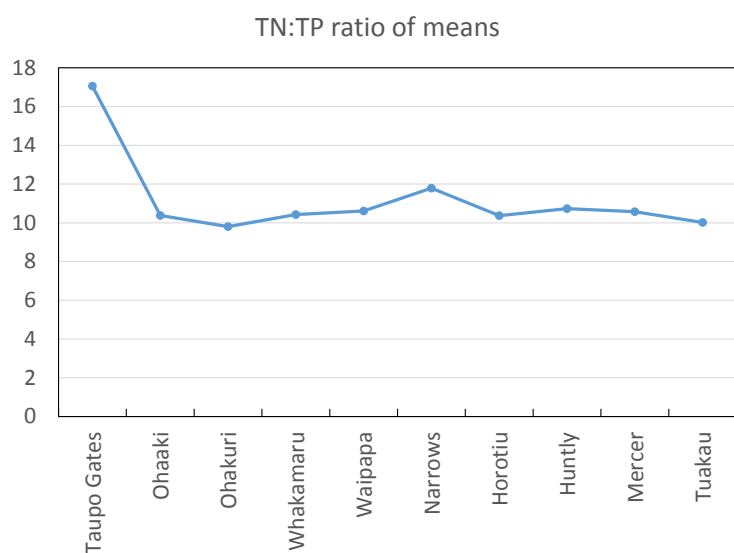
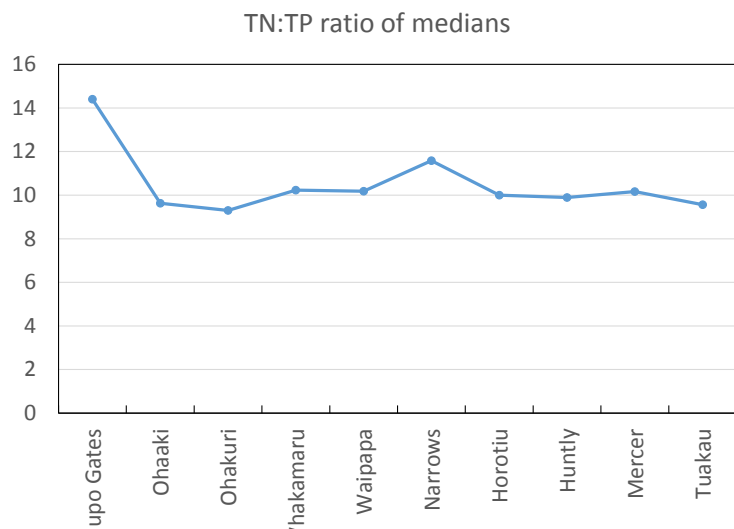


Fig. B10. Station comparisons, in order from Taupo on the left to downstream on the right, of the TN:TP ratio (weight ratios, not atomic), overall medians, overall means, and means of annual medians. Data of 1990-2014 (Tuakau and Whakamaru from 1995).

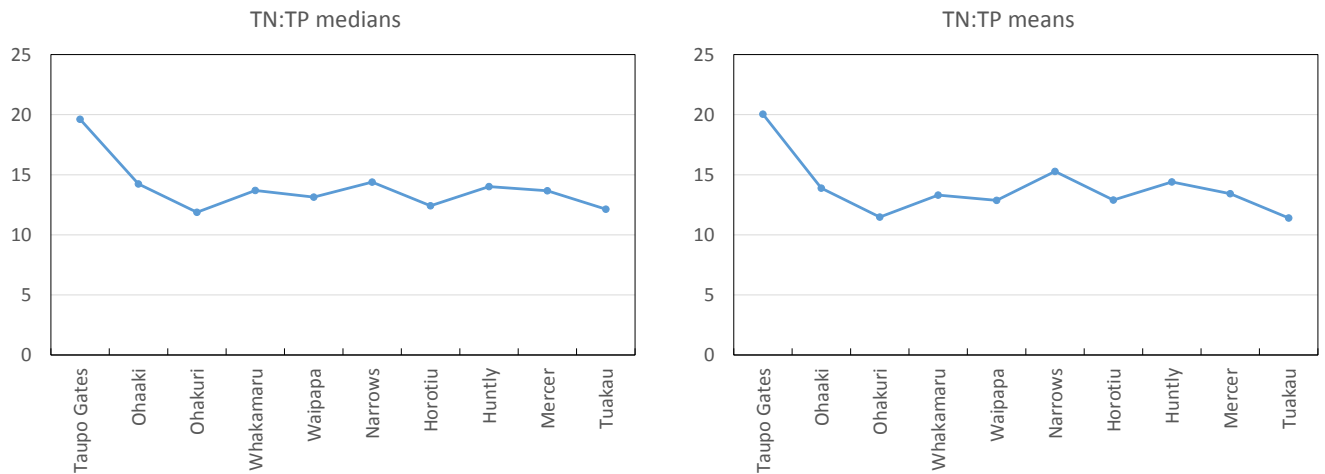


Fig. B11. Station comparisons, in order from Taupo, of the TN:TP ratios, ratios of means of annual medians, and ratios of overall means (weight ratios). Data of 2010-2014.



Fig. B12. Station comparisons, in order from Taupo, of DRP, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

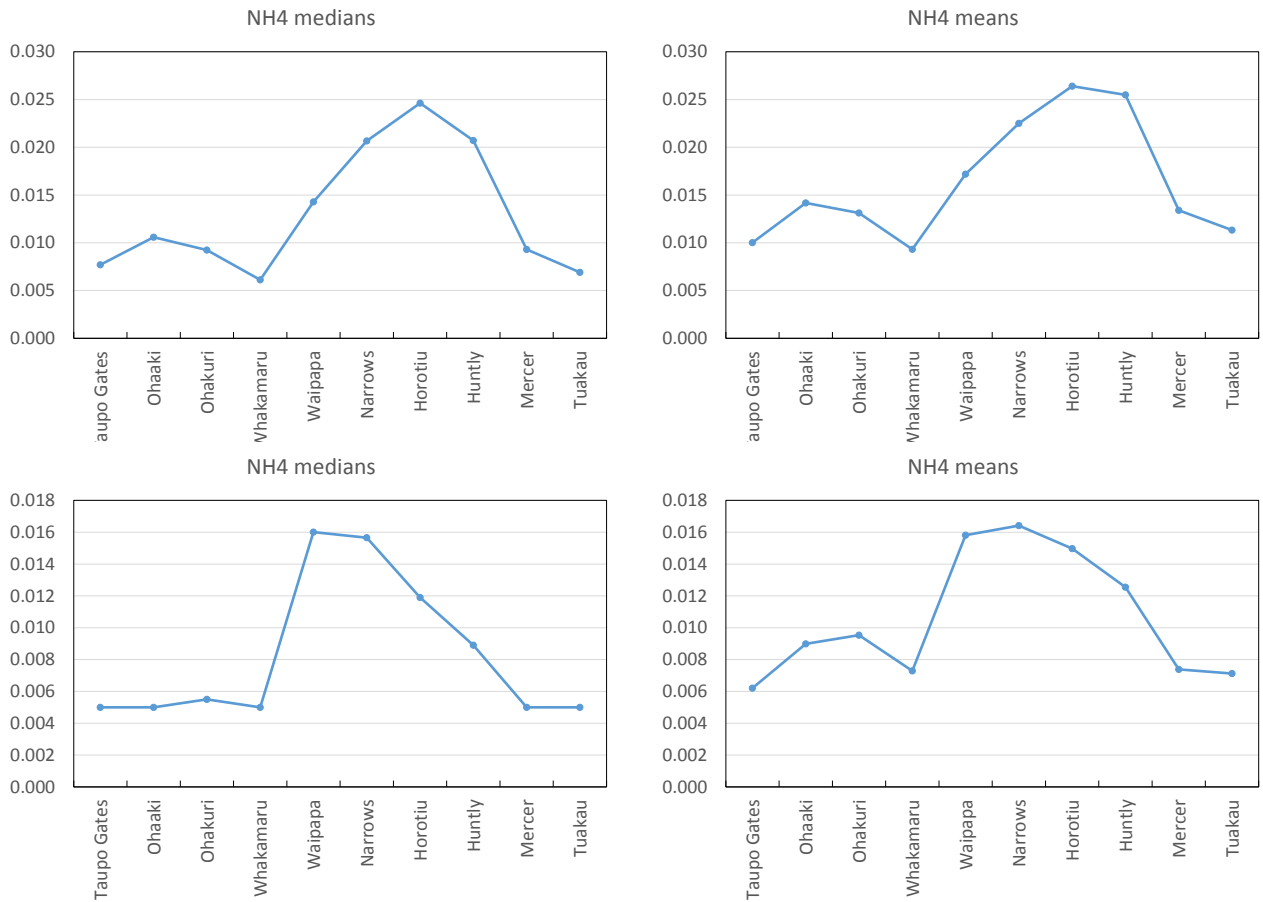


Fig. B13. Station comparisons, in order from Taupo, of NH<sub>4</sub>, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

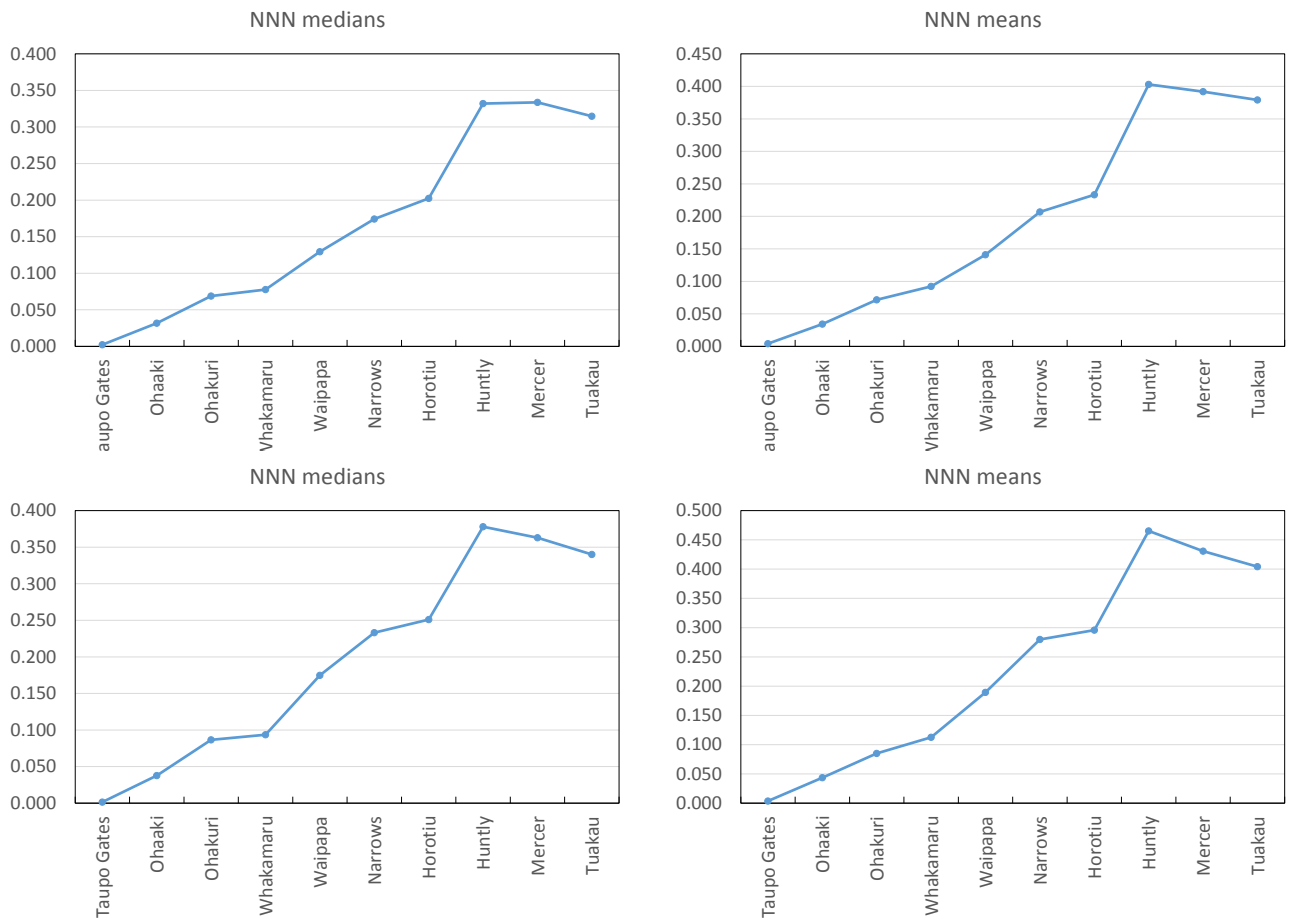


Fig. B14. Station comparisons, in order from Taupo, of NO<sub>3</sub>, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

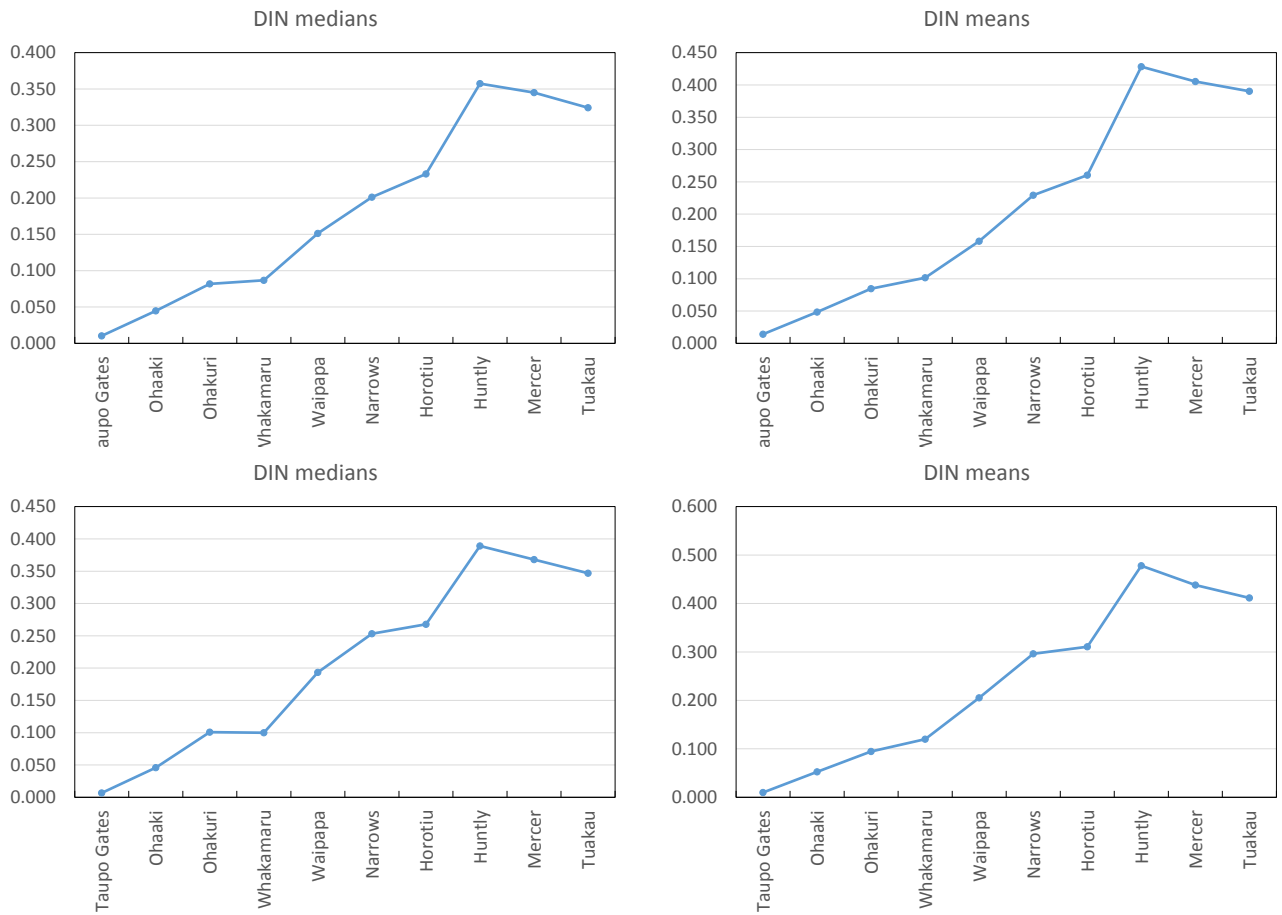


Fig. B15. Station comparisons, in order from Taupo, of DIN, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

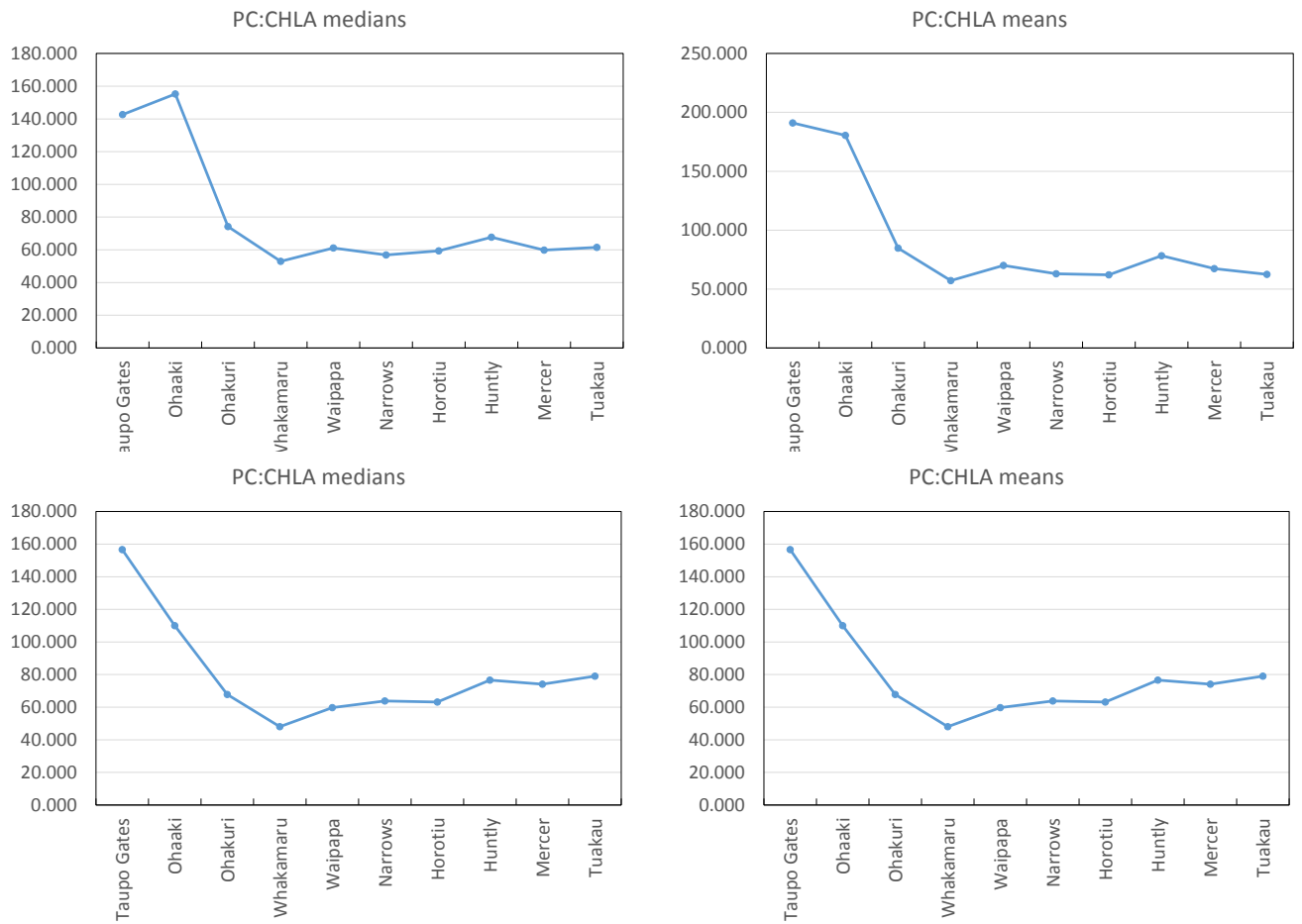


Fig. B16. Station comparisons, in order from Taupo, of PC : chlorophyll *a*, the ratio of means of annual medians, and the ratio of overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

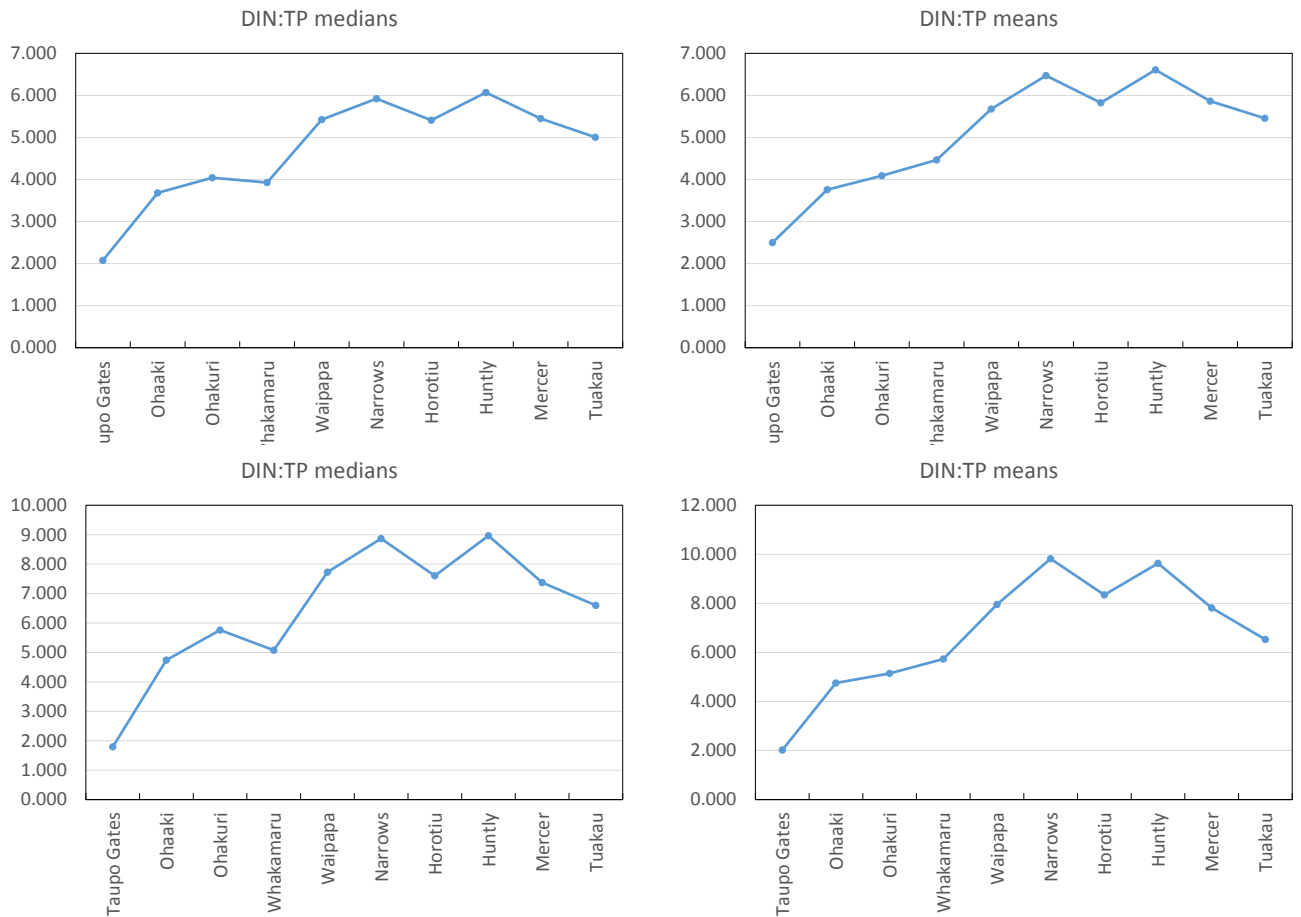


Fig. B17. Station comparisons, in order from Taupo, of DIN : TP, the ratio of means of annual medians, and the ratio of overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.





Fig. B18. Station comparisons, in order from Taupo, of DIN : DRP, the ratio of means of annual medians, and the ratio of overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

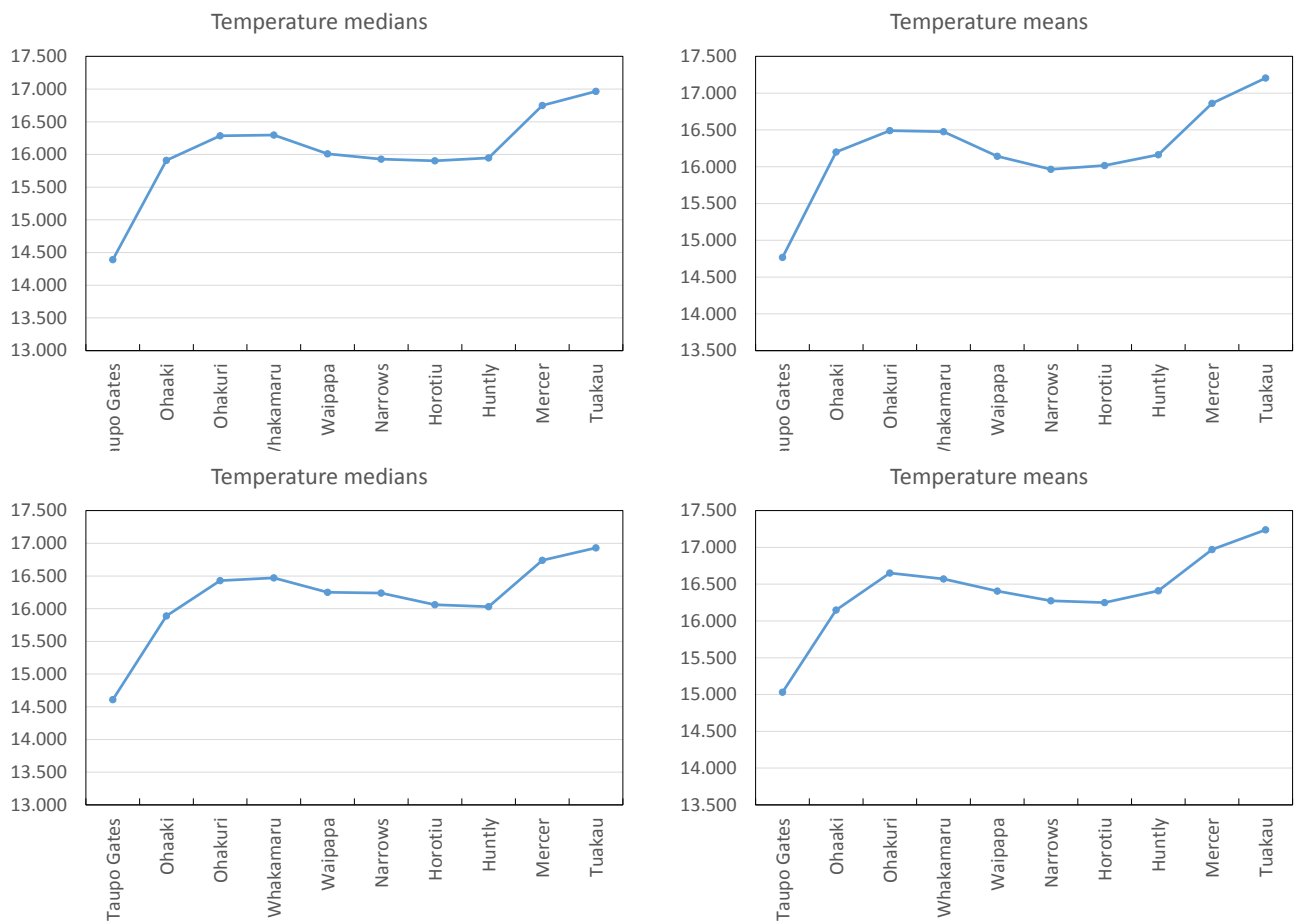


Fig. B19. Station comparisons, in order from Taupo, of water temperature, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

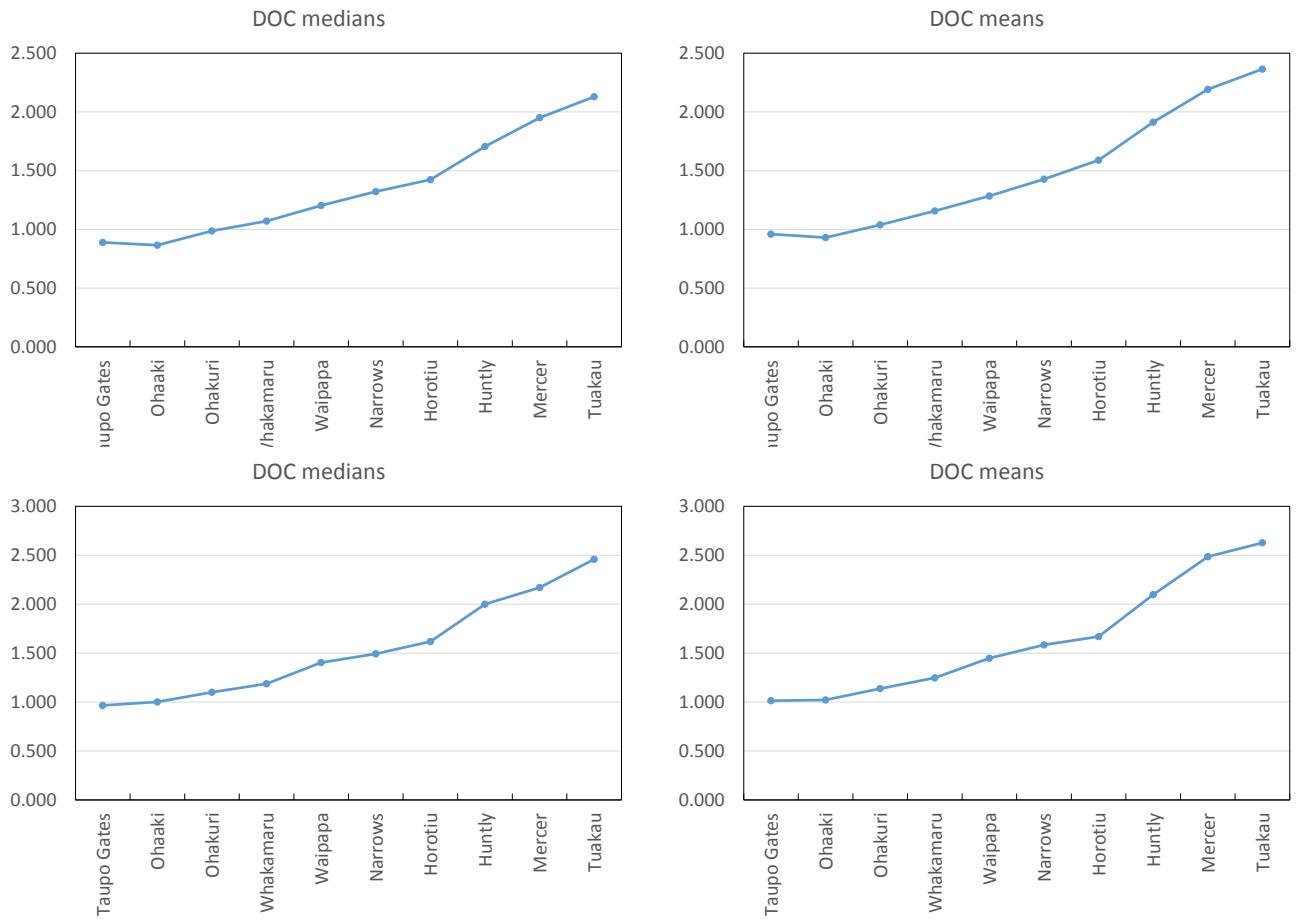


Fig. B20. Station comparisons, in order from Taupo, of DOC, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

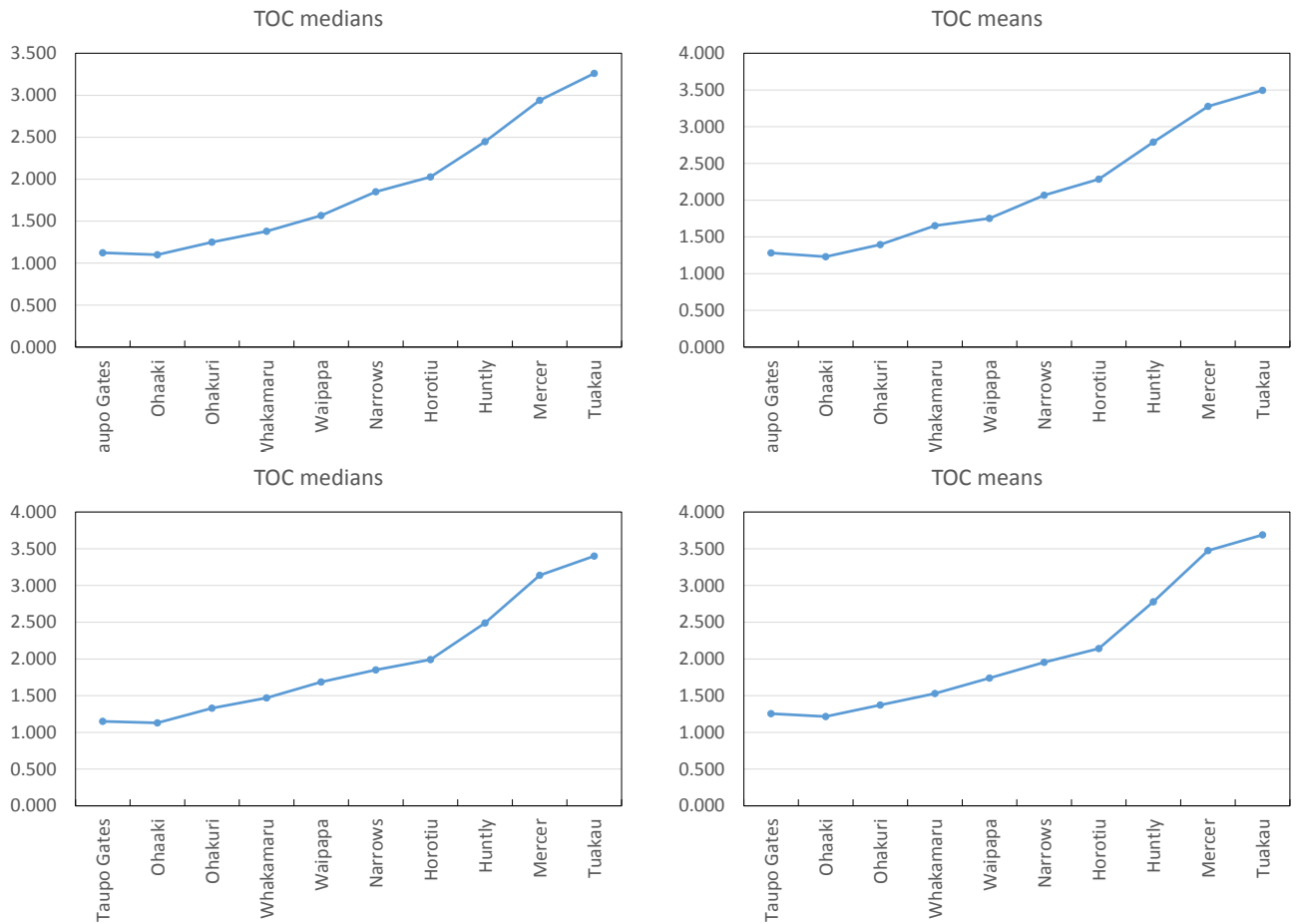


Fig. B21. Station comparisons, in order from Taupo, of TOC, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

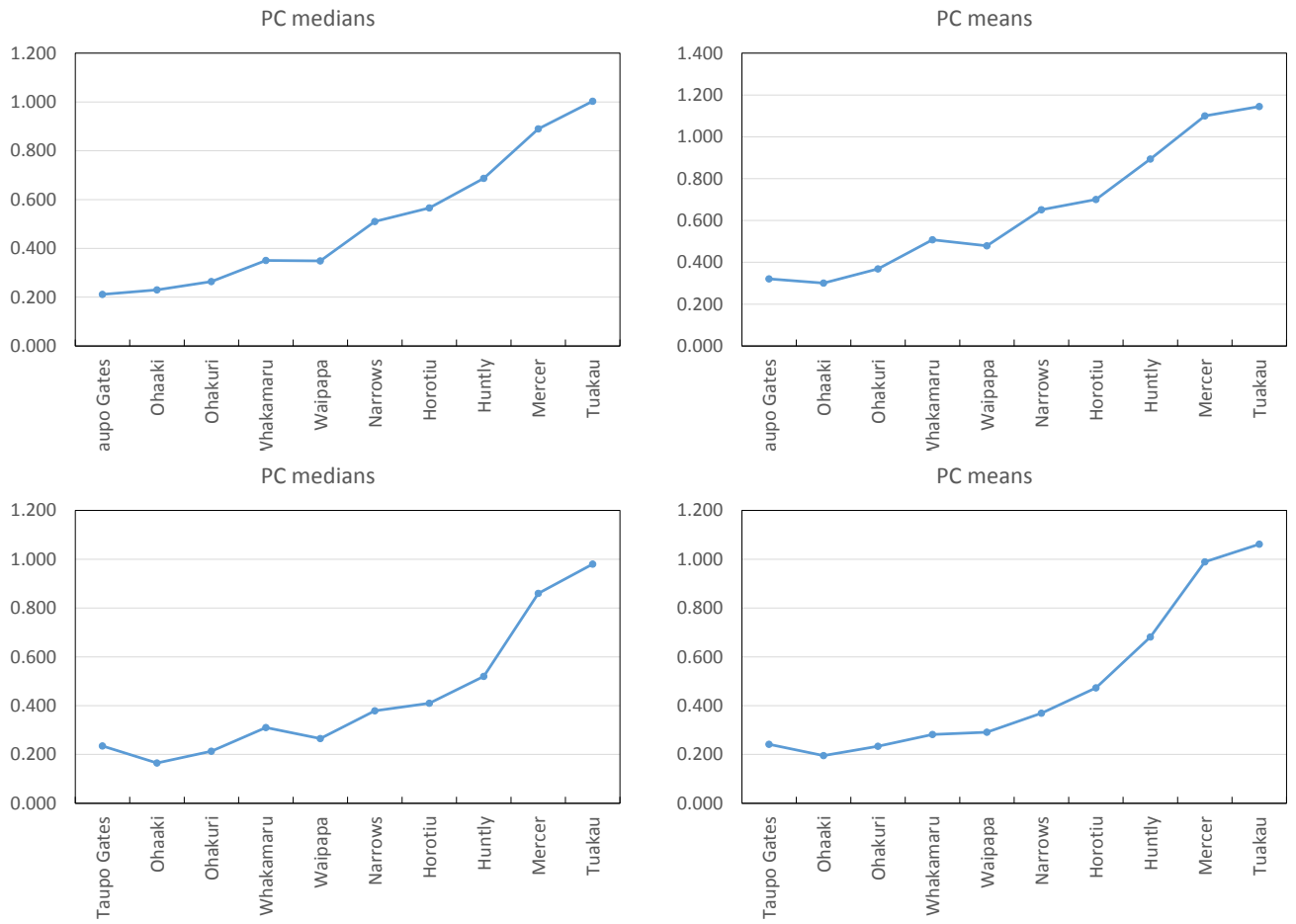


Fig. B22. Station comparisons, in order from Taupo, of PC, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

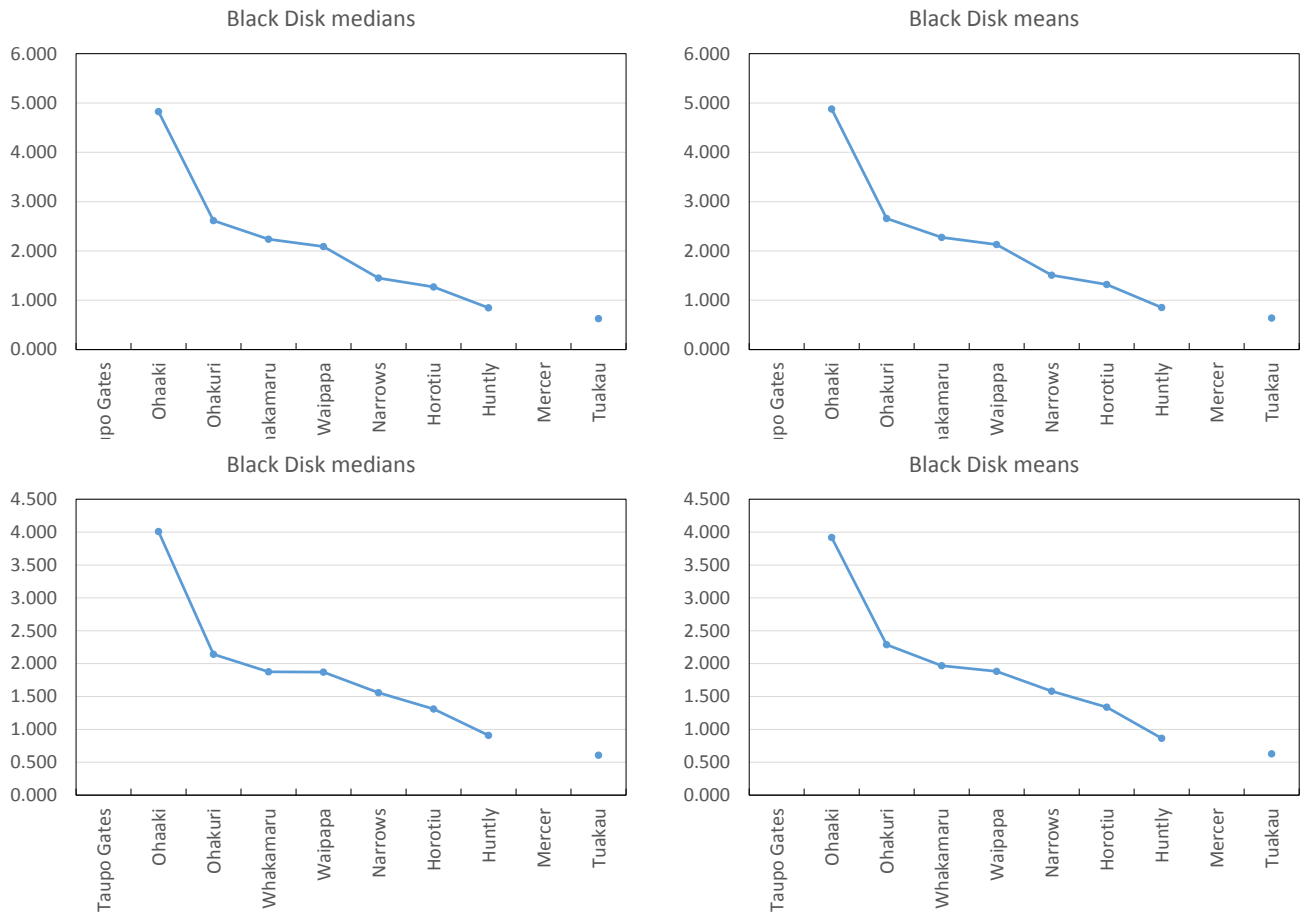


Fig. B23. Station comparisons, in order from Taupo, of Black Disk water clarity, means of annual medians, and overall means. Top: Data of 1990-2014 (Tuakau and Whakamaru from 1995). Bottom: Data of 2010-2014.

## Appendix C Seasonality in variables

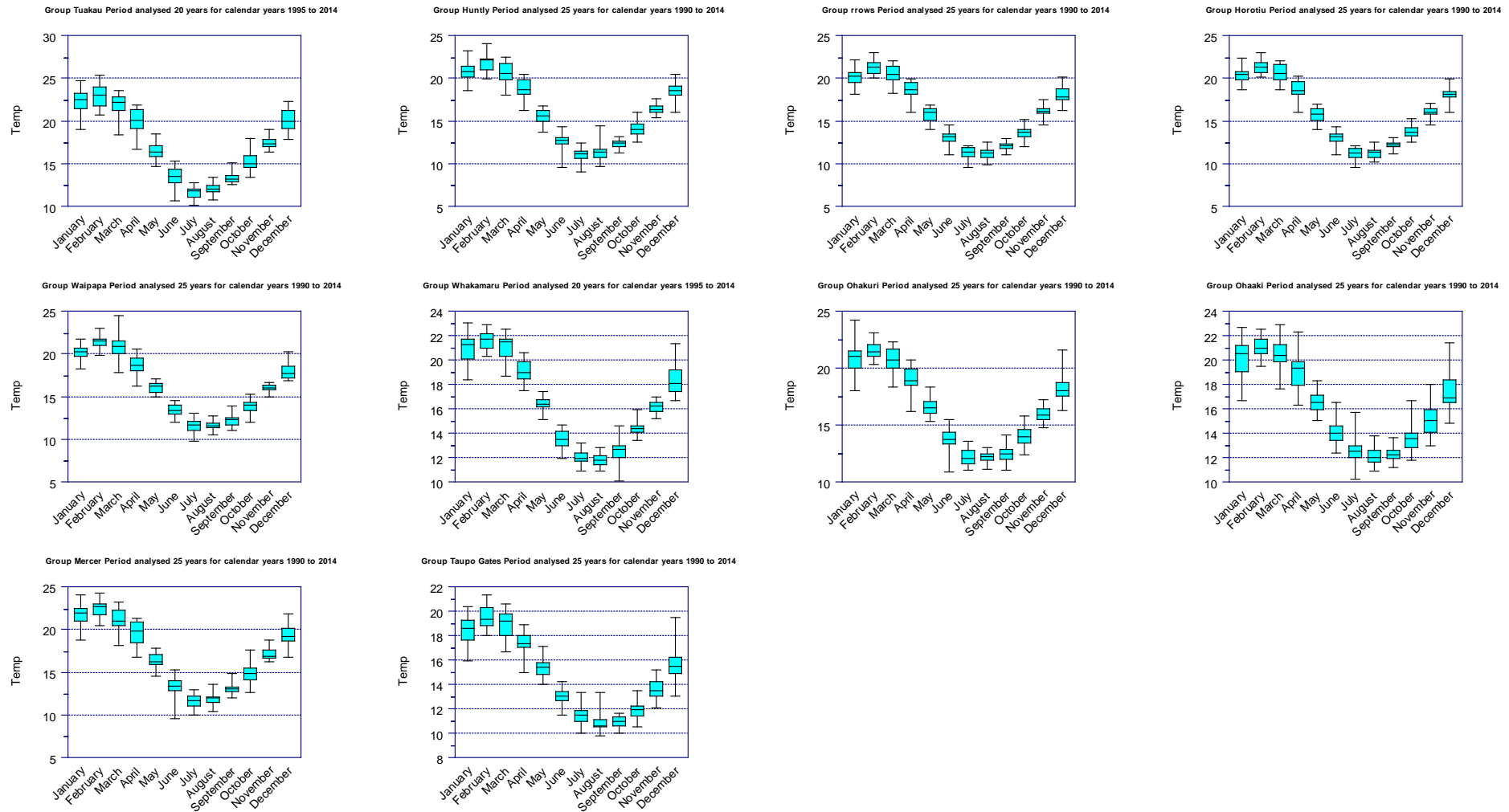


Fig. C1. Seasonality in 1990-2014 in water temperature.

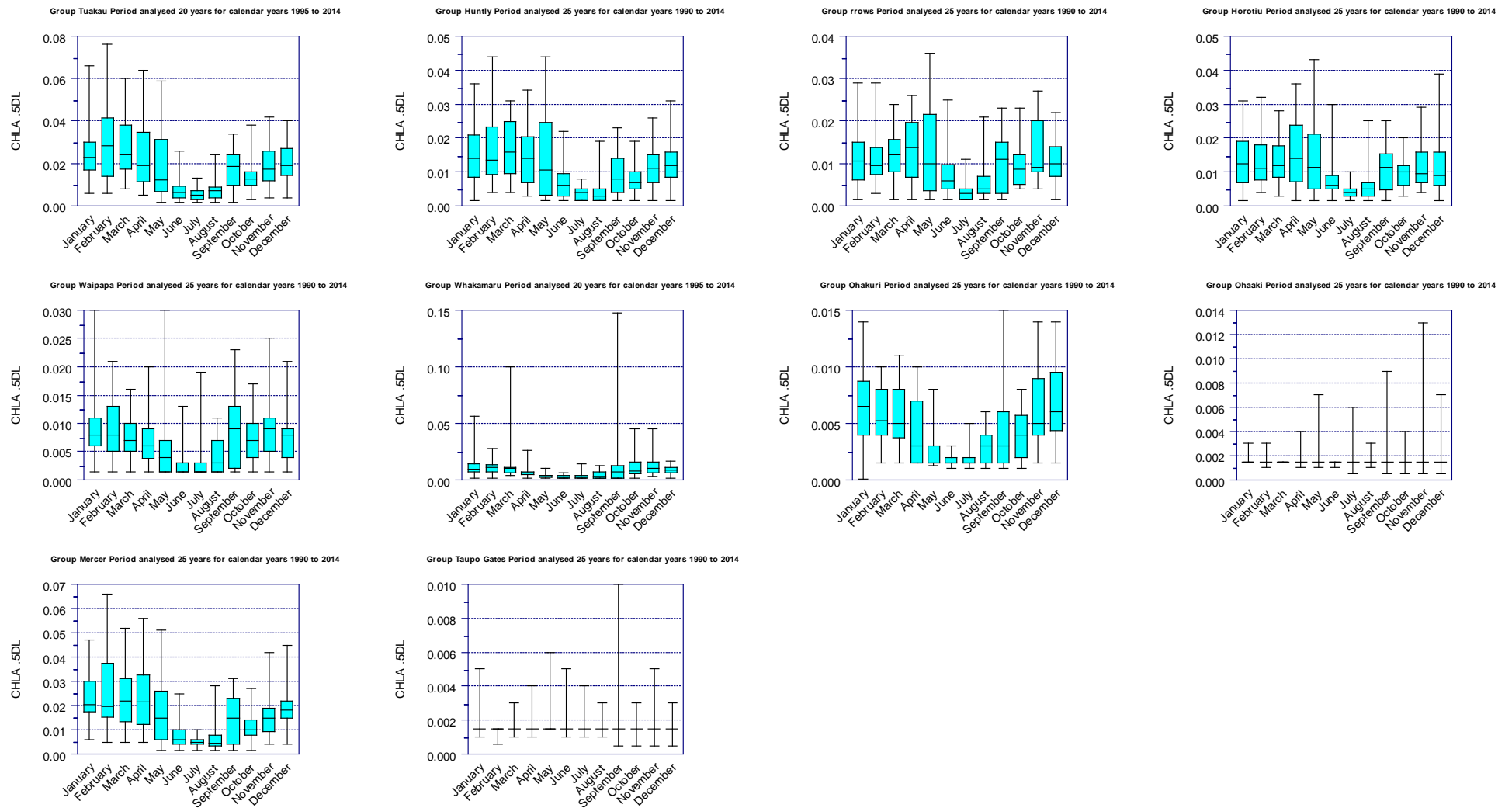


Fig. C2. Seasonality in 1990-2014 in chlorophyll *a*.



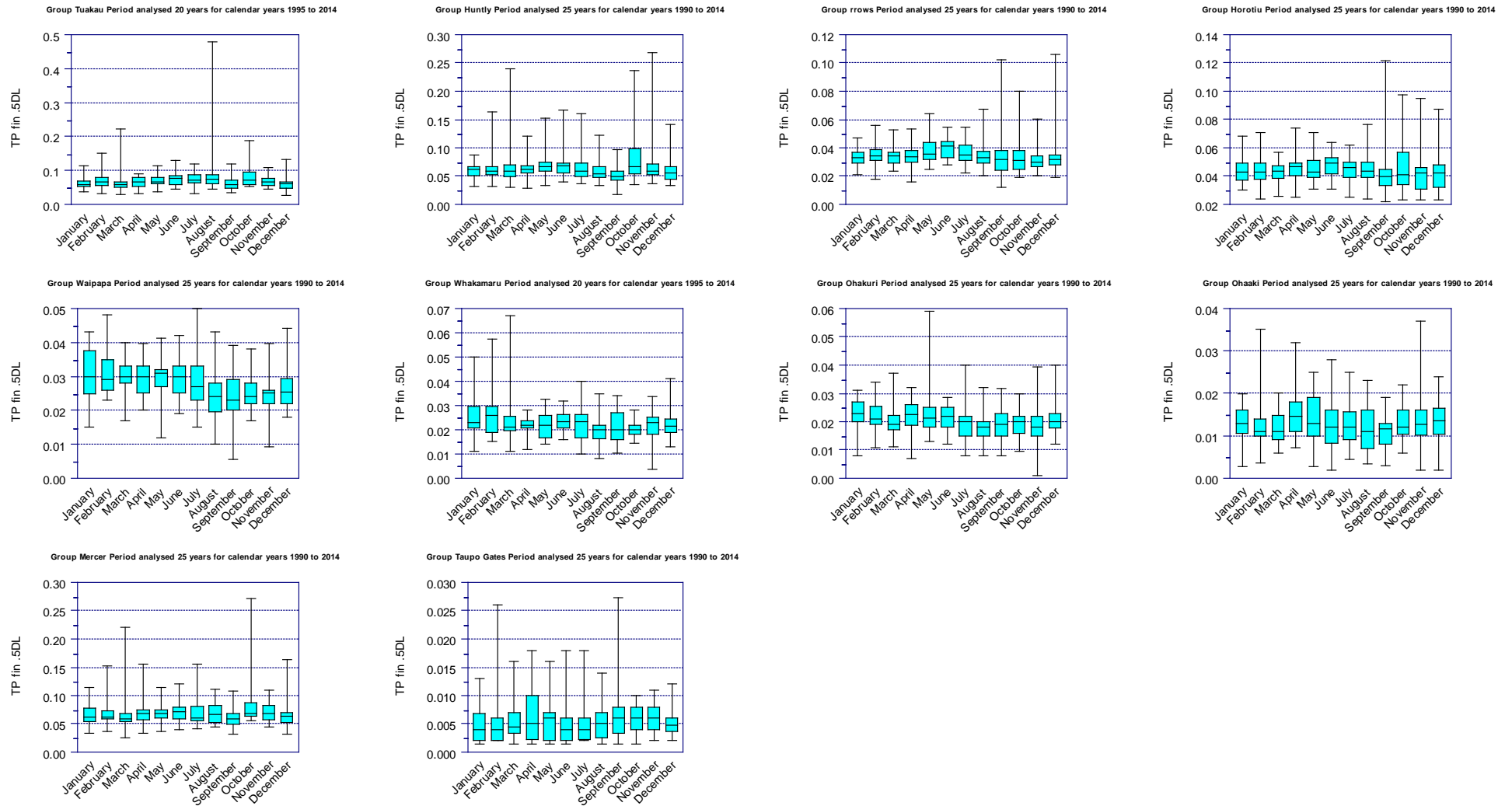


Fig. C3. Seasonality in 1990-2014 in TP.

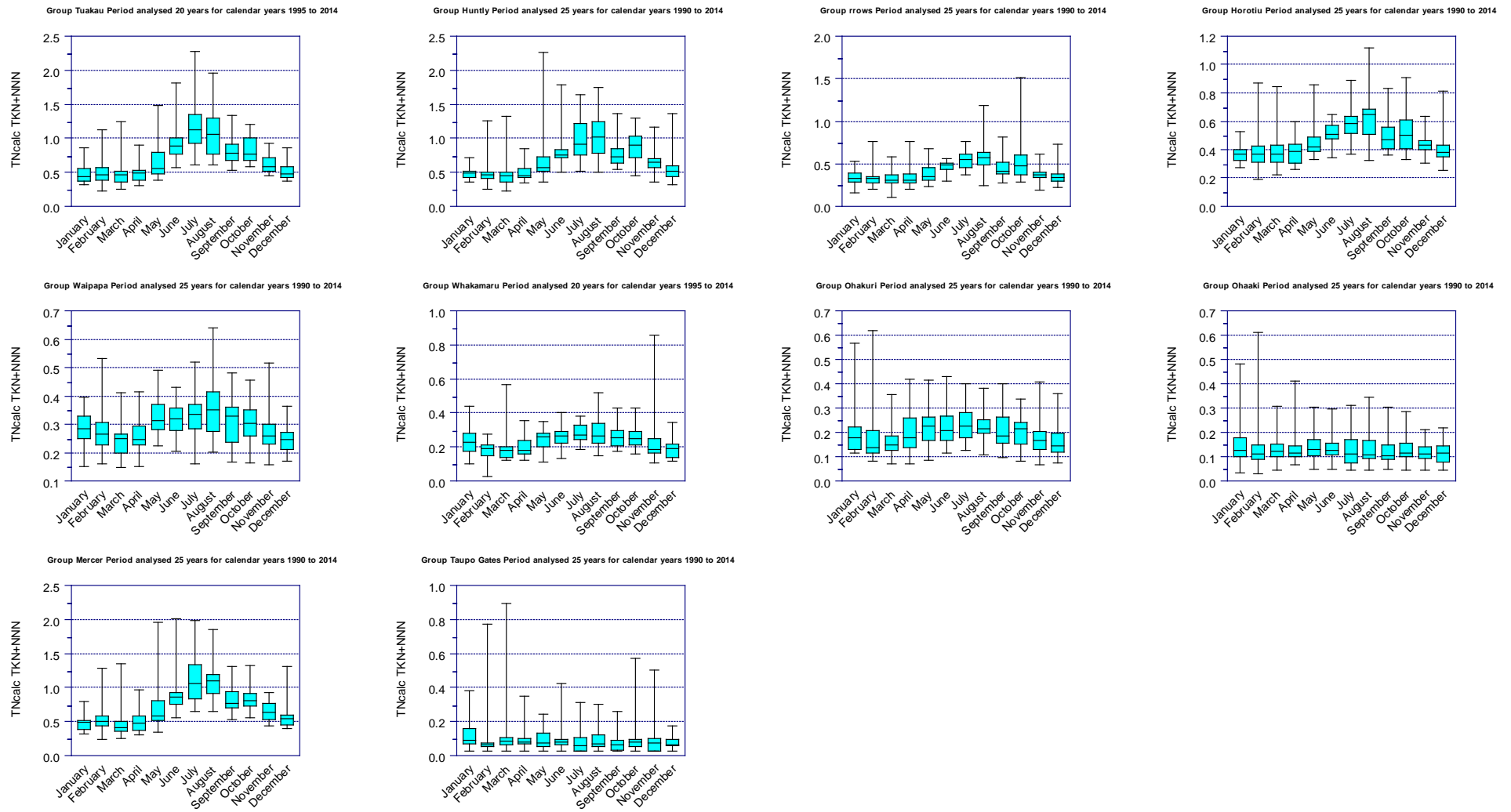


Fig. C4. Seasonality in 1990-2014 in TN.

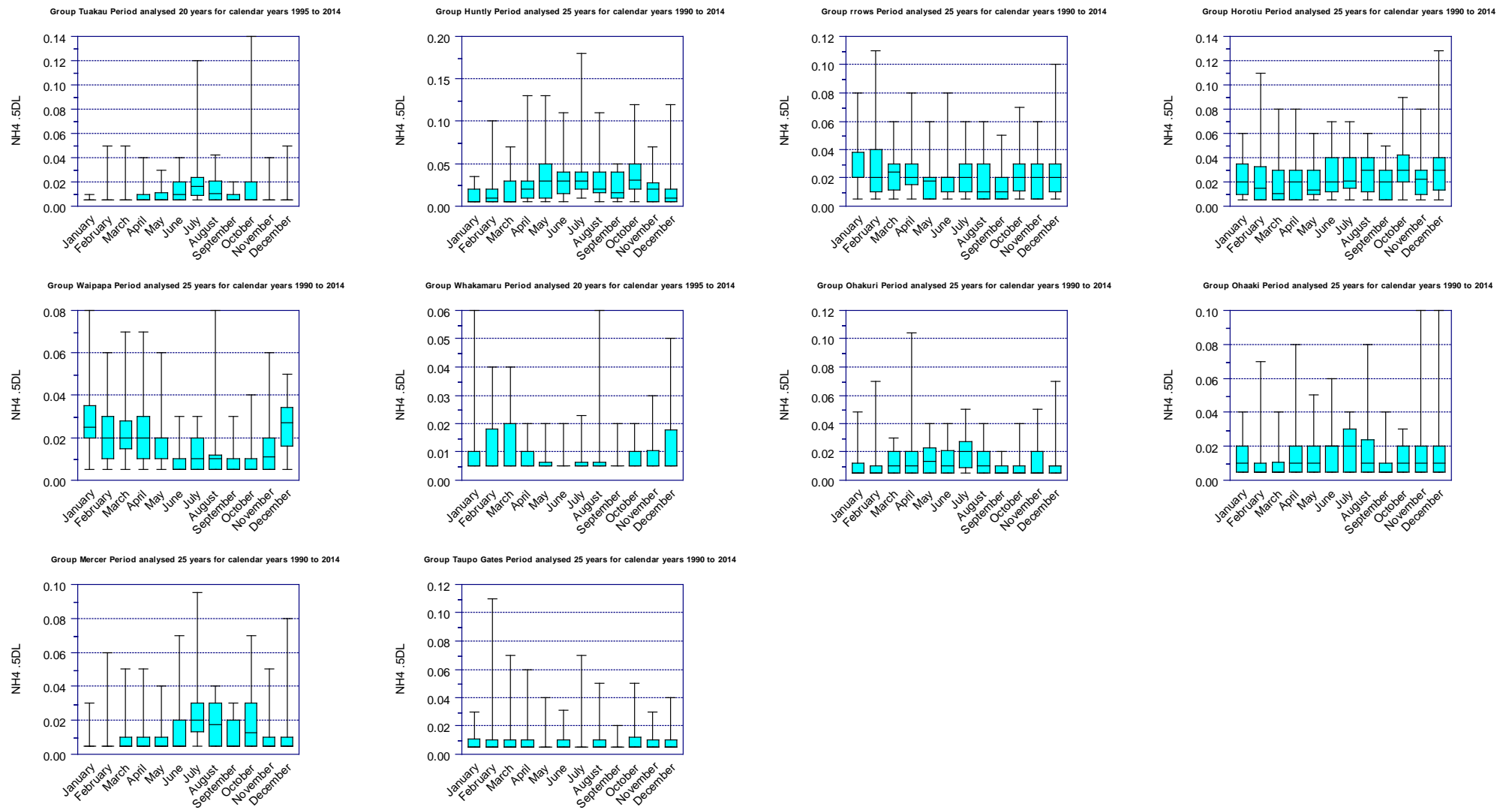


Fig. C5. Seasonality in 1990-2014 in NH<sub>4</sub>.

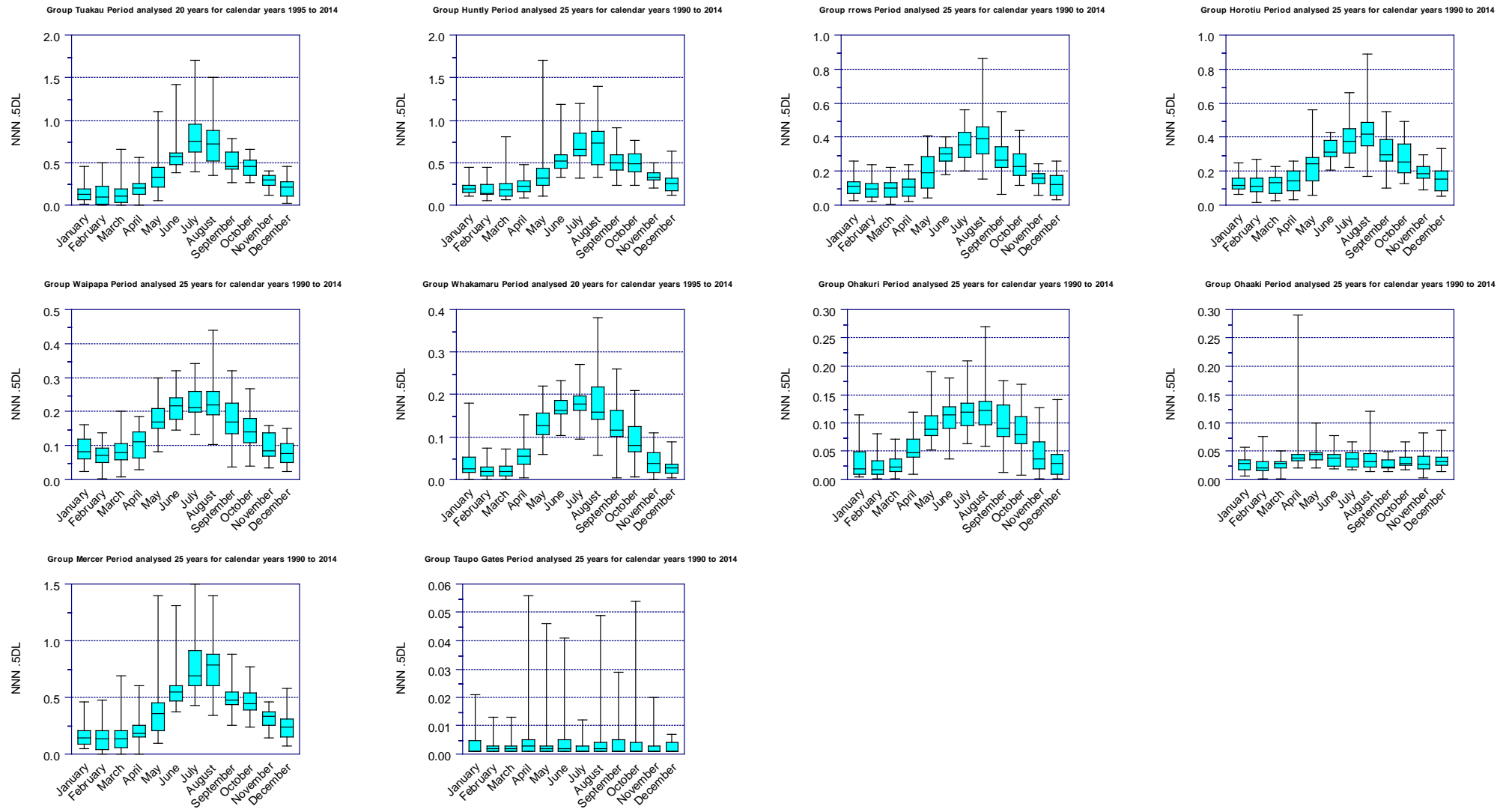


Fig. C6. Seasonality in 1990-2014 in  $\text{NO}_3$  (+  $\text{NO}_2$  which is typically negligible relative to  $\text{NO}_3$ ).

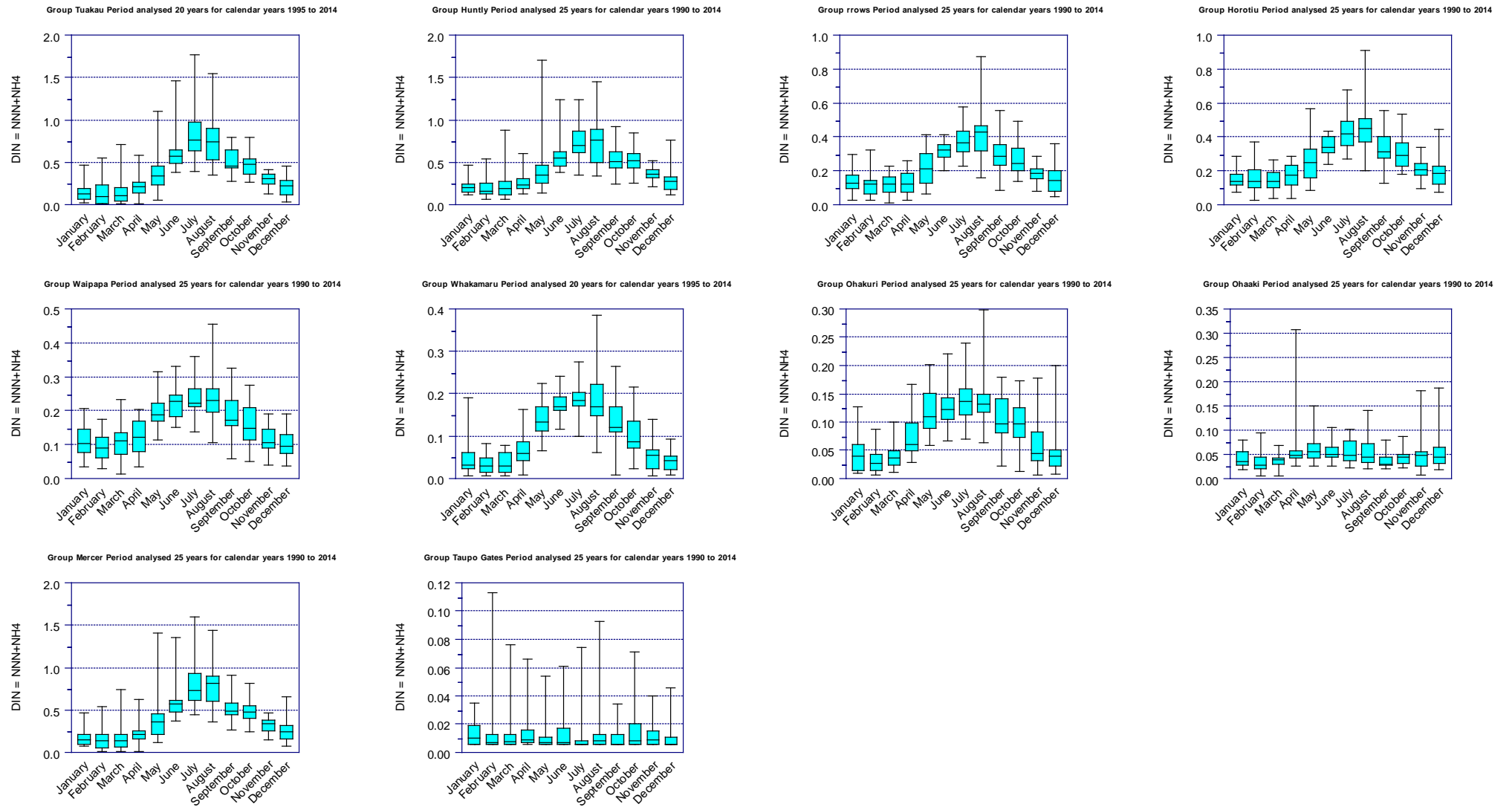


Fig. C7. Seasonality in 1990-2014 in DIN (= dissolved inorganic nitrogen =  $\text{NO}_3 + \text{NO}_2 + \text{NH}_4$ ).

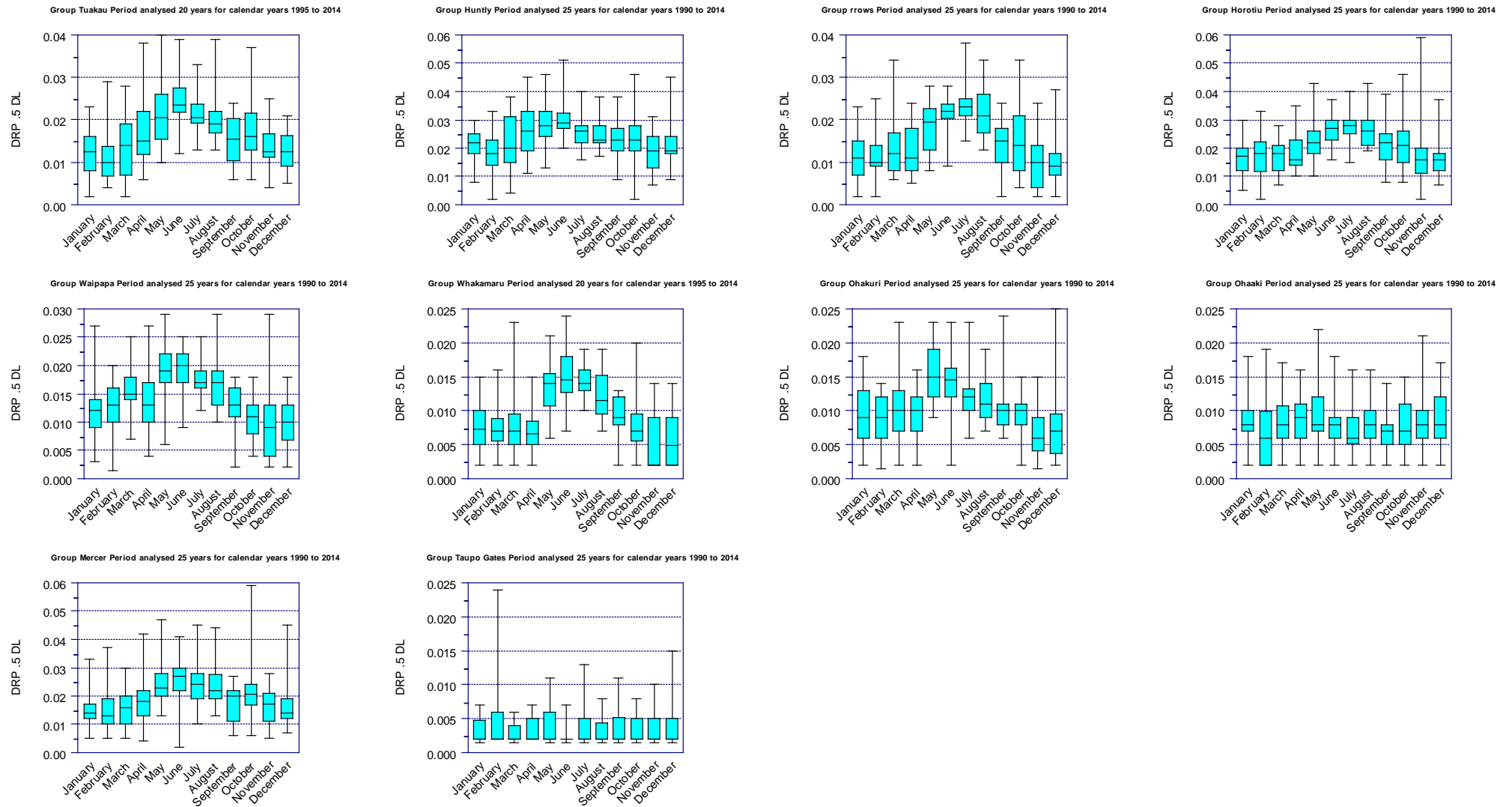


Fig. C8. Seasonality in 1990-2014 in DRP (= dissolved reactive phosphorus).

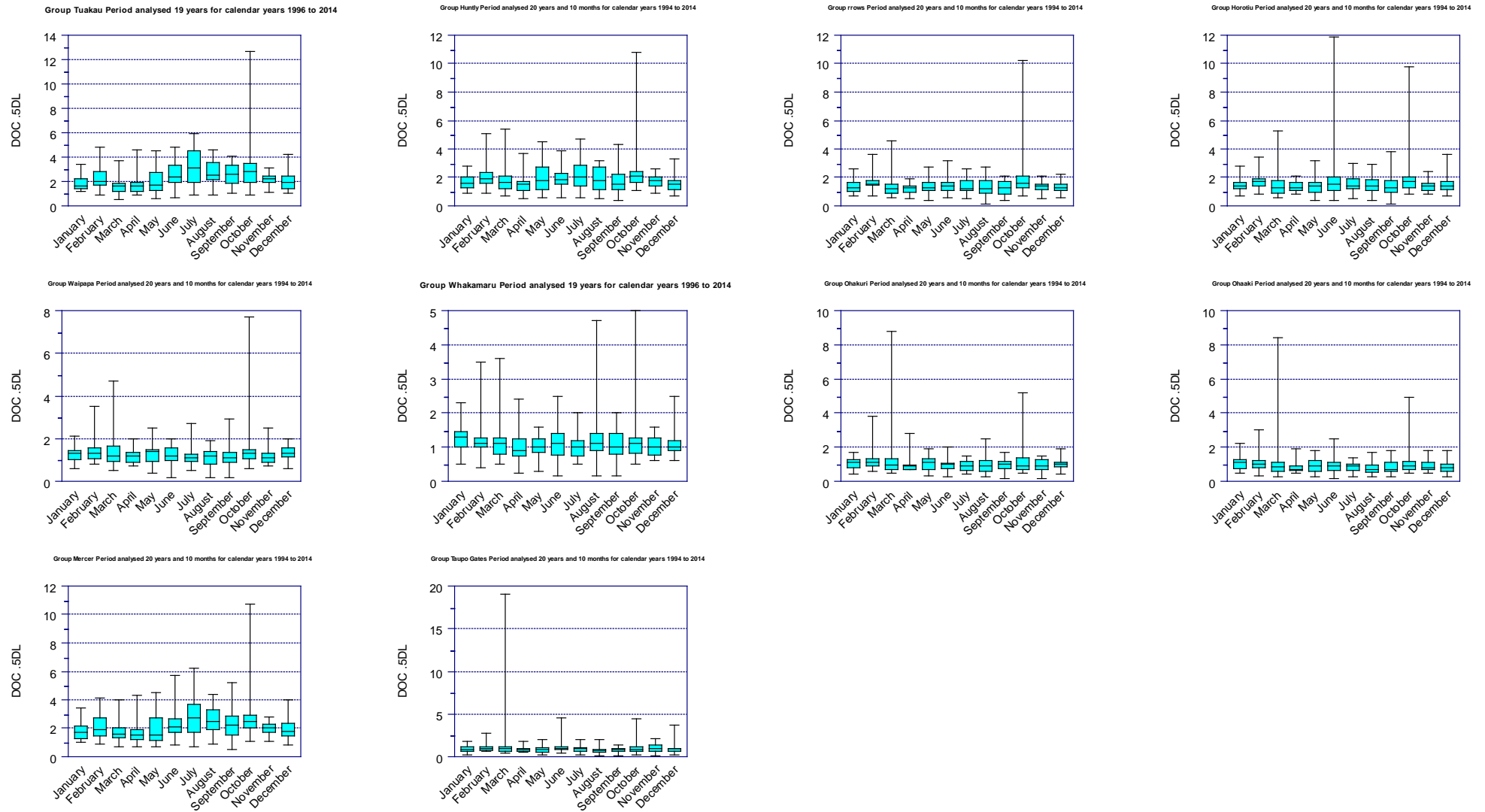


Fig. C9. Seasonality in 1990-2014 in DOC (= dissolved organic carbon).

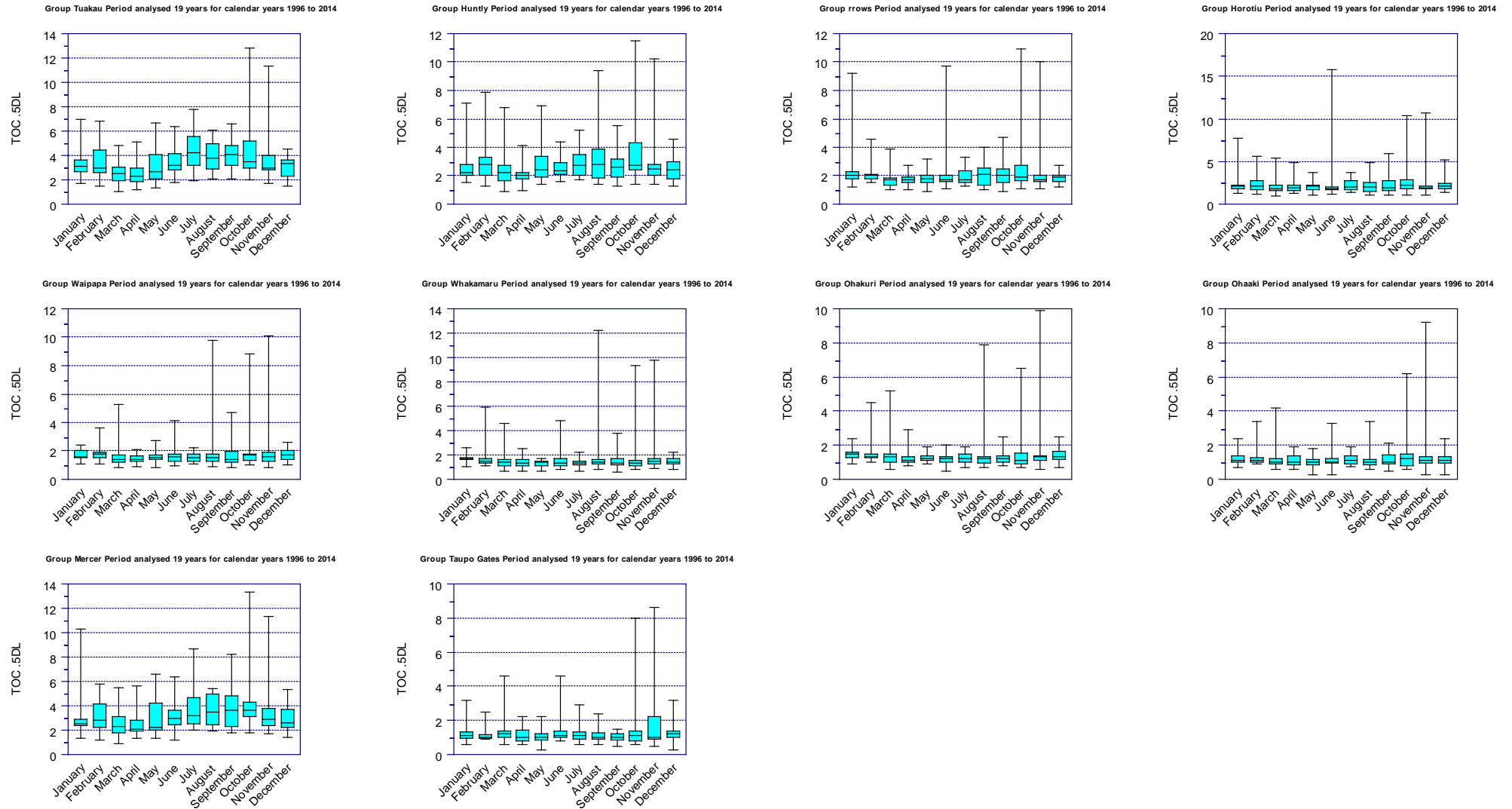


Fig. C10. Seasonality in 1990-2014 in TOC (= total organic carbon).



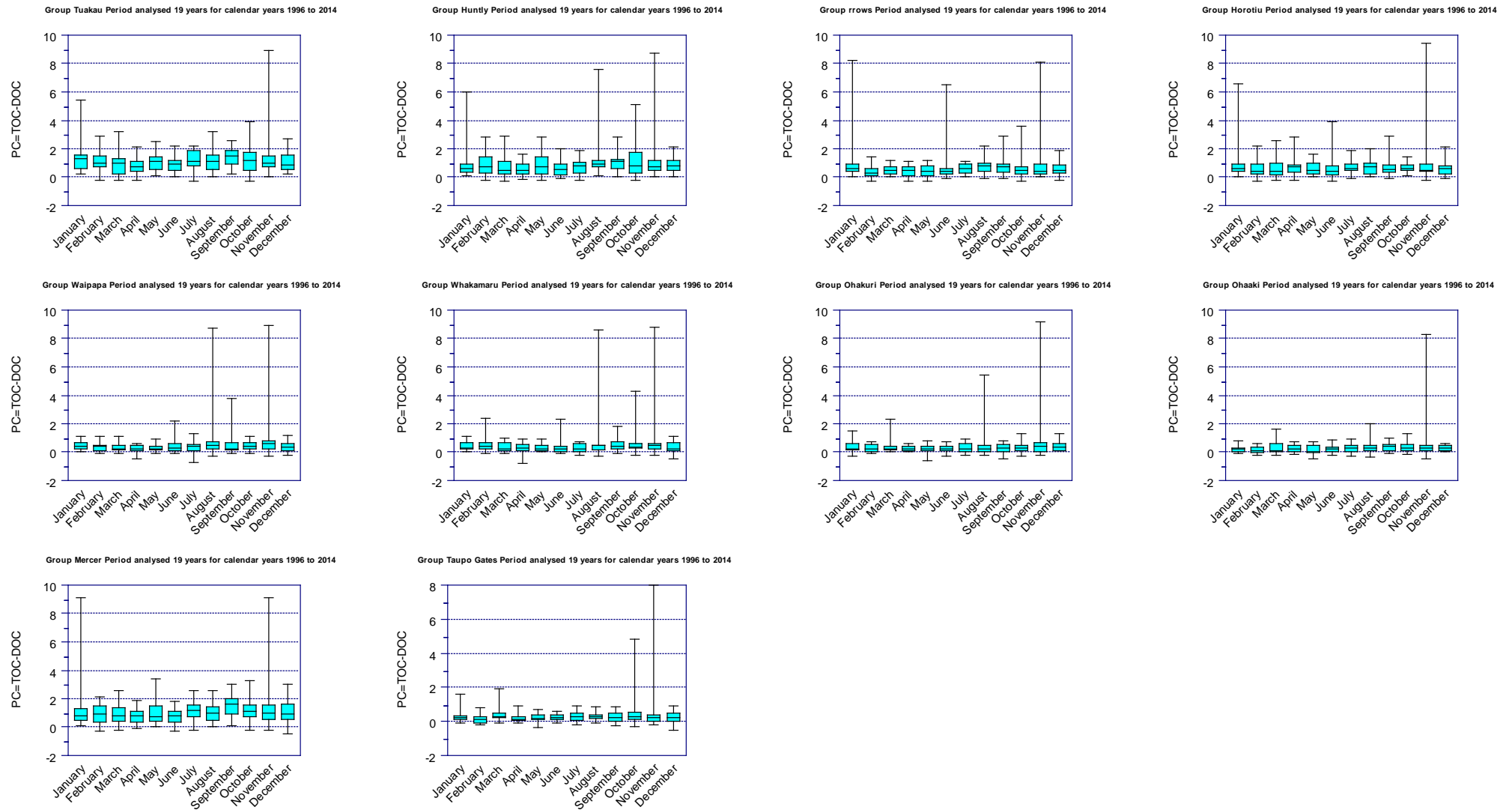


Fig. C11. Seasonality in 1990-2014 in POC (= particulate organic carbon = TOC-DOC).

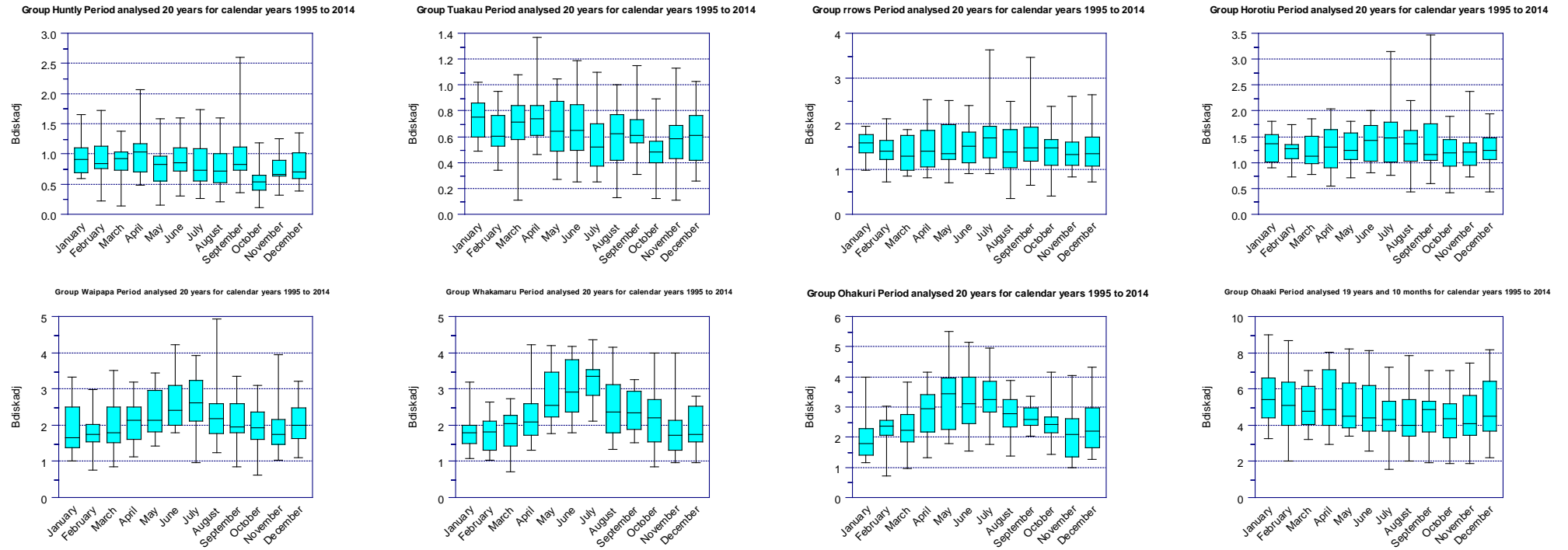


Fig. C12. Seasonality in 1990-2014 in Black Disk water clarity.

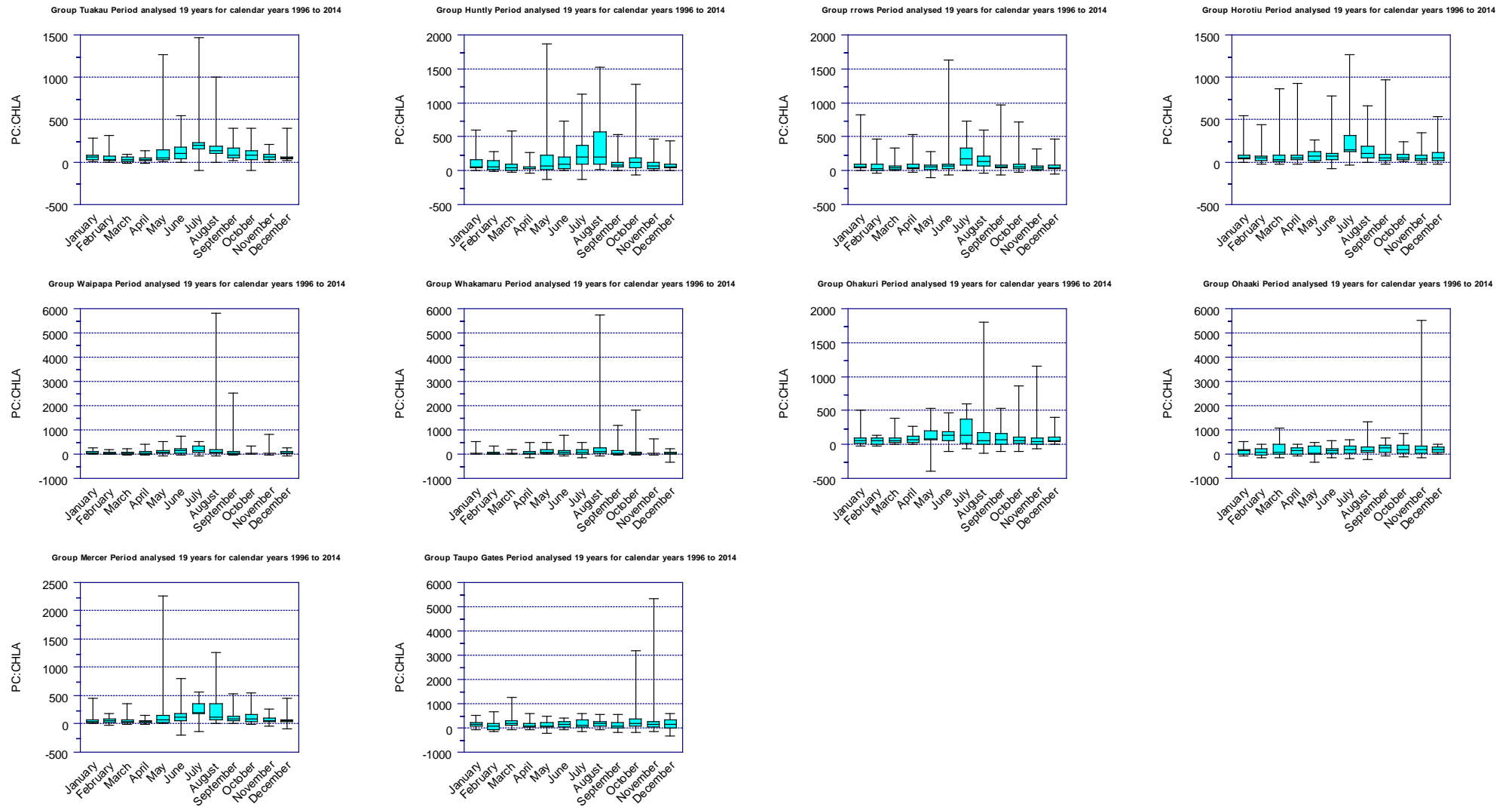


Fig. C13. Seasonality in 1990-2014 in the PC : Chlorophyll *a* ratio.

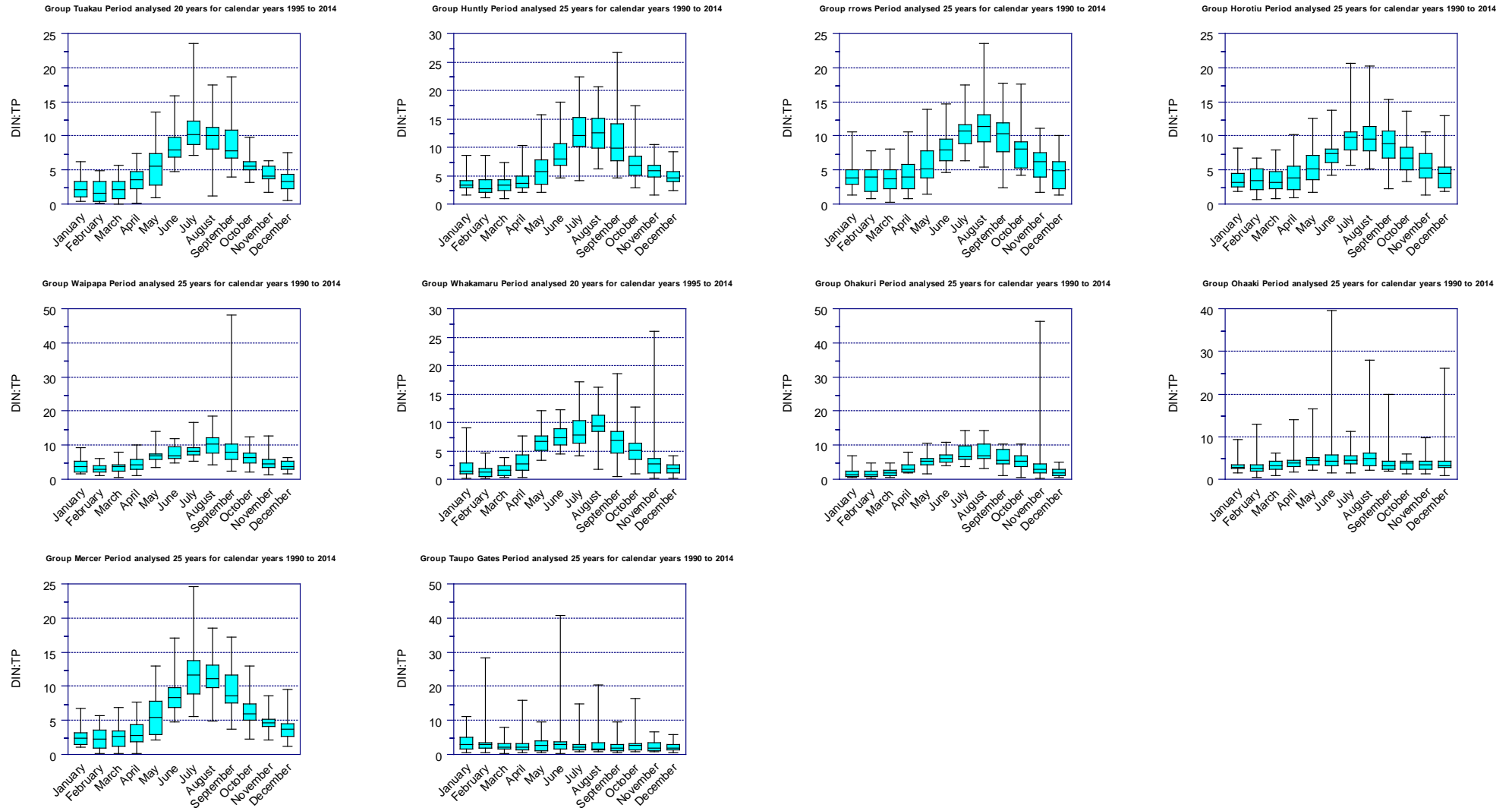


Fig. C14. Seasonality in 1990-2014 in the DIN : TP ratio.

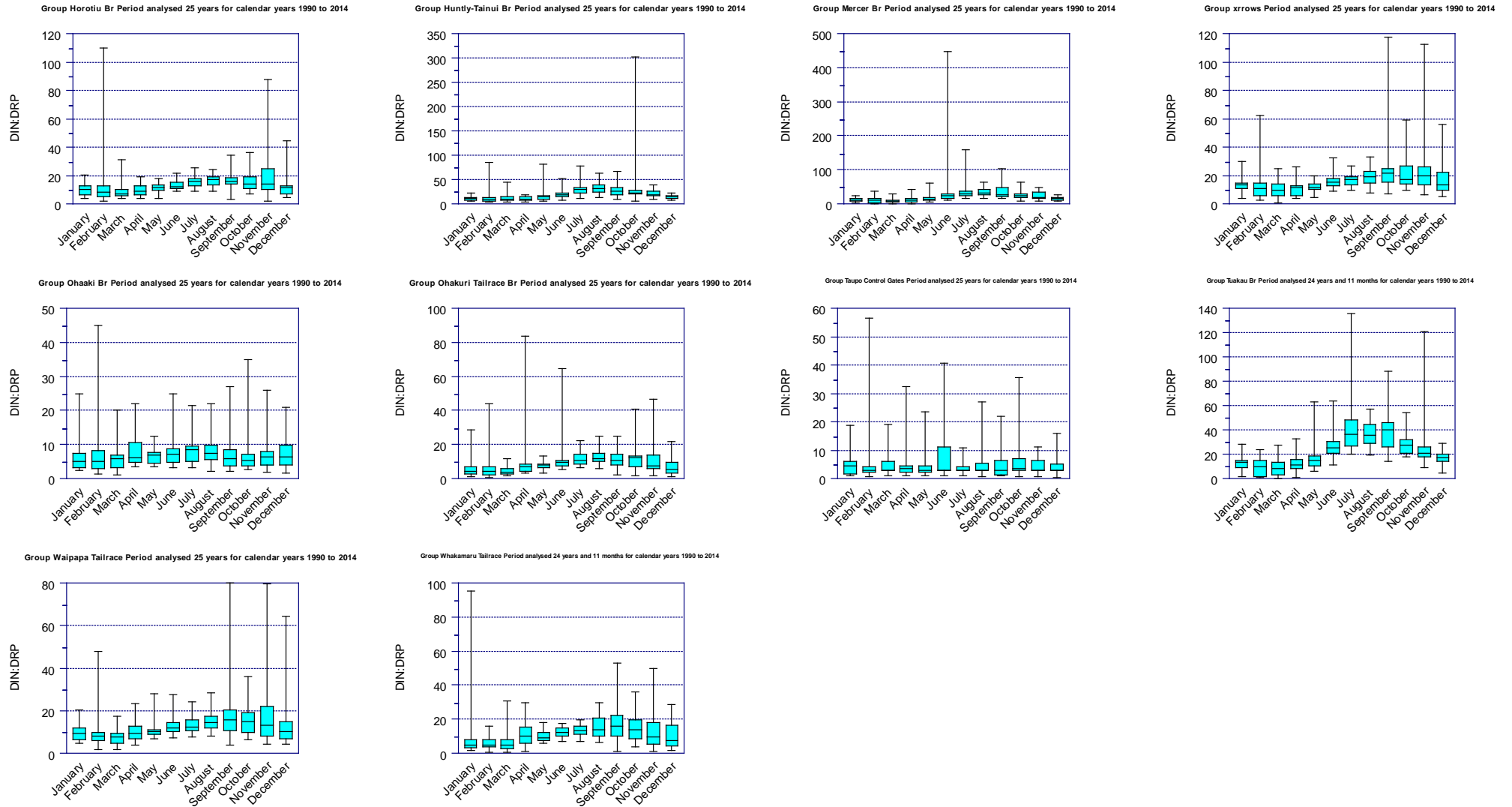


Fig. C15. Seasonality in 1990-2014 in the DIN : DRP ratio.

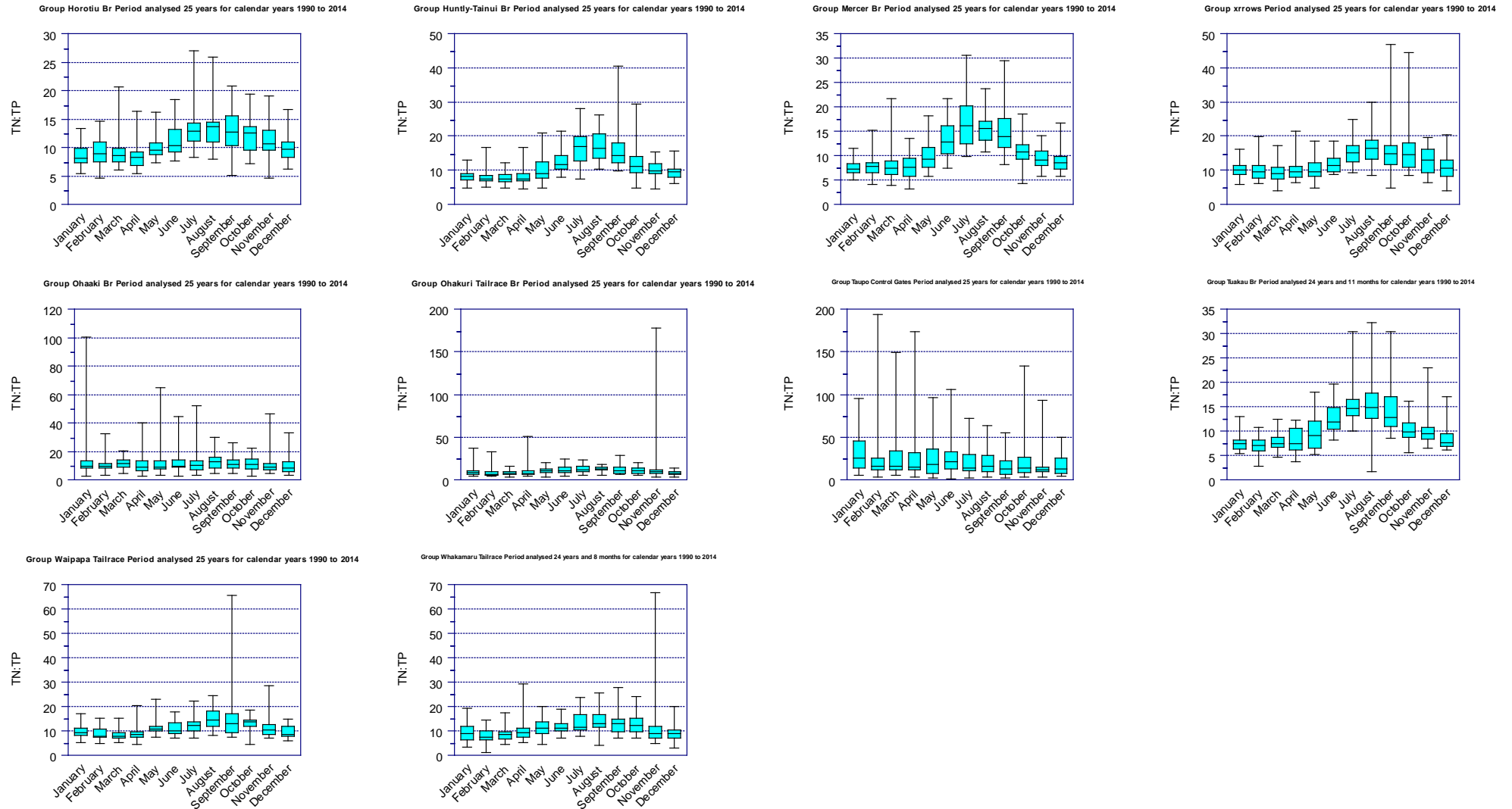
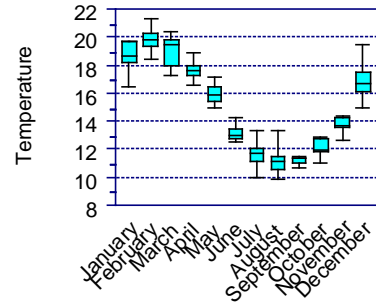
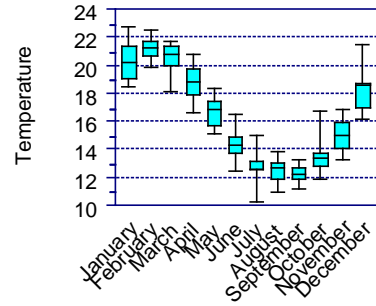


Fig. C16. Seasonality in 1990-2014 in the TN : TP ratio.

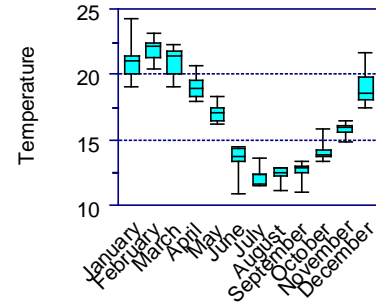
Group Taupo Gates Period analysed 9 years for calendar years 2006 to 2014



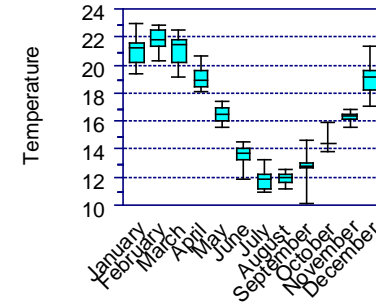
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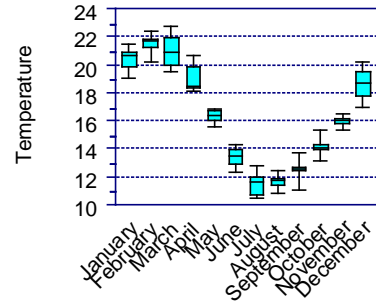
Group Ohakuri Period analysed 9 years for calendar years 2006 to 2014



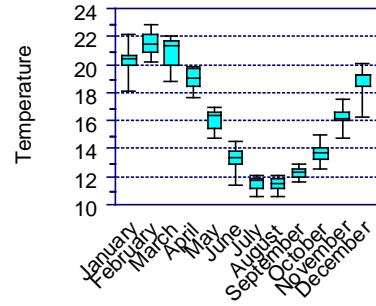
Group Whakamaru Period analysed 9 years for calendar years 2006 to 2014



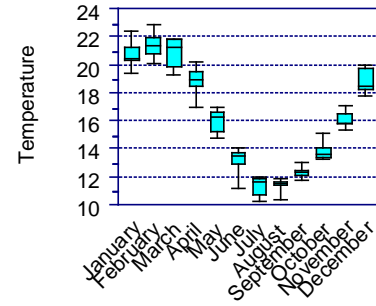
Group Waipapa Period analysed 9 years for calendar years 2006 to 2014



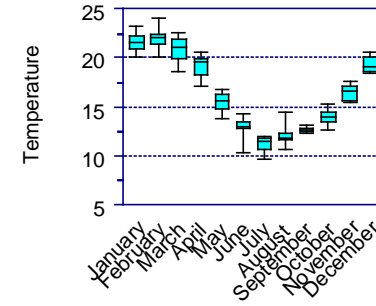
Group rrows Period analysed 9 years for calendar years 2006 to 2014



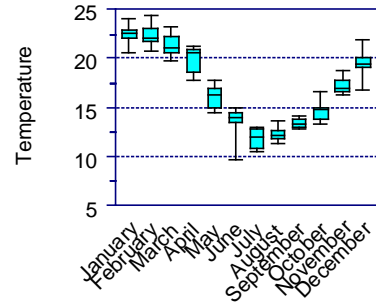
Group Horotiu Period analysed 9 years for calendar years 2006 to 2014



Group Huntly Period analysed 9 years for calendar years 2006 to 2014



Group Mercer Period analysed 9 years for calendar years 2006 to 2014



Group Tuakau Period analysed 9 years for calendar years 2006 to 2014

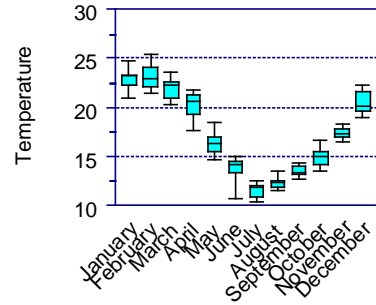


Fig. C17. Seasonality in 2006-2014 in water temperature.

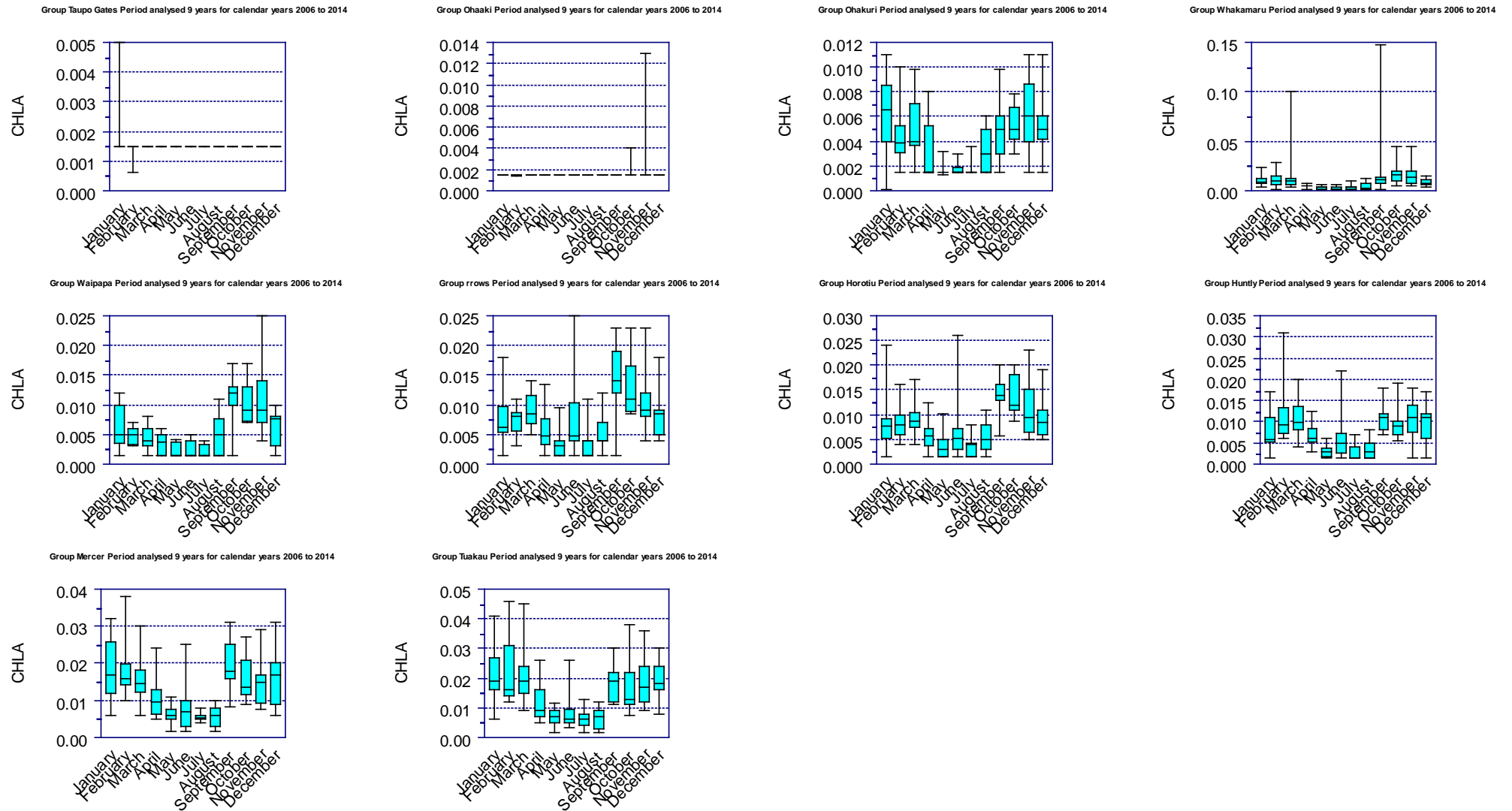


Fig. C18. Seasonality in 2006-2014 in chlorophyll *a*.



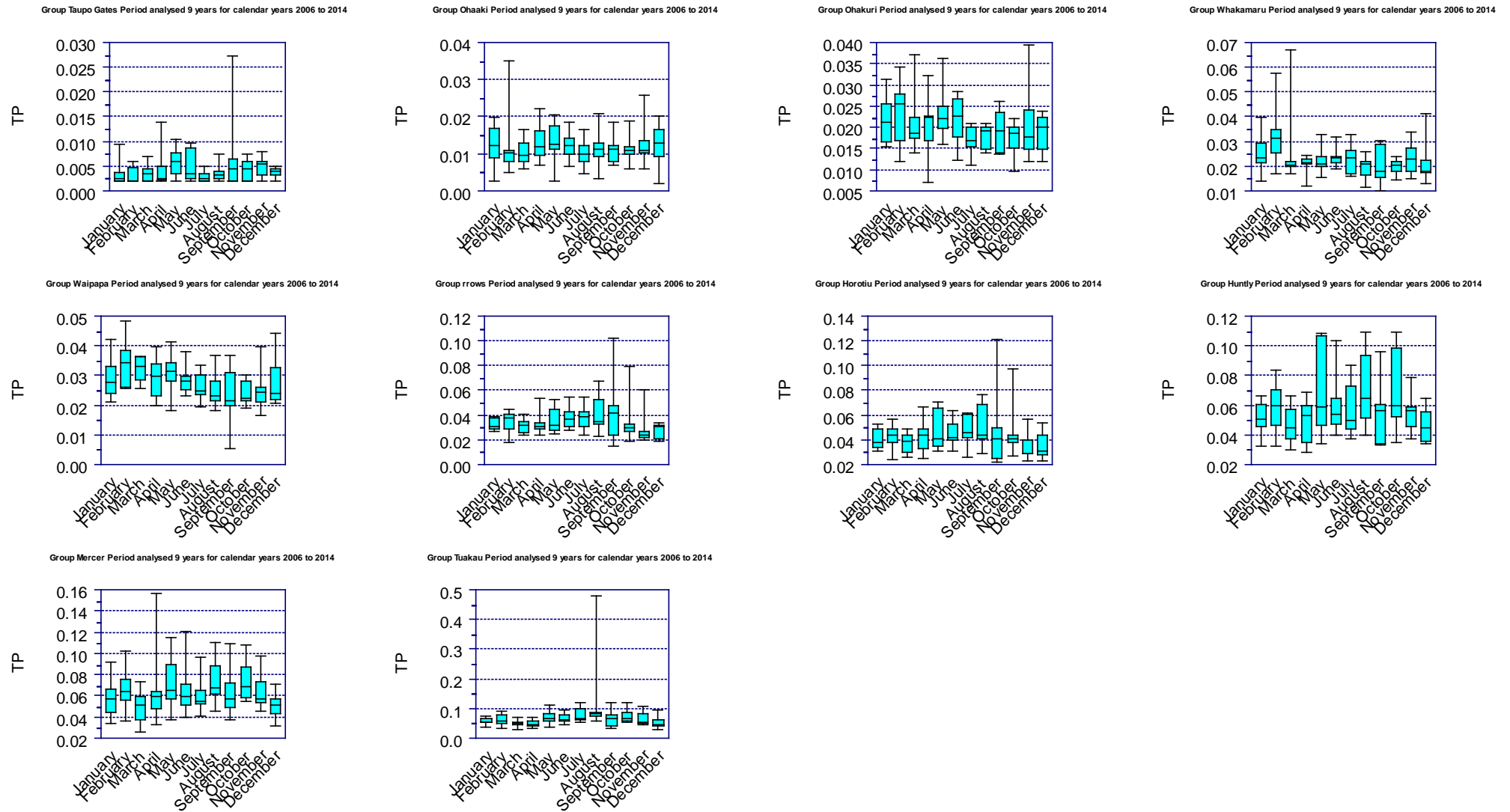


Fig. C19. Seasonality in 2006-2014 in TP.

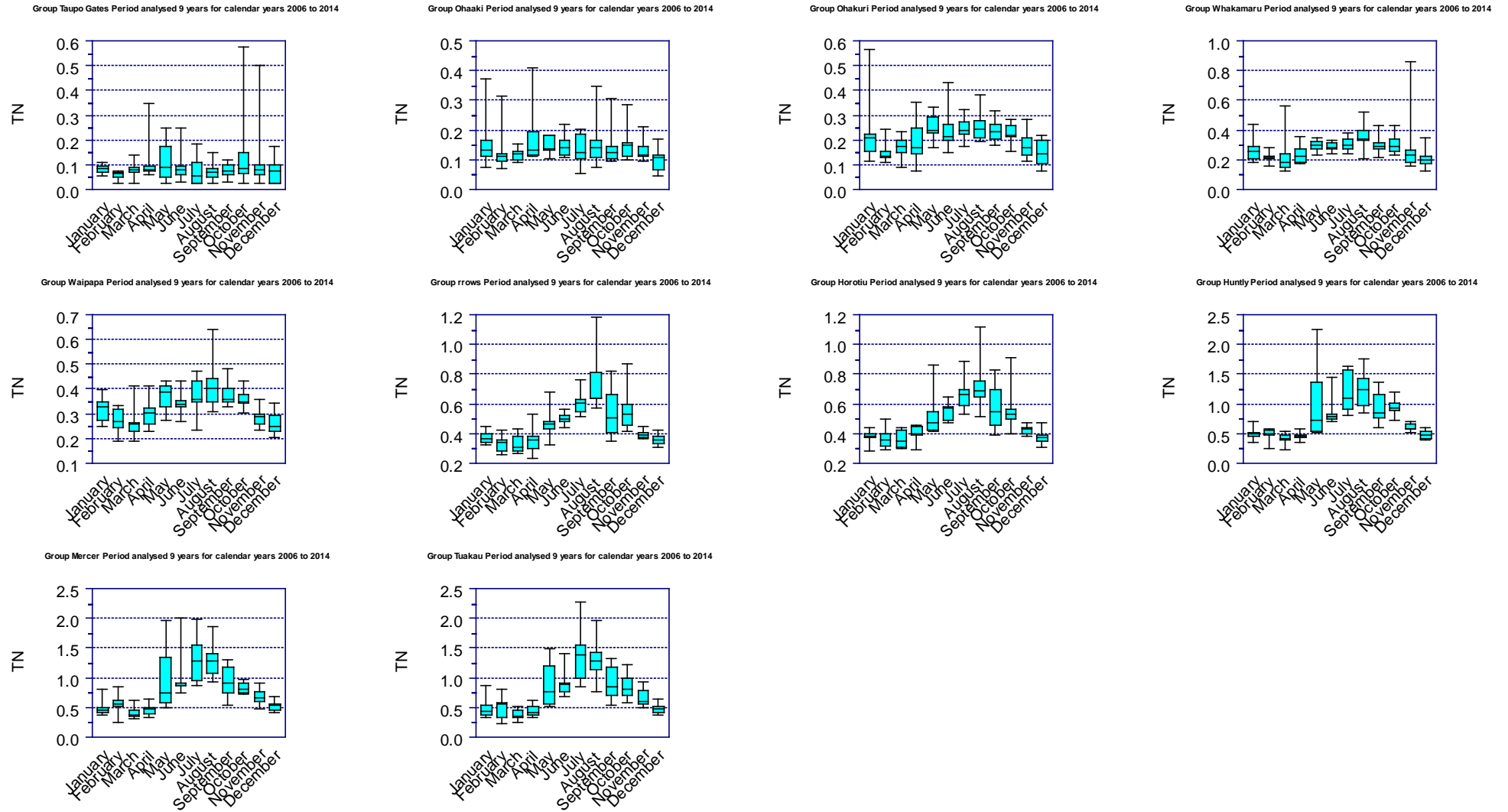
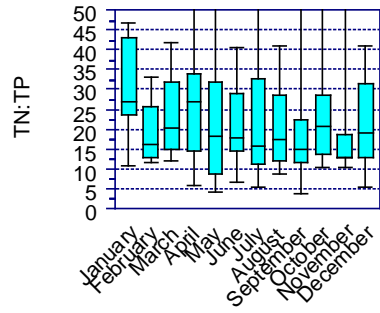
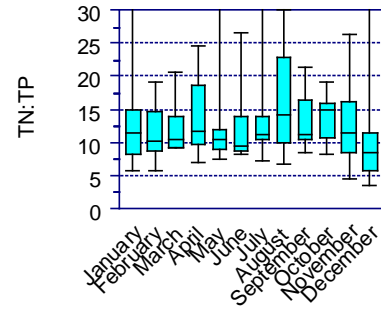


Fig. C20. Seasonality in 2006-2014 in TN.

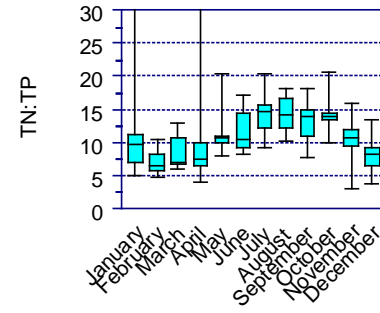
Group Taupo Gates Period analysed 9 years for calendar years 2006 to 2014



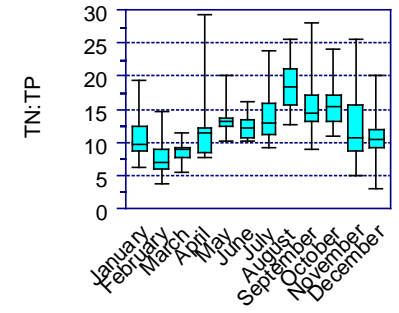
Group Ohaaki Period analysed 9 years for calendar years 2006 to 2014



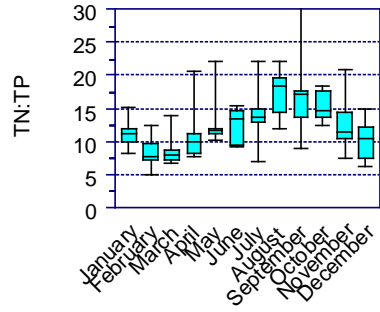
Group Ohakuri Period analysed 9 years for calendar years 2006 to 2014



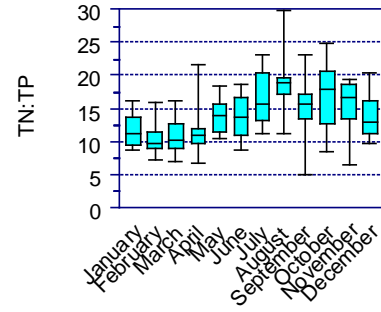
Group Whakamaru Period analysed 9 years for calendar years 2006 to 2014



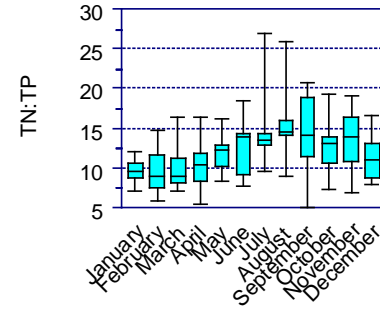
Group Waipapa Period analysed 9 years for calendar years 2006 to 2014



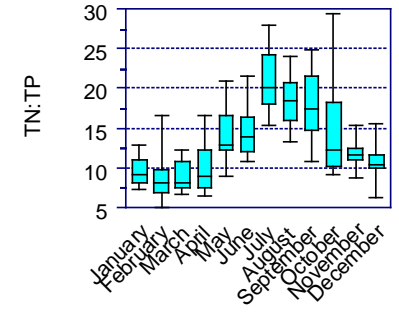
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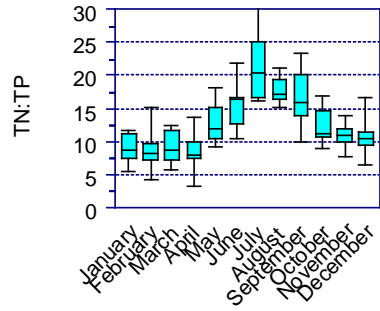
Group Horotiu Period analysed 9 years for calendar years 2006 to 2014



Group Huntly Period analysed 9 years for calendar years 2006 to 2014



Group Mercer Period analysed 9 years for calendar years 2006 to 2014



Group Tuakau Period analysed 9 years for calendar years 2006 to 2014

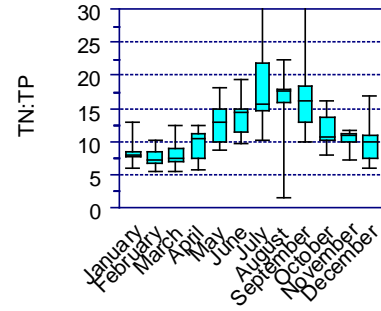


Fig. C21. Seasonality in 2006-2014 in the TN : TP ratio.

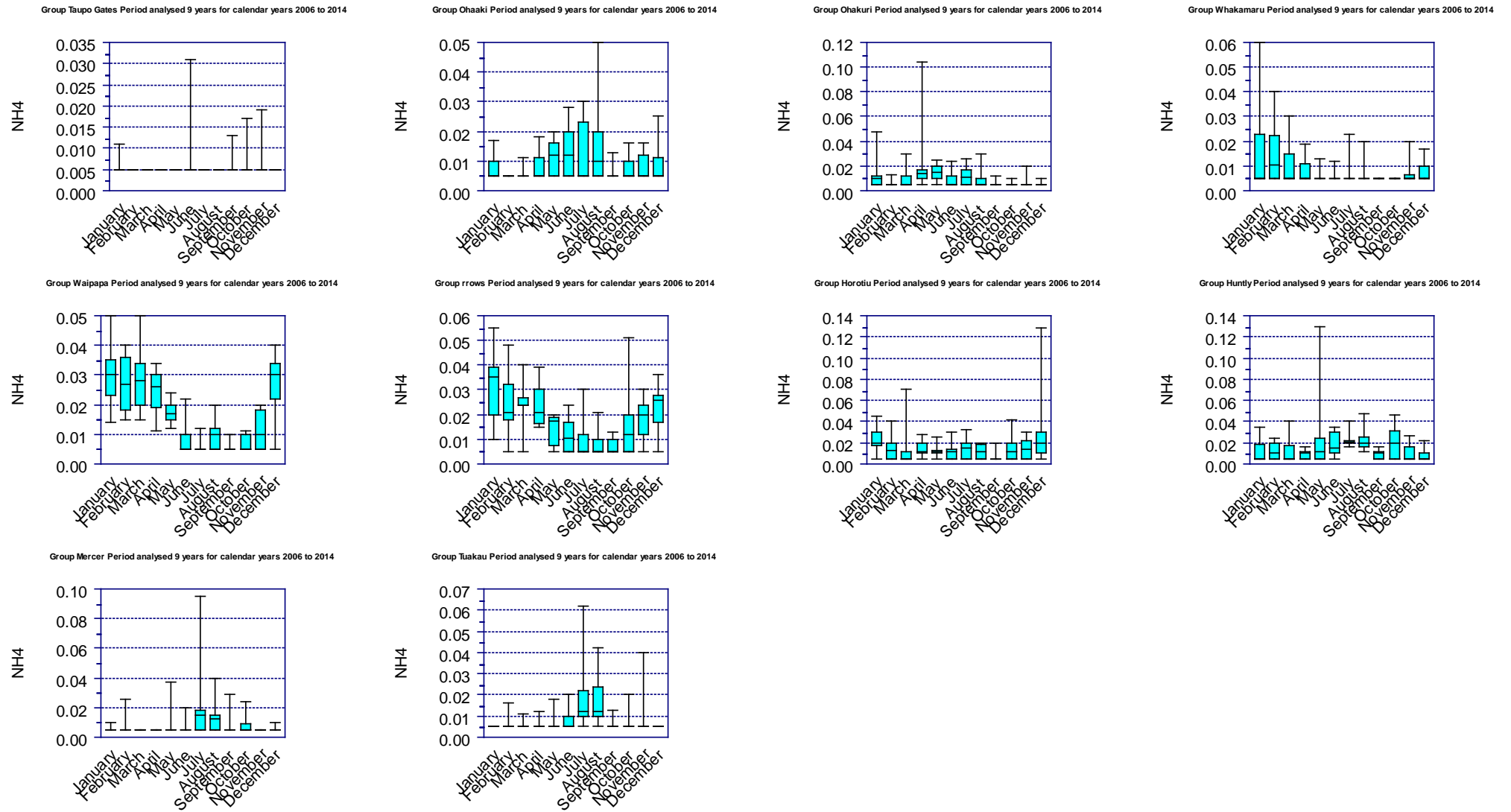


Fig. C22. Seasonality in 2006-2014 in NH<sub>4</sub>.

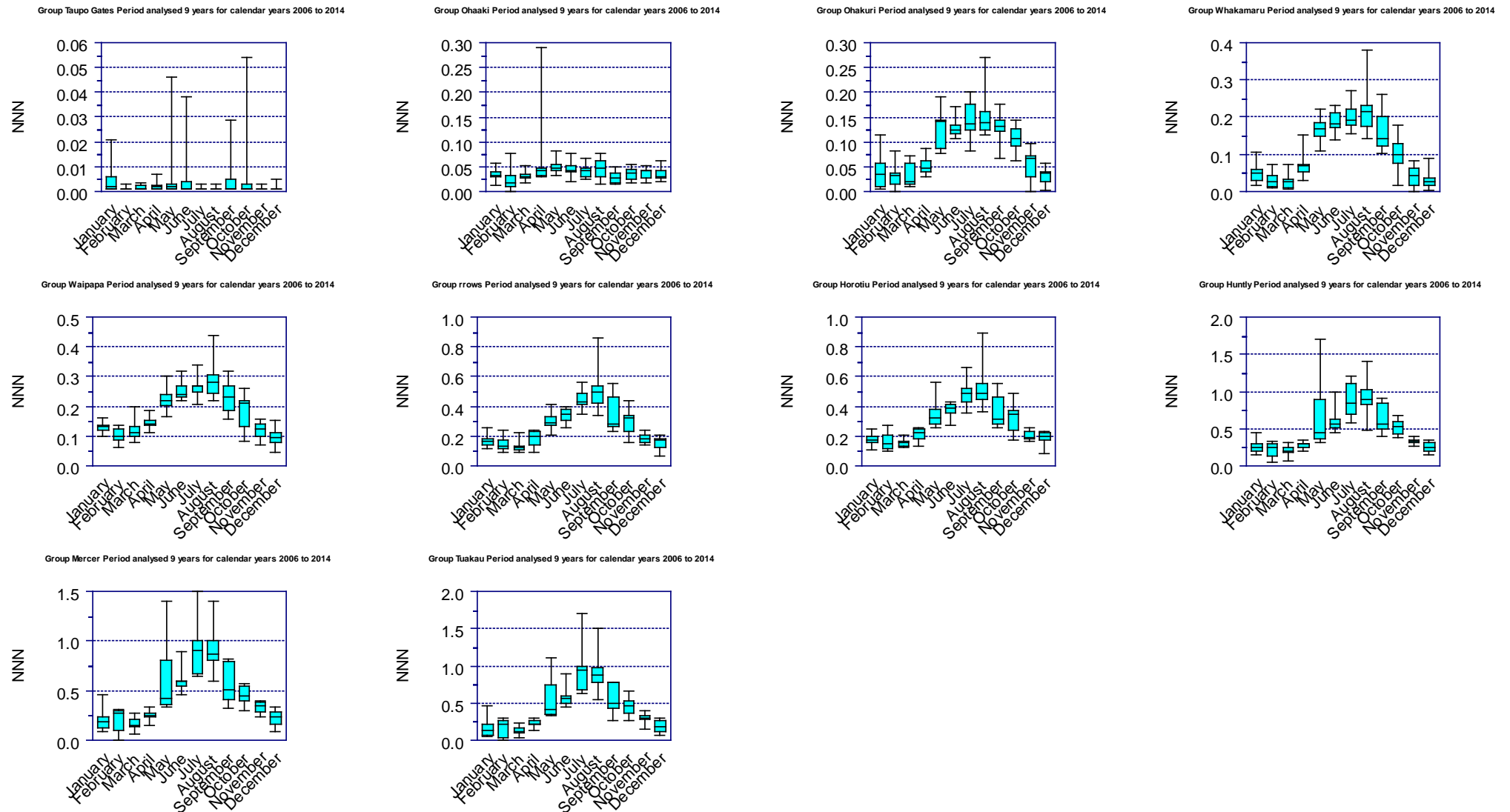


Fig. C23. Seasonality in 2006-2014 in  $\text{NO}_3$  (+  $\text{NO}_2$  which is typically negligible relative to  $\text{NO}_3$ ).

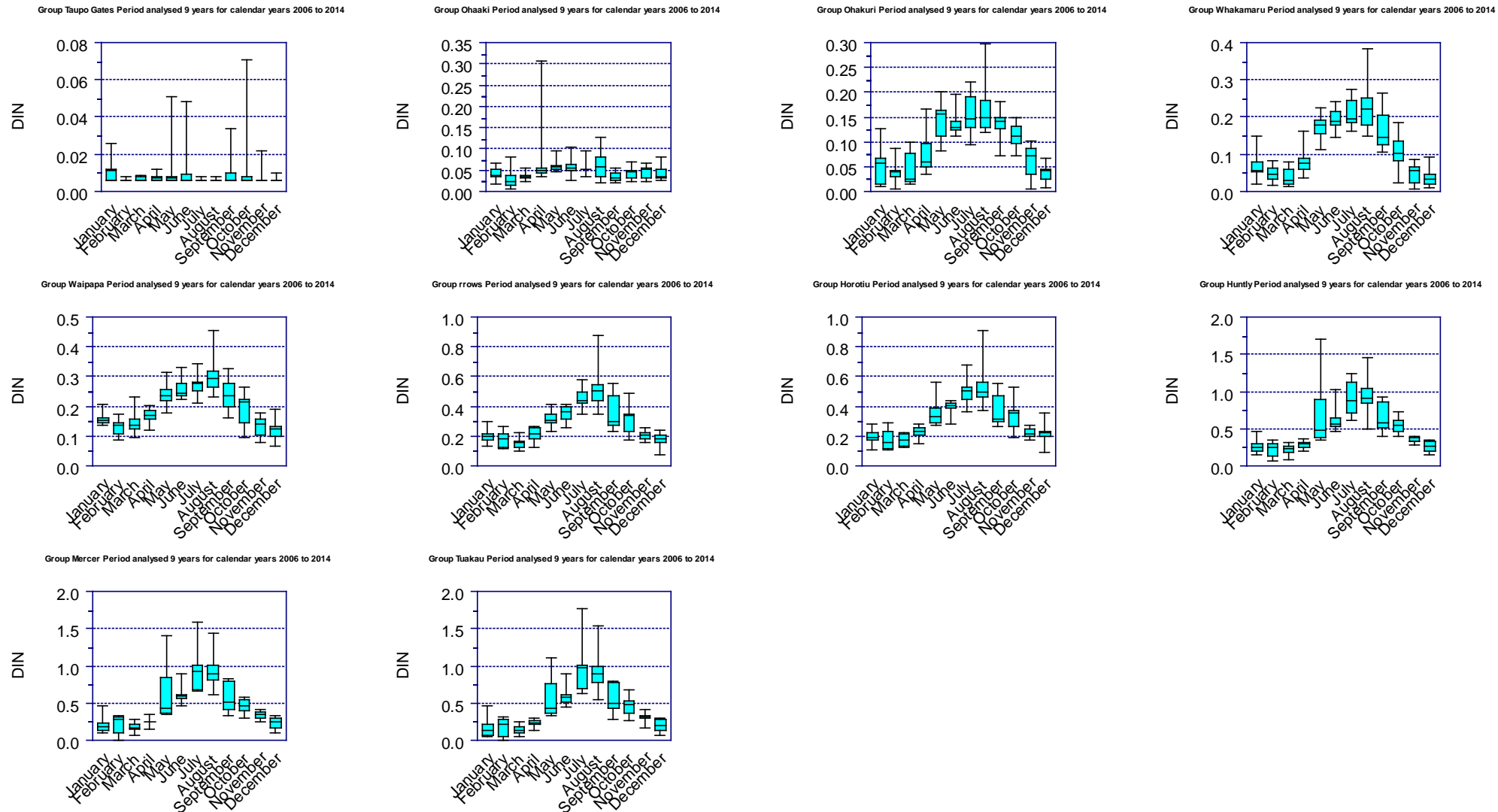


Fig. C24. Seasonality in 2006-2014 in DIN (= dissolved inorganic nitrogen =  $\text{NO}_3 + \text{NO}_2 + \text{NH}_4$ ).

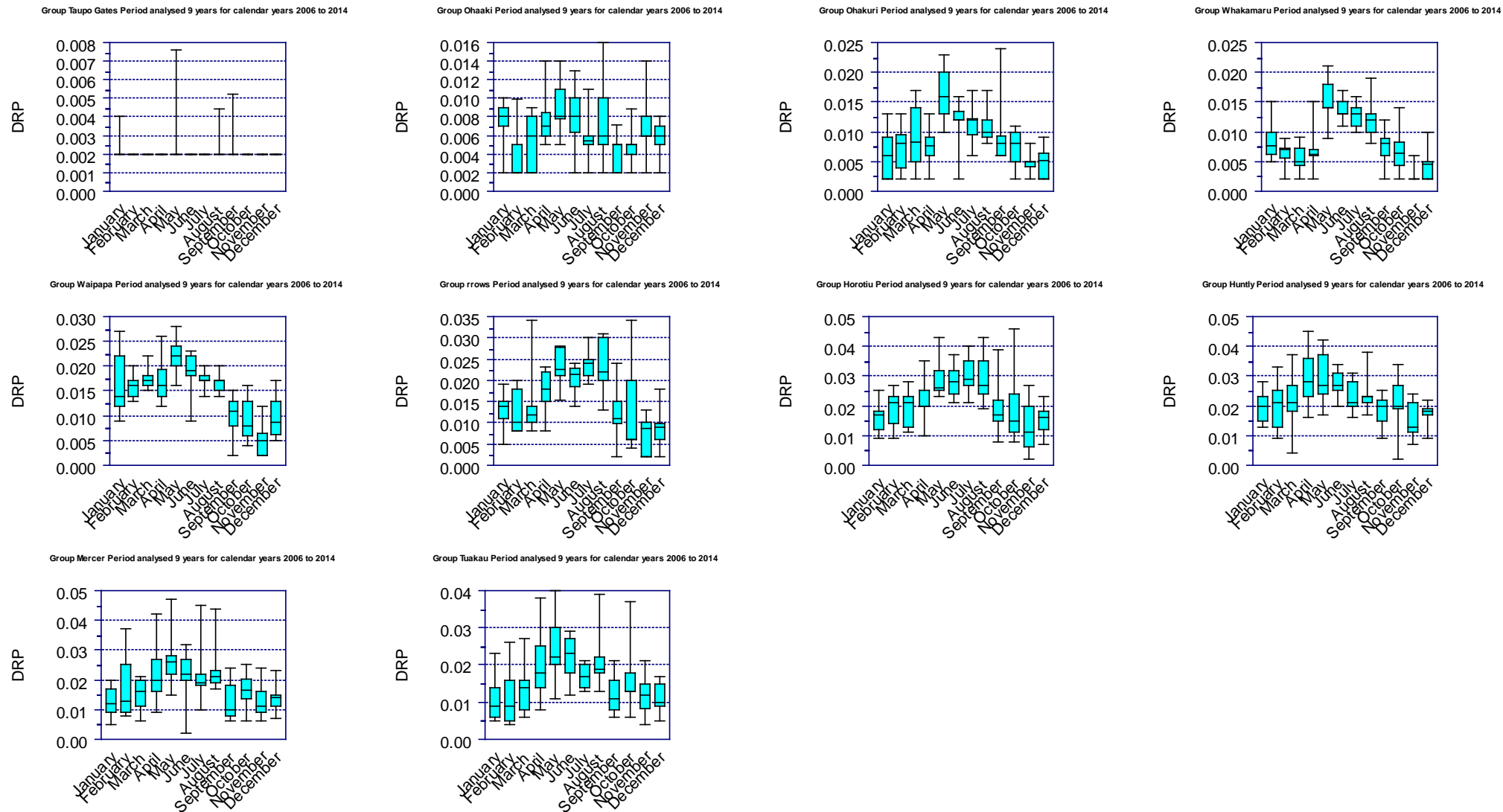
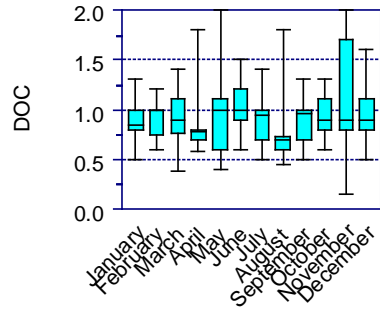
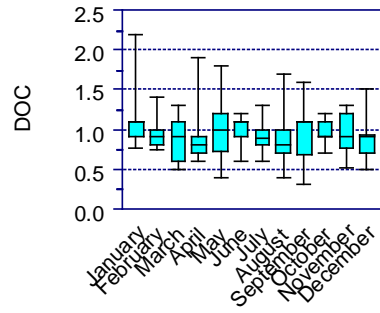


Fig. C25. Seasonality in 2006-2014 in DRP (= dissolved reactive phosphorus).

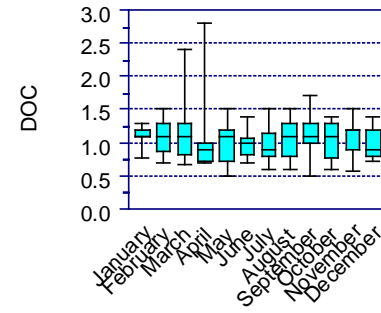
Group Taupo Gates Period analysed 9 years for calendar years 2006 to 2014



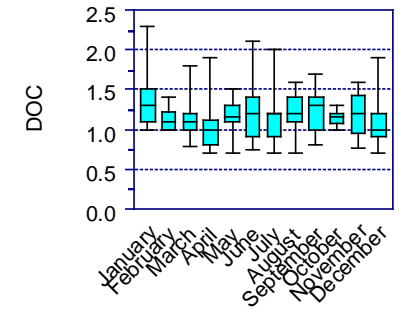
Group Ohaaki Period analysed 9 years for calendar years 2006 to 2014



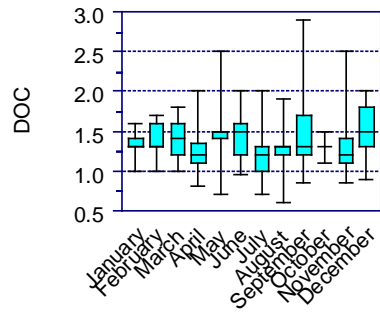
Group Ohakuri Period analysed 9 years for calendar years 2006 to 2014



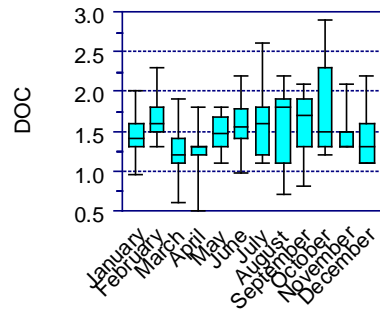
Group Whakamaru Period analysed 9 years for calendar years 2006 to 2014



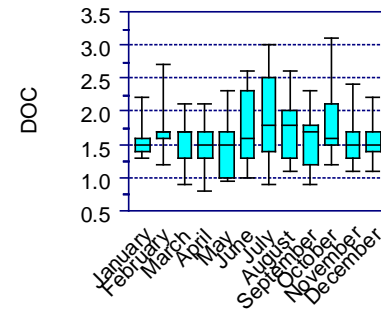
Group Waipapa Period analysed 9 years for calendar years 2006 to 2014



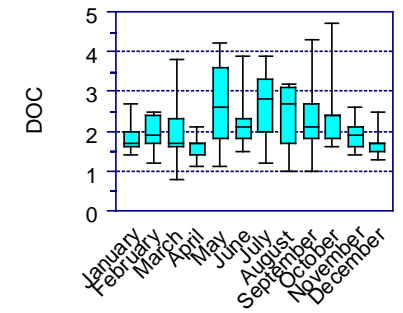
Group rrows Period analysed 9 years for calendar years 2006 to 2014



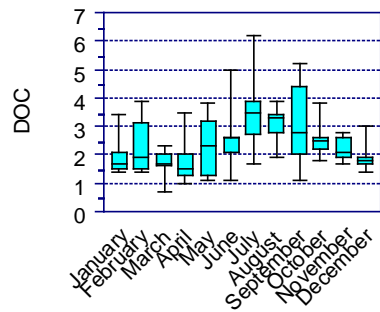
Group Horotiu Period analysed 9 years for calendar years 2006 to 2014



Group Huntly Period analysed 9 years for calendar years 2006 to 2014



Group Mercer Period analysed 9 years for calendar years 2006 to 2014



Group Tuakau Period analysed 9 years for calendar years 2006 to 2014

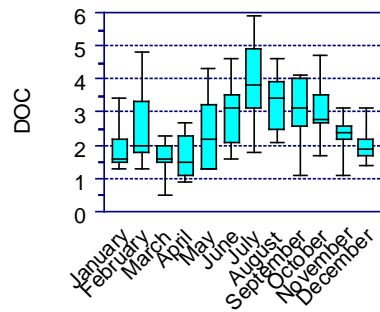


Fig. C26. Seasonality in 2006-2014 in DOC (= dissolved organic carbon).



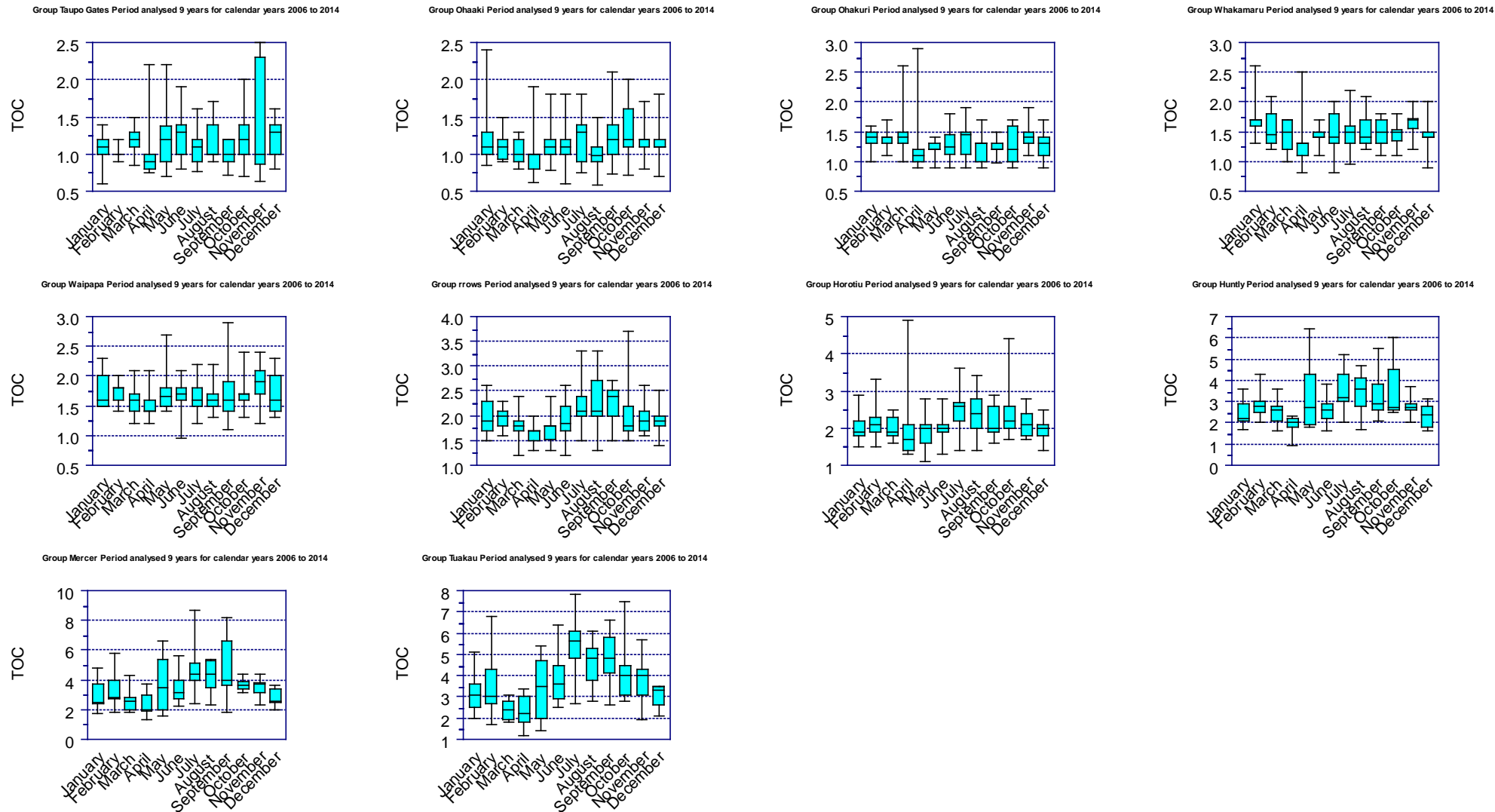


Fig. C27. Seasonality in 2006-2014 in TOC (= total organic carbon).

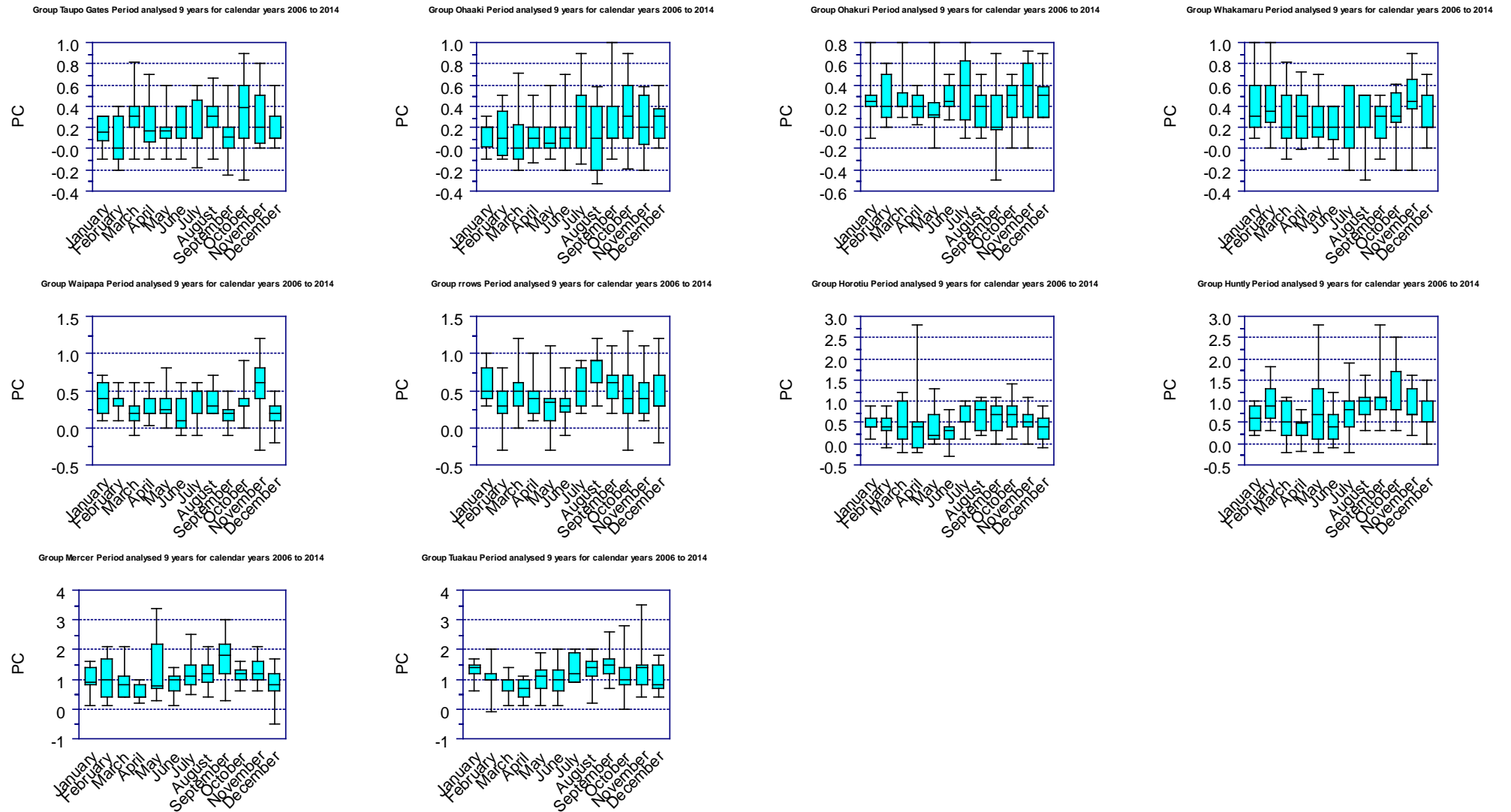


Fig. C28. Seasonality in 2006-2014 in PC (= particulate organic carbon = TOC - DOC).

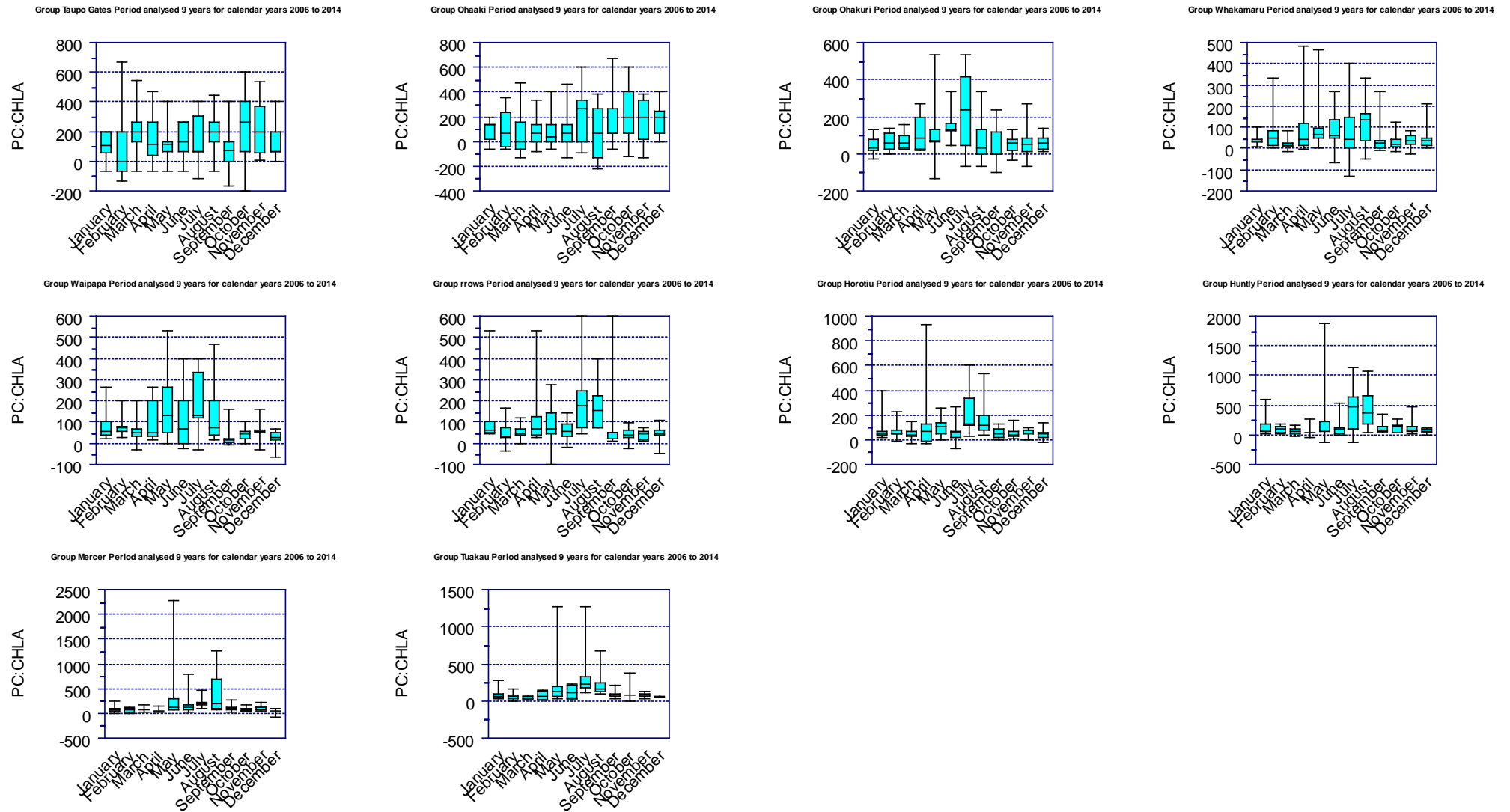


Fig. C29. Seasonality in 2006-2014 in the PC : chlorophyll *a* ratio.

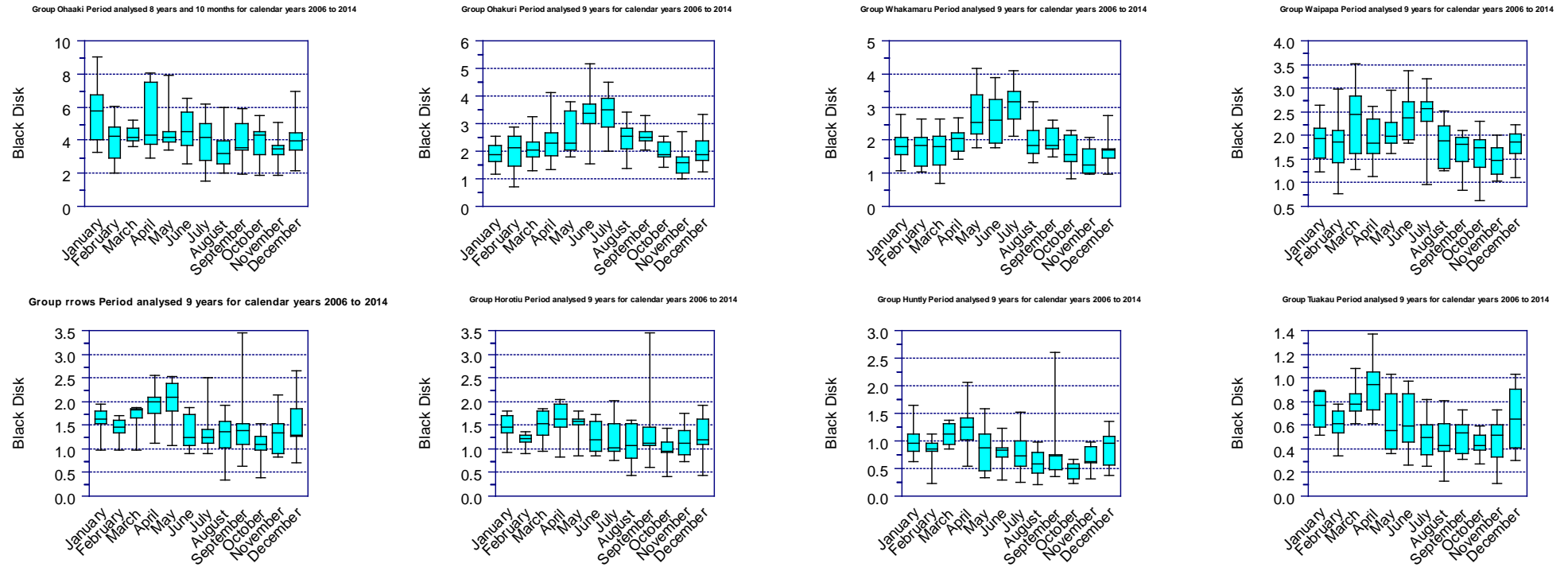


Fig. C30. Seasonality in 2006-2014 in Black Disk water clarity.

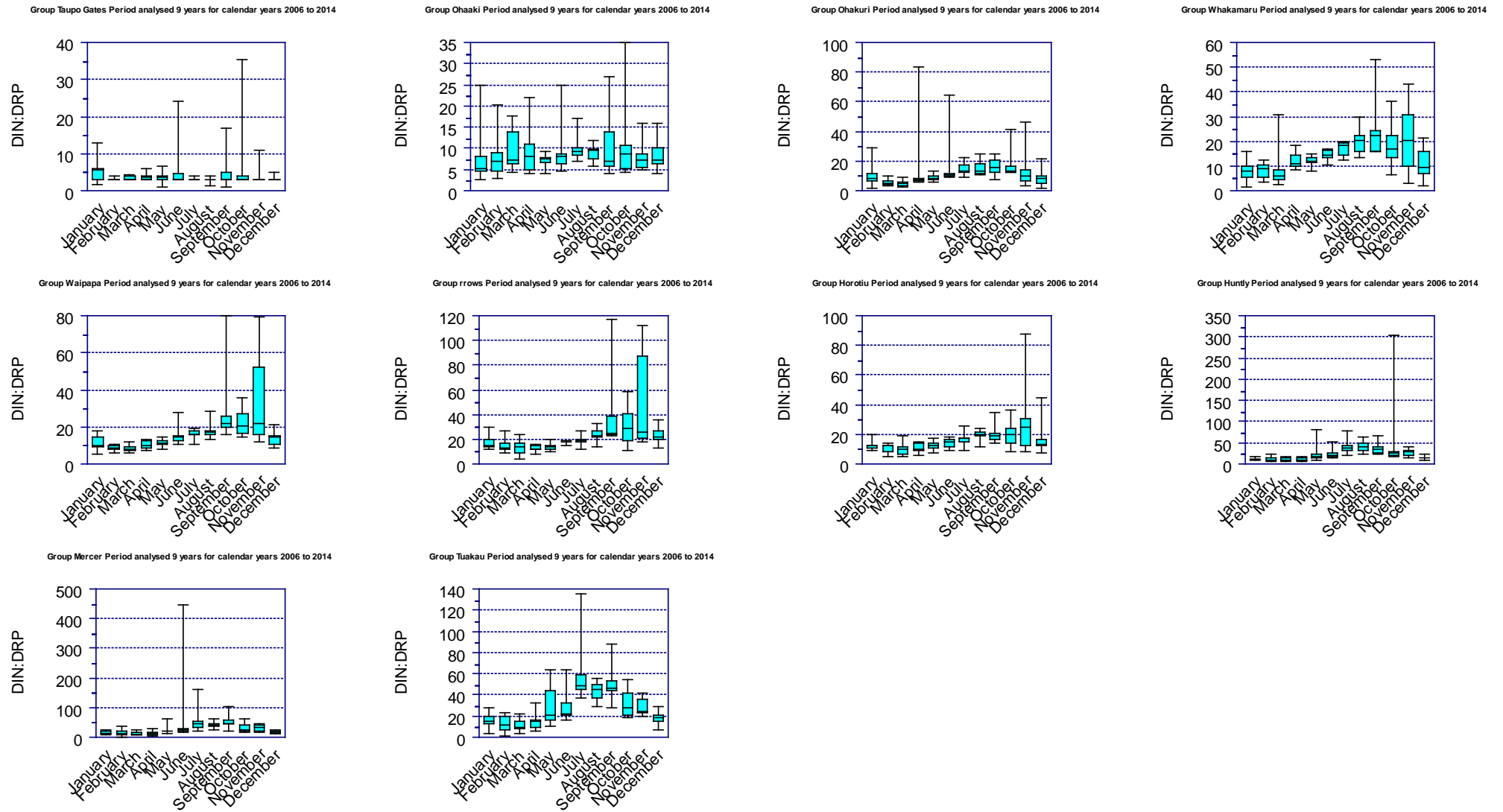
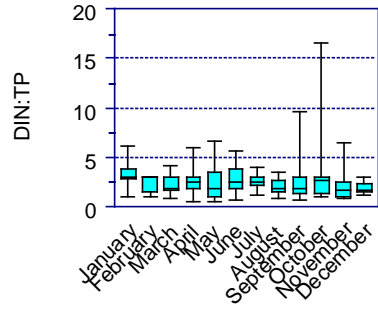
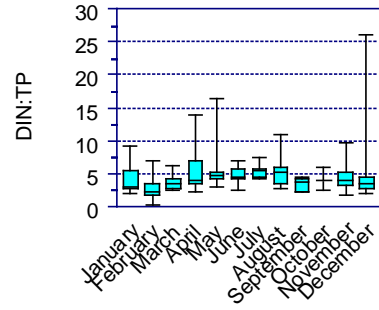


Fig. C31. Seasonality in 2006-2014 in the DIN : DRP ratio.

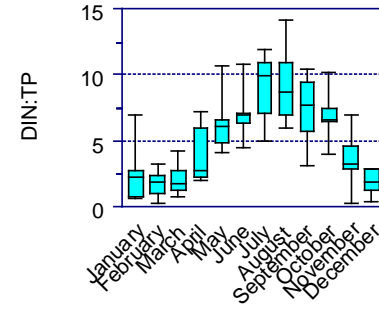
Group Taupo Gates Period analysed 9 years for calendar years 2006 to 2014



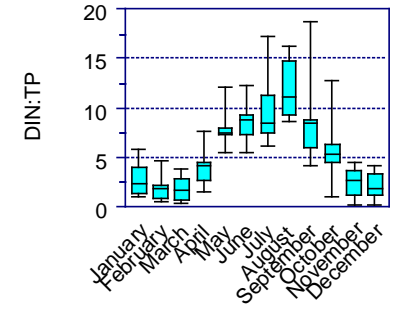
Group Ohaaki Period analysed 9 years for calendar years 2006 to 2014



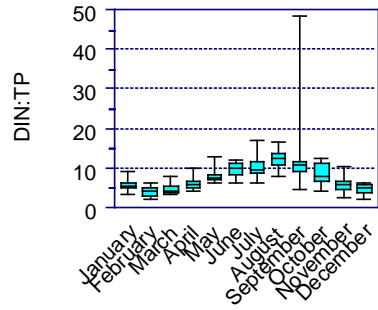
Group Ohakuri Period analysed 9 years for calendar years 2006 to 2014



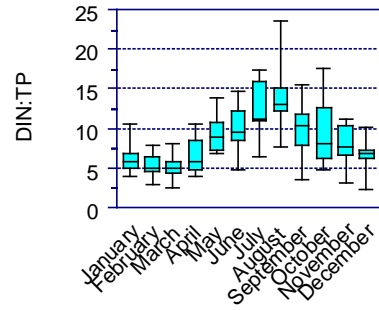
Group Whakamaru Period analysed 9 years for calendar years 2006 to 2014



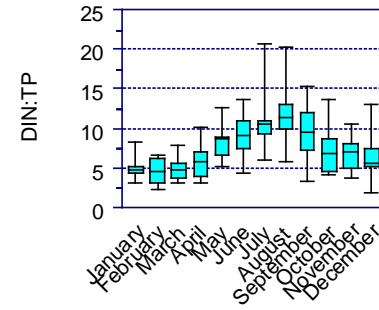
Group Waipapa Period analysed 9 years for calendar years 2006 to 2014



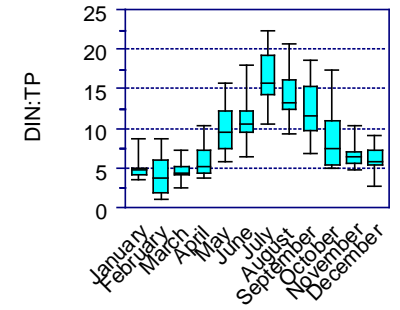
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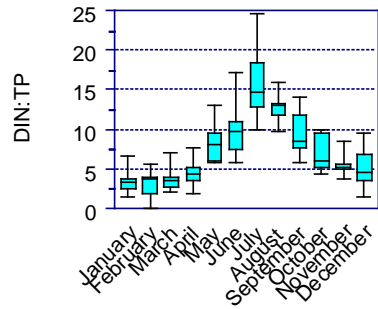
Group Horotiu Period analysed 9 years for calendar years 2006 to 2014



Group Huntly Period analysed 9 years for calendar years 2006 to 2014



Group Mercer Period analysed 9 years for calendar years 2006 to 2014



Group Tuakau Period analysed 9 years for calendar years 2006 to 2014

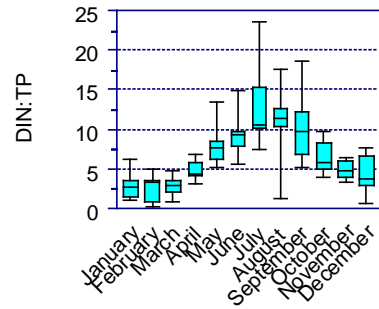


Fig. C32. Seasonality in 2006-2014 in the DIN : TP ratio.

## Appendix D Long-term trends

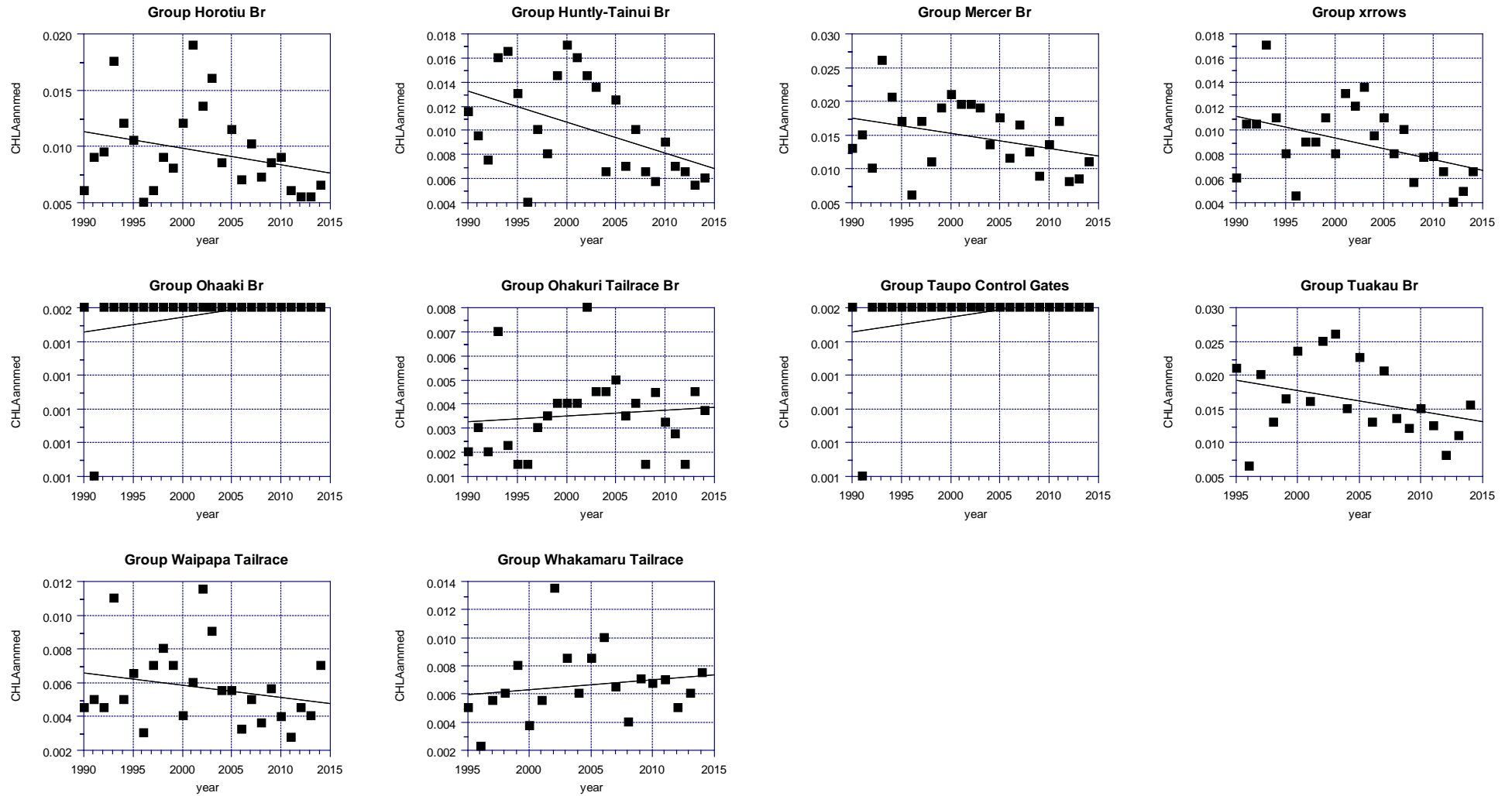


Fig. D1. Trends since 1990 in annual median chlorophyll  $a$ .

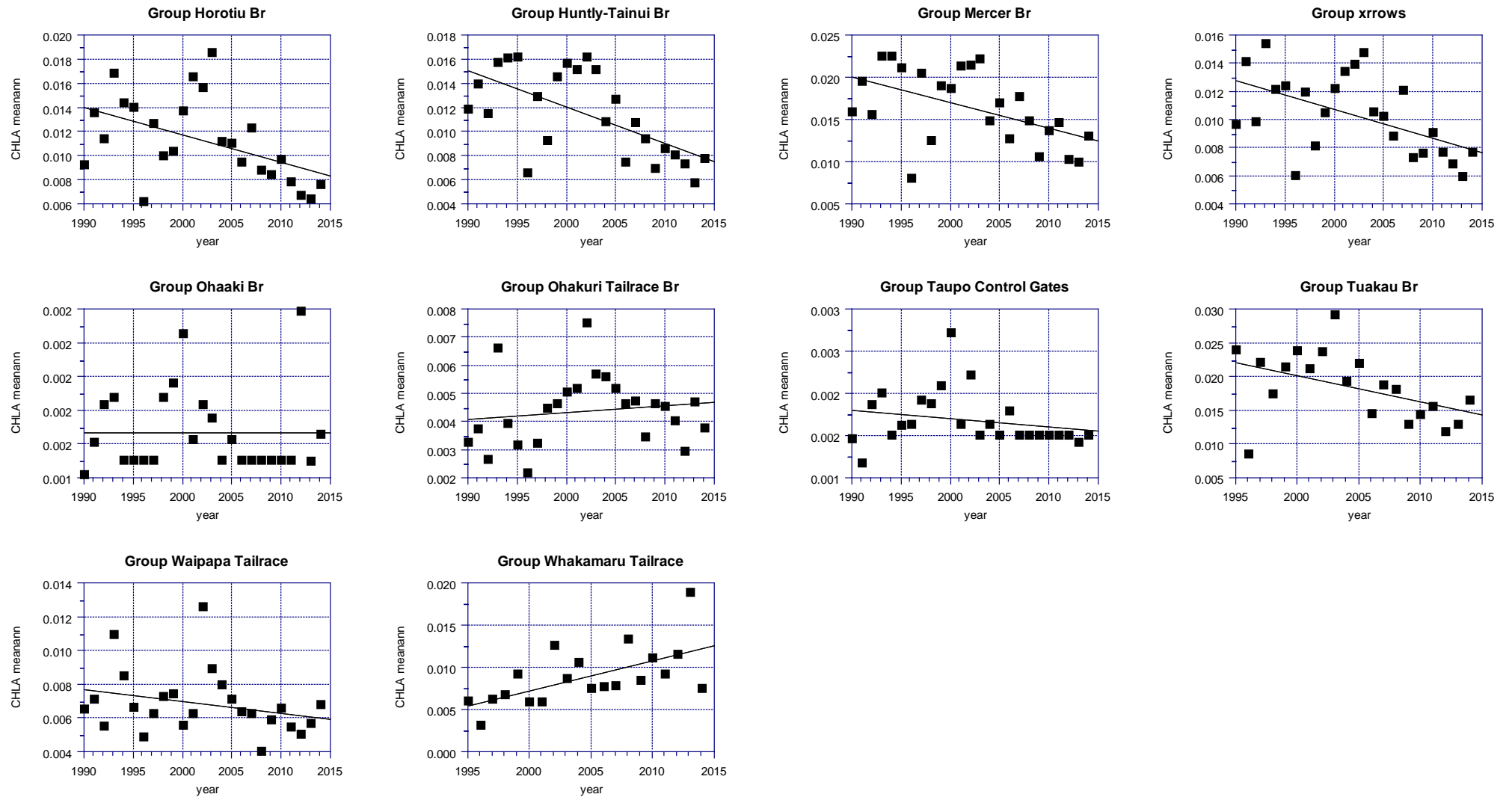


Fig. D2. Trends since 1990 in annual mean chlorophyll  $a$ .



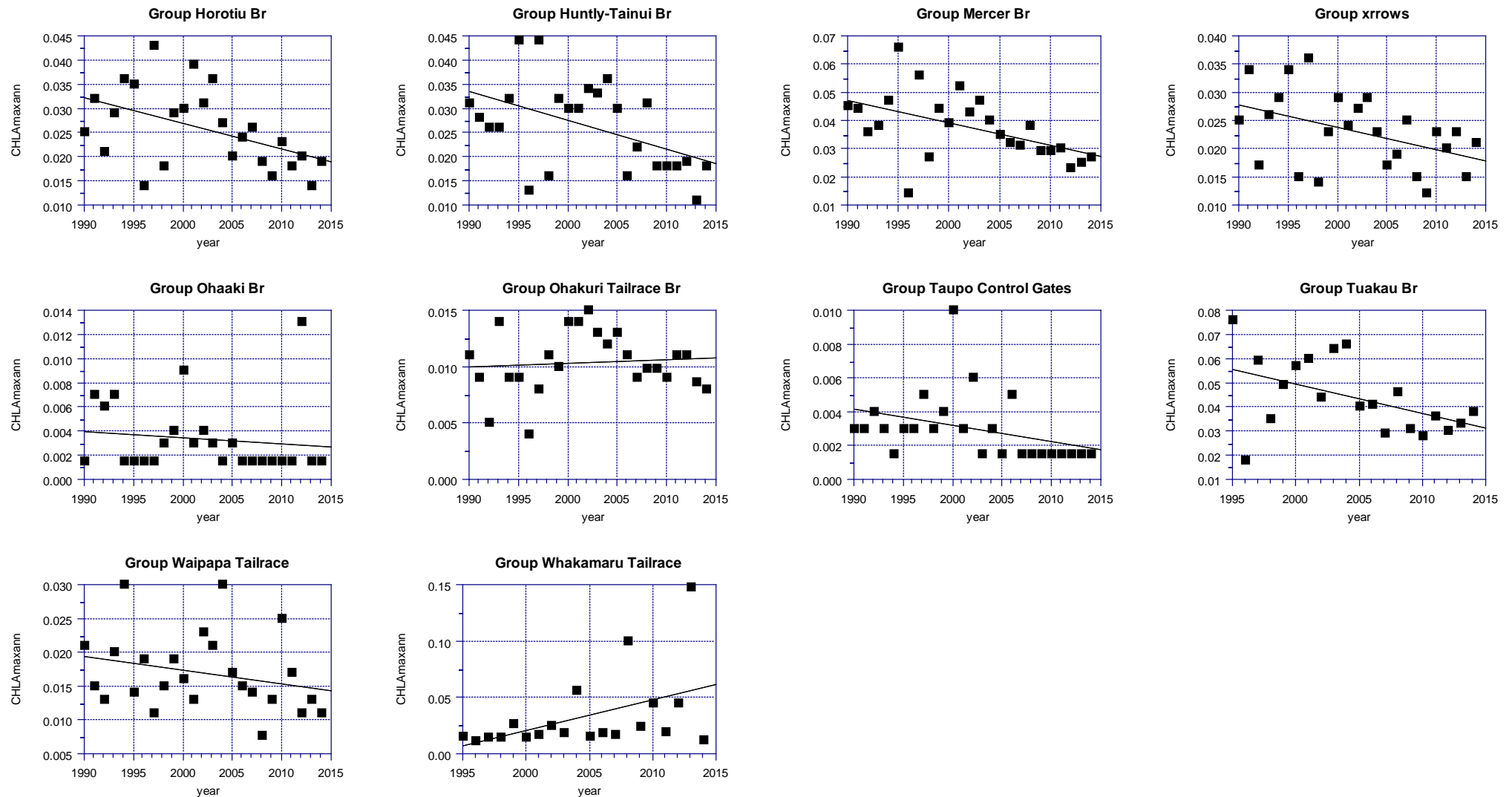


Fig. D3. Trends since 1990 in annual maximum chlorophyll  $a$ .

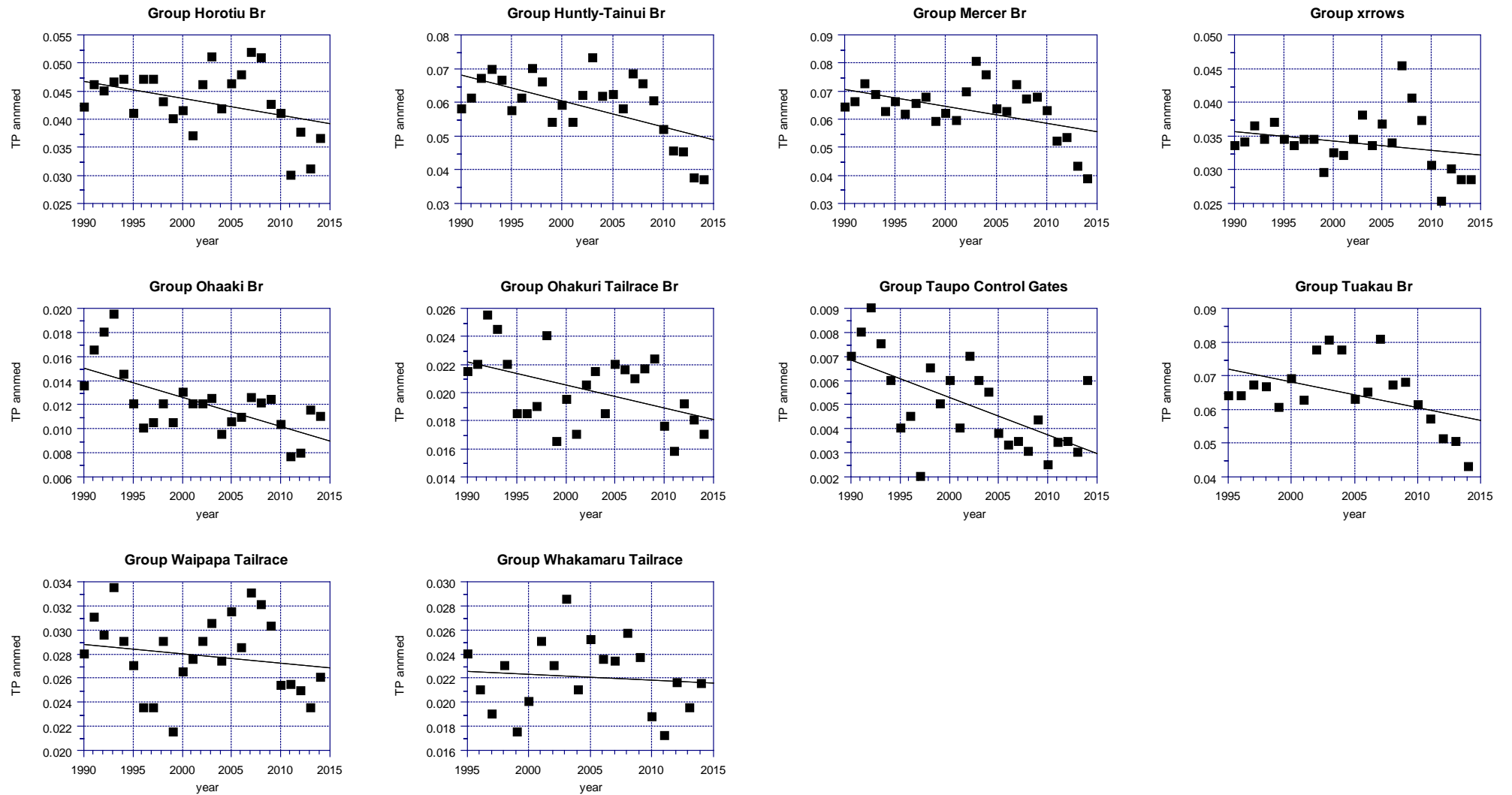


Fig. D4. Trends since 1990 in annual median TP.

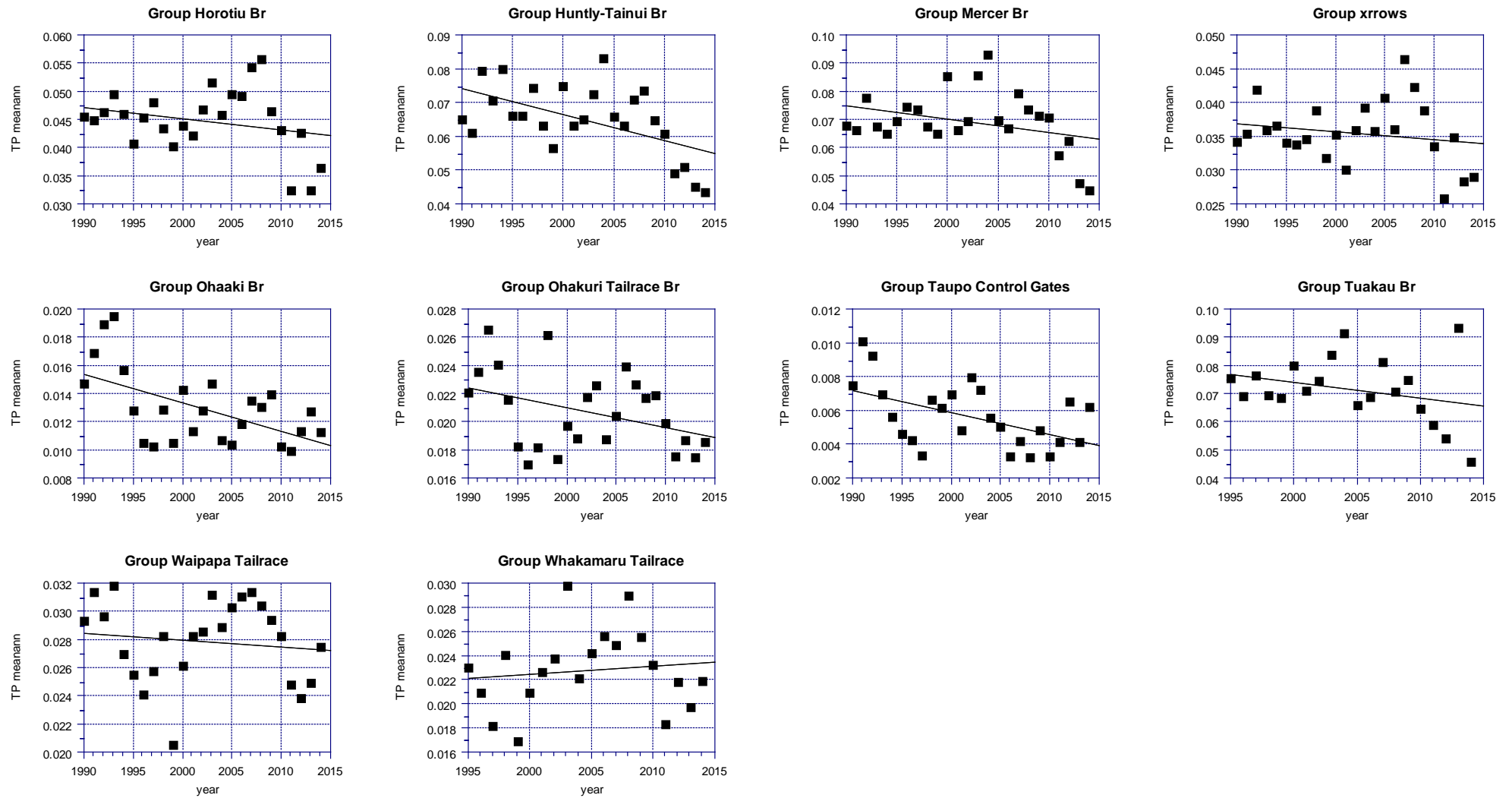


Fig. D5. Trends since 1990 in annual mean TP.

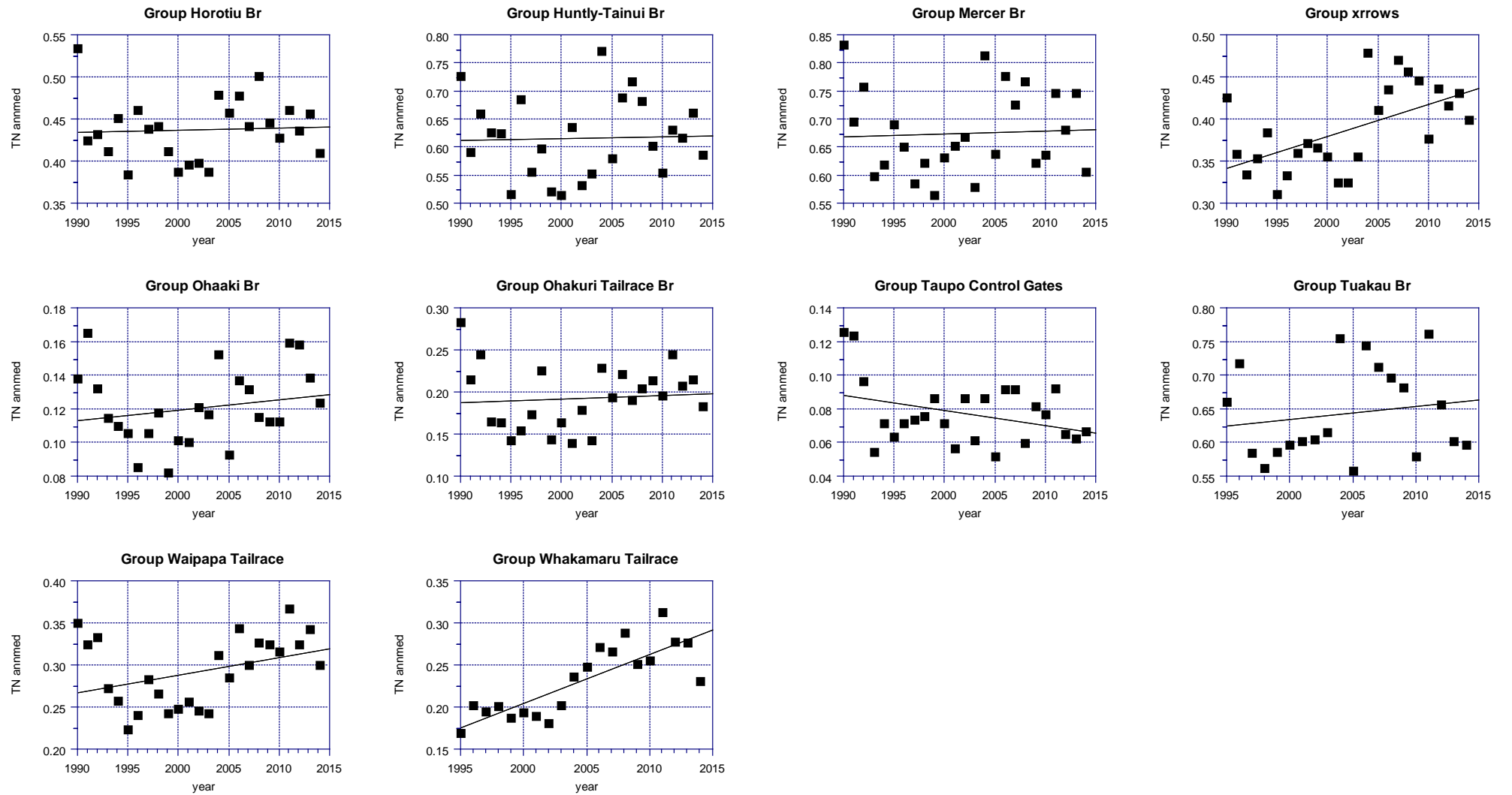


Fig. D6. Trends since 1990 in annual median TN.

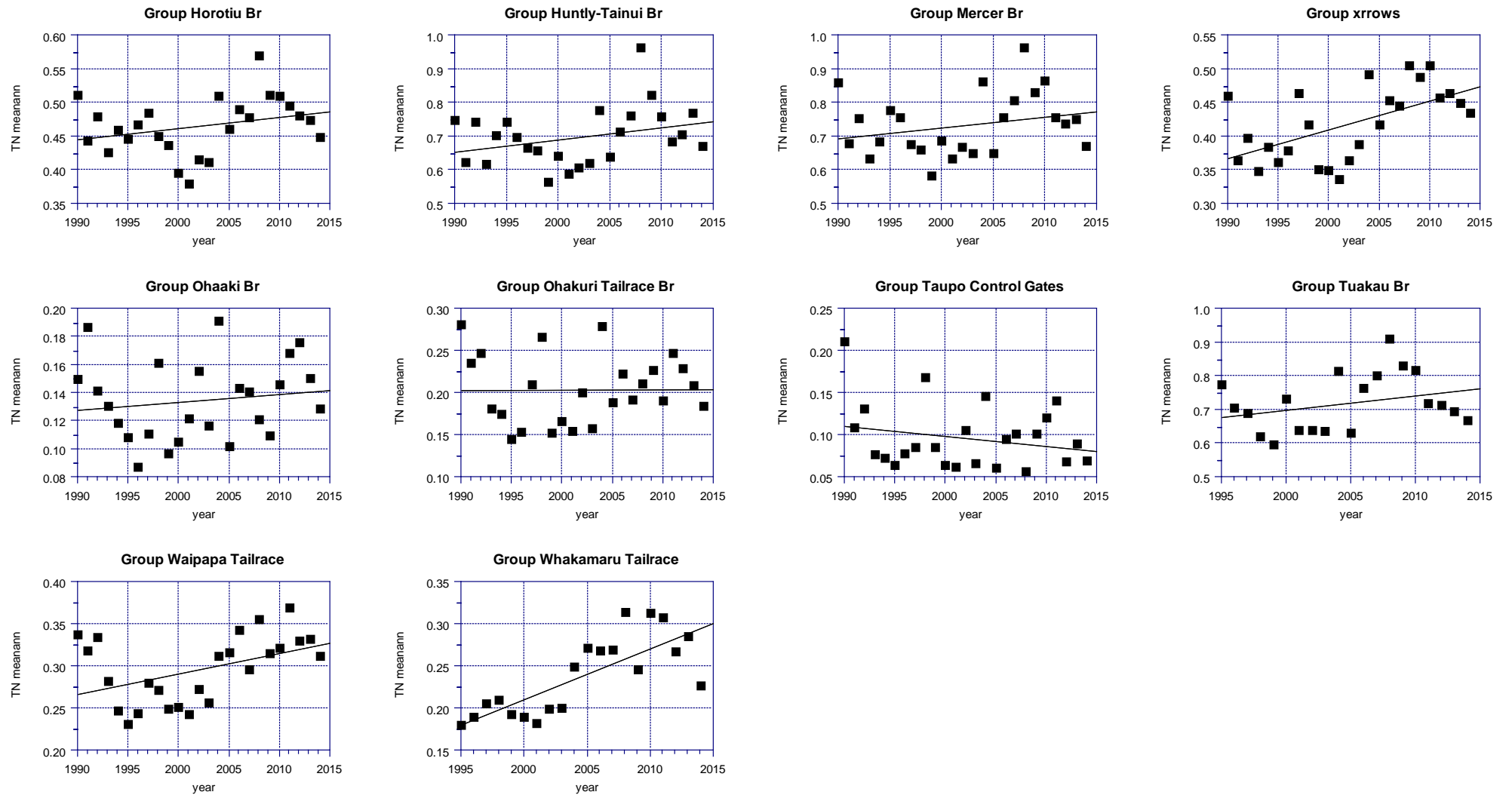


Fig. D7. Trends since 1990 in annual mean TN.

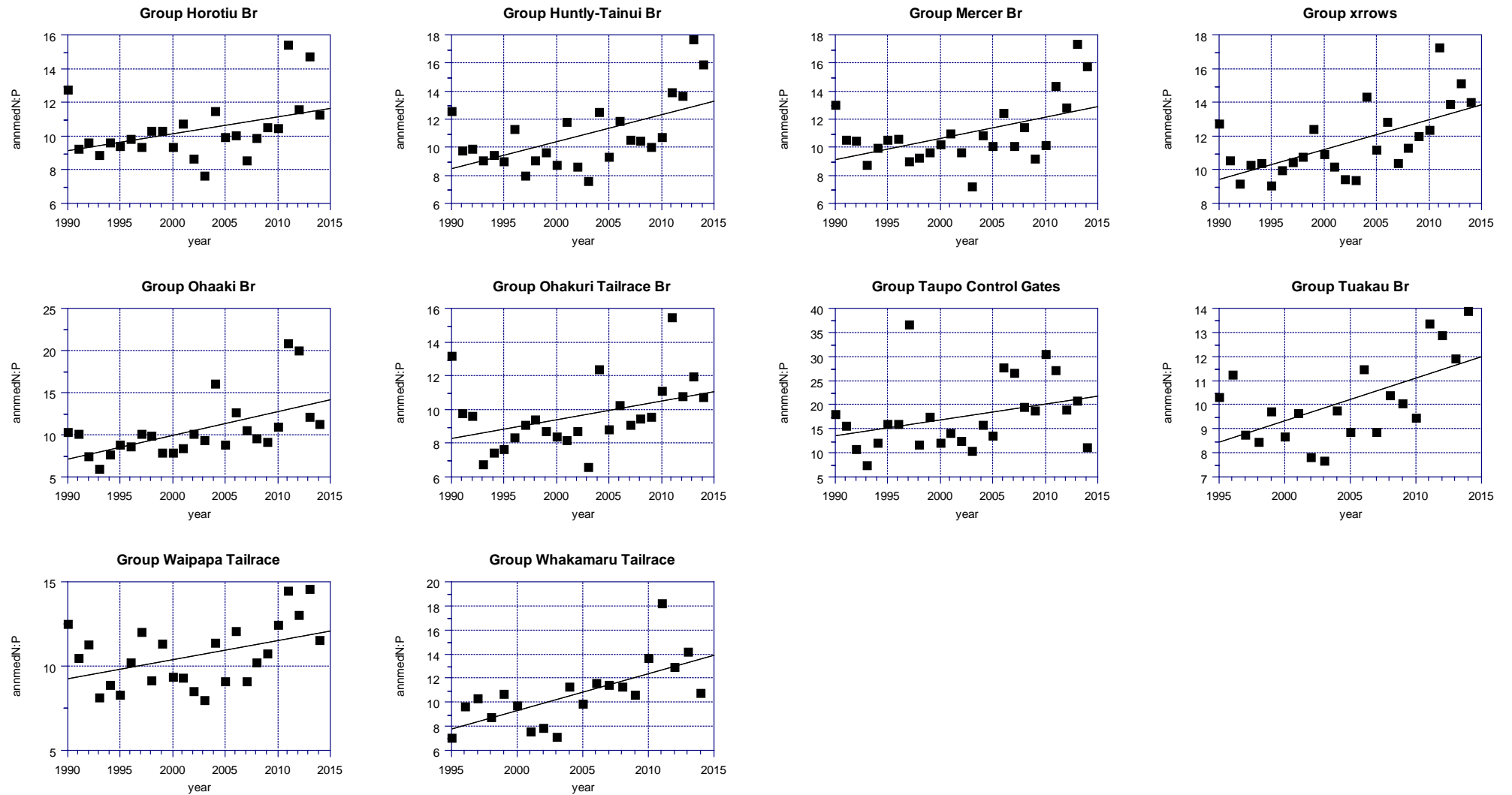


Fig. D8. Trends since 1990 in ratios of annual medians of TN and TP (by weight).

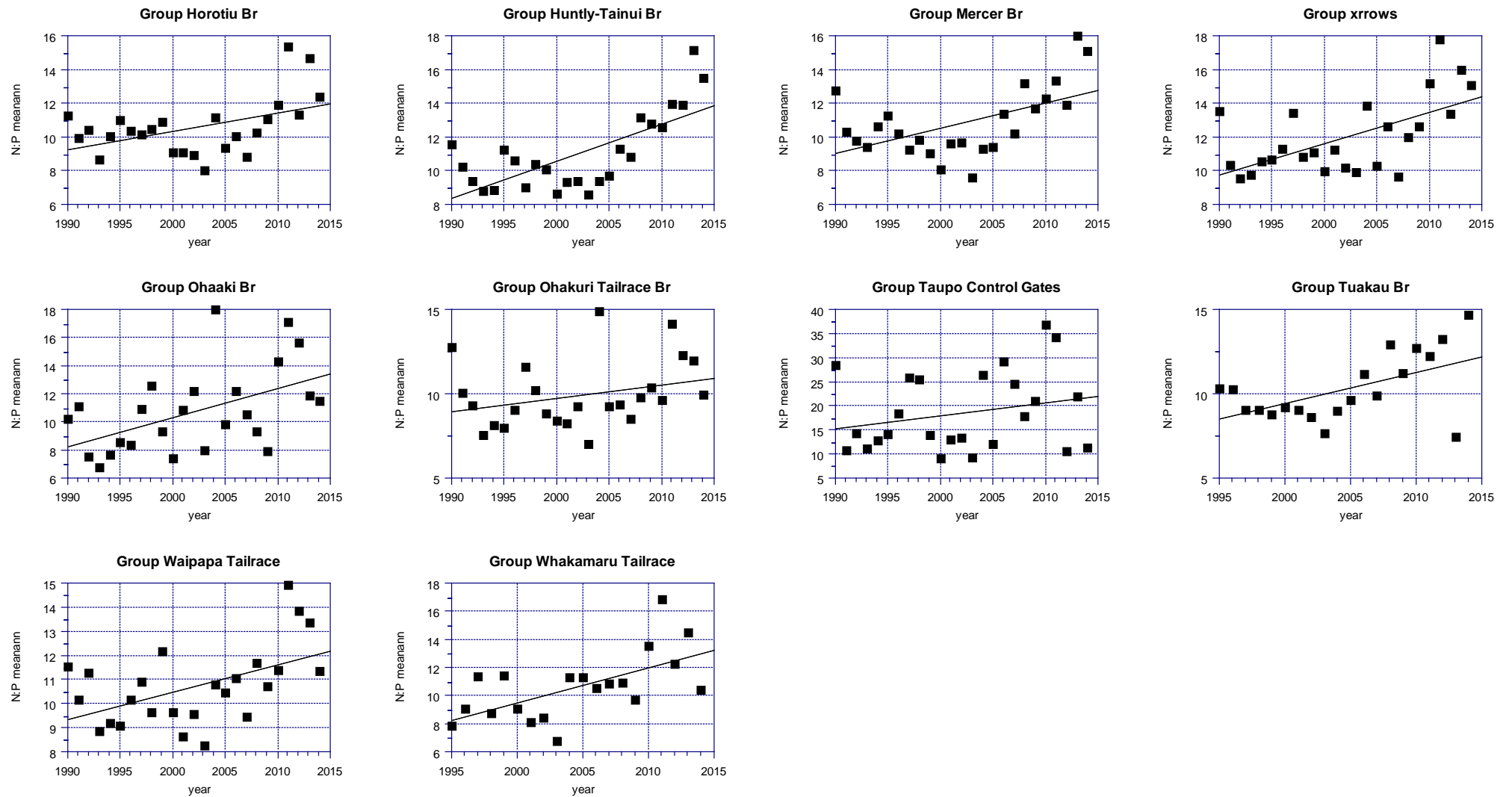


Fig. D9. Trends since 1990 in ratios of annual means of TN and TP (by weight).

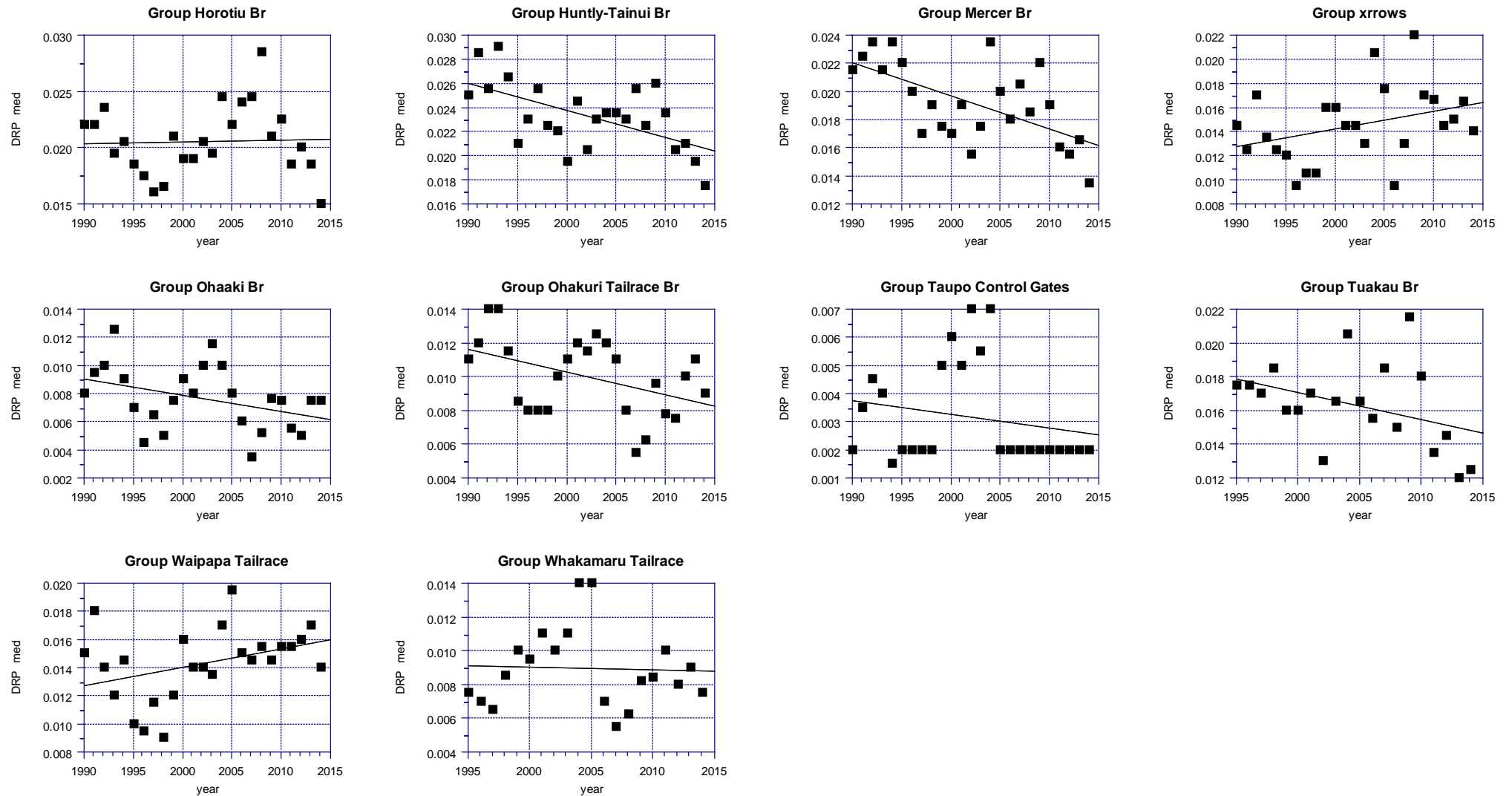


Fig. D10. Trends since 1990 in annual median DRP.



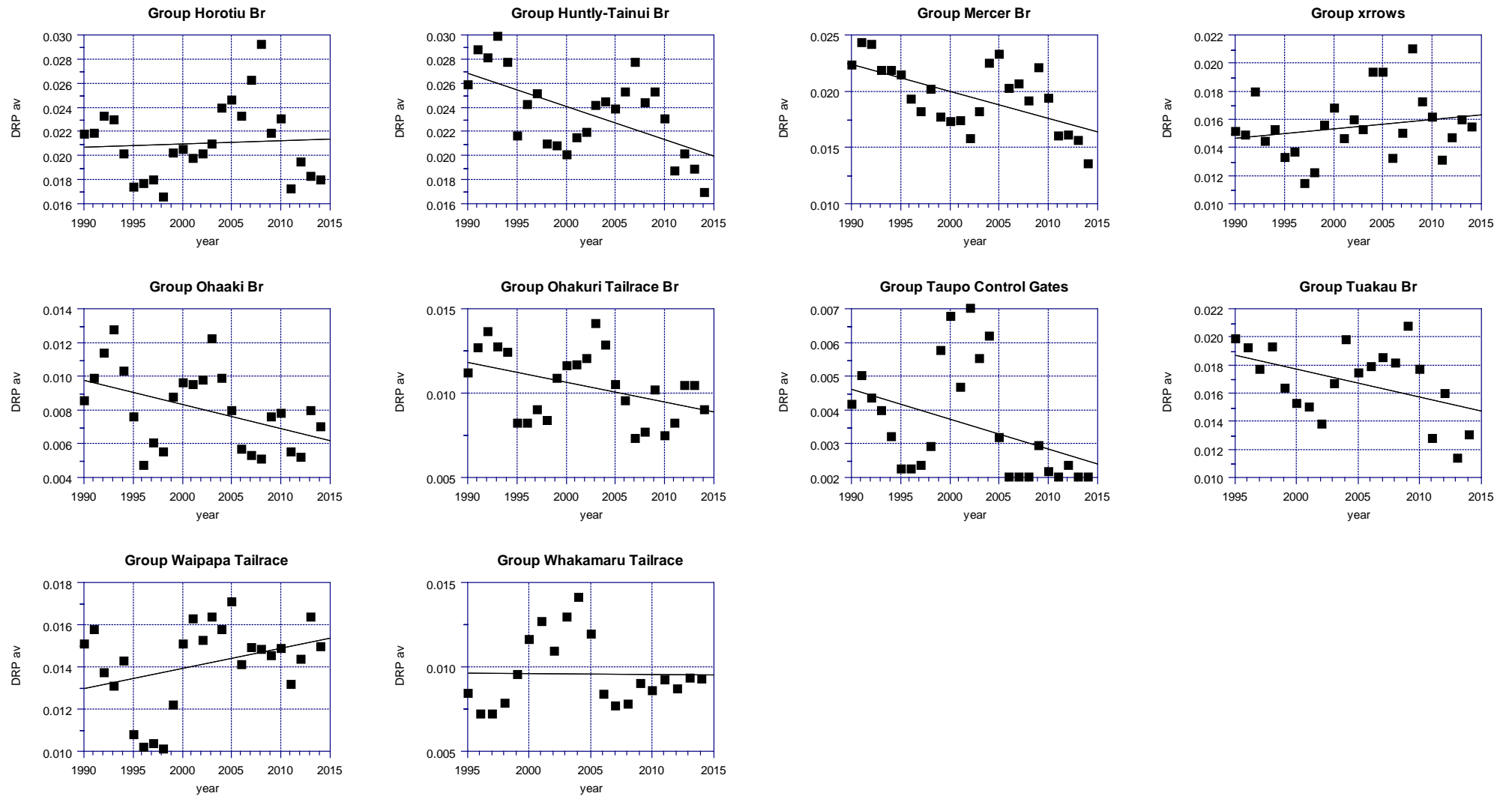


Fig. D11. Trends since 1990 in annual mean DRP.

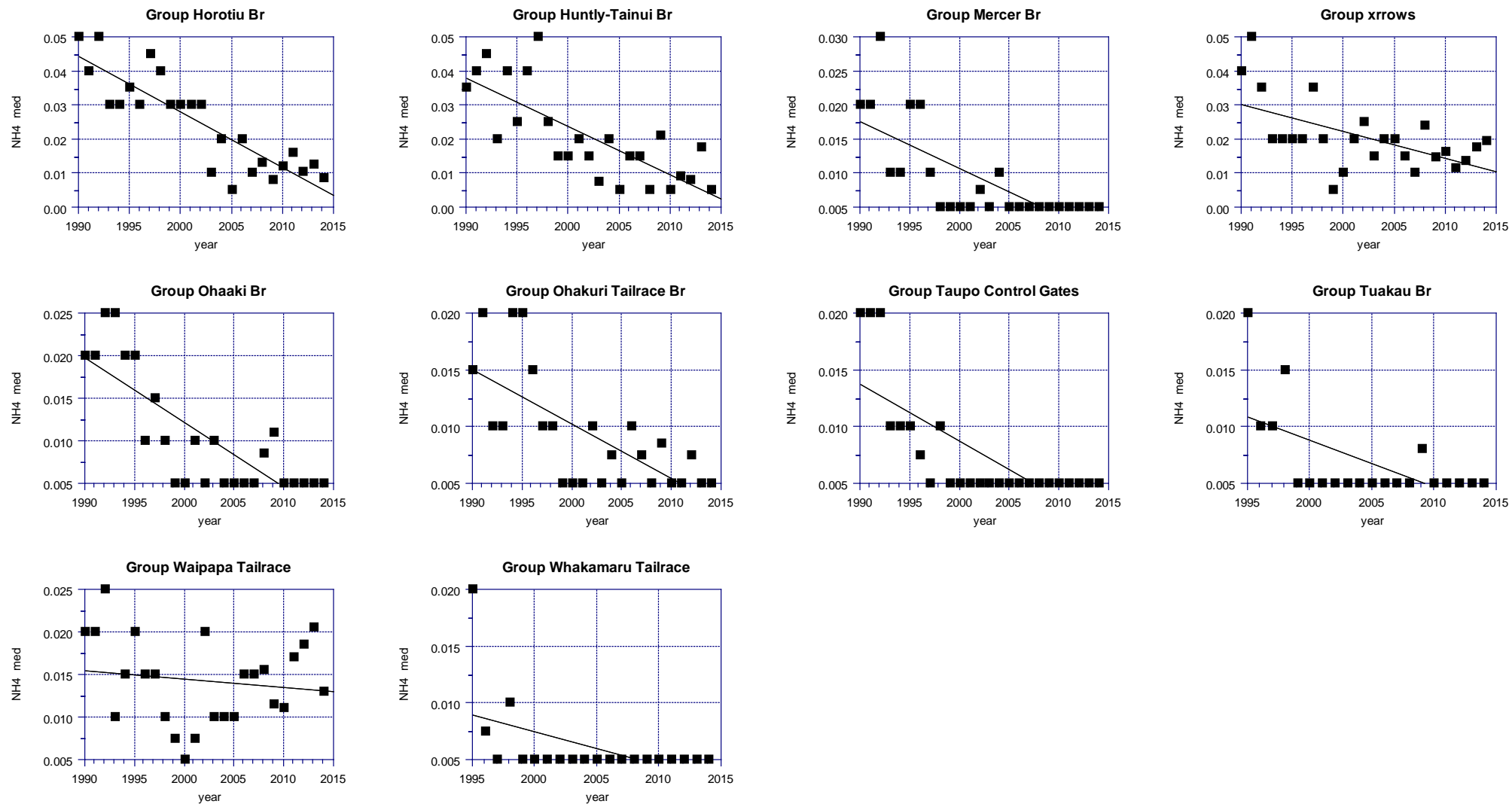


Fig. D12. Trends since 1990 in annual median NH<sub>4</sub>.

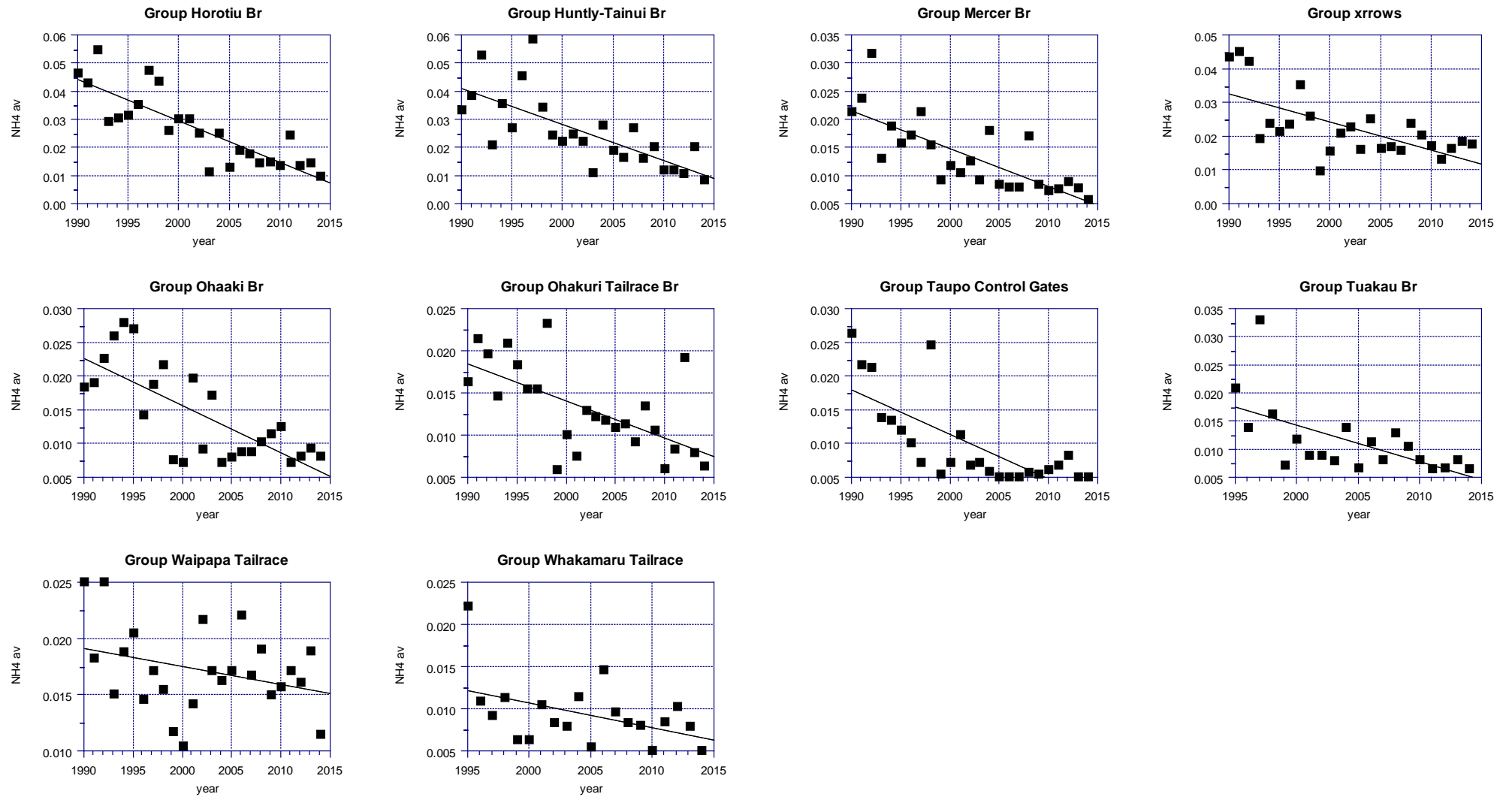


Fig. D13. Trends since 1990 in annual mean NH<sub>4</sub>.

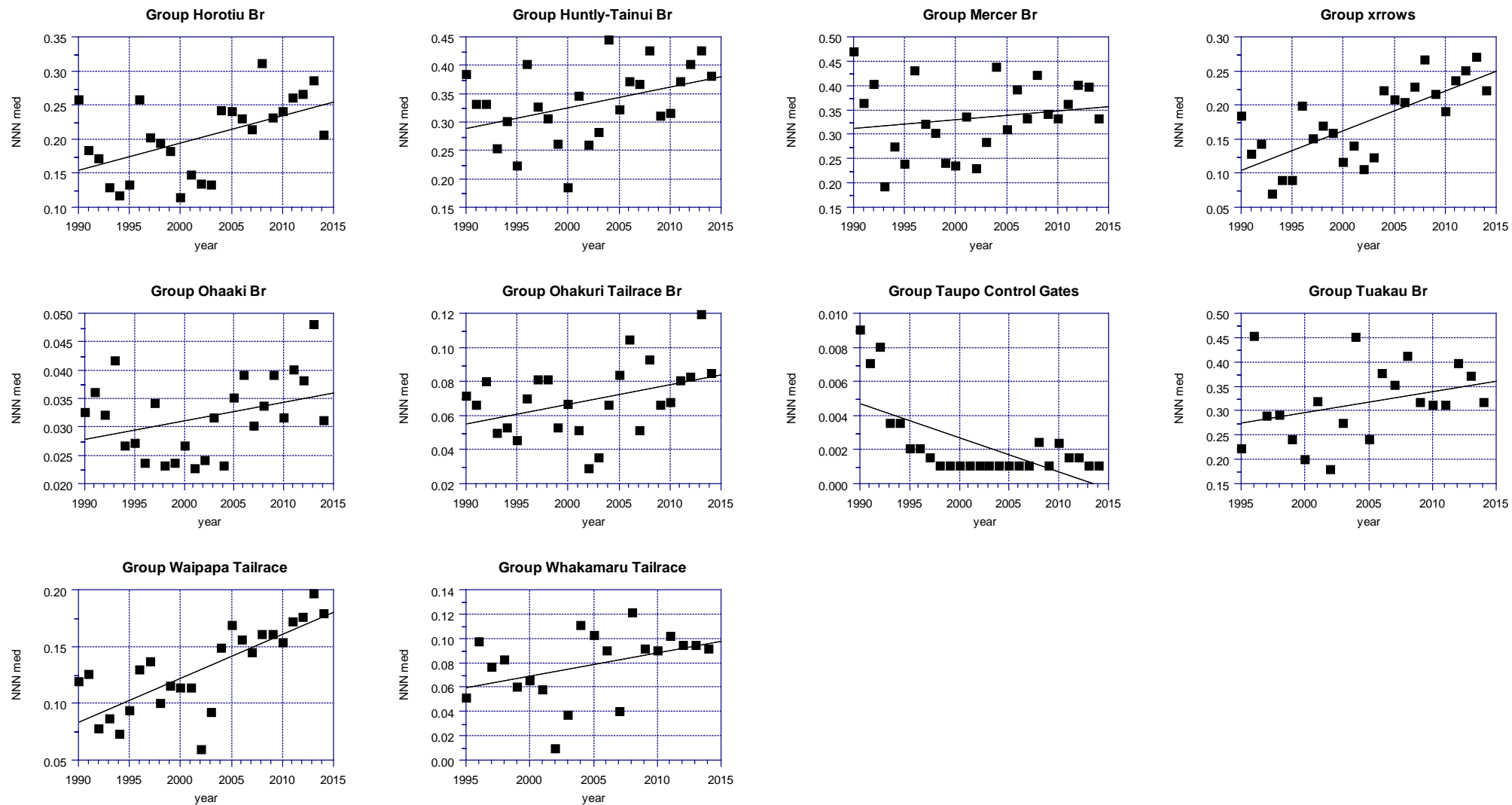


Fig. D14. Trends since 1990 in annual median NO<sub>3</sub>.

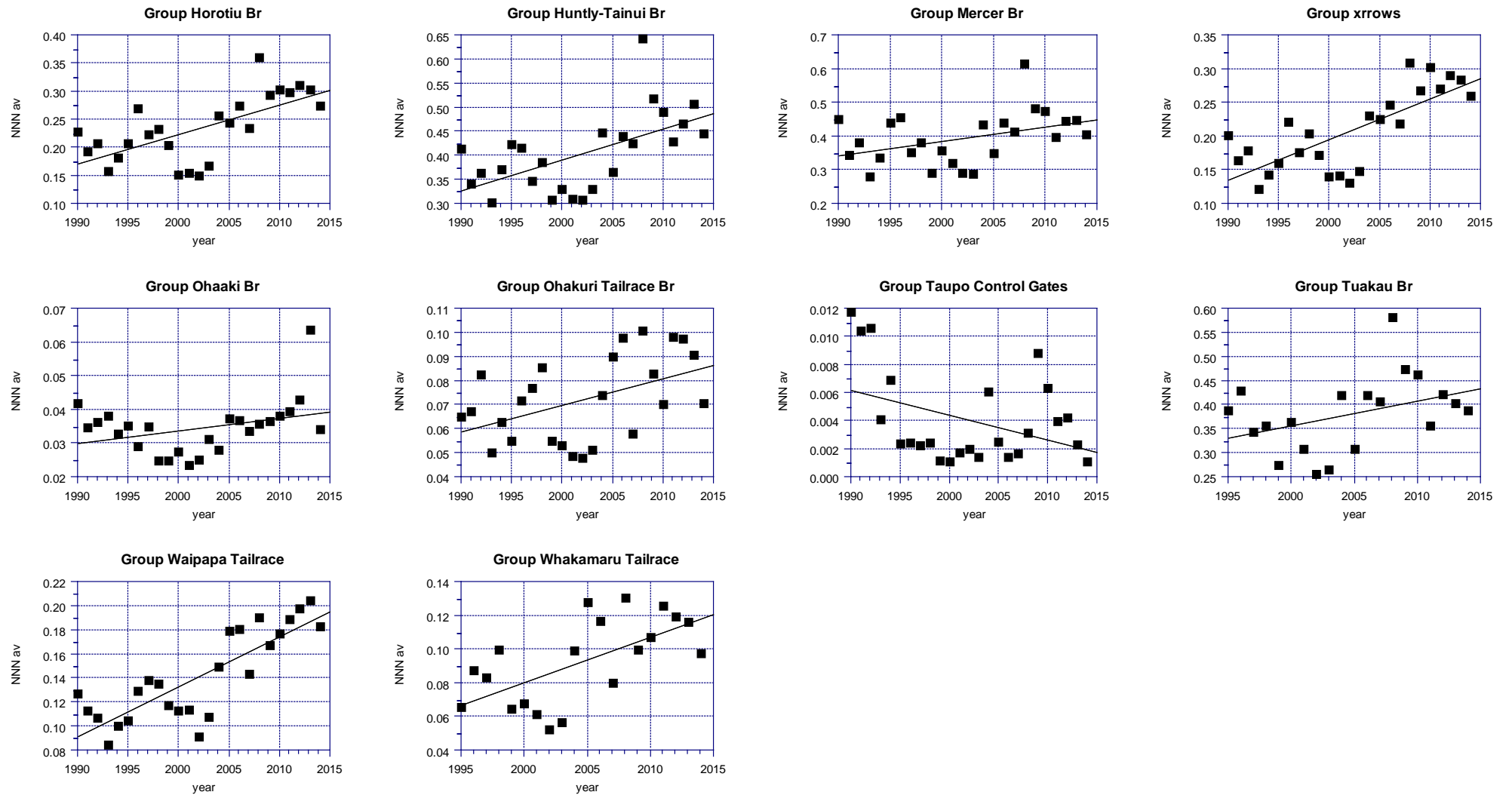


Fig. D15. Trends since 1990 in annual mean NO<sub>3</sub>.

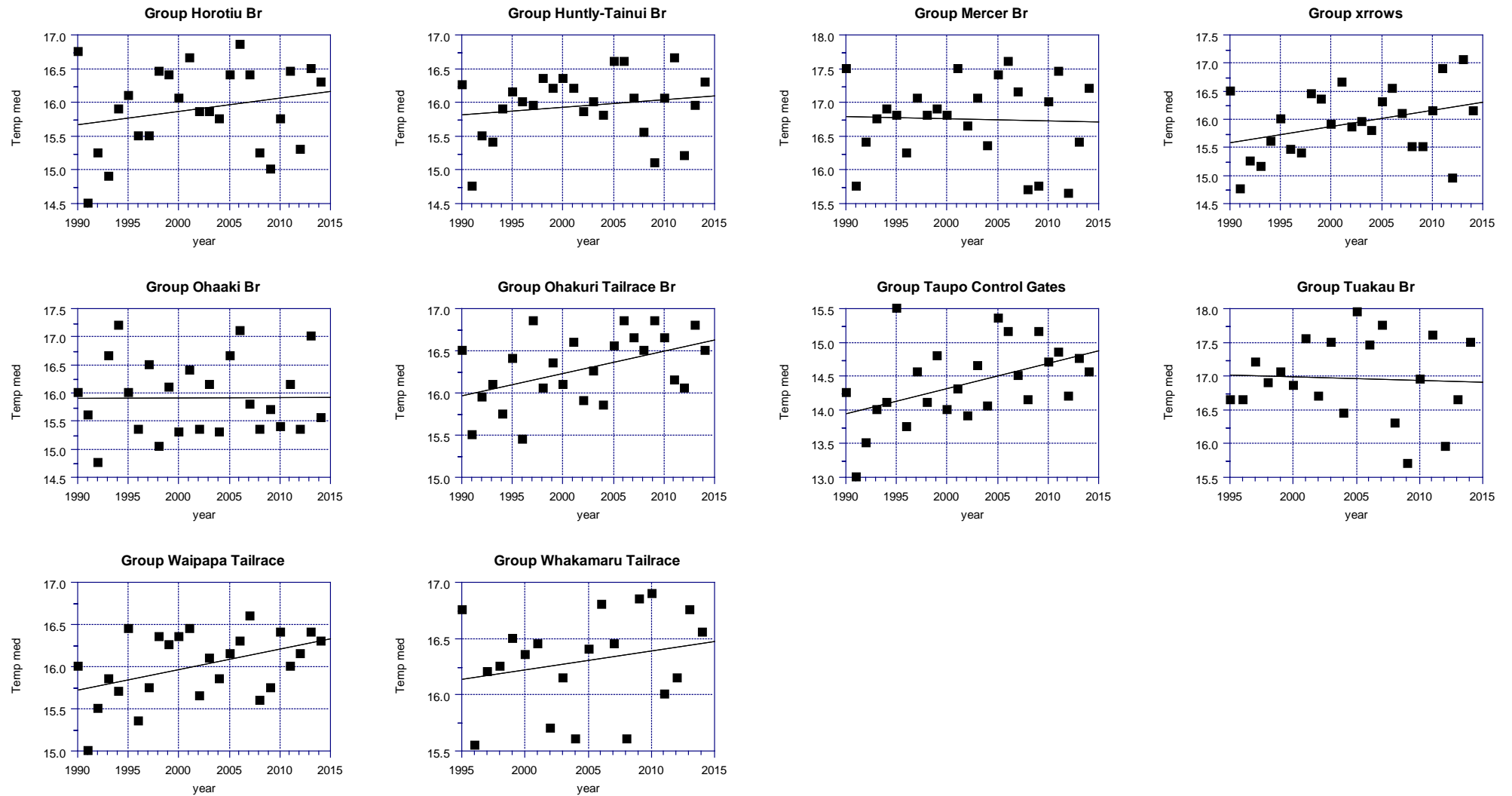


Fig. D16. Trends since 1990 in annual median water temperature.

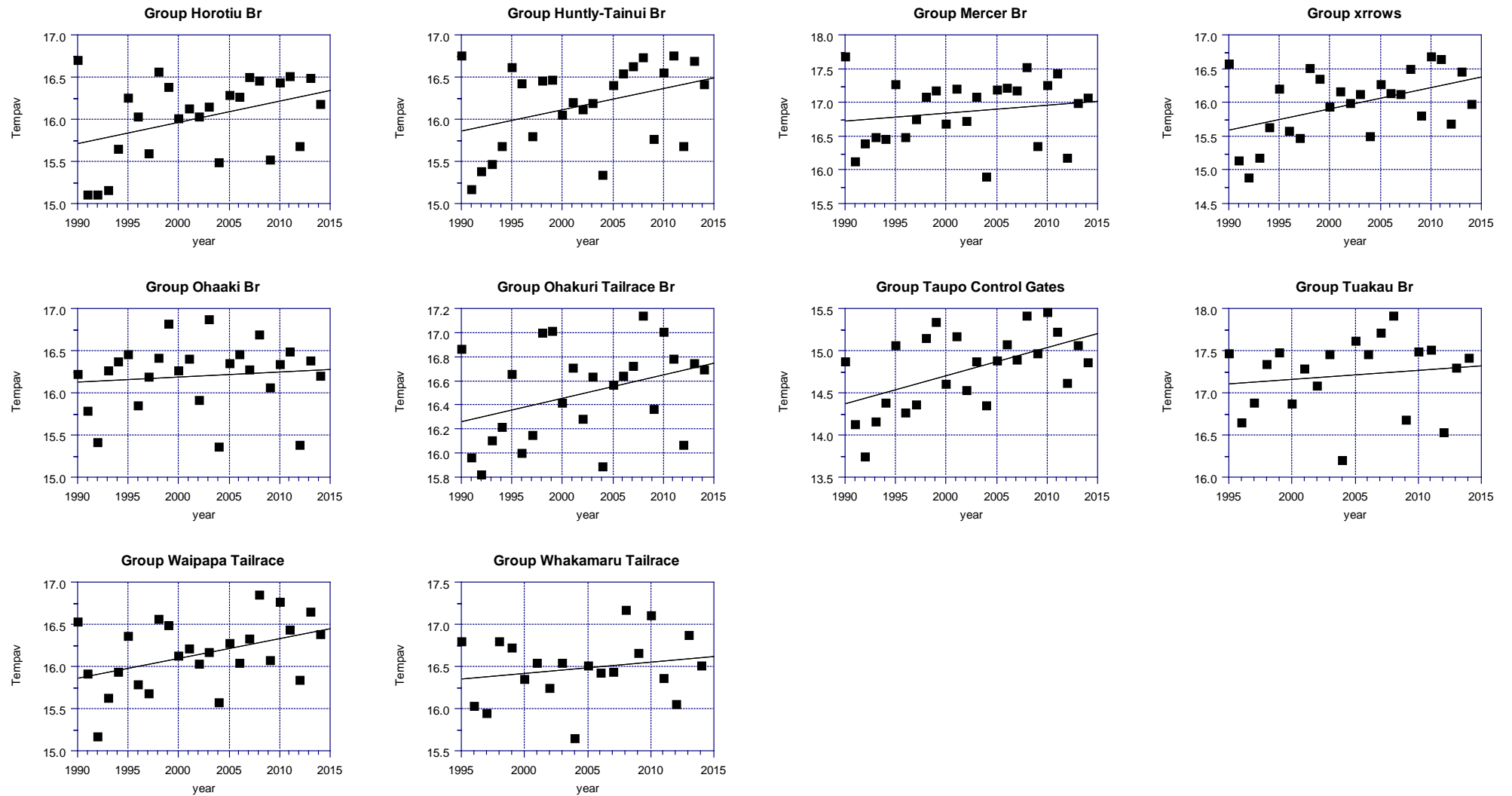


Fig. D17. Trends since 1990 in annual mean water temperature.

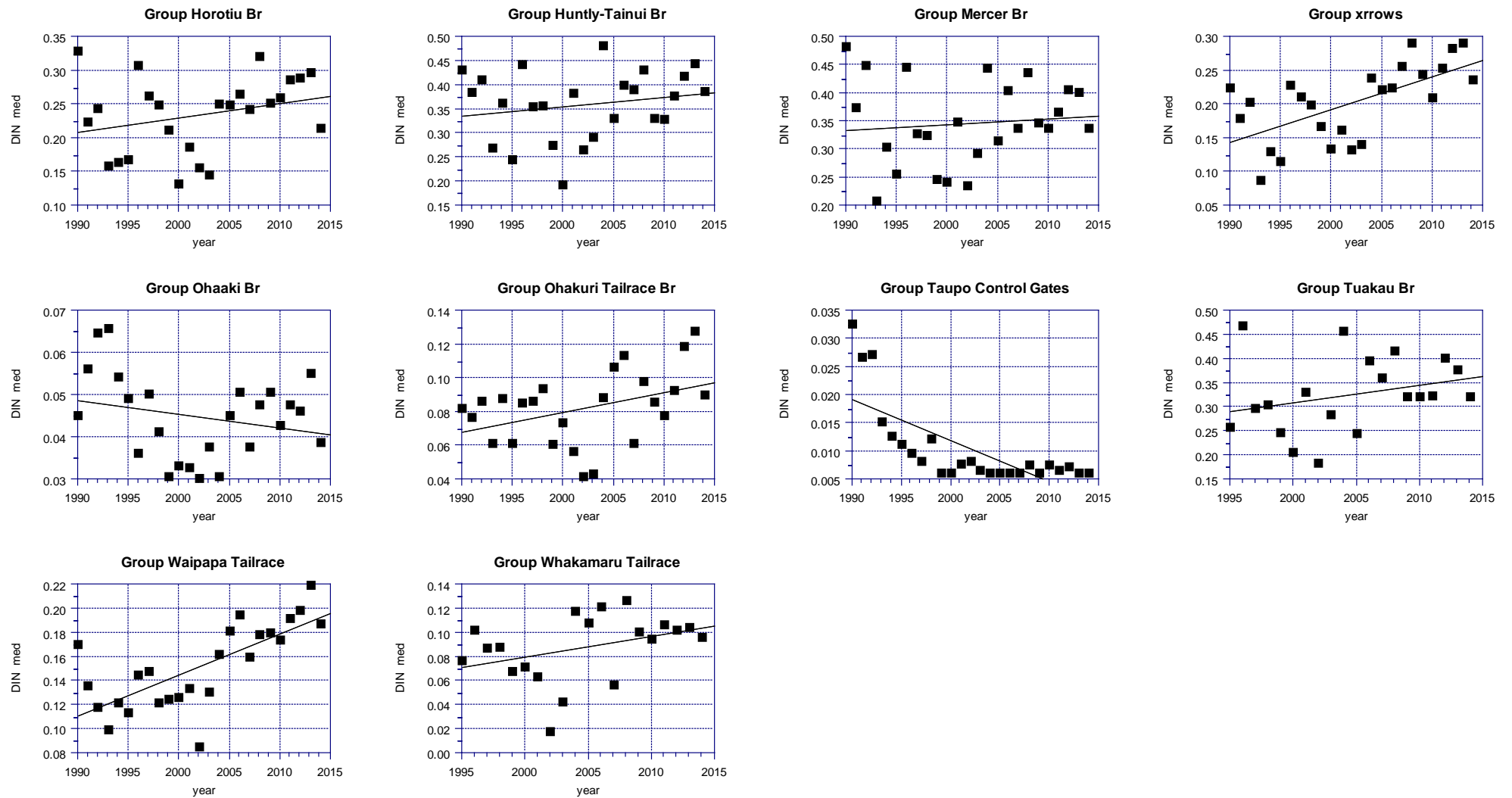


Fig. D18. Trends since 1990 in annual median DIN.



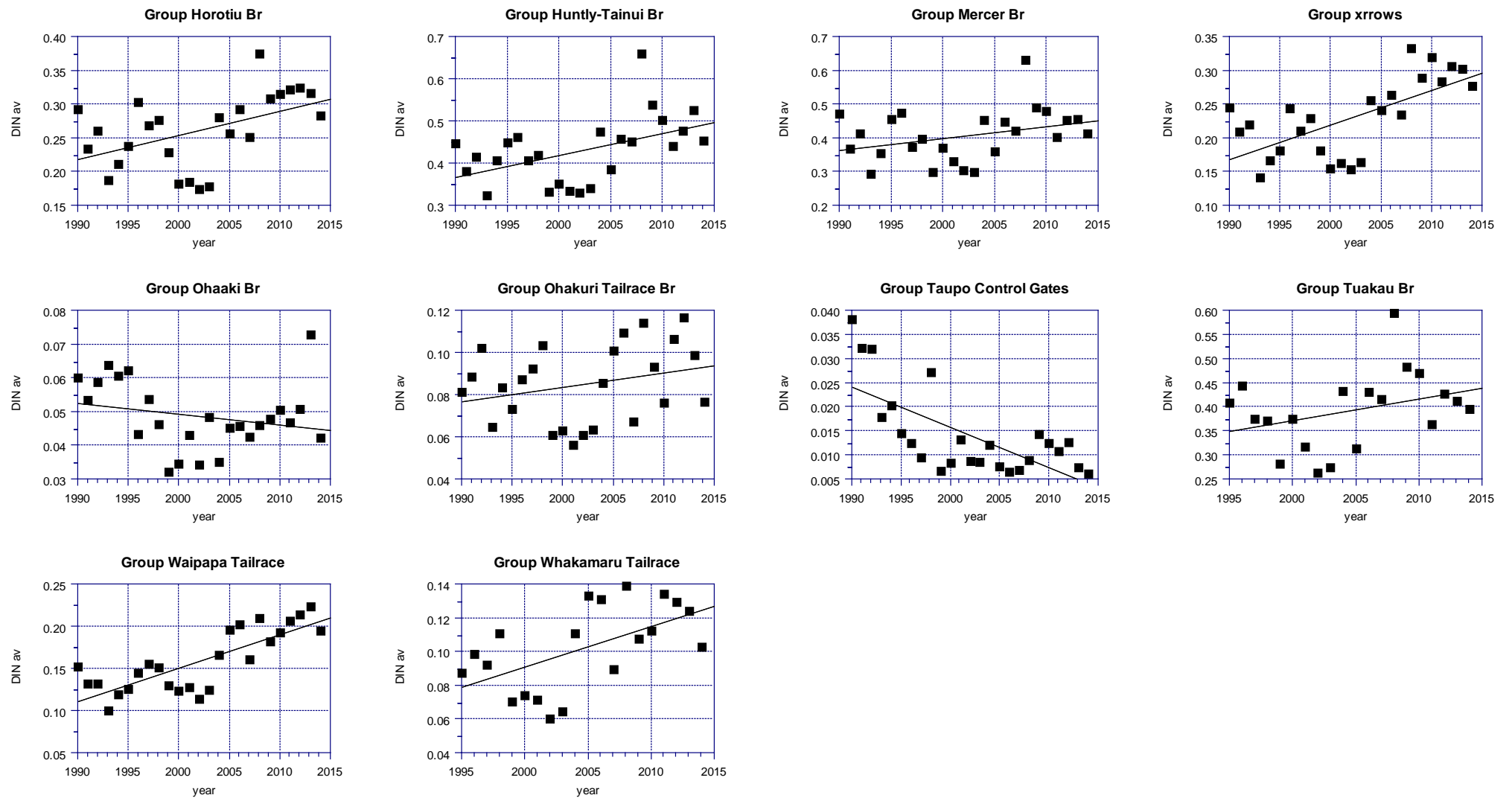


Fig. D19. Trends since 1990 in annual mean DIN.

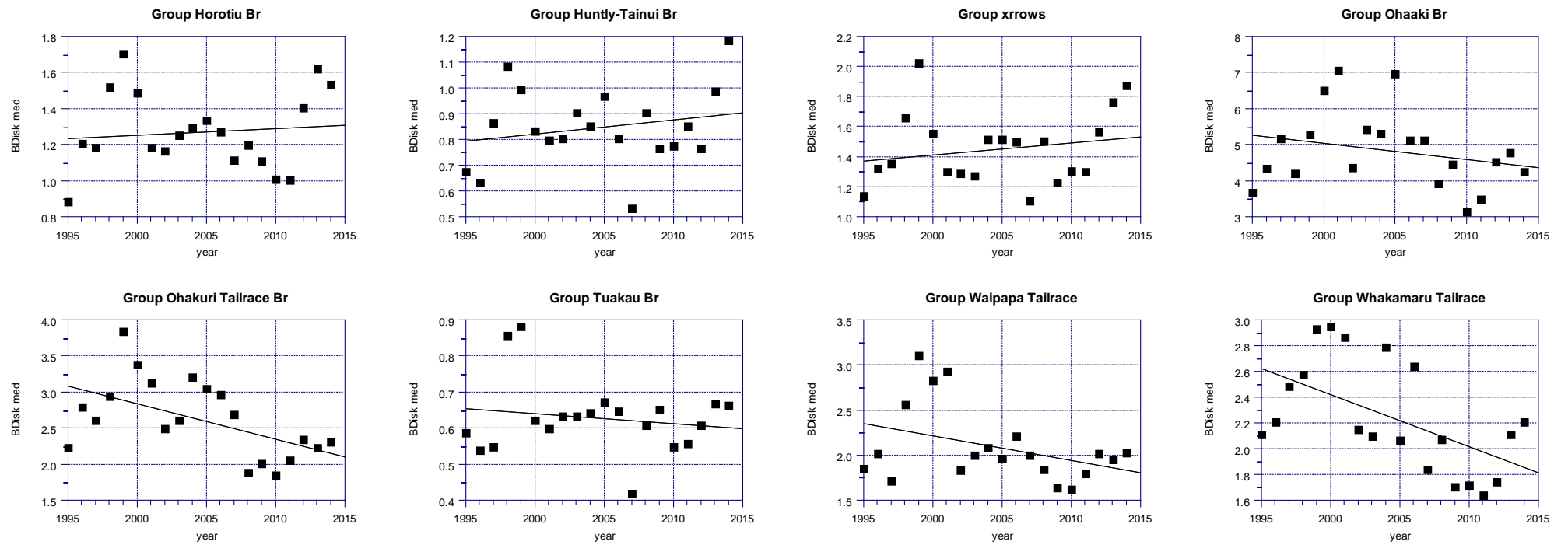


Fig. D20. Trends since 1990 in annual median Black Disk water clarity.

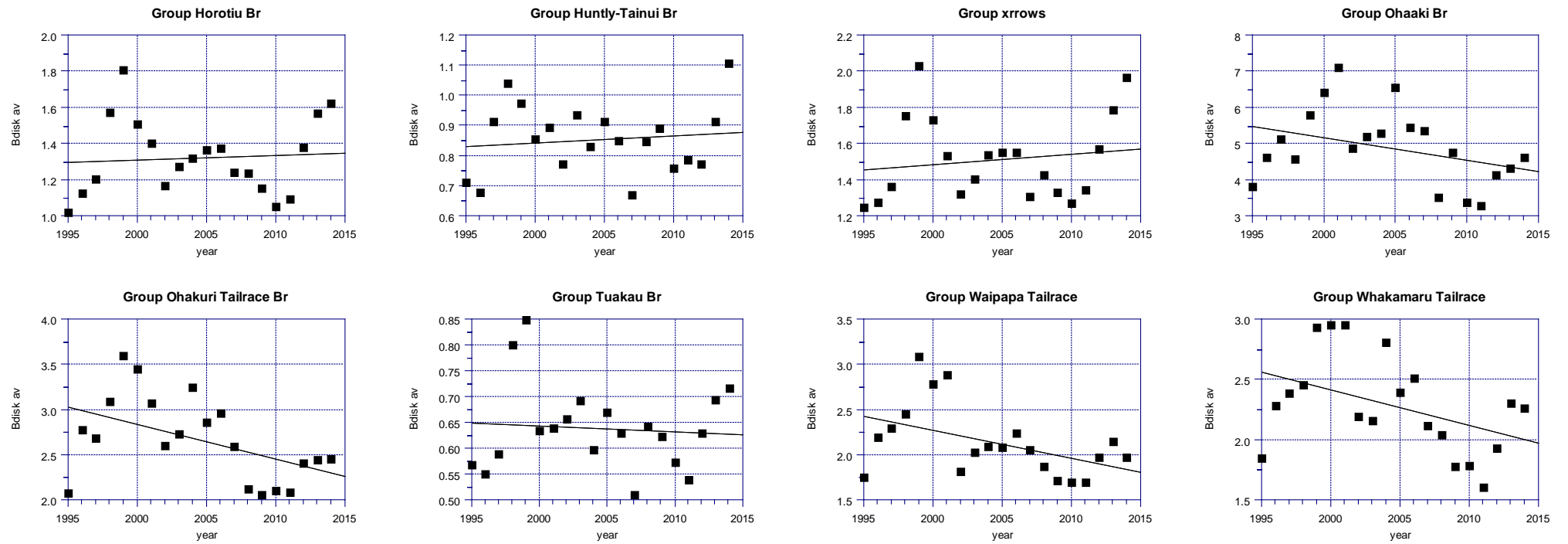


Fig. D21. Trends since 1990 in annual mean Black Disk water clarity.

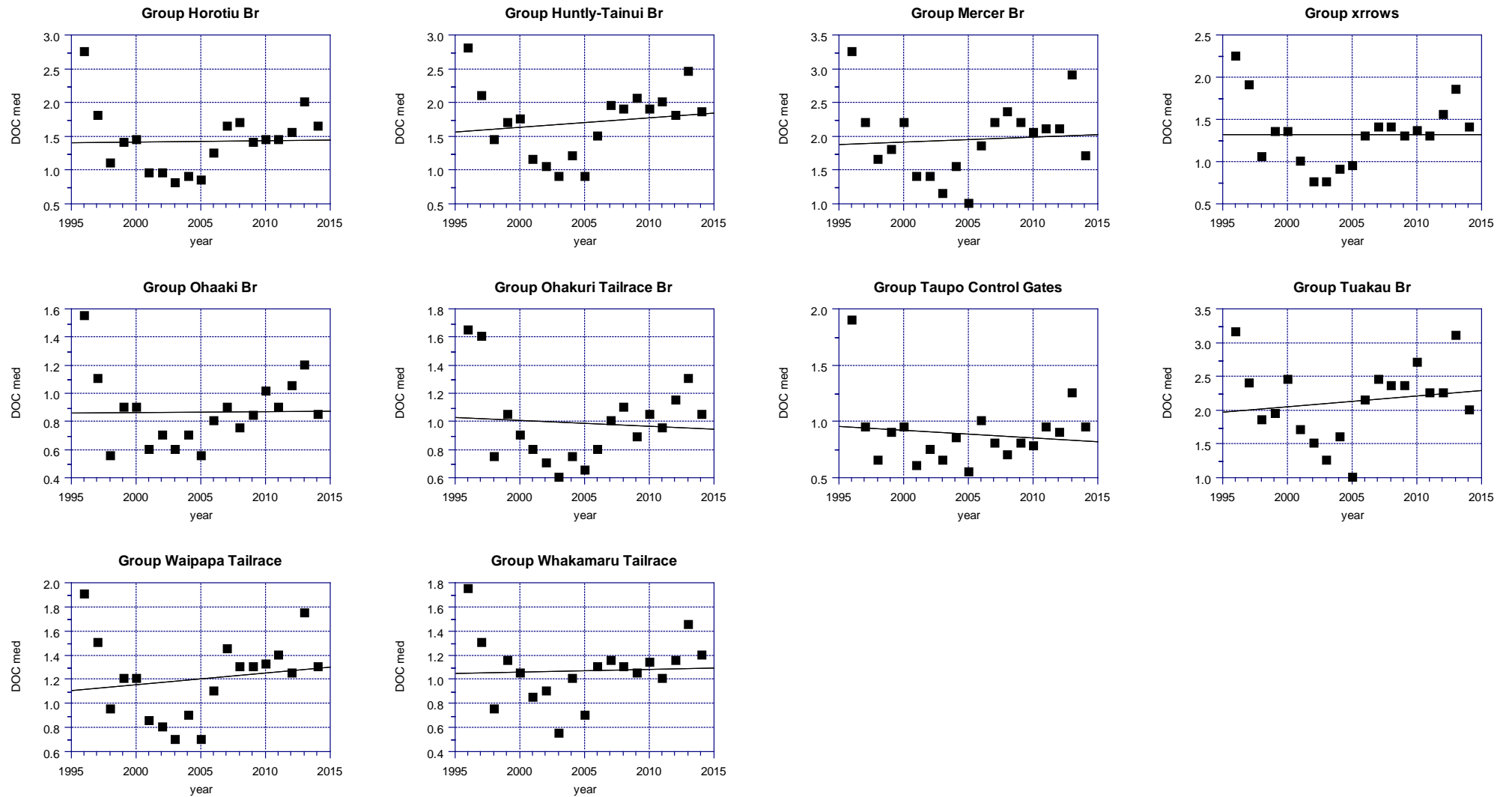


Fig. D22. Trends since 1990 in annual median DOC.

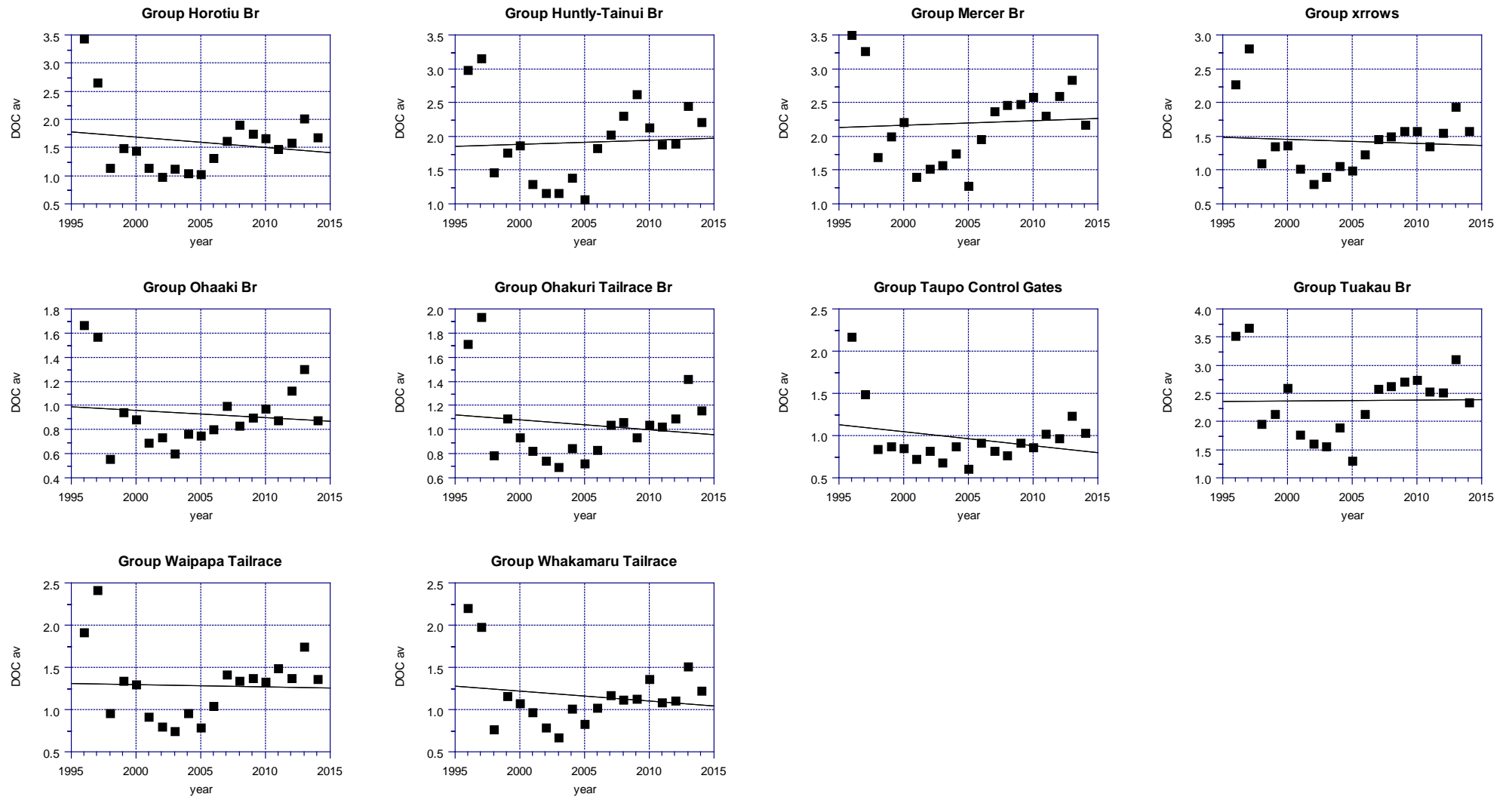


Fig. D23. Trends since 1990 in annual mean DOC.

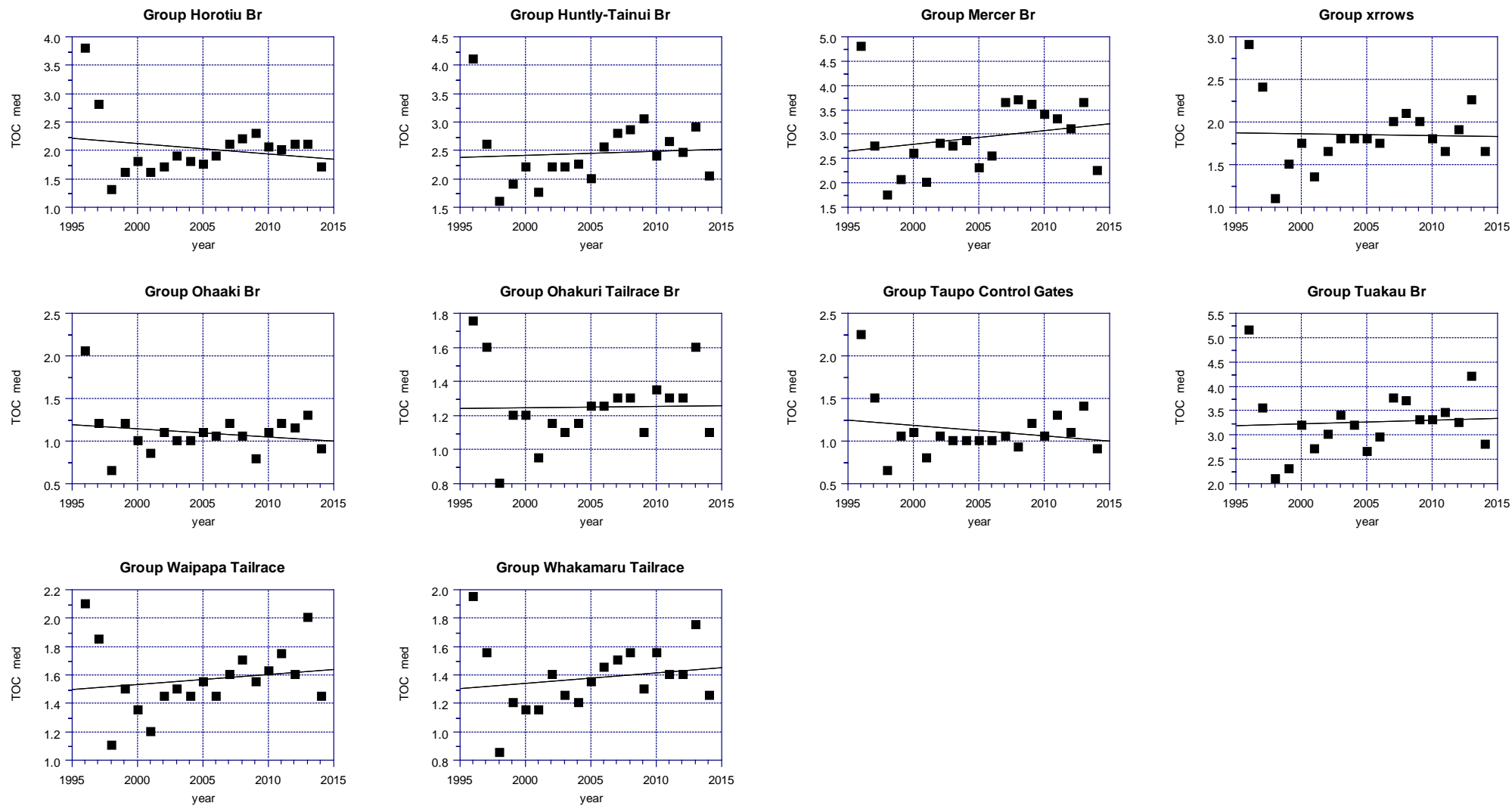


Fig. D24. Trends since 1990 in annual median TOC.

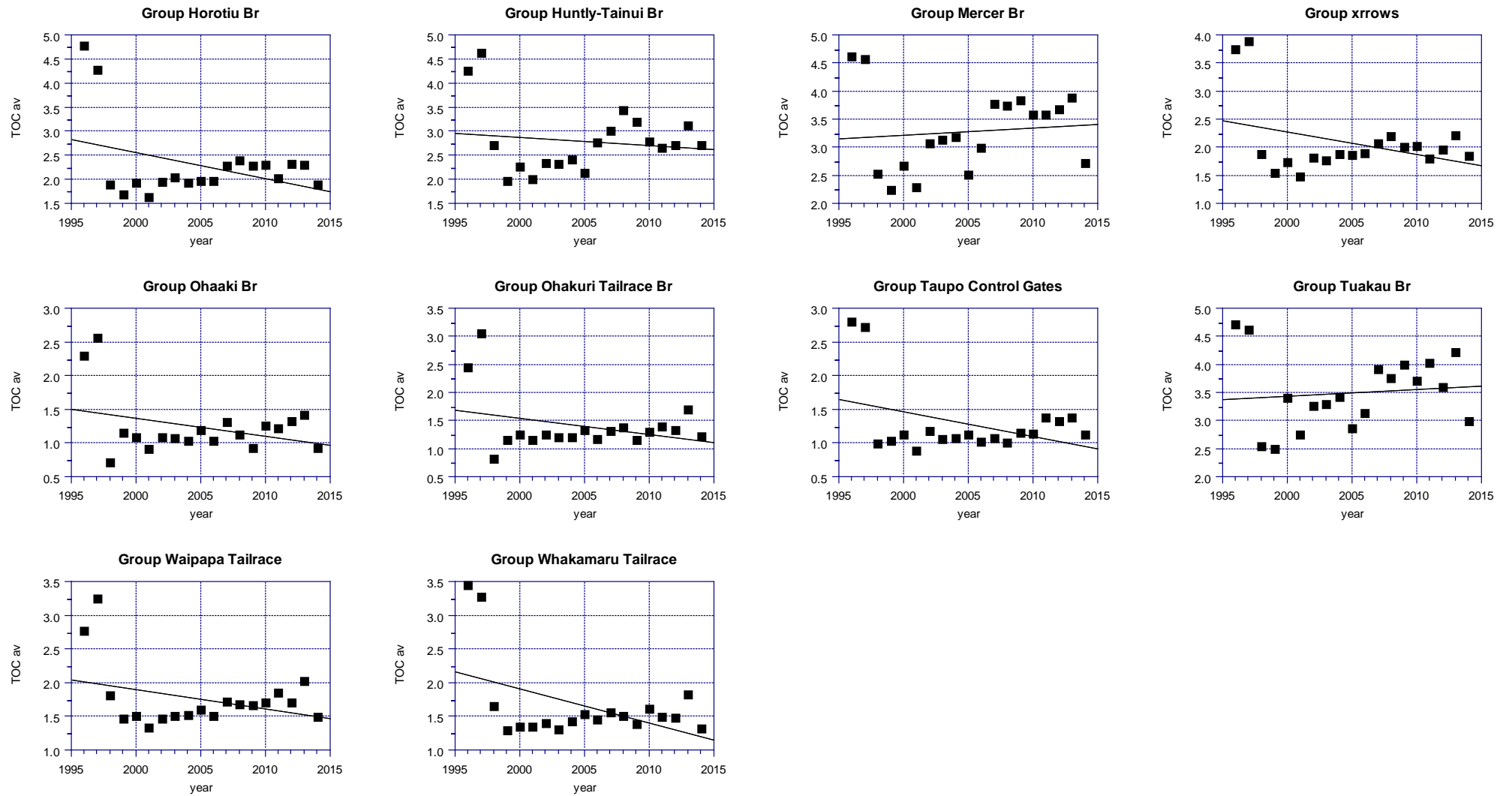


Fig. D25. Trends since 1990 in annual mean TOC.

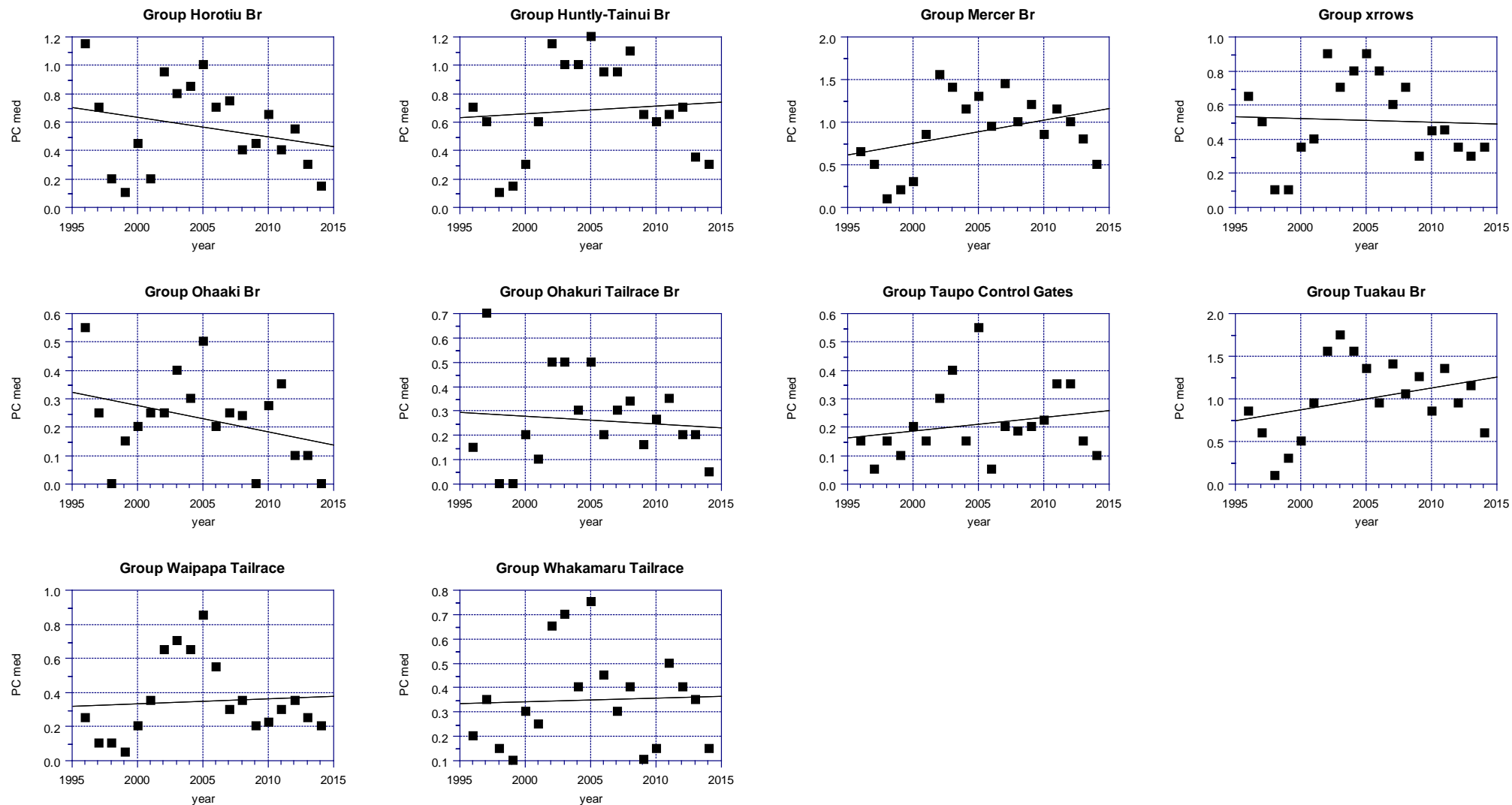


Fig. D26. Trends since 1990 in annual median PC.



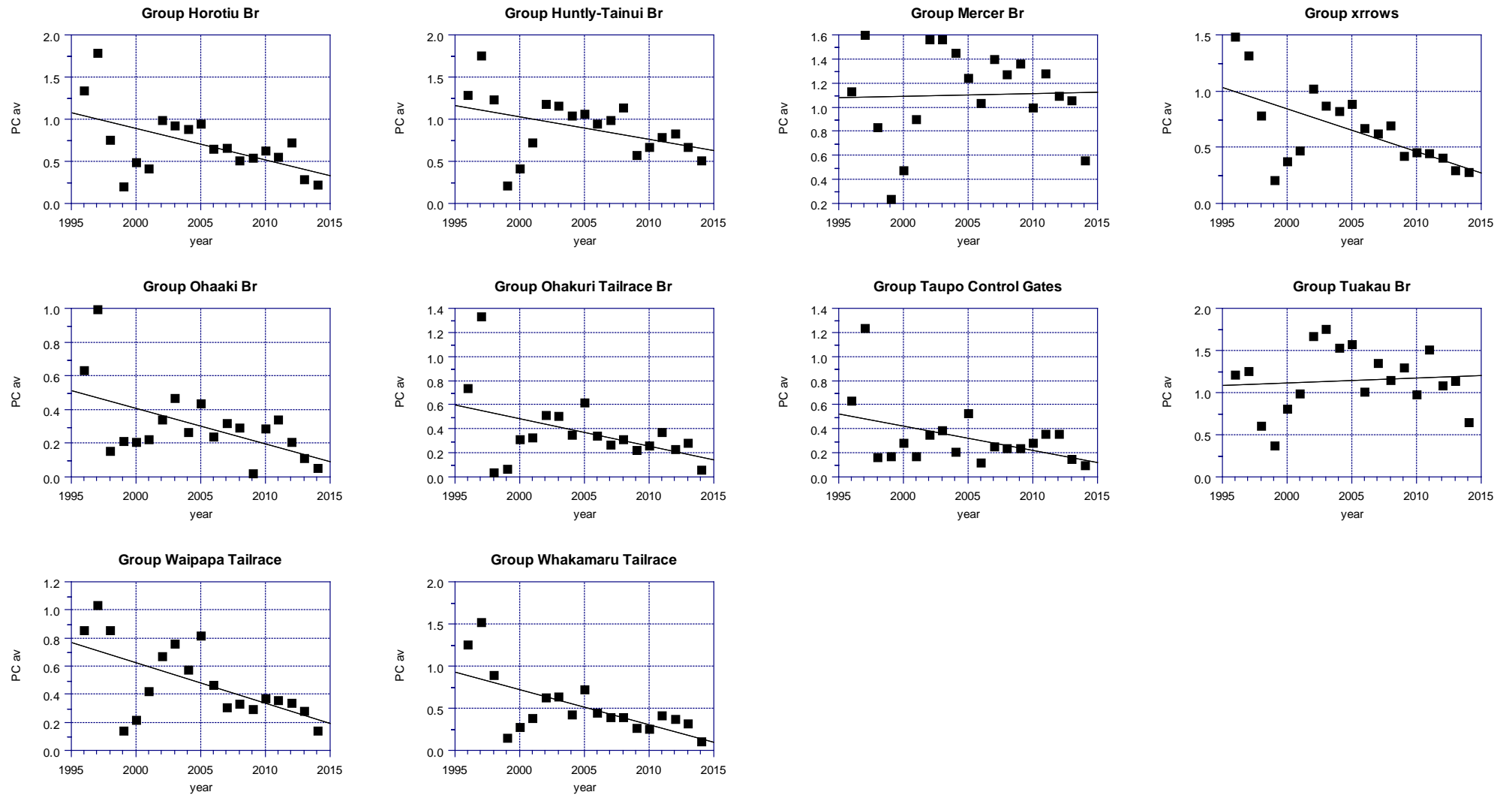


Fig. D27. Trends since 1990 in annual mean PC.

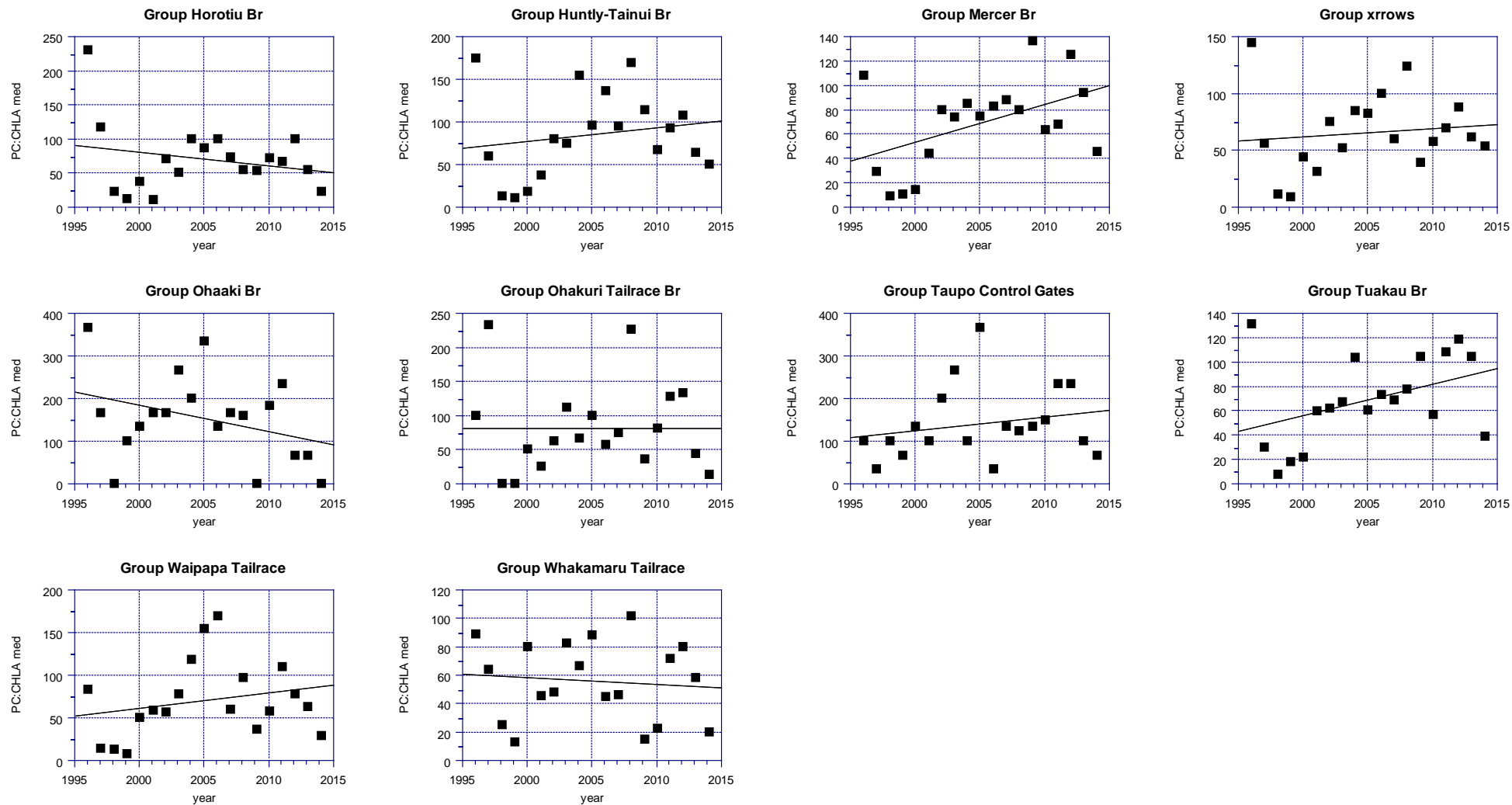


Fig. D28. Trends since 1990 in the ratio of annual median PC and chlorophyll *a*.

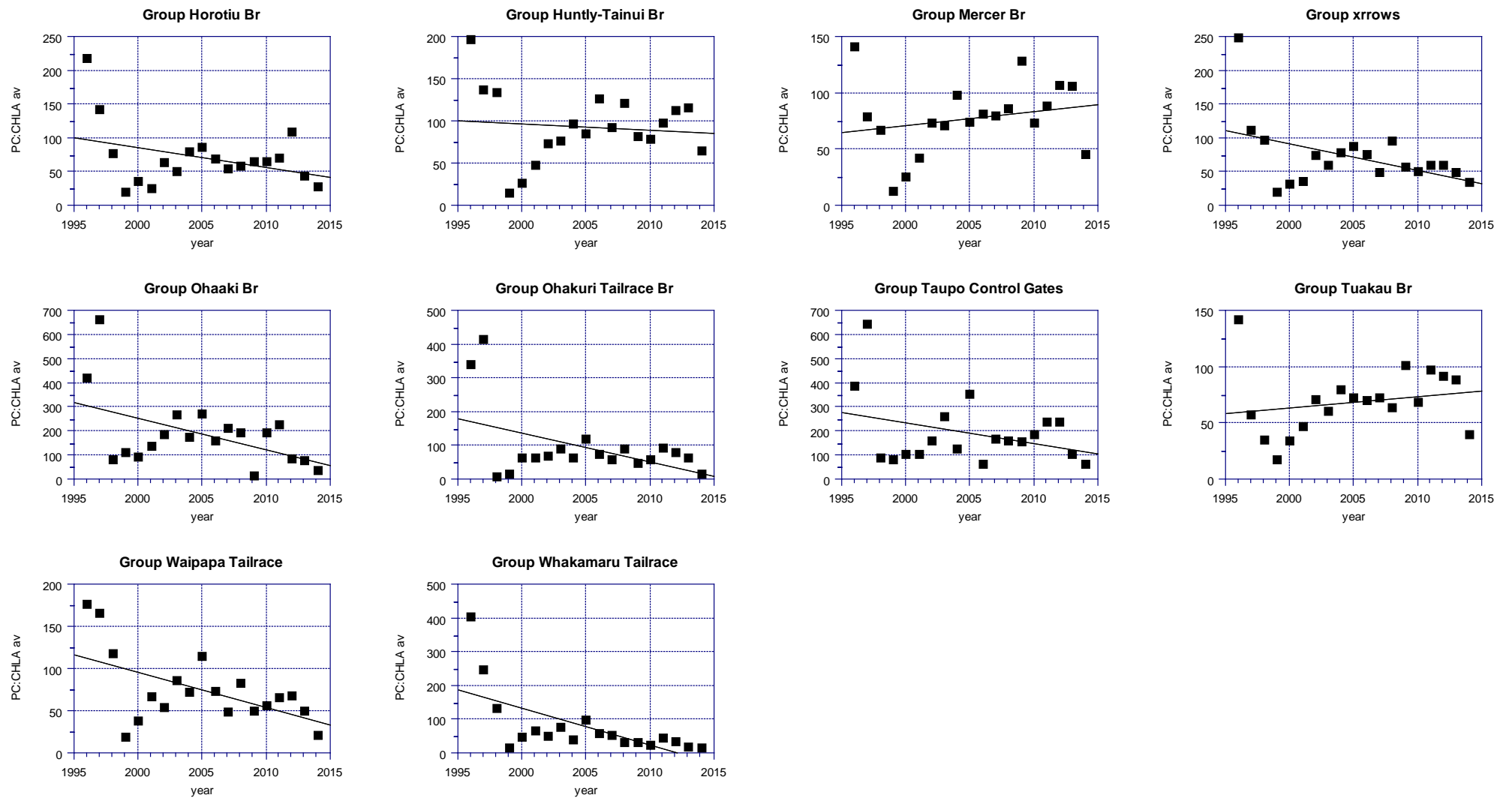


Fig. D29. Trends since 1990 in the ratio of annual mean PC and chlorophyll  $a$ .

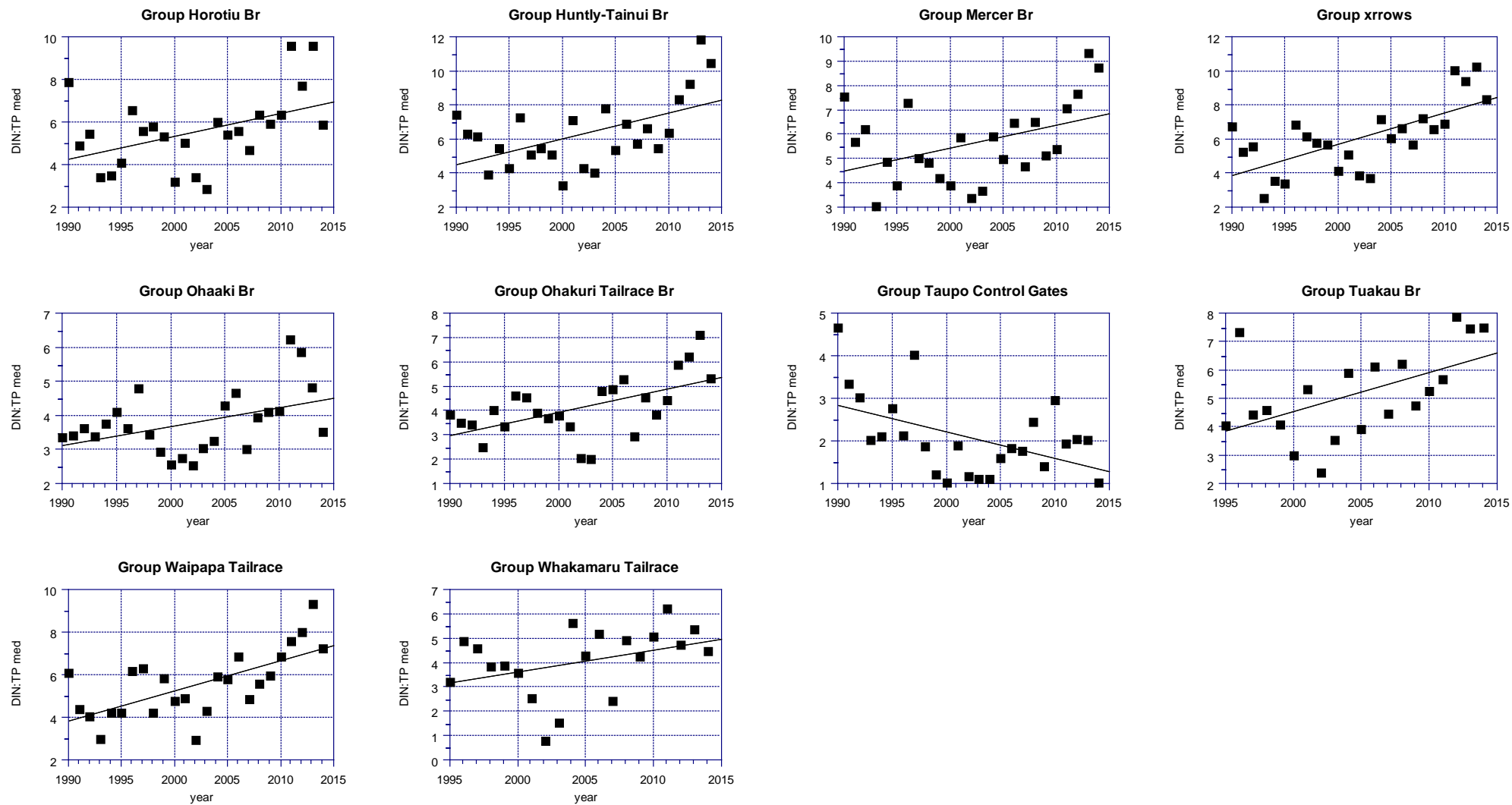


Fig. D30. Trends since 1990 in the ratio of annual medians of DIN and TP.

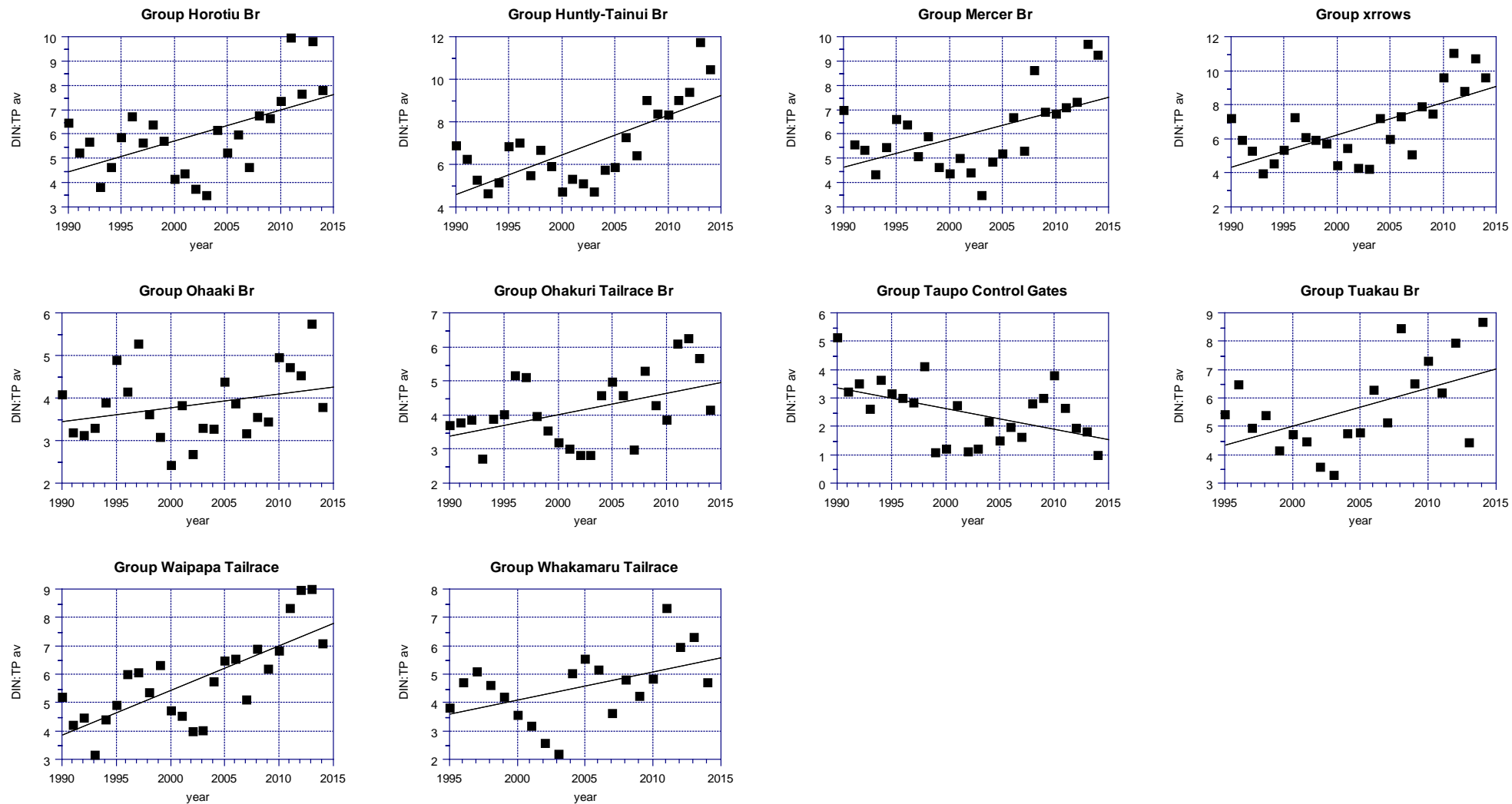


Fig. D31. Trends since 1990 in the ratio of annual means of DIN and TP.

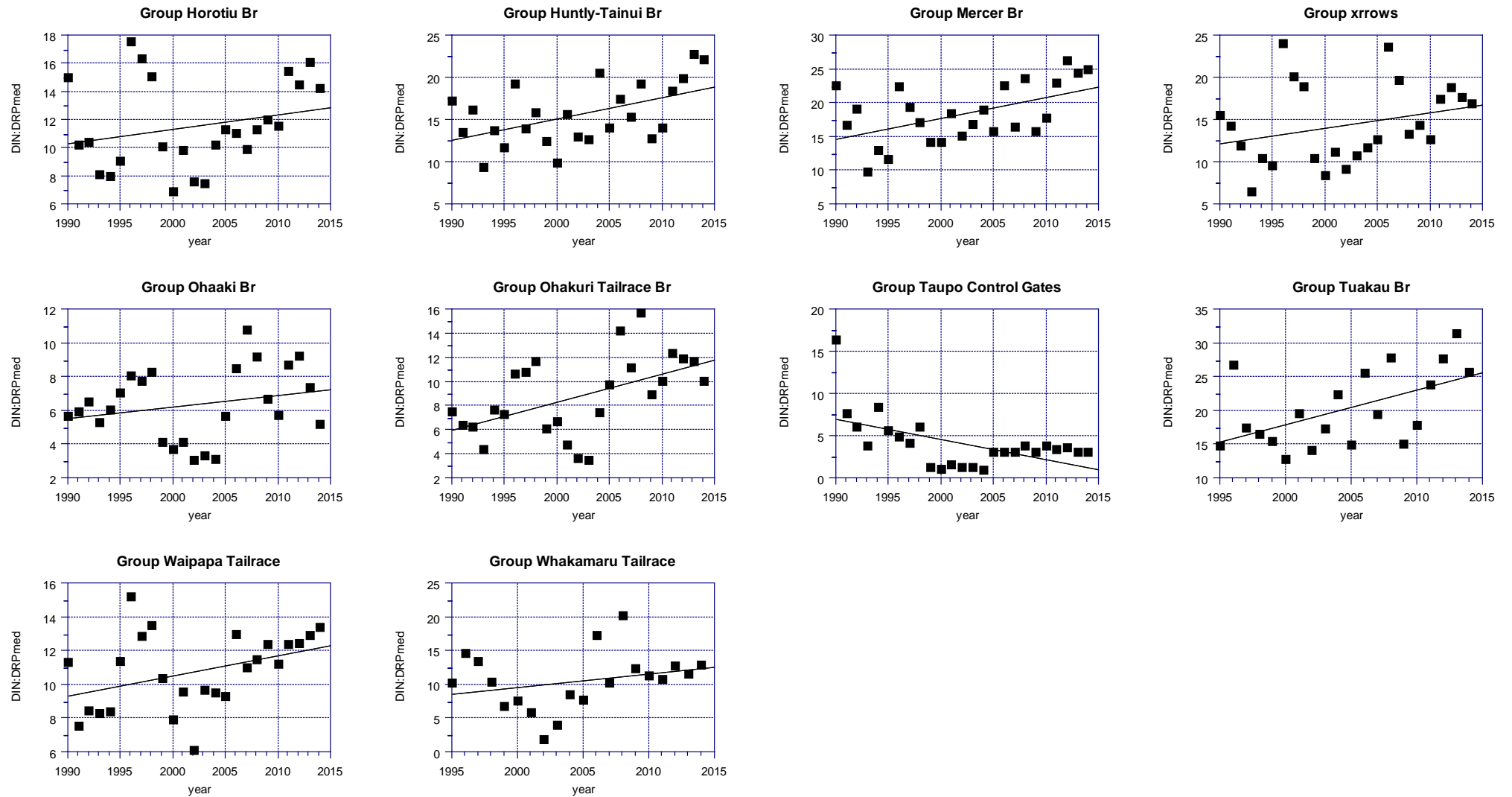


Fig. D32. Trends since 1990 in the ratio of annual medians of DIN and DRP.

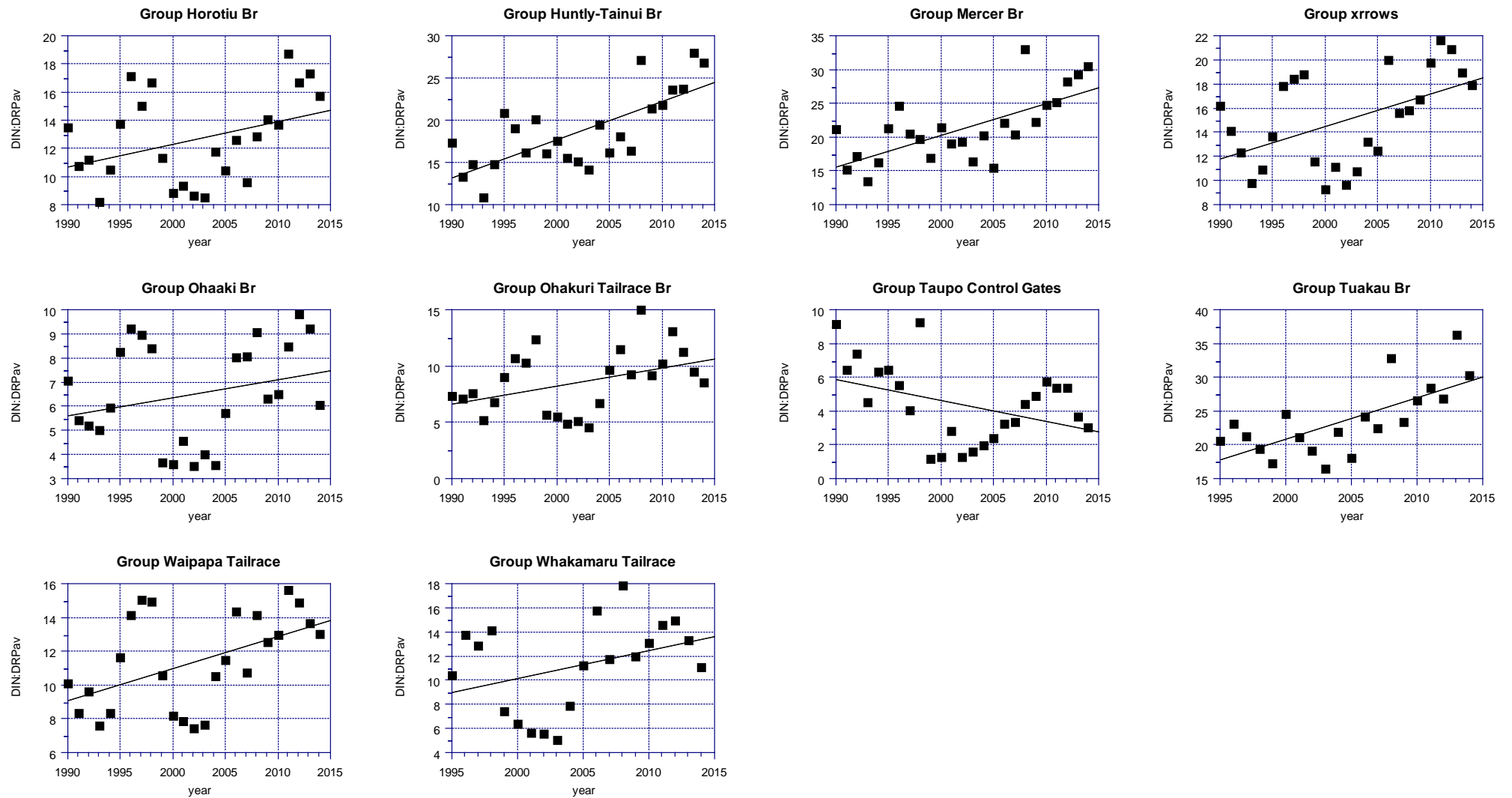


Fig. D33. Trends since 1990 in the ratio of annual means of DIN and DRP.

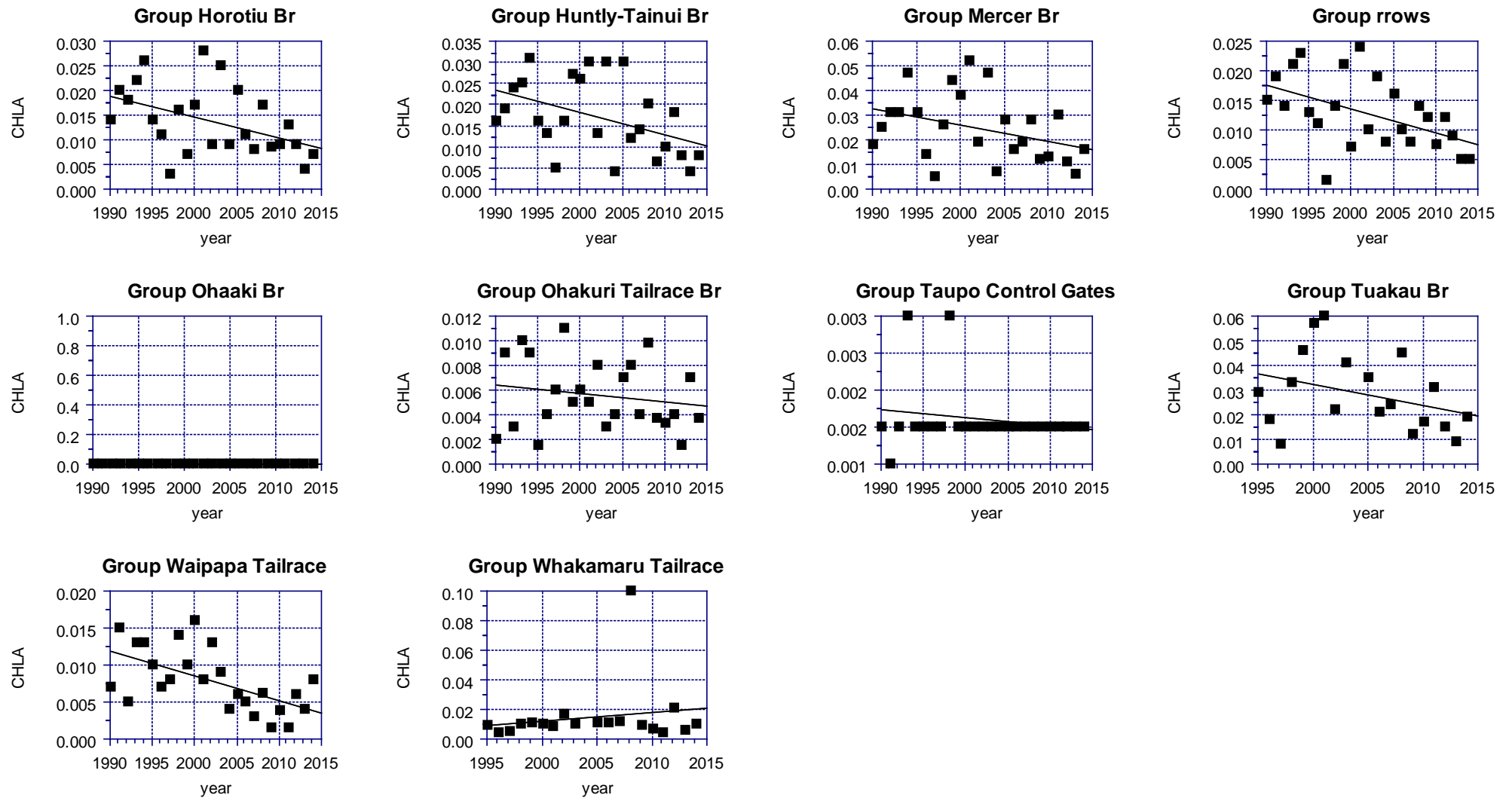


Fig. D34. Trends since 1990 in chlorophyll *a*, March data only.



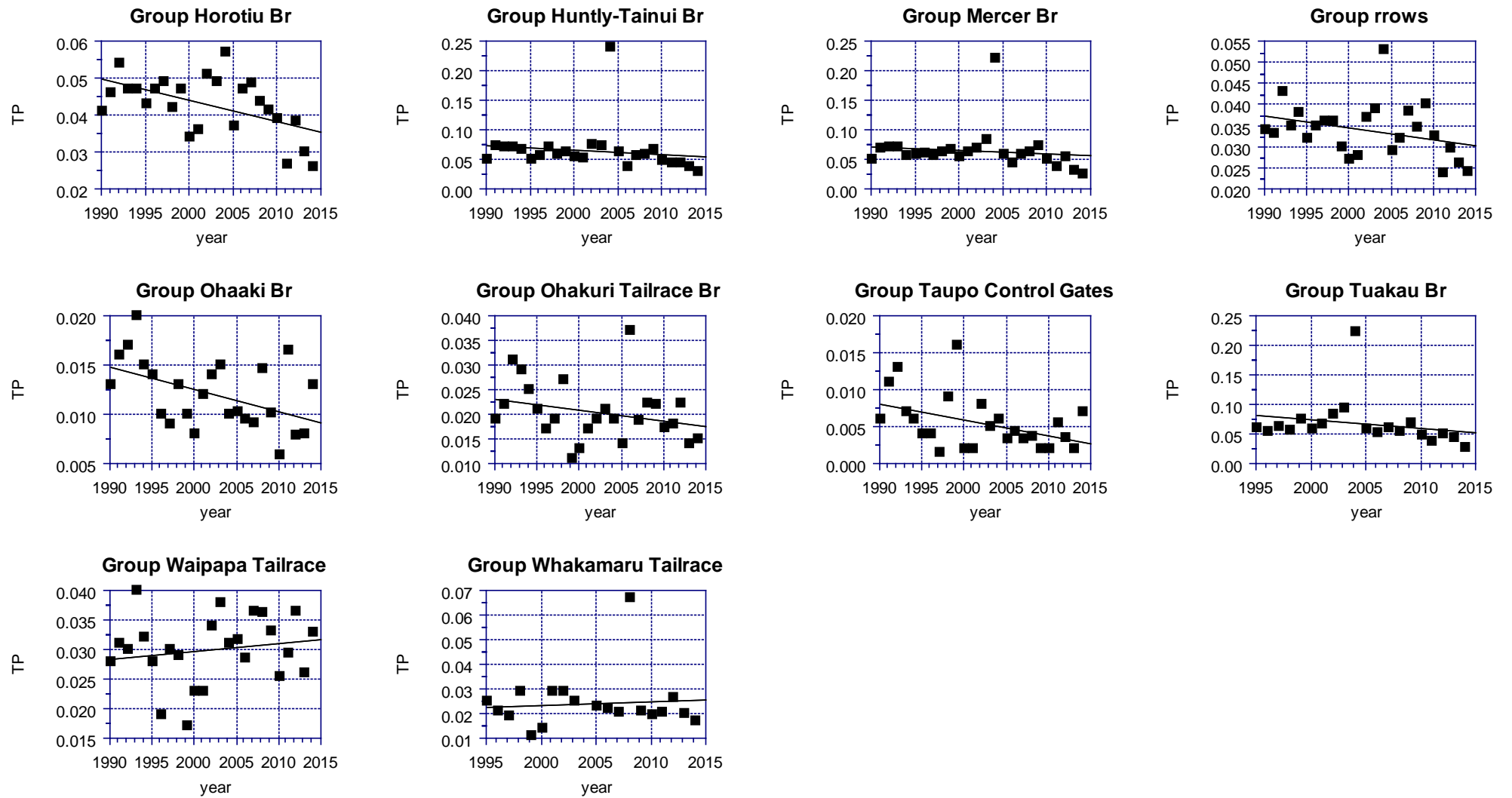


Fig. D35. Trends since 1990 in TP, March data only.

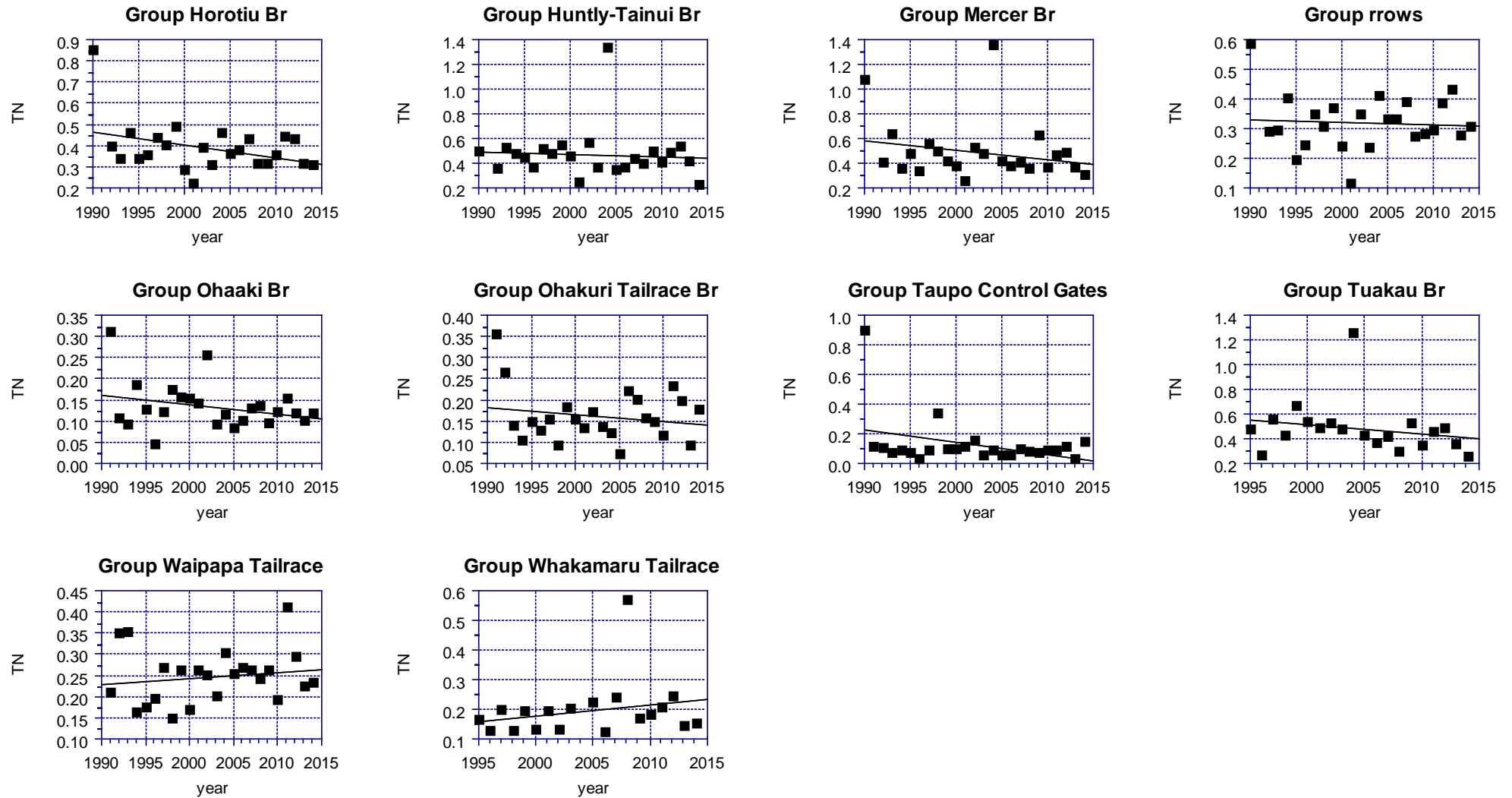


Fig. D36. Trends since 1990 in TN, March data only.

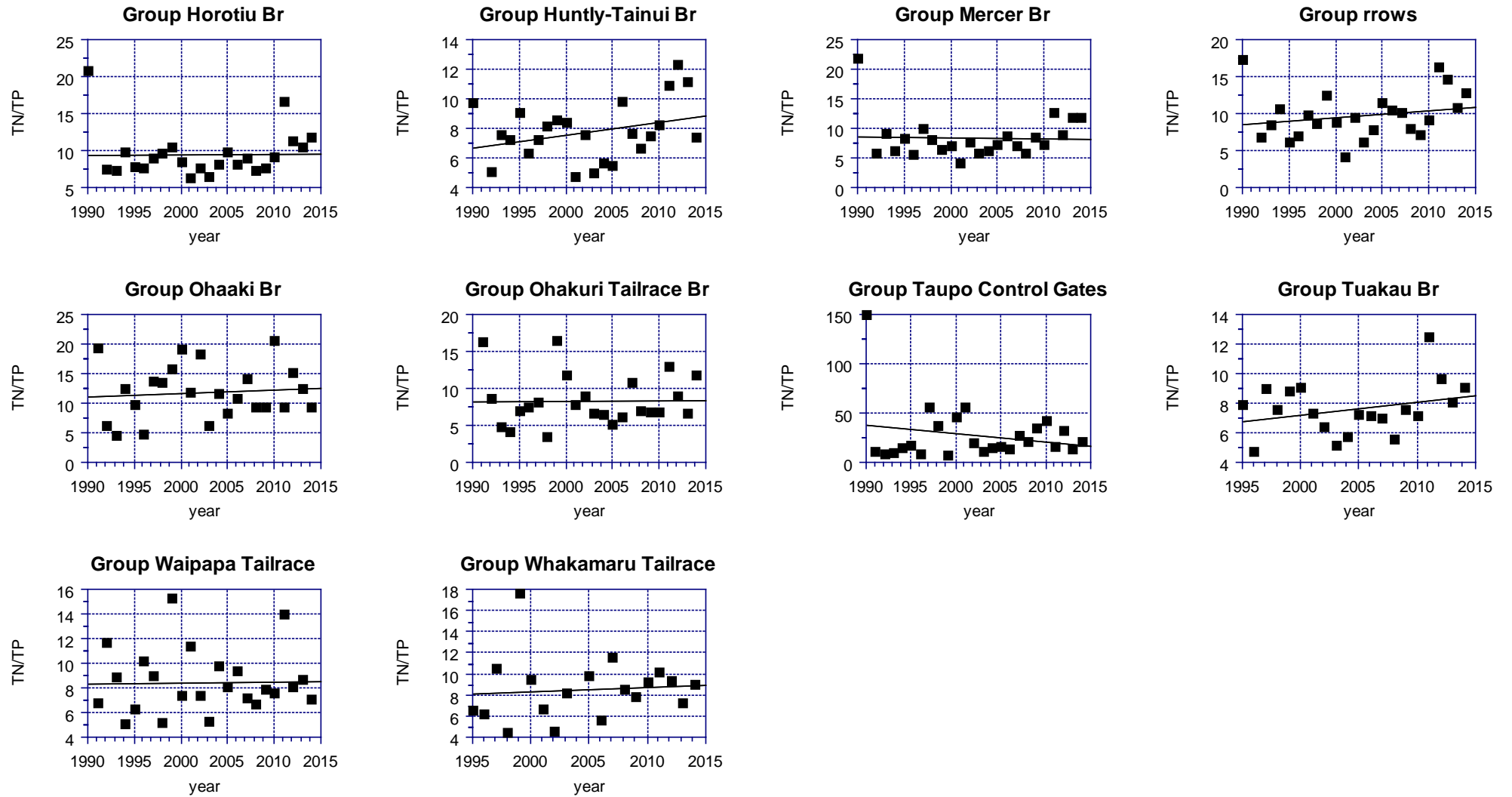


Fig. D37. Trends since 1990 in the TN:TP ratio, March data only.

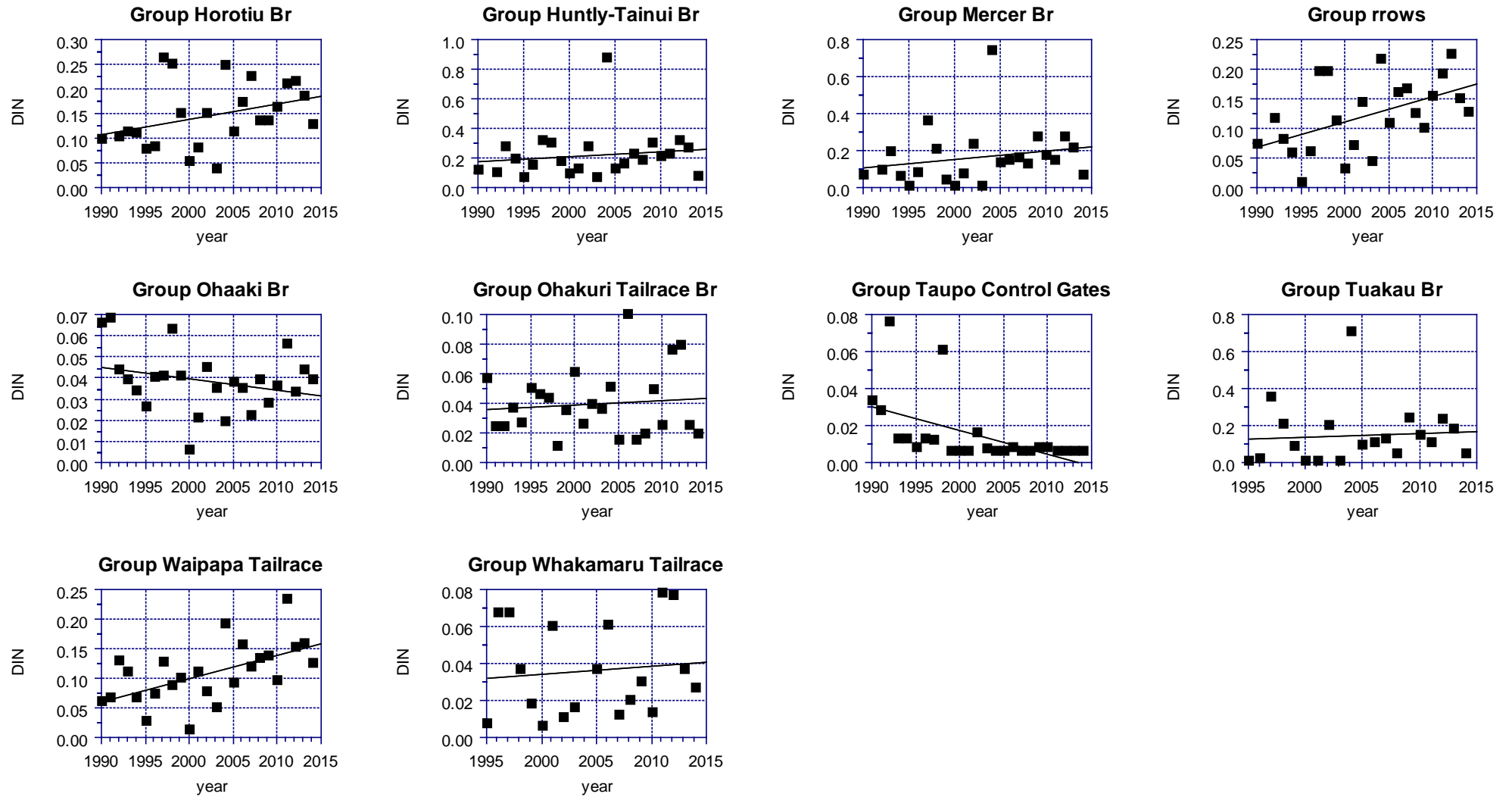


Fig. D38. Trends since 1990 in DIN, March data only.

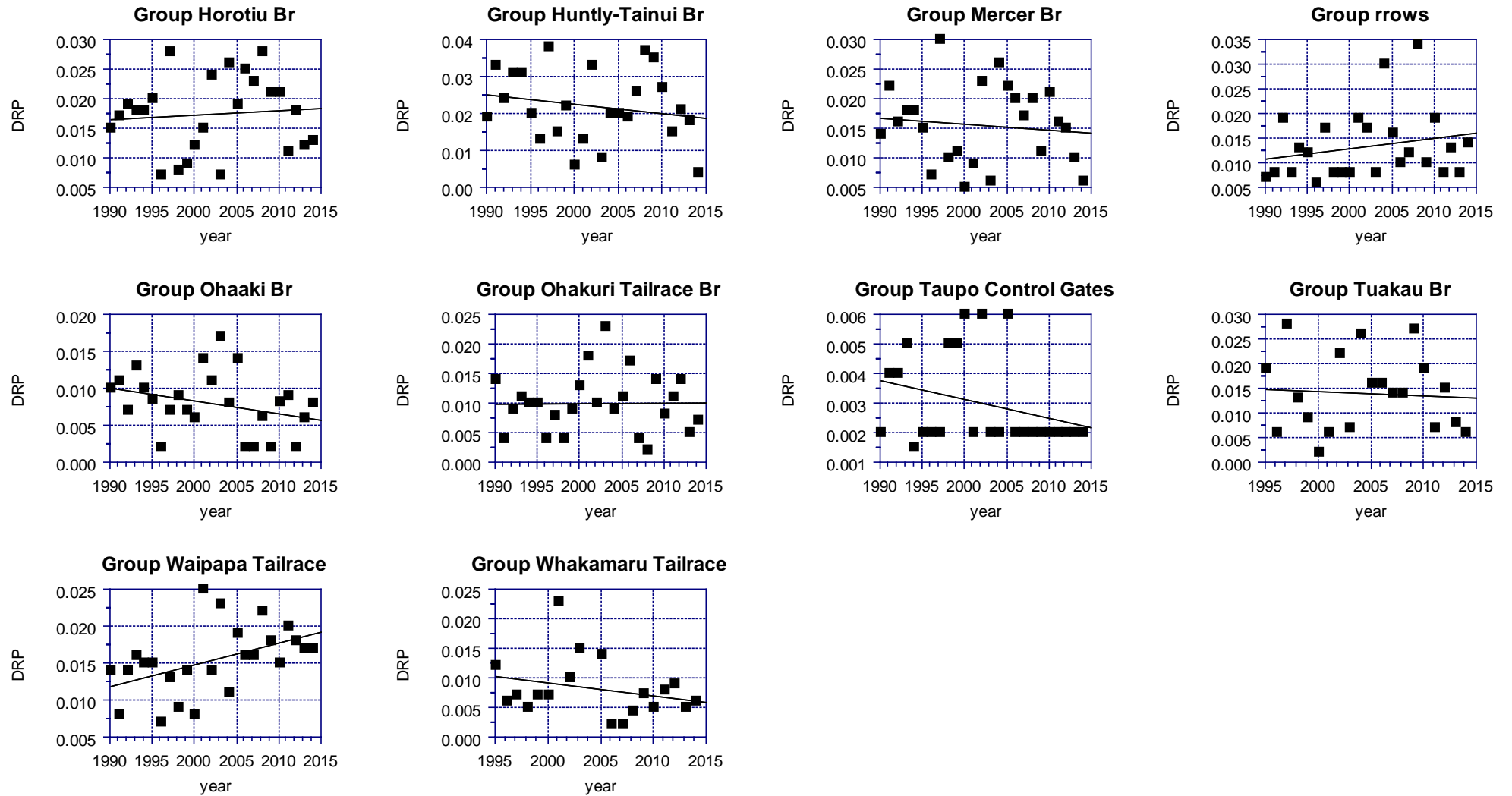


Fig. D39. Trends since 1990 in DRP, March data only.

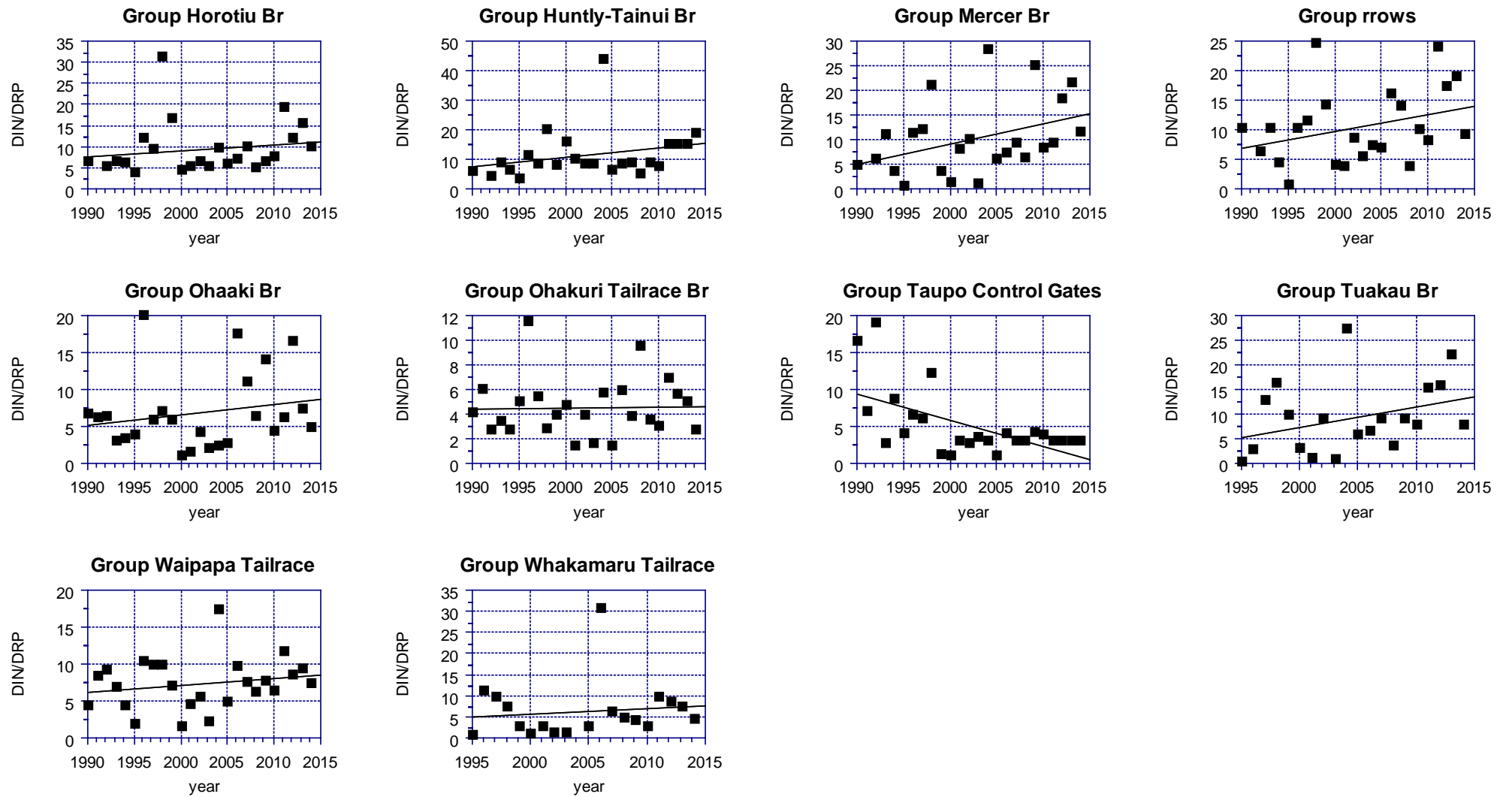


Fig. D40. Trends since 1990 in the DIN : DRP ratio, March data only.

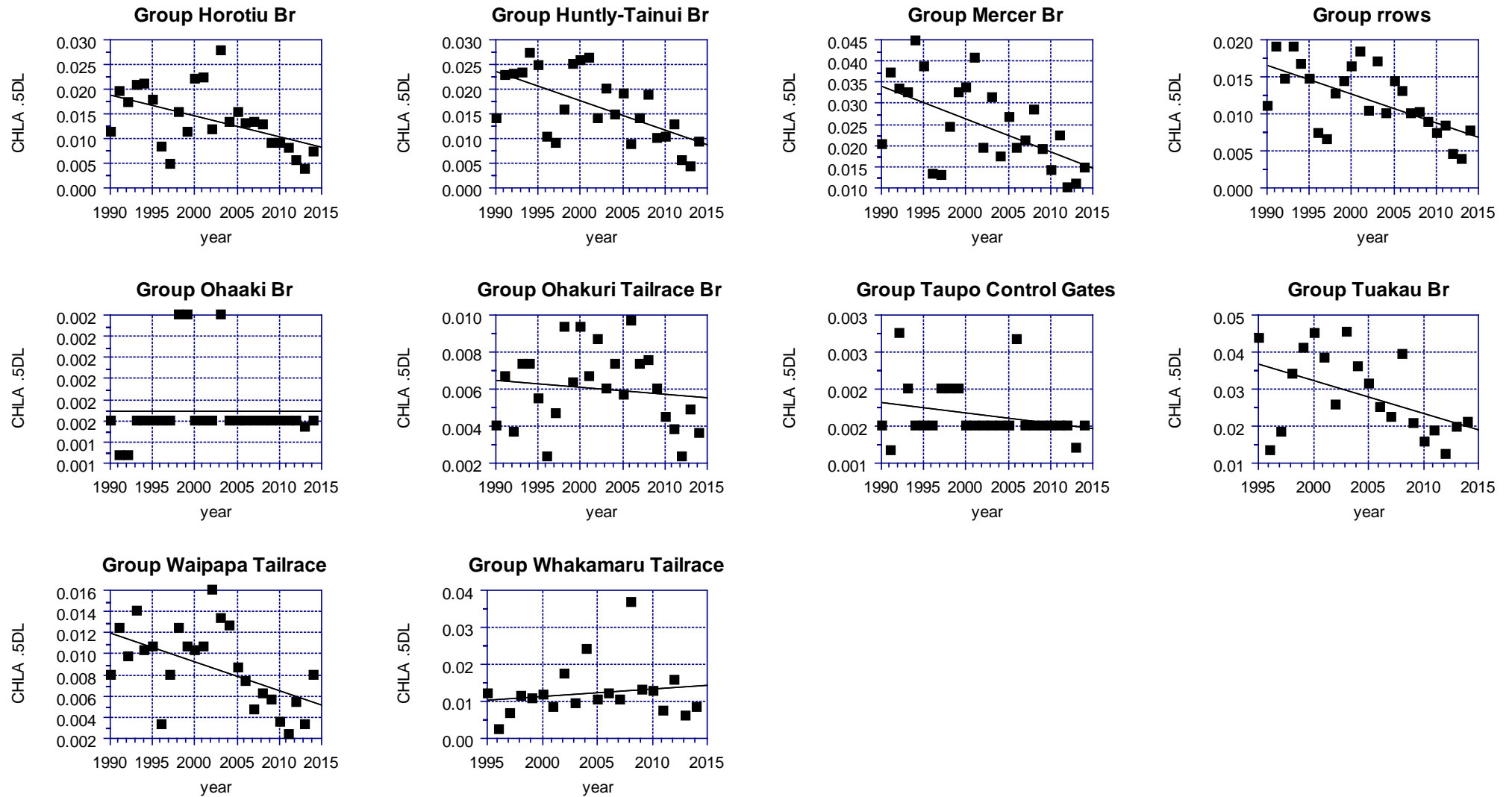


Fig. D41. Trends since 1990 in mean chlorophyll  $a$ , January to March data only.

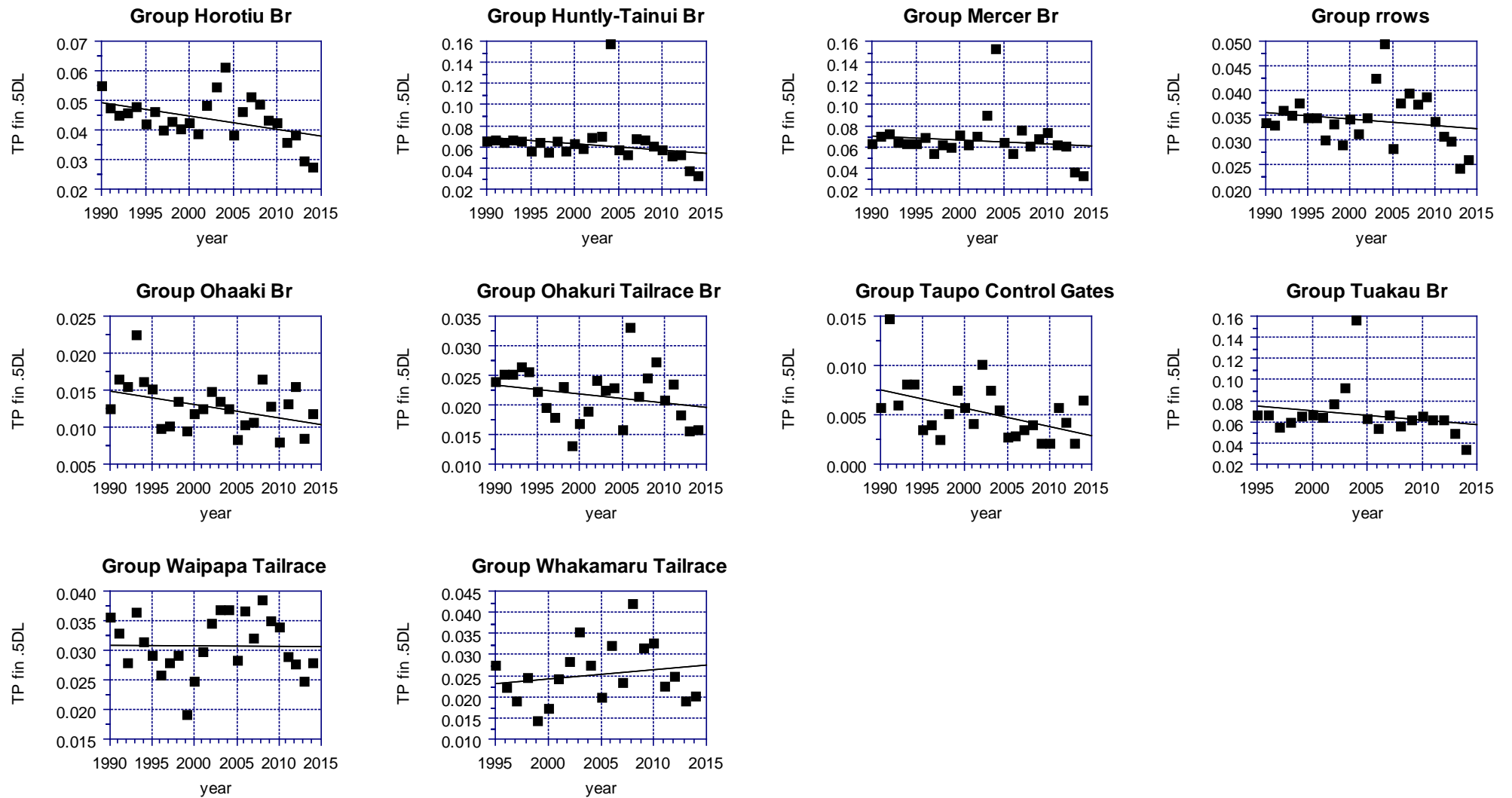


Fig. D42. Trends since 1990 in mean TP, January to March data only.



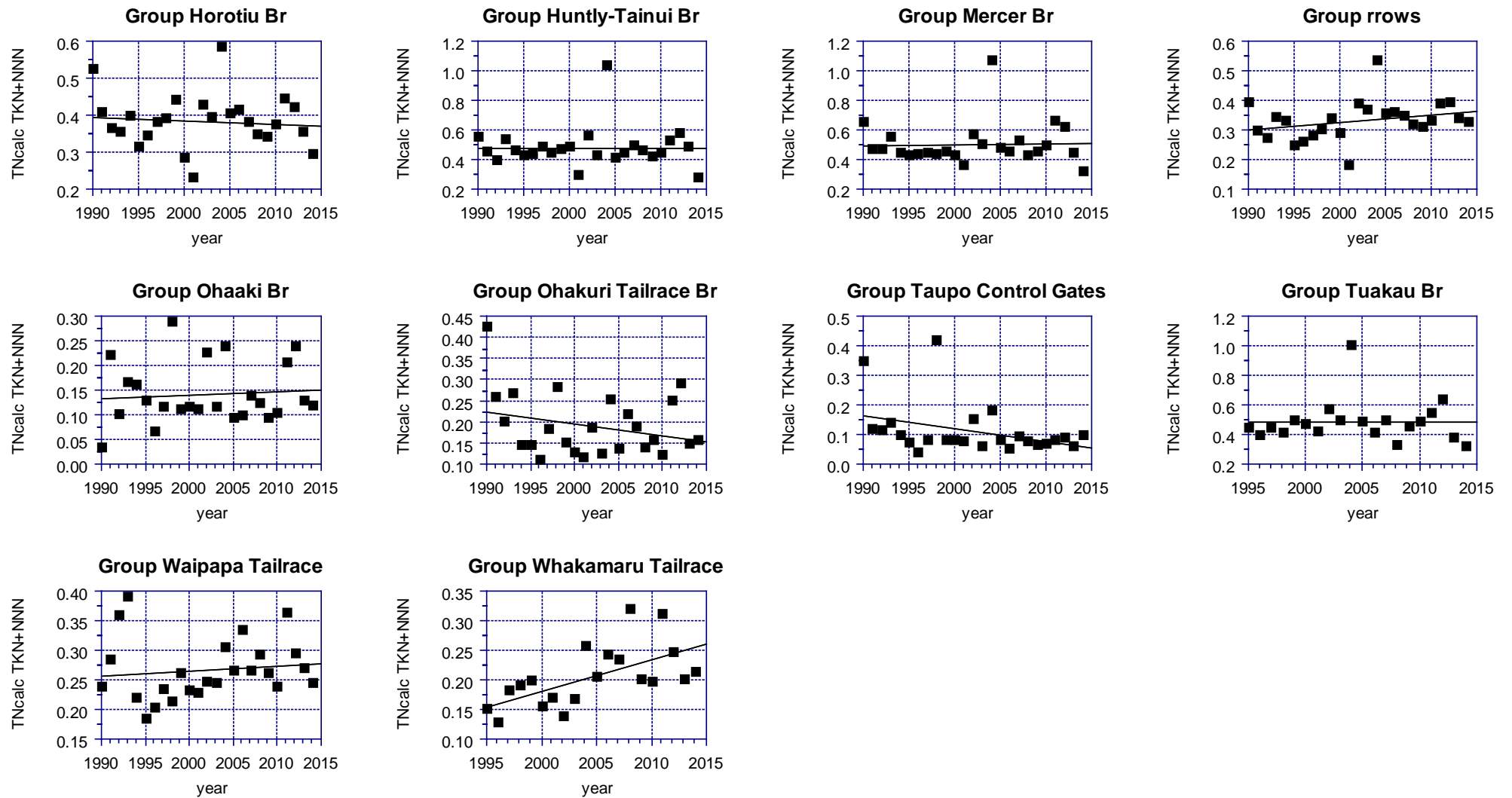


Fig. D43. Trends since 1990 in mean TN, January to March data only.

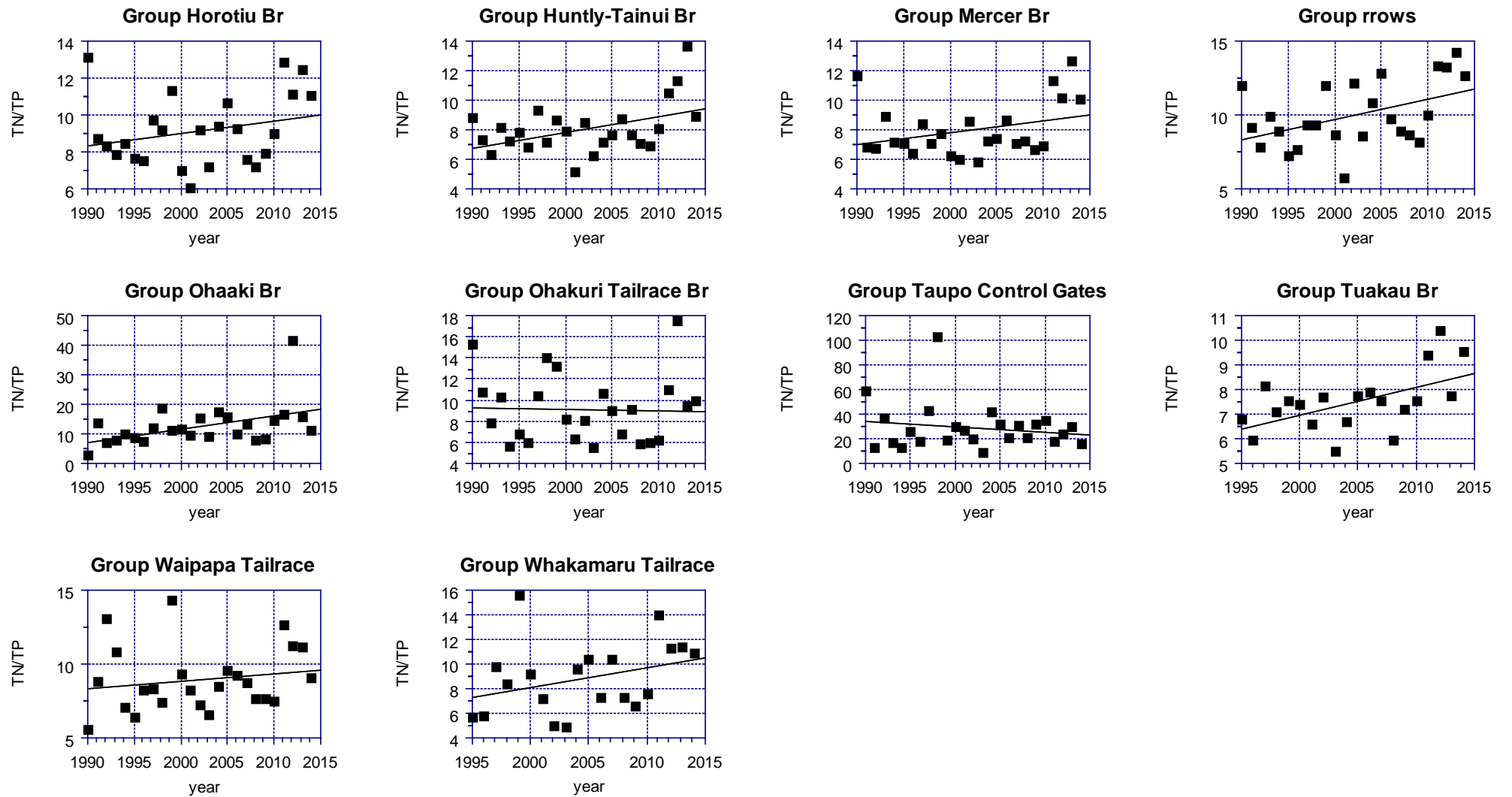


Fig. D44. Trends since 1990 in the ratio of mean TN and TP, January to March data only.

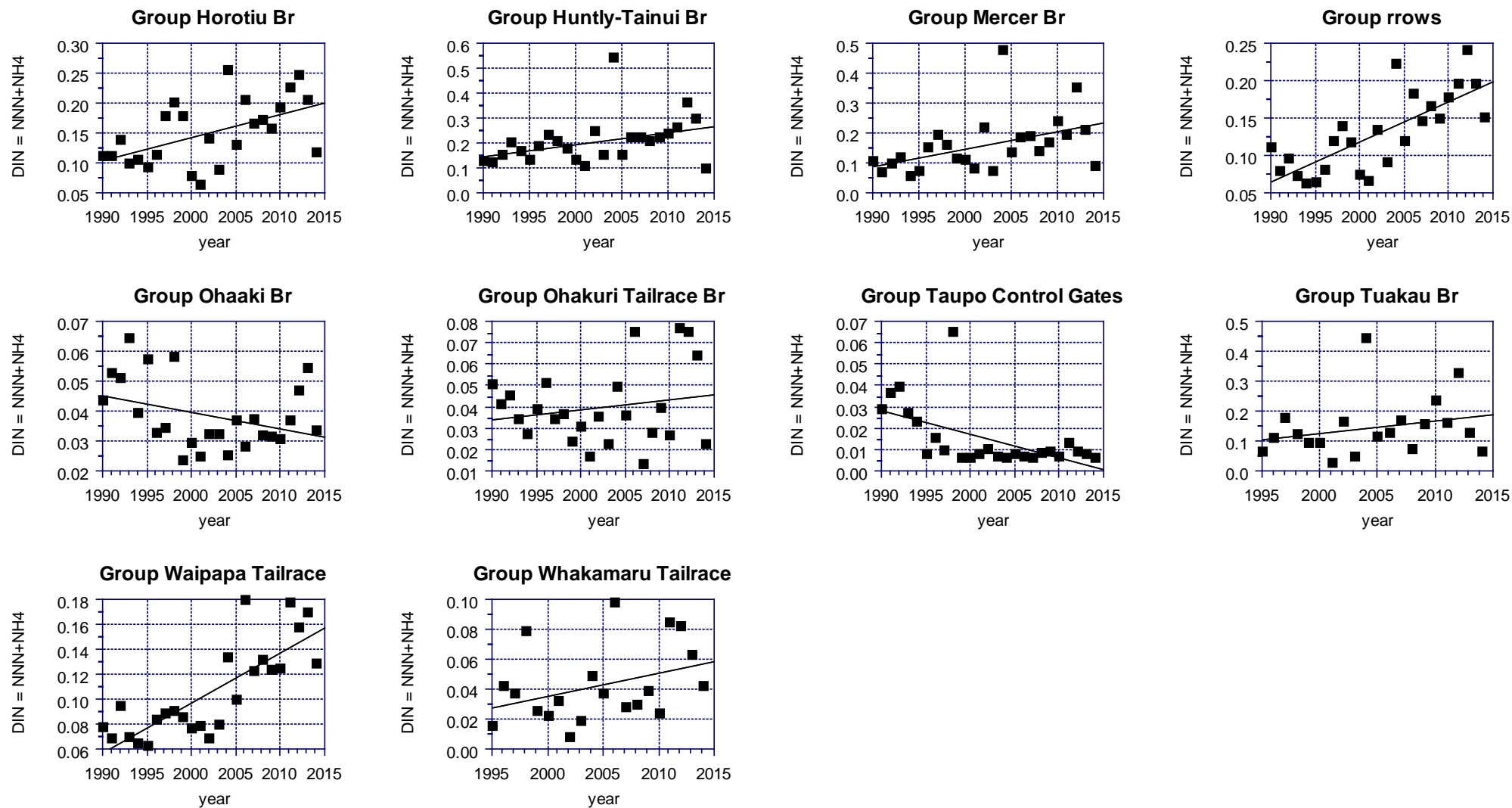


Fig. D45. Trends since 1990 in mean DIN, January to March data only.

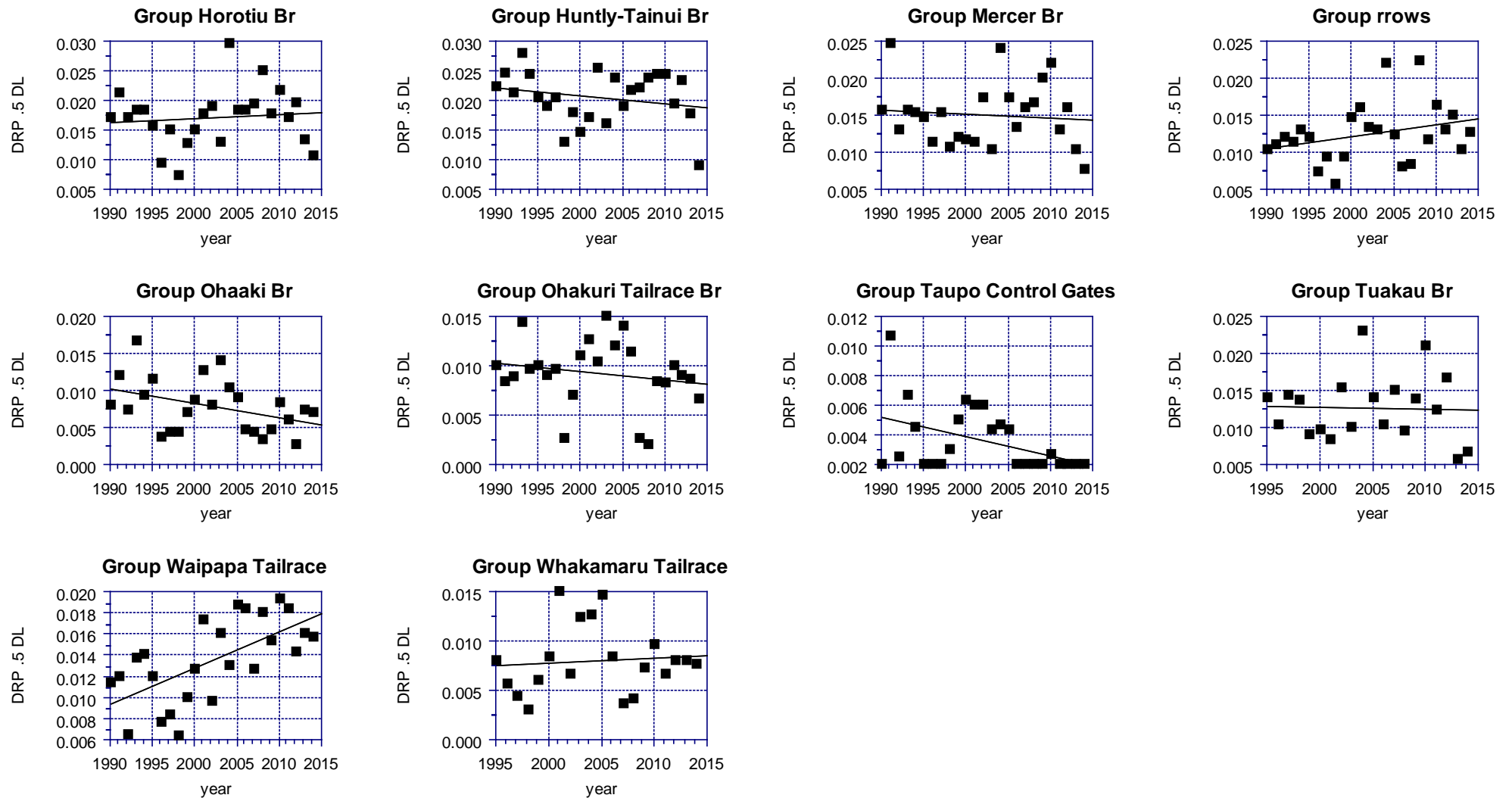


Fig. D46. Trends since 1990 in mean DRP, January to March data only.

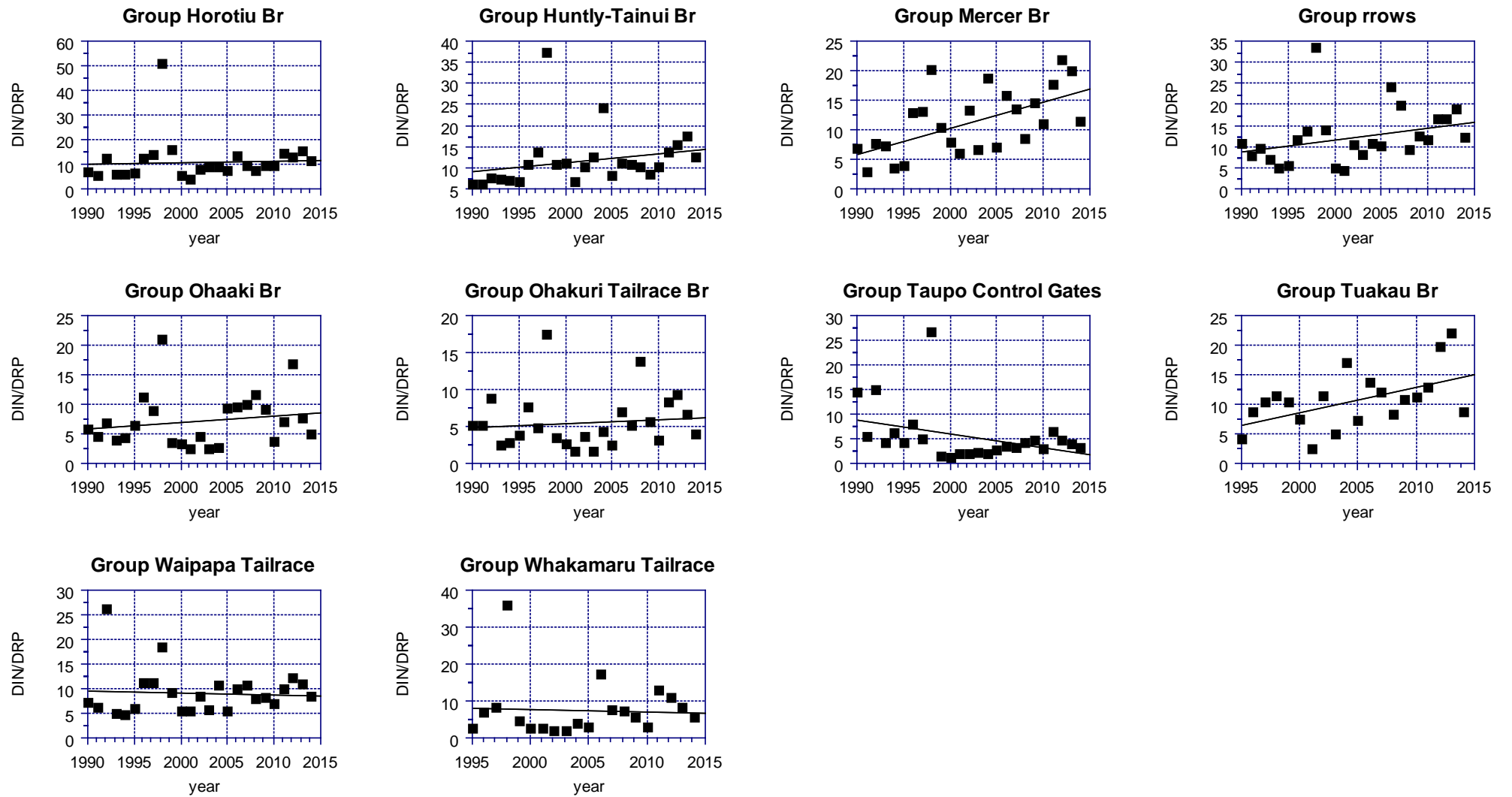


Fig. D47. Trends since 1990 in the ratio of mean DIN and DRP, January to March data only.

## Appendix E Chlorophyll a versus upstream nutrients

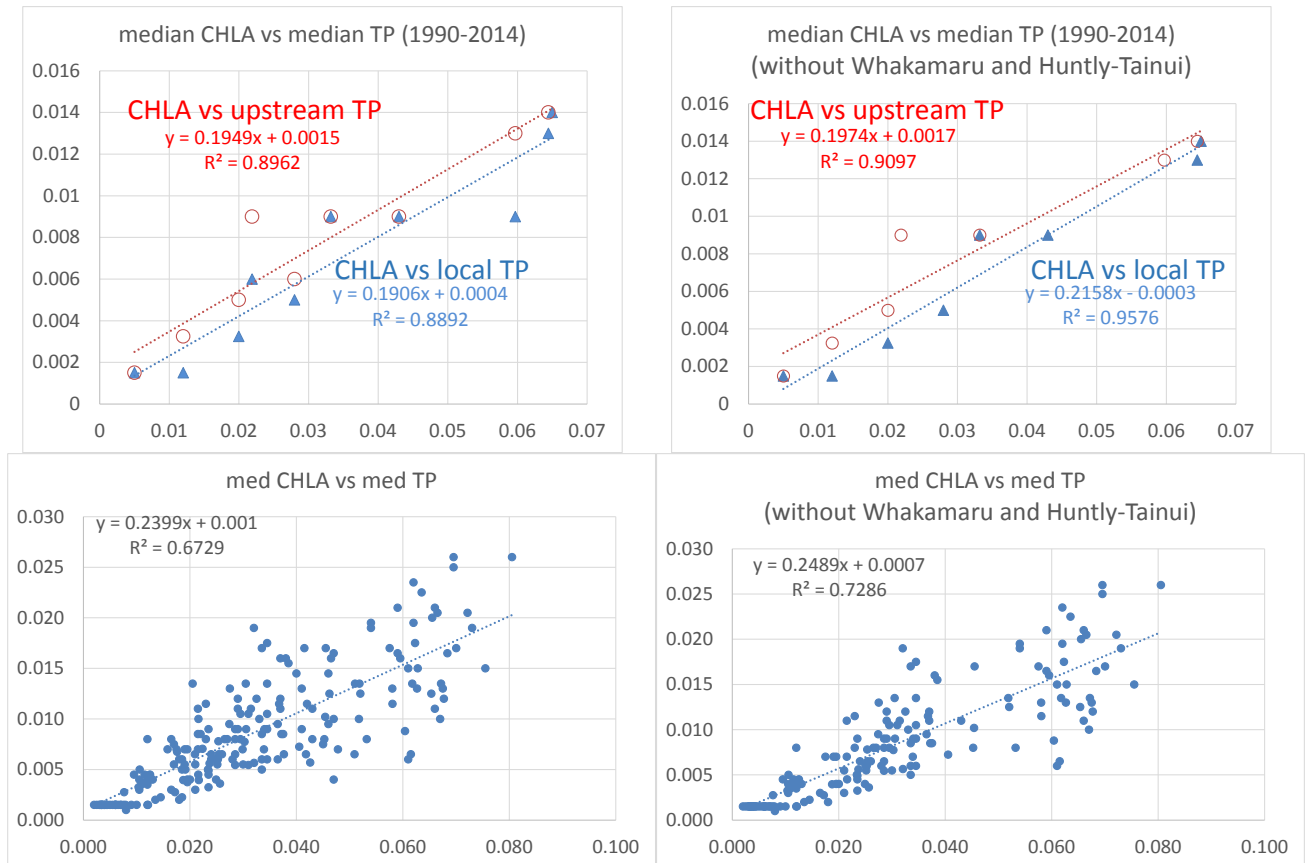


Fig. E1. Chlorophyll *a* versus upstream TP, annual medians 1990-2014. Top: overall station medians (includes comparisons with a regression of chlorophyll *a* against local TP), Bottom: medians for each year and station.

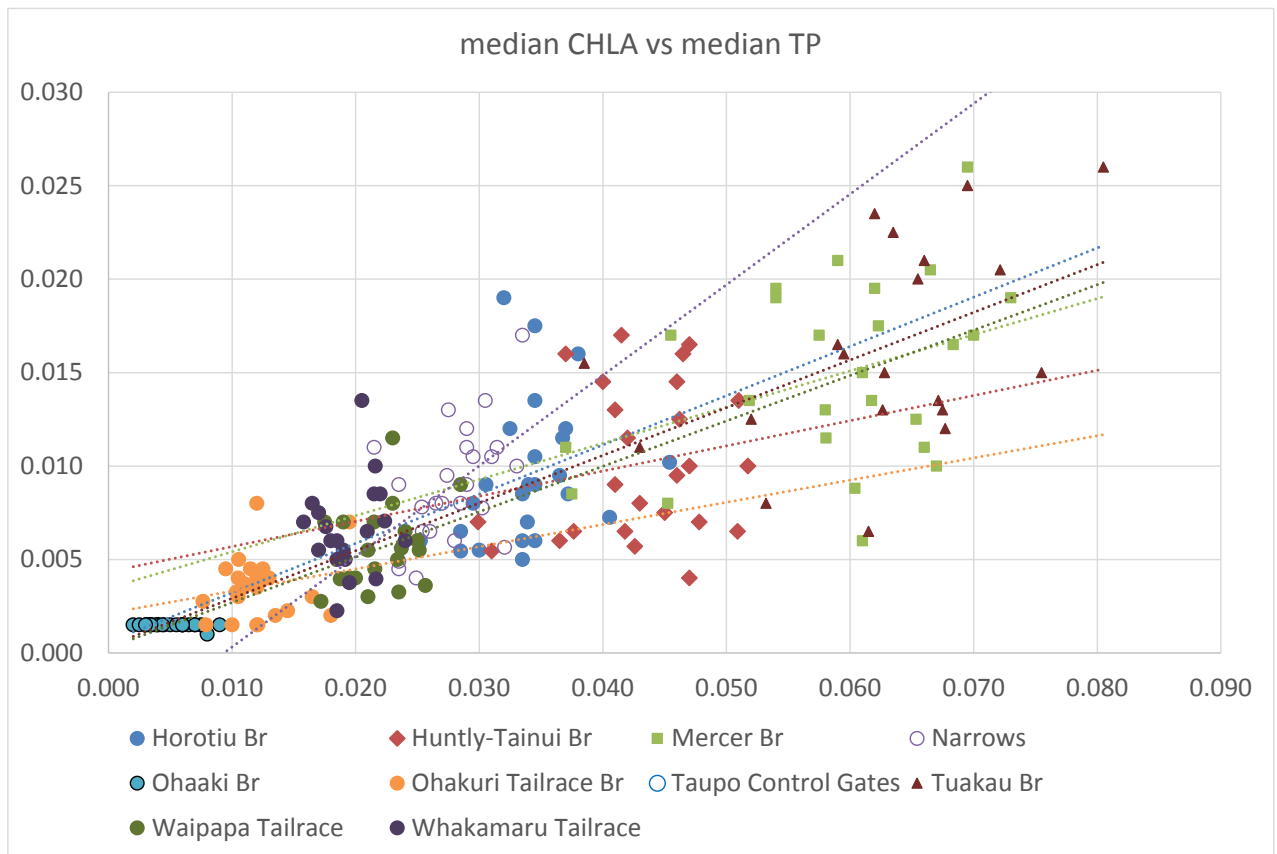


Fig. E2. Chlorophyll *a* versus upstream TP, annual medians 1990-2014. Regressions for each station except Whakamaru, Ohaaki, Taupo Gates.

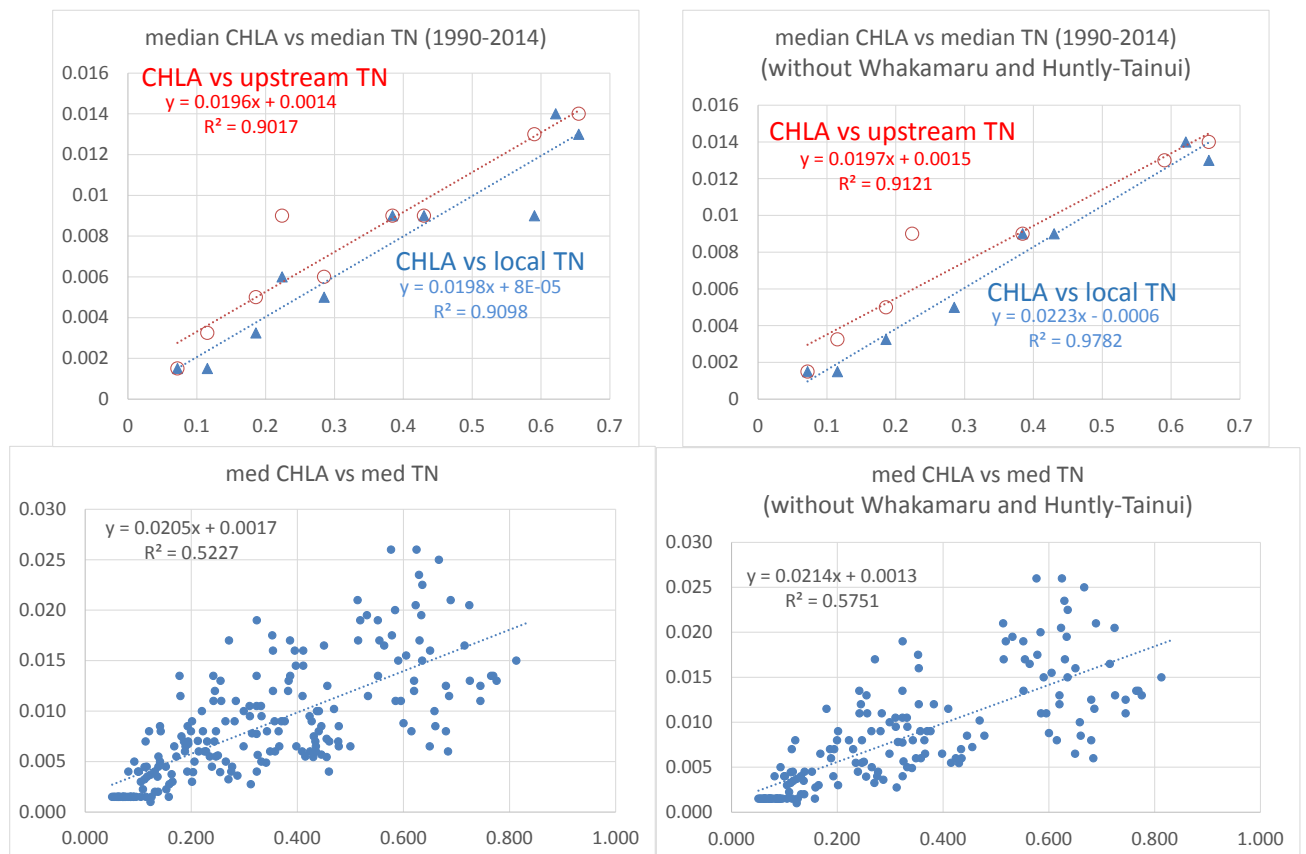


Fig. E3. Chlorophyll *a* versus upstream TN, annual medians 1990-2014. Top: overall station medians (includes comparisons with a regression of chlorophyll *a* against local TN), Bottom: medians for each year and station.



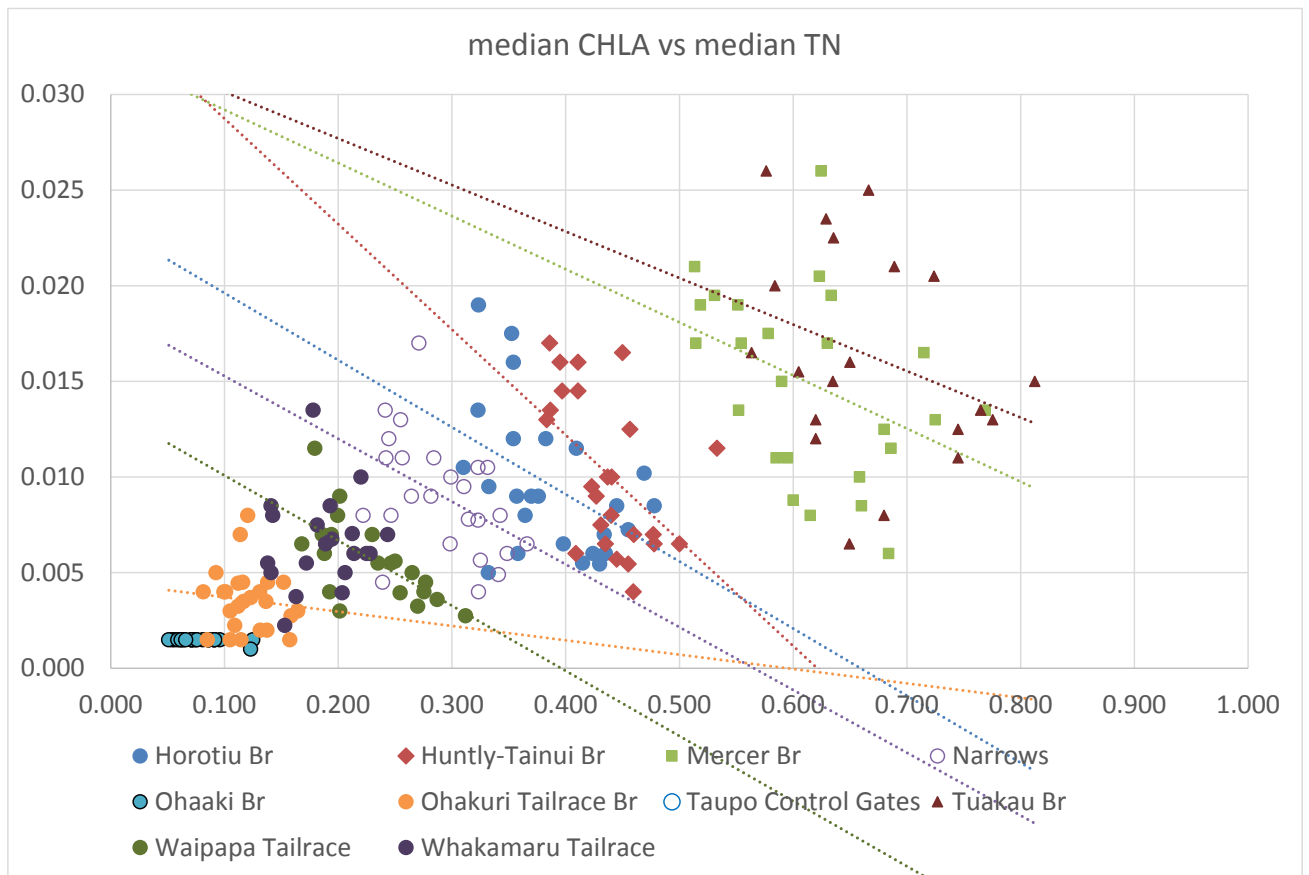


Fig. E4. Chlorophyll *a* versus upstream TN, annual medians 1990-2014. Regressions for each station except Whakamaru, Ohaaki, Taupo Gates.

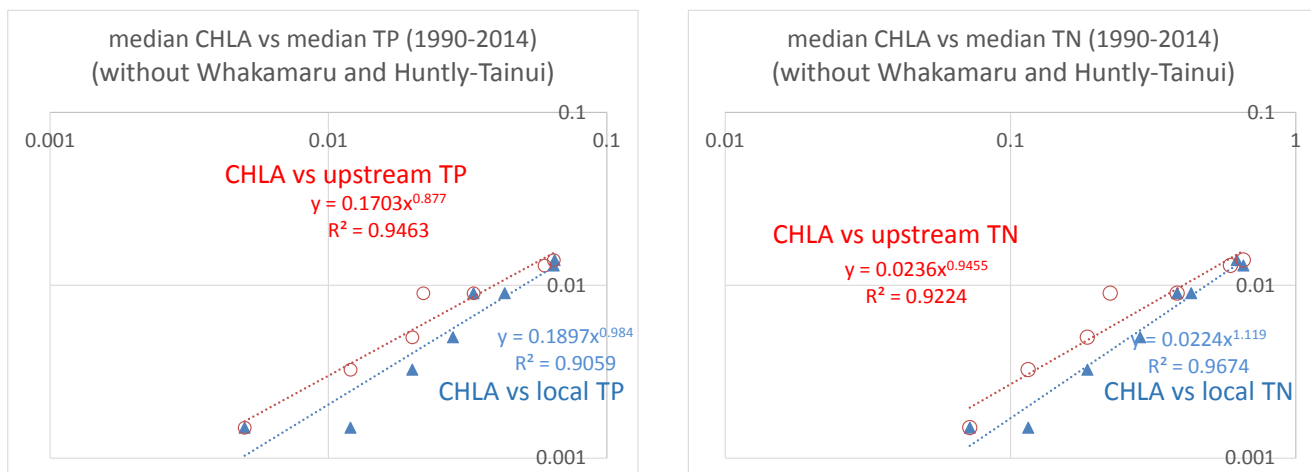


Fig. E5. Chlorophyll *a* versus upstream TN, annual medians 1990-2014, including a comparisons with a regression of chlorophyll *a* against local TP. Without Whakamaru and Huntly. Logarithmic scales and power regressions instead of linear scales and linear regressions.

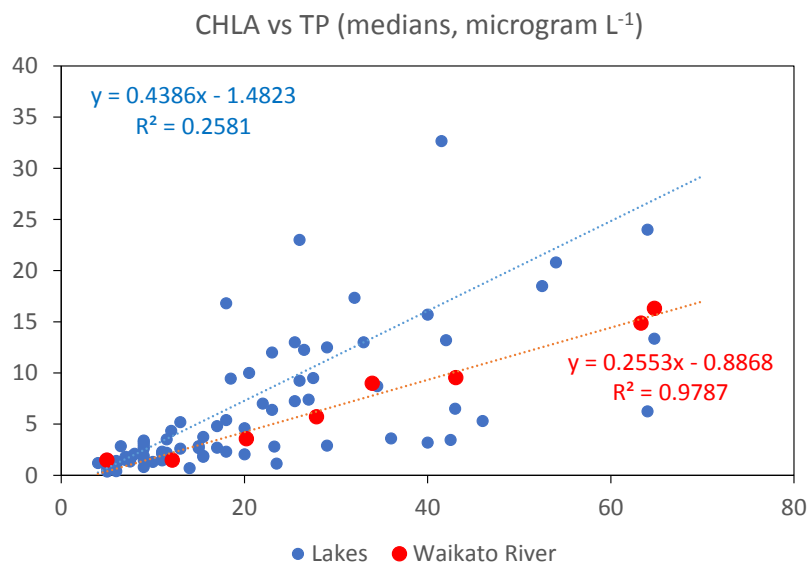
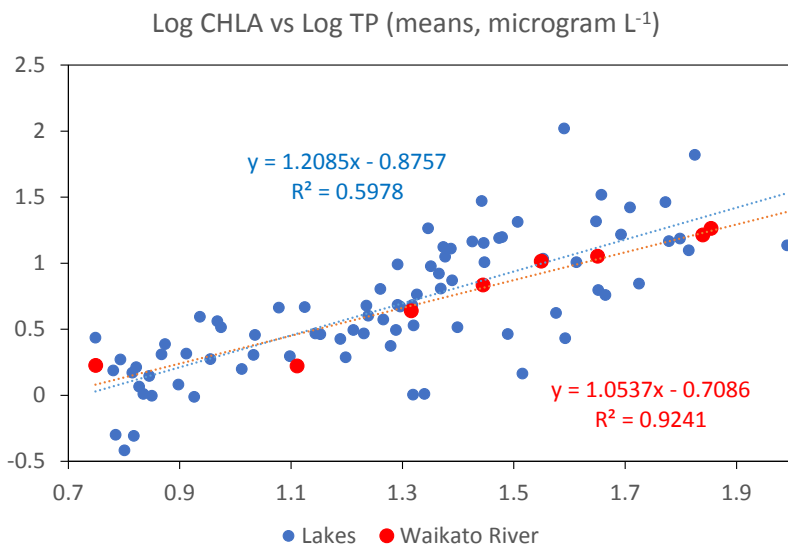
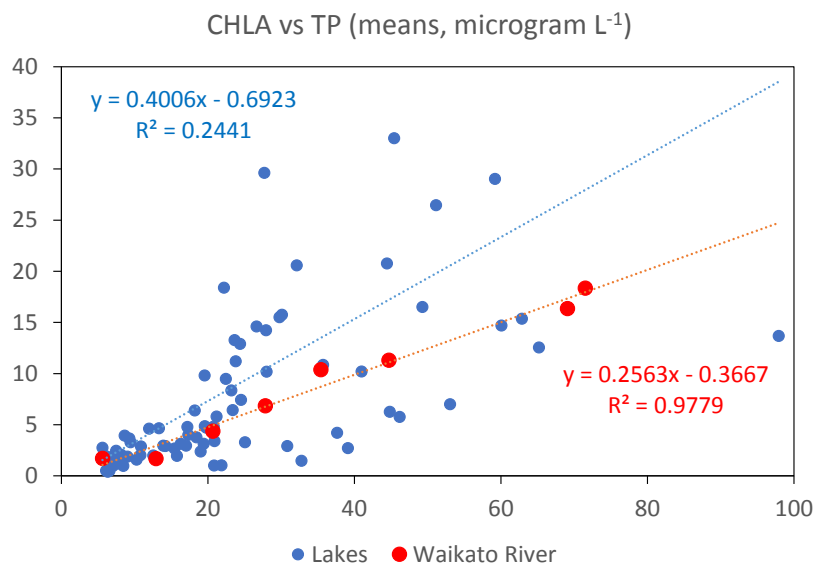


Fig. E6. Comparisons of regressions of chlorophyll *a* against TP, in lakes and in the Waikato River.

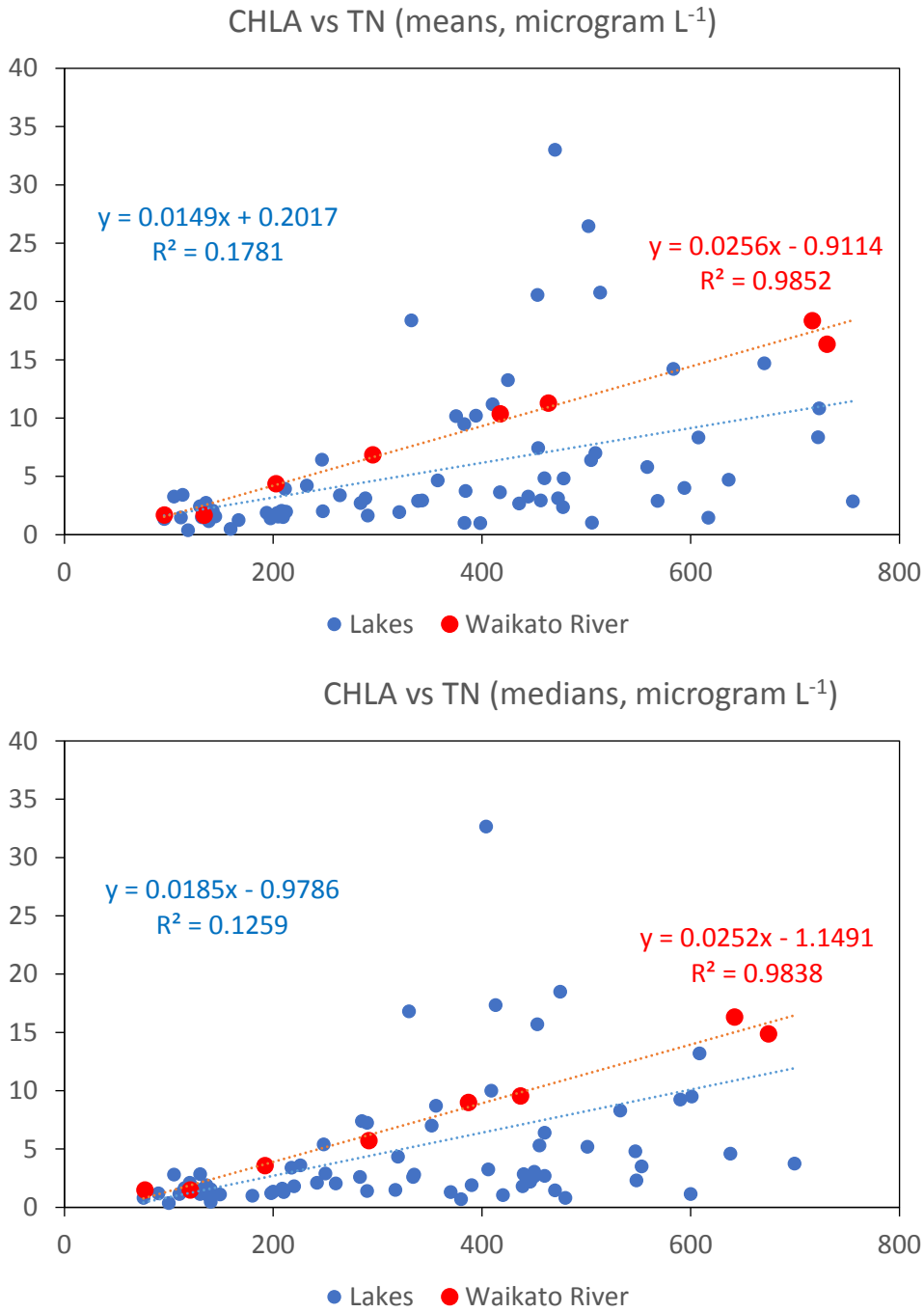
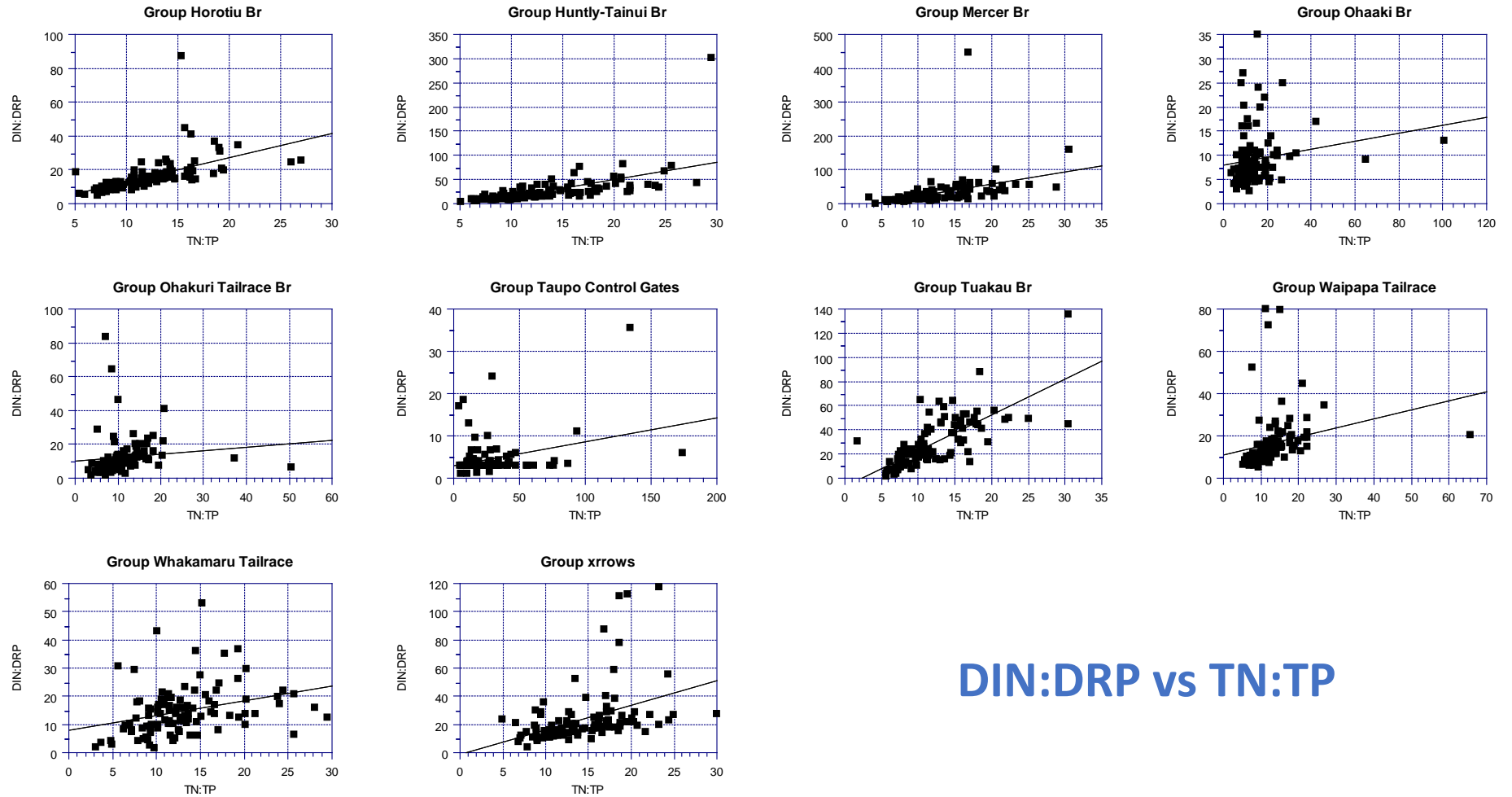


Fig. E7. Comparisons of regressions of chlorophyll *a* against TN, in lakes and in the Waikato River.

## Appendix F DIN:DRP ratio versus TN:TP ratio by station



**DIN:DRP vs TN:TP**

Fig. F1. DIN:DRP ratio versus TN:TP ratio by station. All data of 2006-2014.

## Appendix G Histograms of DIN:DRP ratios

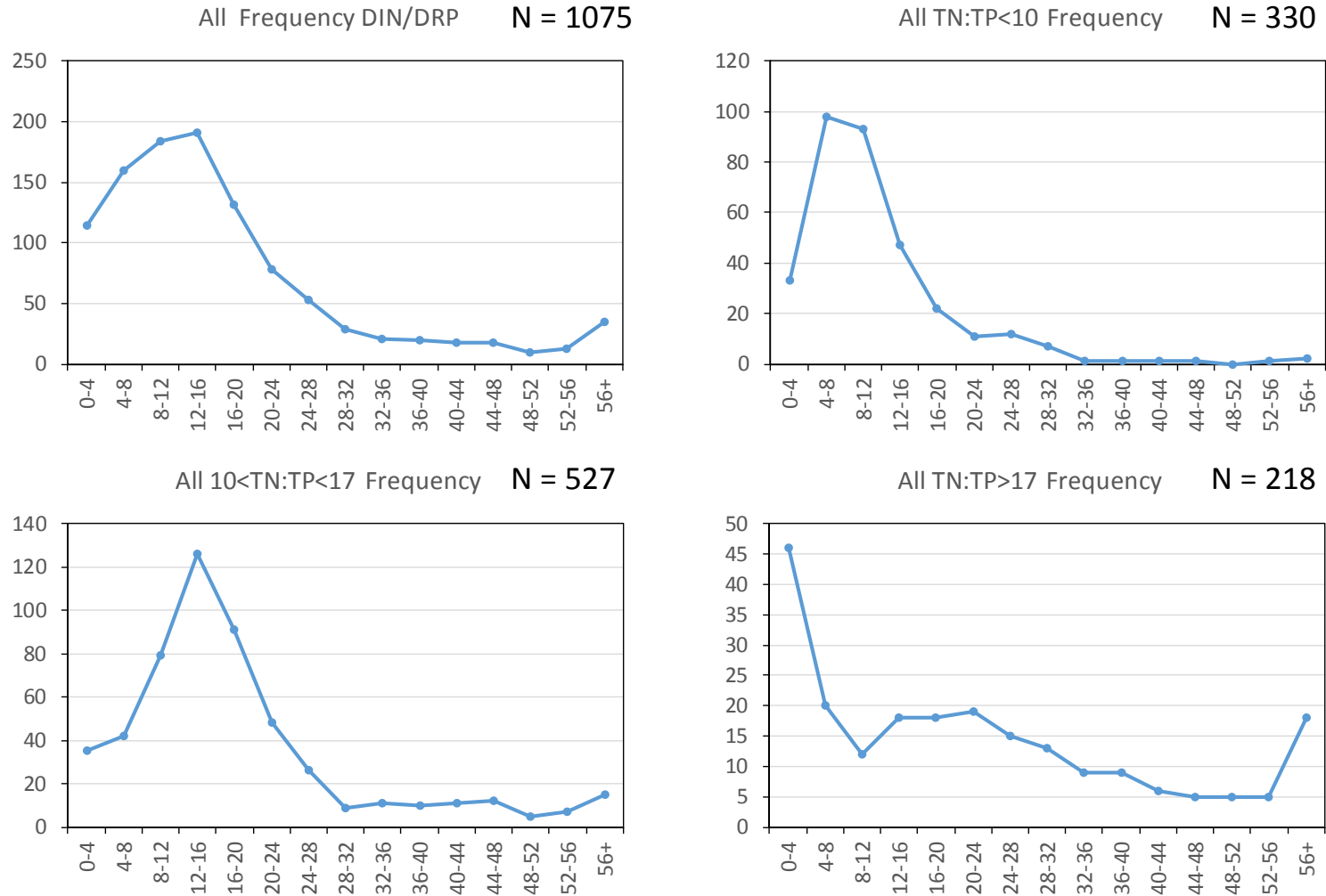


Fig. G1. Frequency distributions of DIN:DRP ratios. All data of all stations combined and separate for different brackets of TN:TP ratios (2006-2014).

## Appendix H Chlorophyll *a* : nutrient ratios

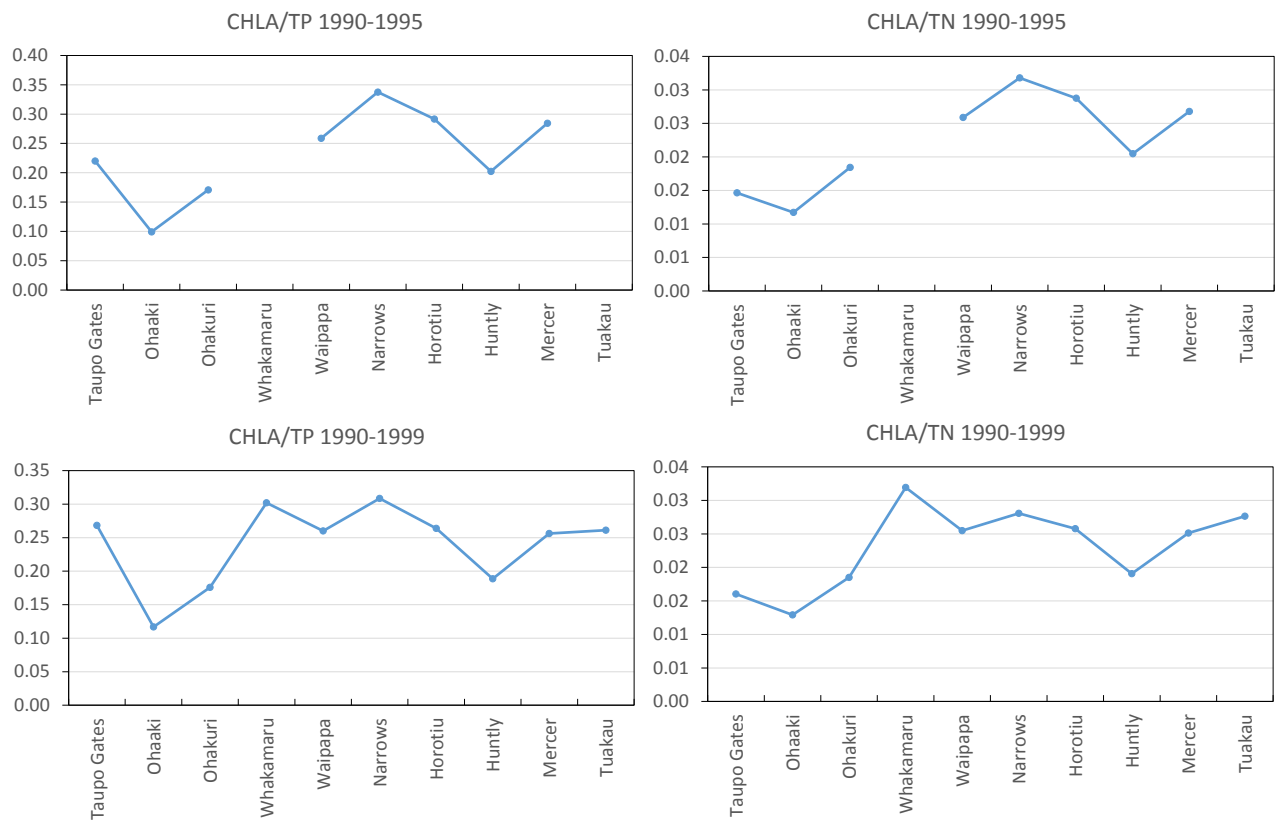


Fig. H1. Ratios of annual means of chlorophyll *a* to TP and TN, from upstream on the left to downstream on the right. Top: data of 1990-1995, Bottom: data of 1990-1999.

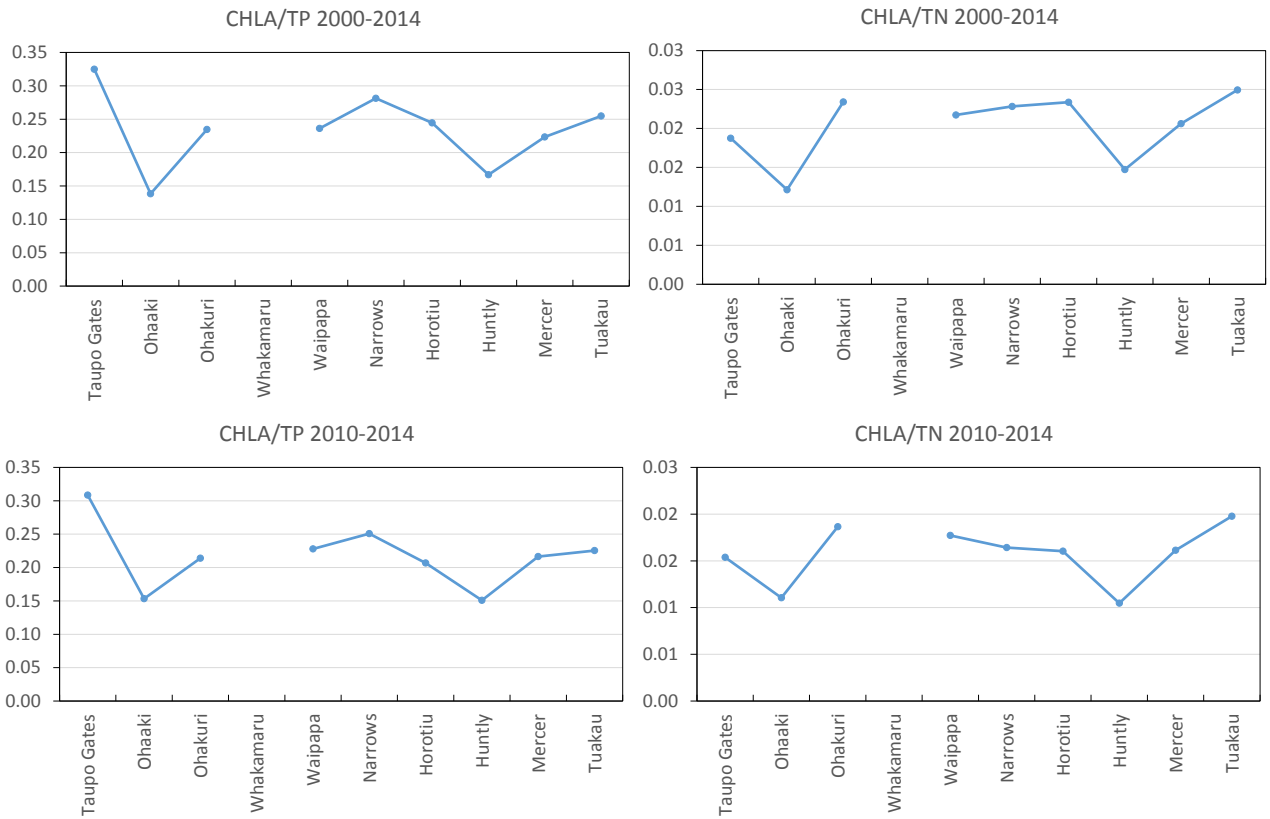


Fig. H2. Ratios of annual means of chlorophyll *a* to TP and TN, from upstream on the left to downstream on the right. Top: data of 2000-2014, Bottom: data of 2010-2014.



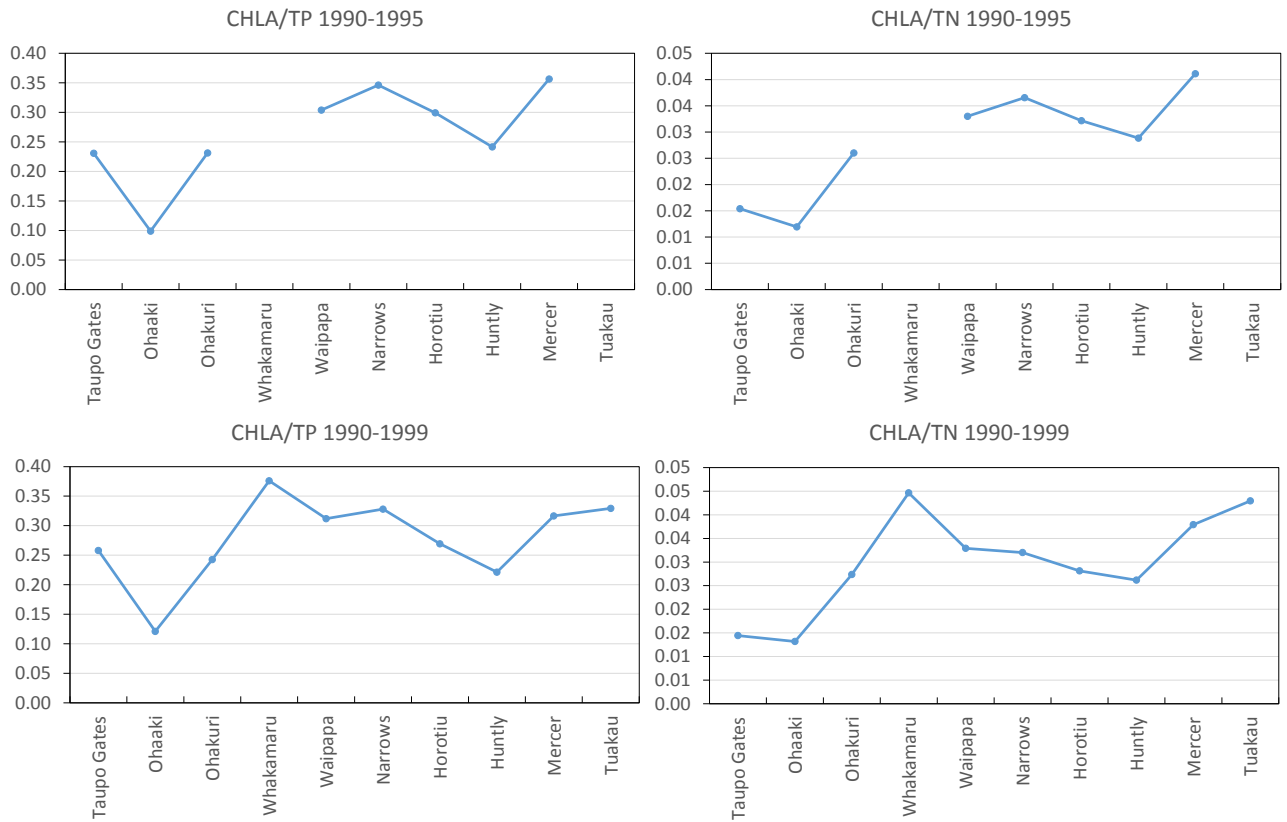


Fig. H3. Ratios of growing season (October-March) means of chlorophyll *a* to TP and TN, from upstream on the left to downstream on the right. Top: data of 1990-1995, Bottom: data of 1990-1999.

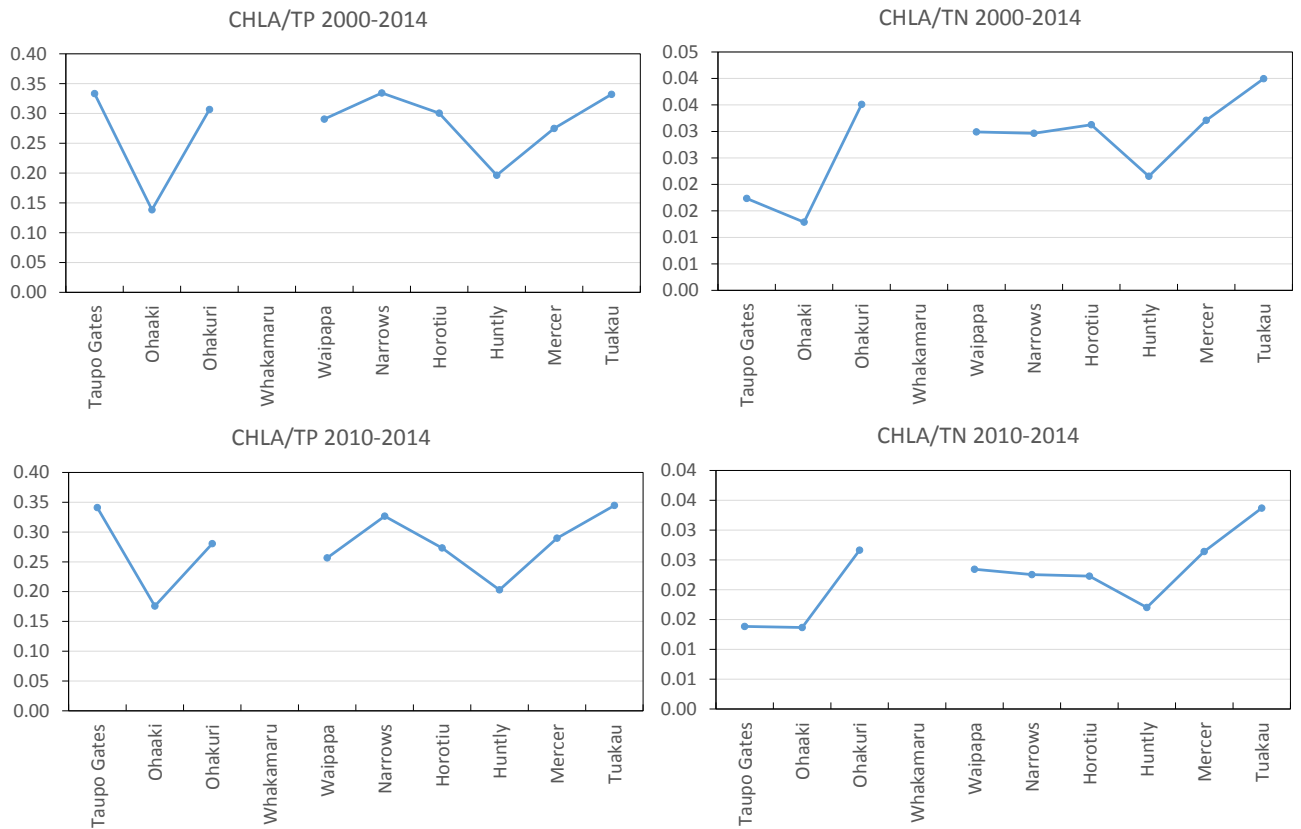


Fig. H4. Ratios of growing season (October-March) means of chlorophyll *a* to TP and TN, from upstream on the left to downstream on the right. Top: data of 2000-2014, Bottom: data of 2010-2014.

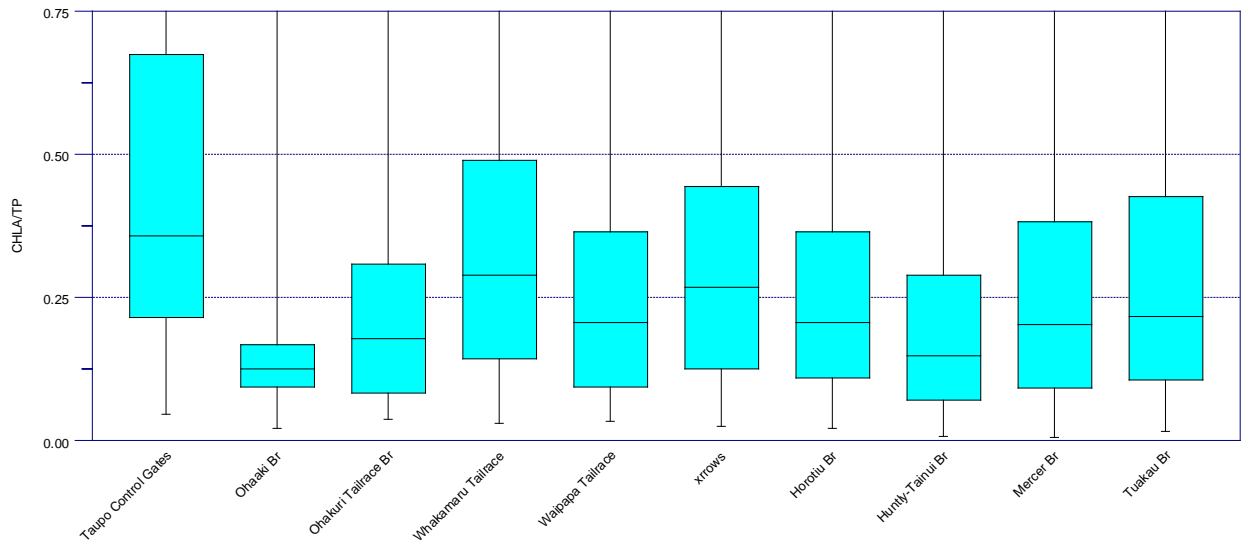


Fig. H5. Boxplot of ratios of chlorophyll *a* to TP, from upstream on the left to downstream on the right. All data of 1990-2014 are included. For Whakamaru this includes suspect chlorophyll *a* samples after approximately 2000.

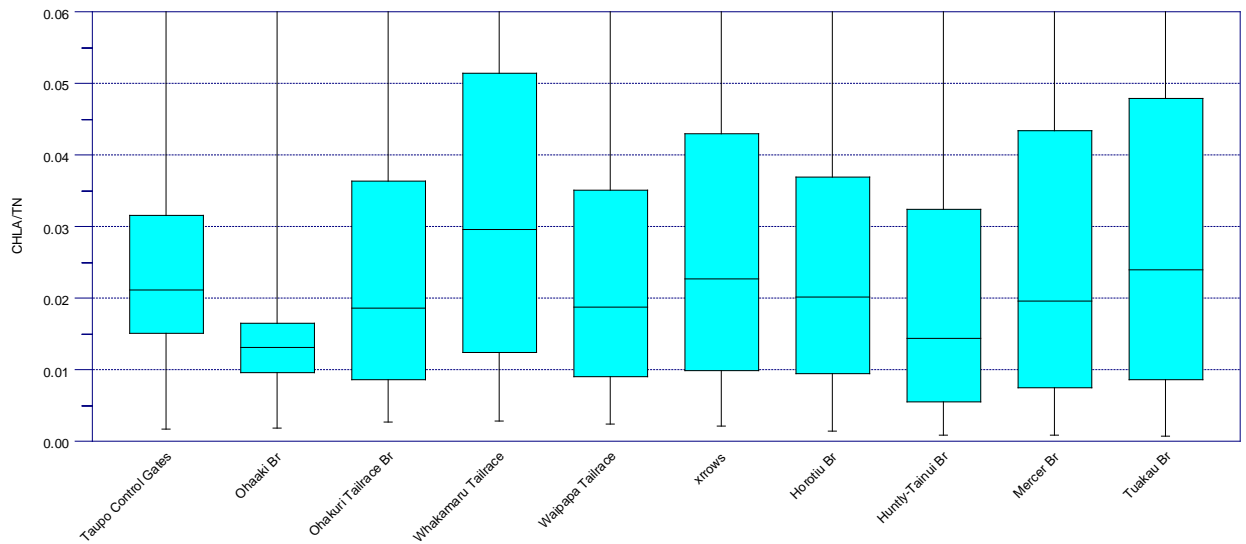


Fig. H6. Boxplot of ratios of chlorophyll *a* to TN, from upstream on the left to downstream on the right. All data of 1990-2014 are included. For Whakamaru this includes suspect chlorophyll *a* samples after approximately 2000.

## Appendix I Chlorophyll *a* versus nutrient concentrations by station

In order from downstream to upstream. Data of 1990-2014, followed by data of 2006-2014. Data of Taupo Gates and Ohaaki not plotted because 90%-95% of data are below the detection limit for chlorophyll *a*. Whakamaru chlorophyll *a* data are suspect after 2000 and are not included here.

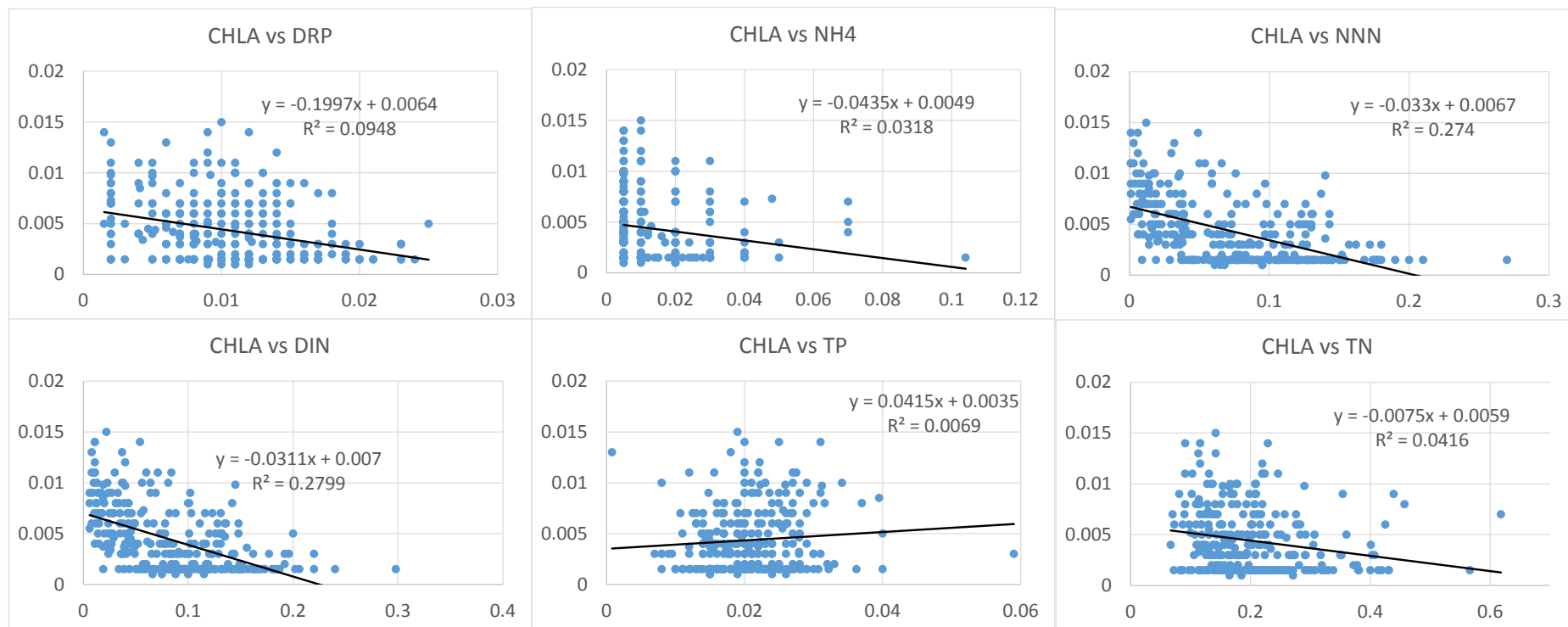


Fig. I1. Chlorophyll *a* versus various nutrient concentrations at Ohakuri. All data of 1990-2014.

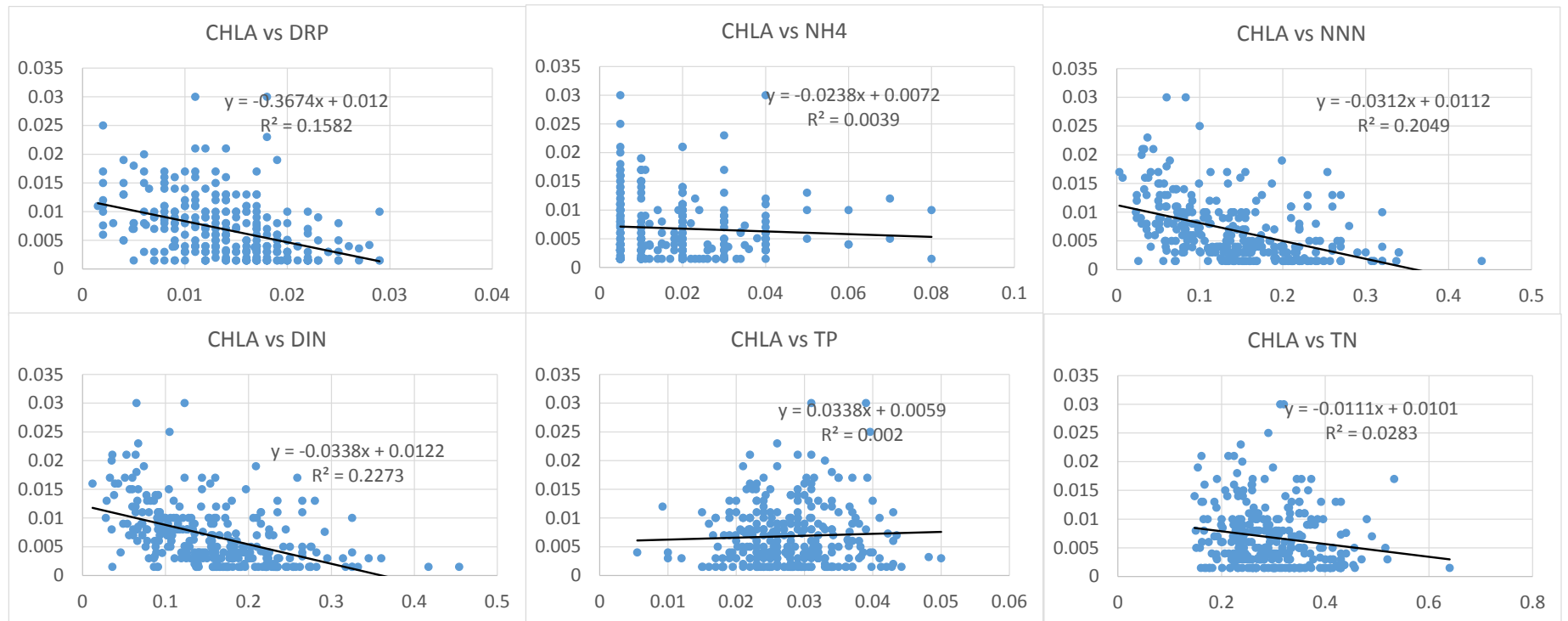


Fig. 12. Chlorophyll *a* versus various nutrient concentrations at Waipapa. All data of 1990-2014.

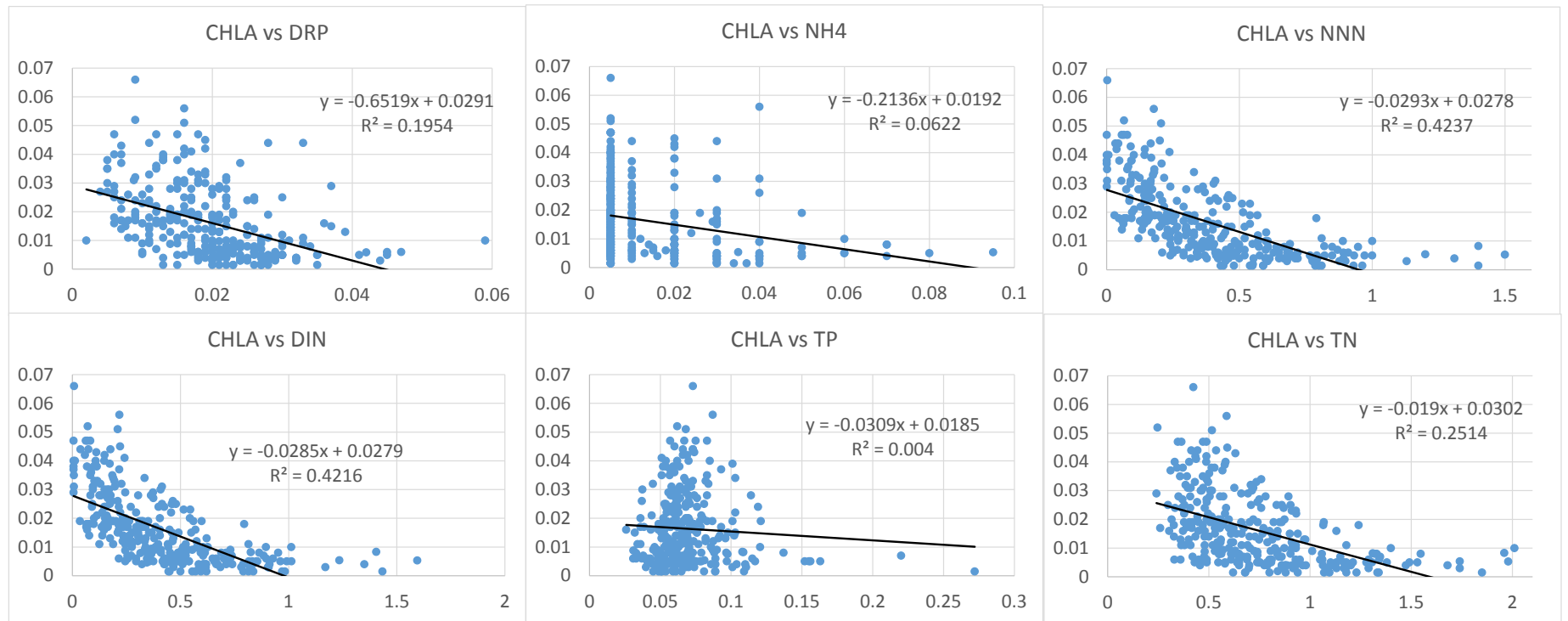


Fig. I3. Chlorophyll *a* versus various nutrient concentrations at the Narrows. All data of 1990-2014.

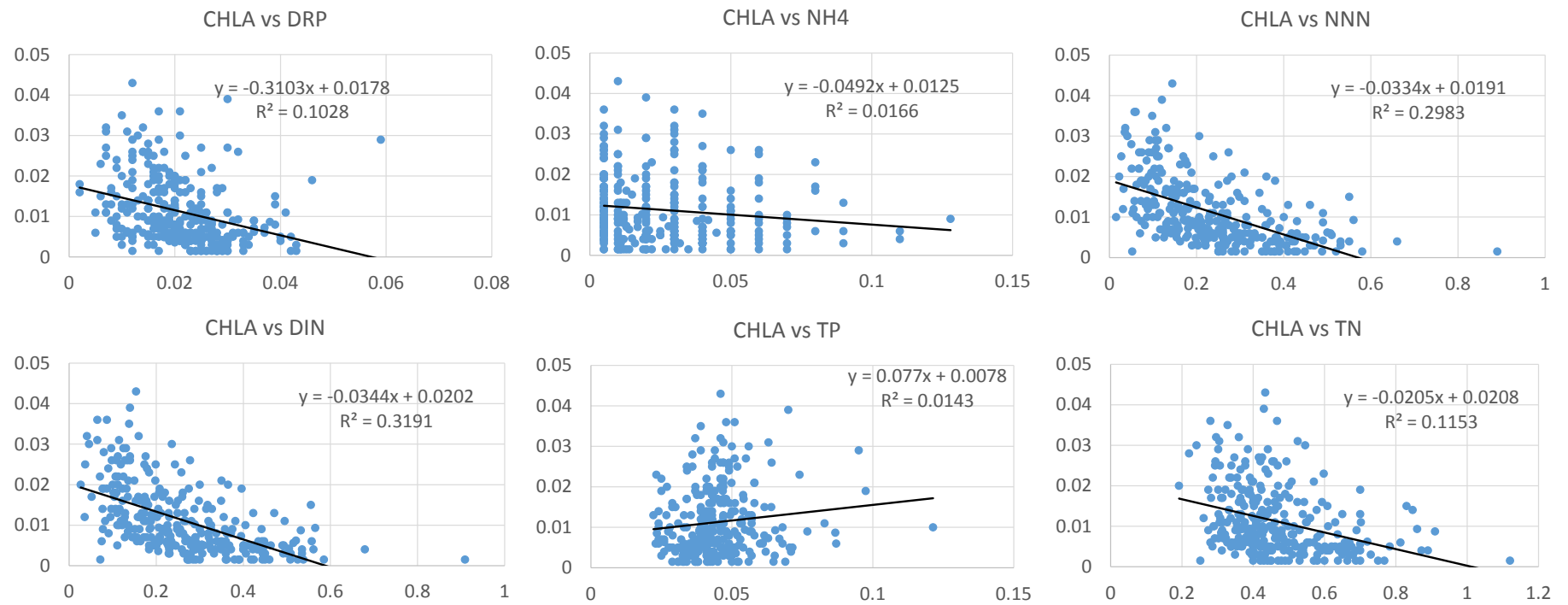


Fig. 14. Chlorophyll *a* versus various nutrient concentrations at Horotiu. All data of 1990-2014.

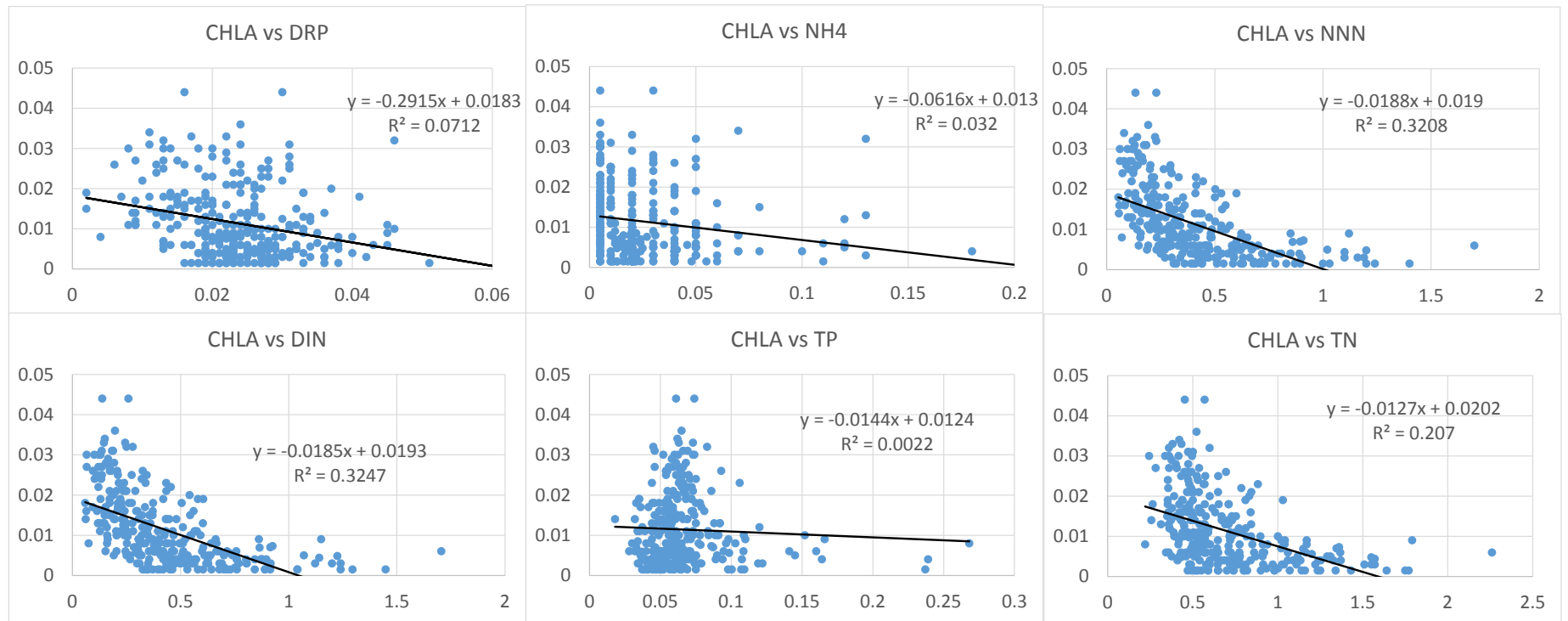


Fig. I5. Chlorophyll *a* versus various nutrient concentrations at Huntly. All data of 1990-2014.



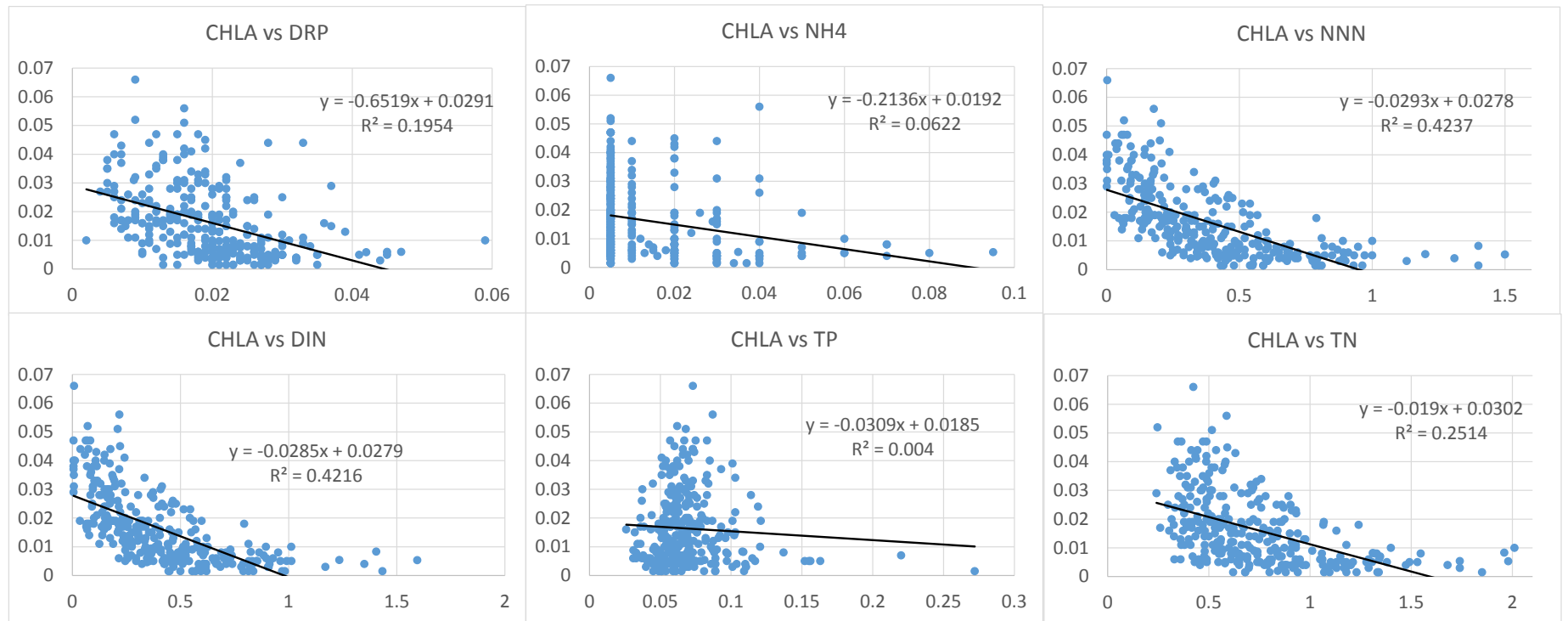


Fig. 16. Chlorophyll *a* versus various nutrient concentrations at Mercer. All data of 1990-2014.

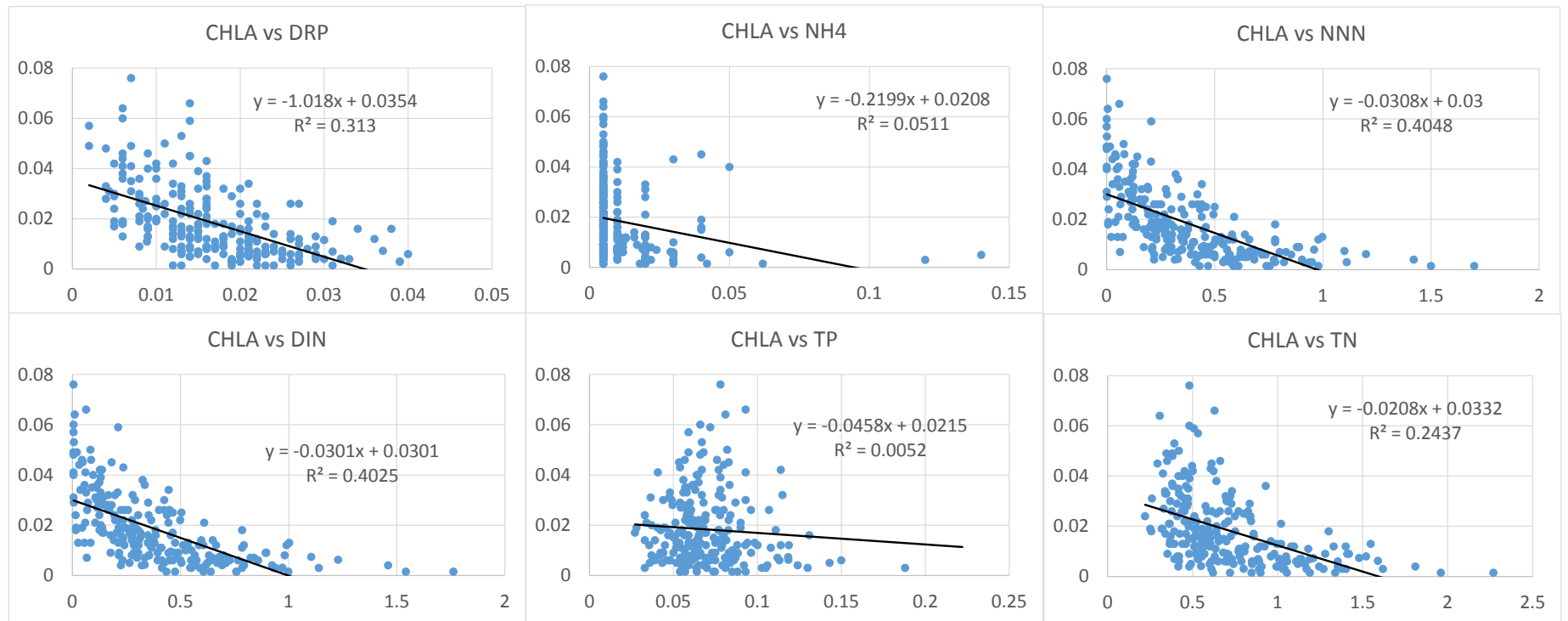


Fig. 17. Chlorophyll *a* versus various nutrient concentrations at Tuakau. All data of 1990-2014.

Data of 2006-2014. Data of Taupo Gates and Ohaaki not plotted because 100% of data are below the detection limit for chlorophyll *a*.

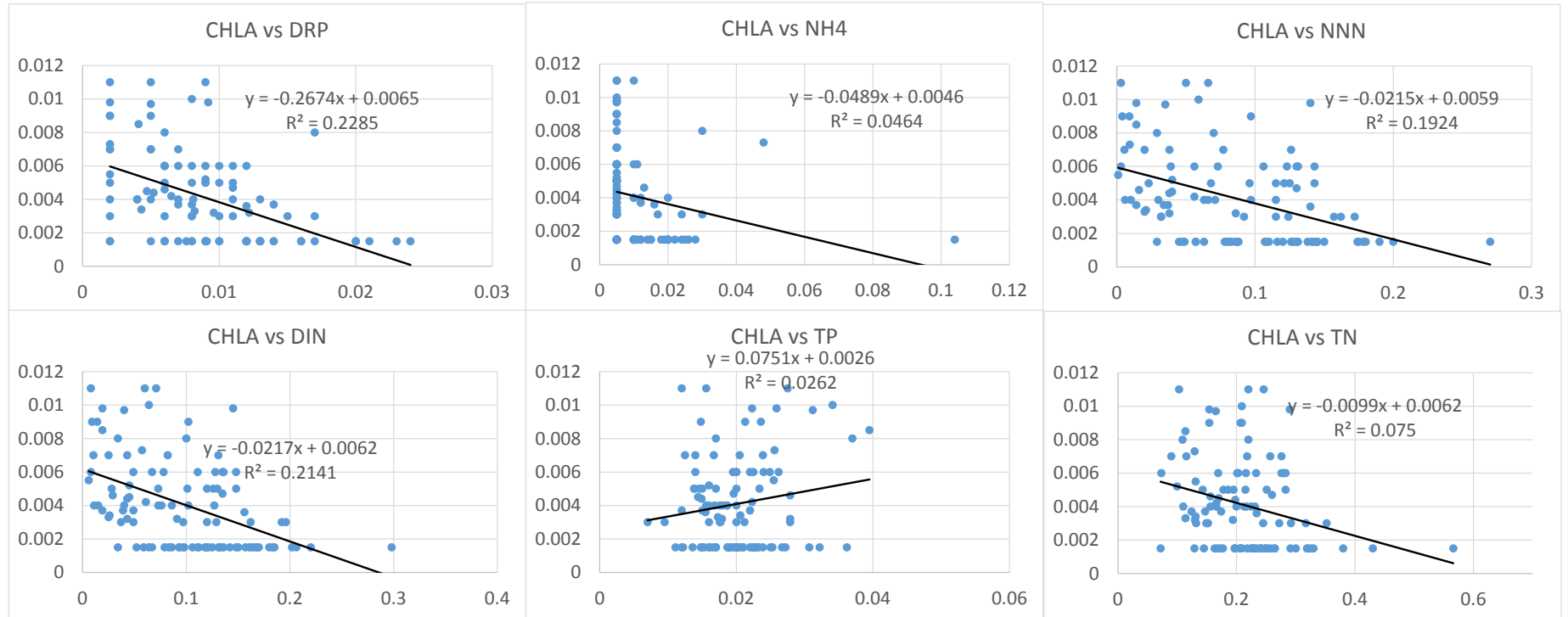


Fig. 18. Chlorophyll *a* versus various nutrient concentrations at Ohakuri. All data of 2006-2014. Of the chlorophyll *a* data 37% were below the detection limit (in the graphs half values of detection limits were used) and therefore the regressions for this station are less reliable.

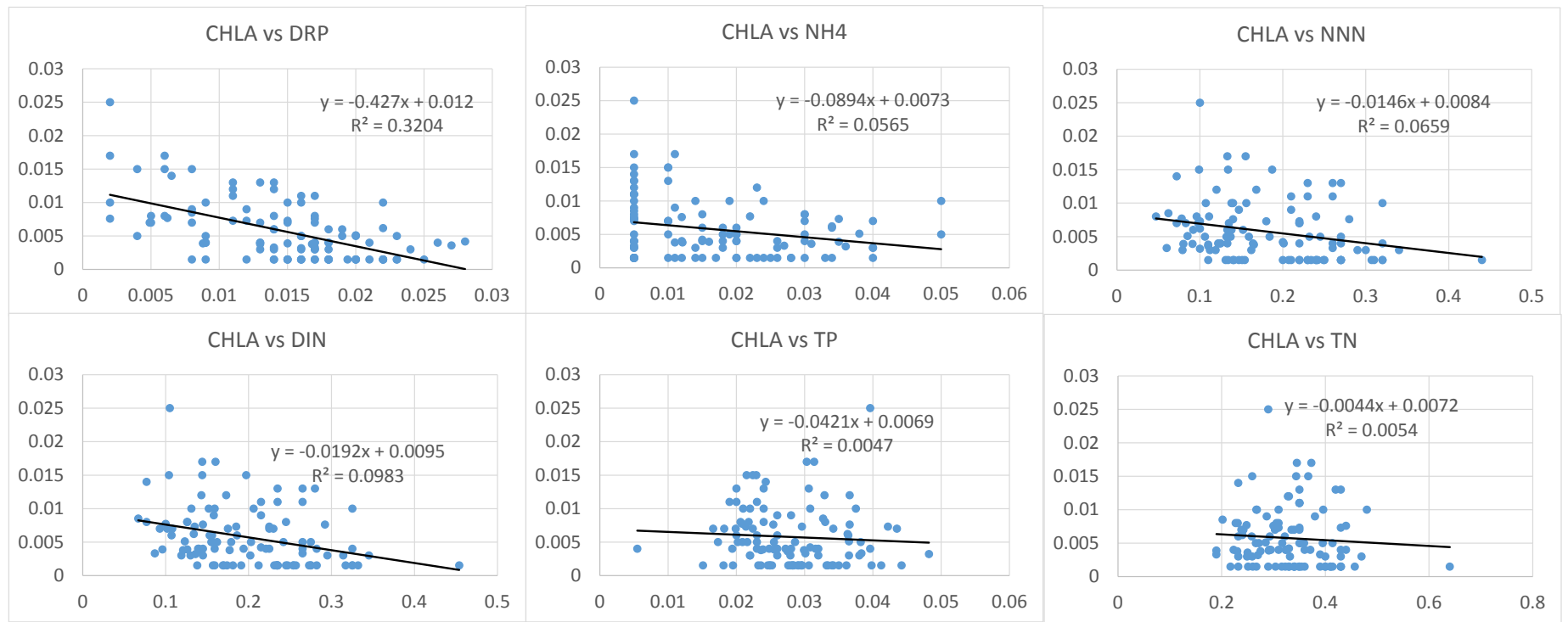


Fig. 19. Chlorophyll *a* versus various nutrient concentrations at Waipapa. All data of 2006-2014.

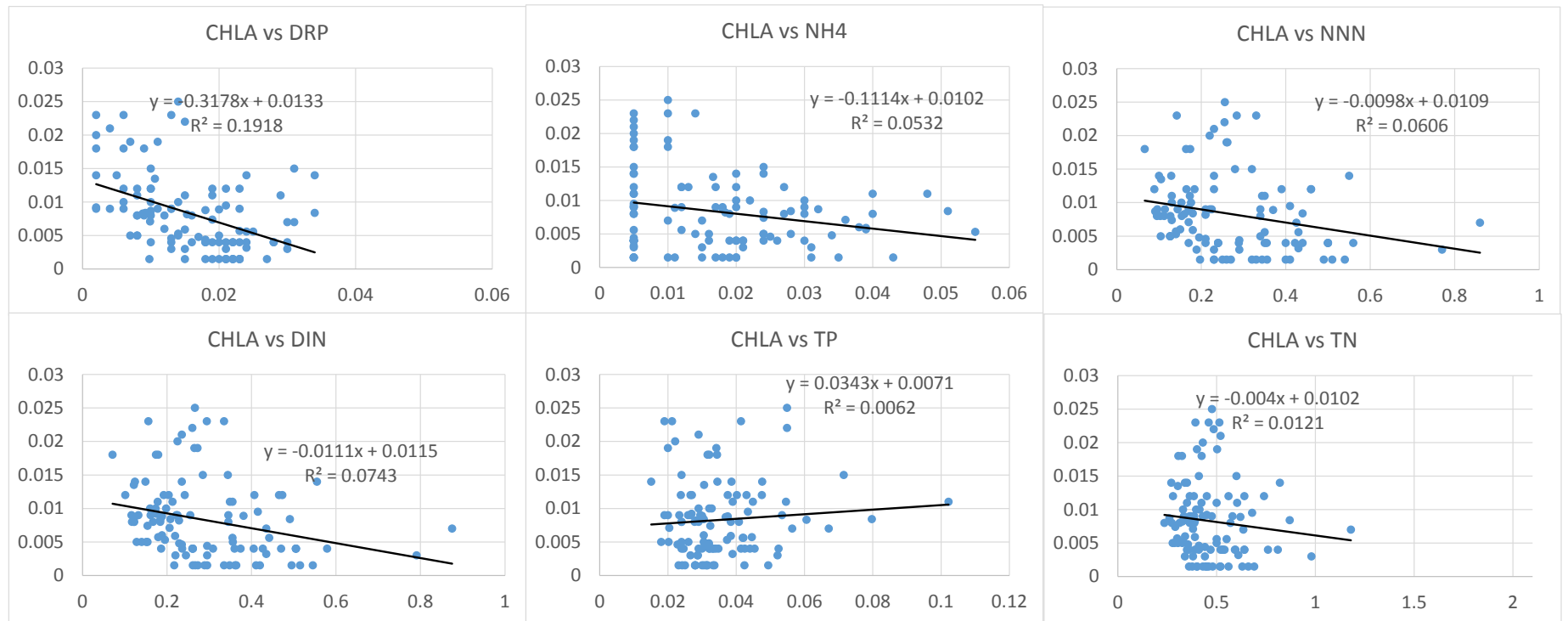


Fig. I10. Chlorophyll *a* versus various nutrient concentrations at the Narrows. All data of 2006-2014.

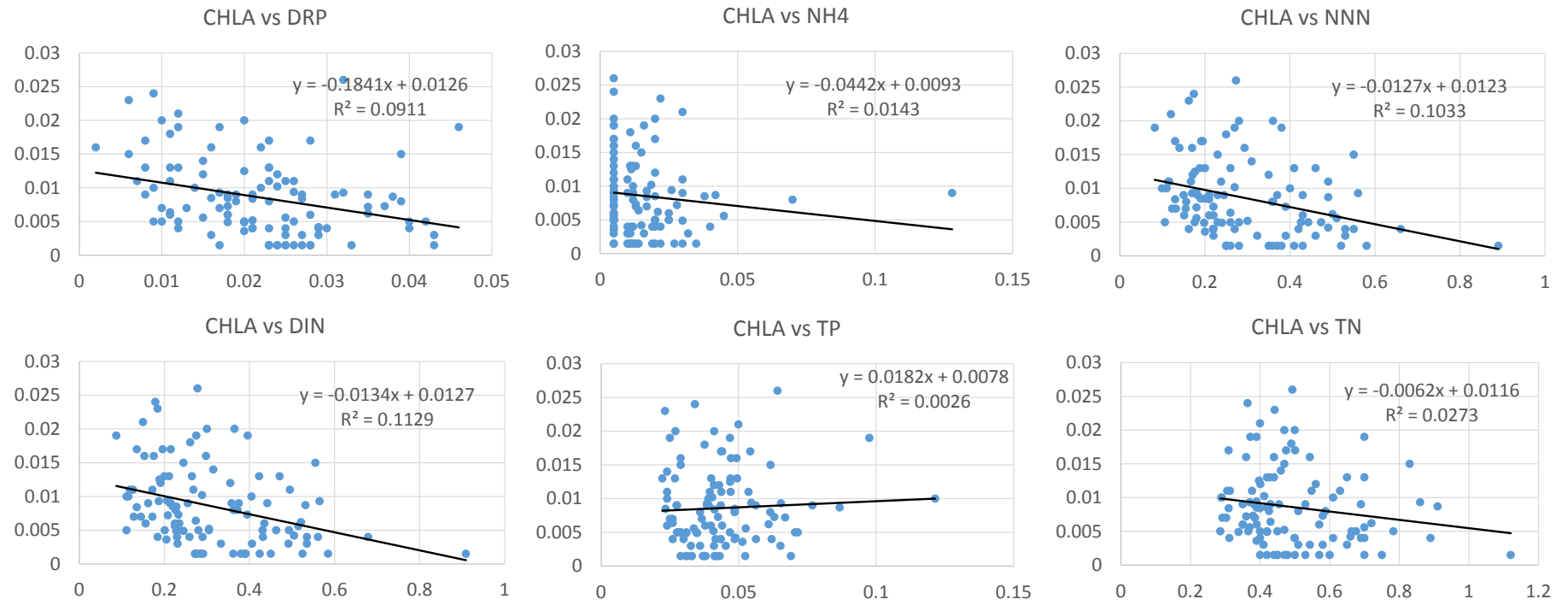


Fig. I11. Chlorophyll *a* versus various nutrient concentrations at Horotiu. All data of 2006-2014.

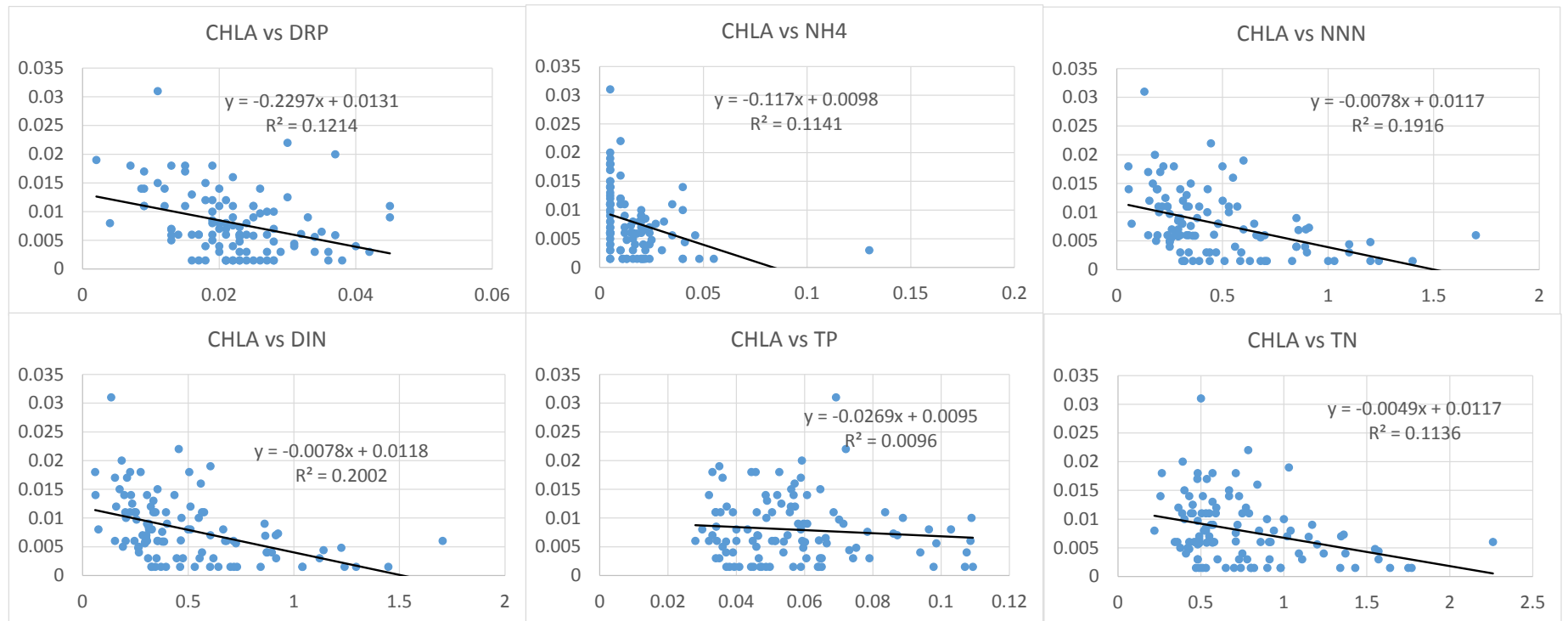


Fig. I12. Chlorophyll *a* versus various nutrient concentrations at Huntly. All data of 2006-2014.

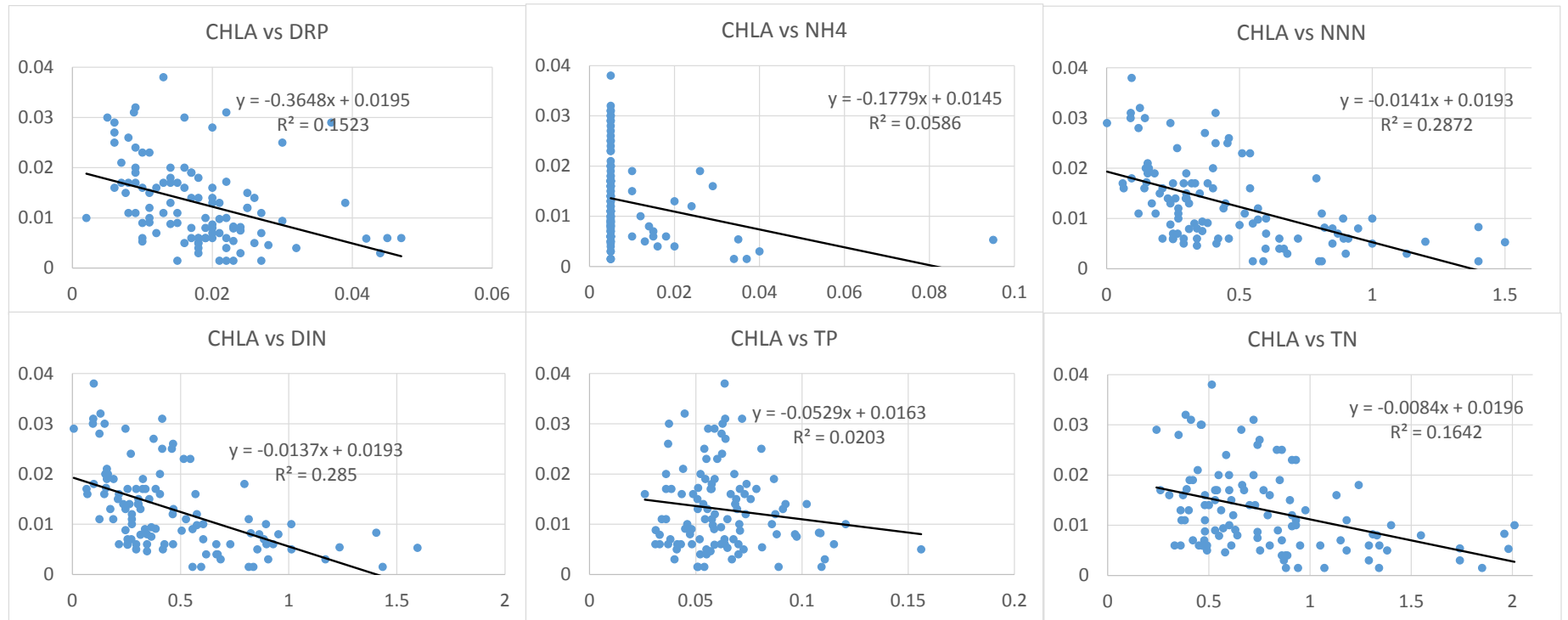


Fig. I13. Chlorophyll *a* versus various nutrient concentrations at Mercer. All data of 2006-2014.



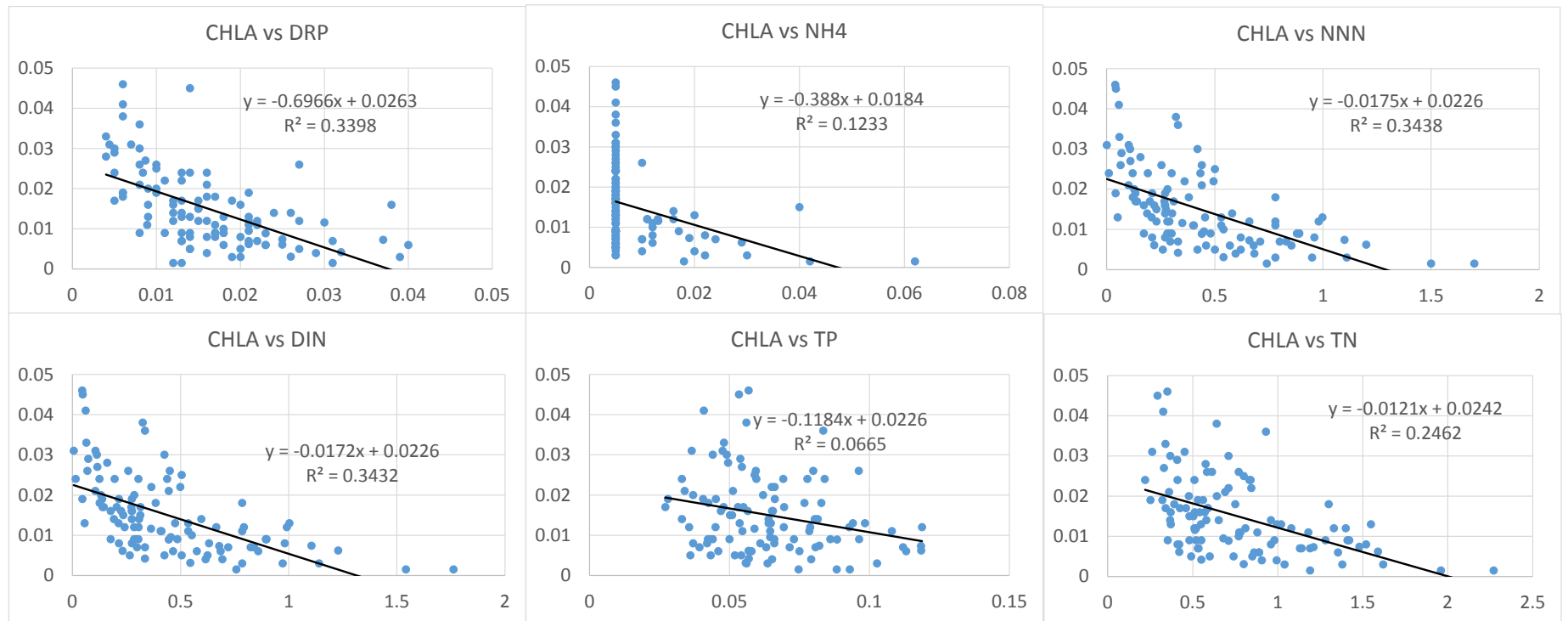


Fig. I14. Chlorophyll *a* versus various nutrient concentrations at Tuakau. All data of 2006-2014.

## Appendix J Dissolved nutrients versus TN:TP ratio by station

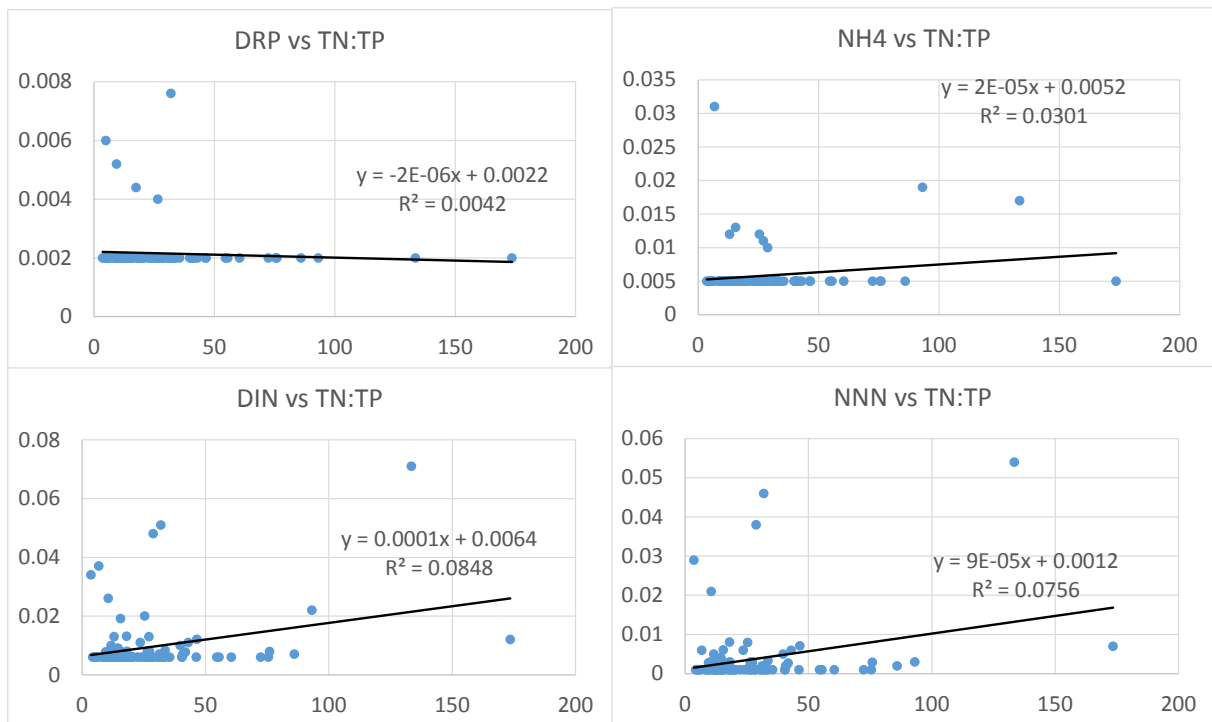


Fig. J1. Taupo Gates. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

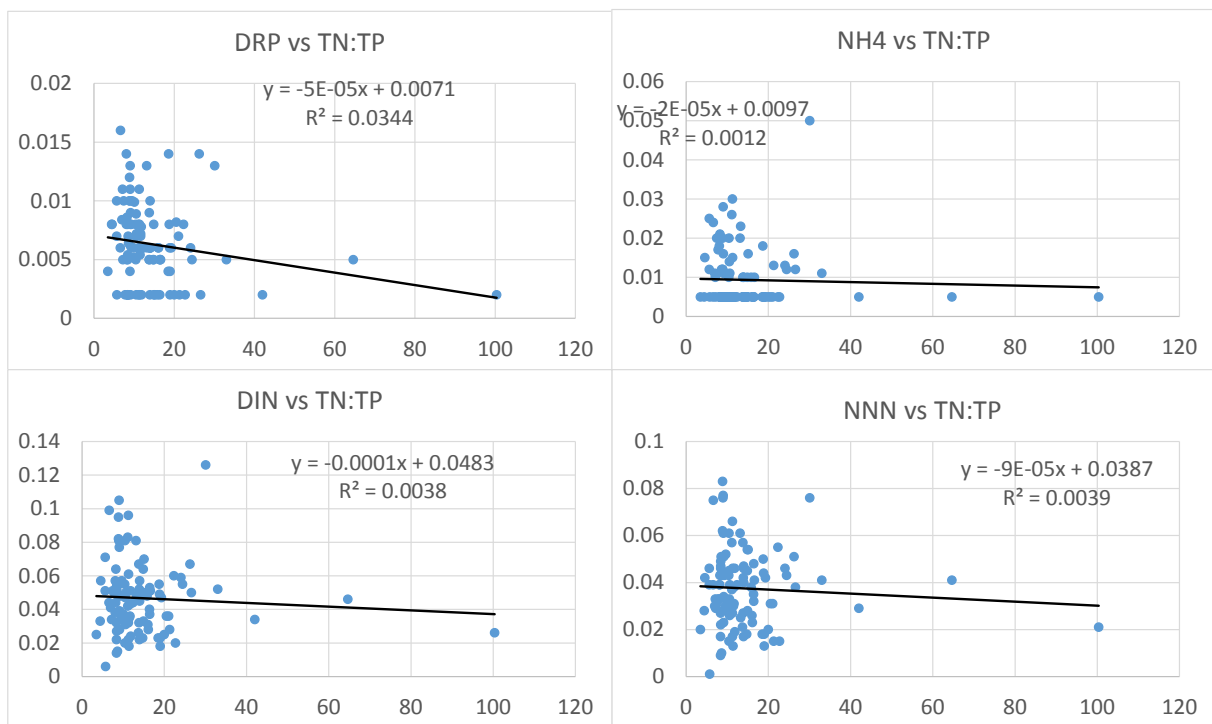


Fig. J2. Ohaaki. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

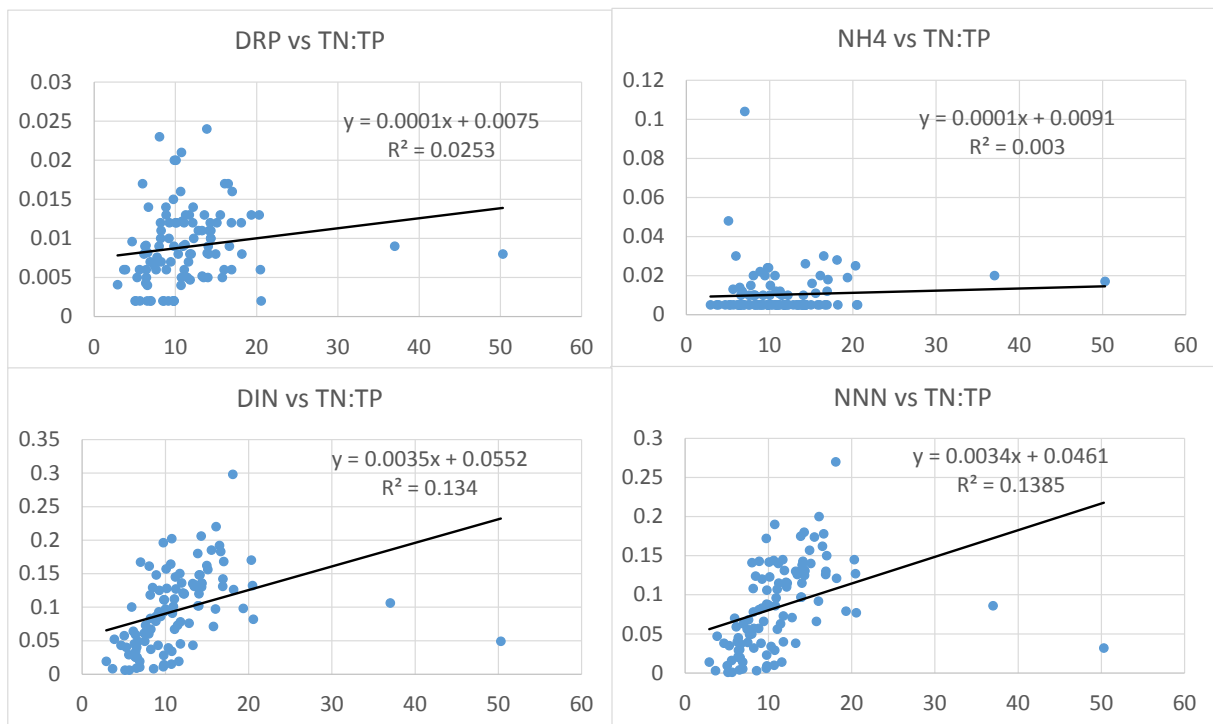


Fig. J3. Ohakuri. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

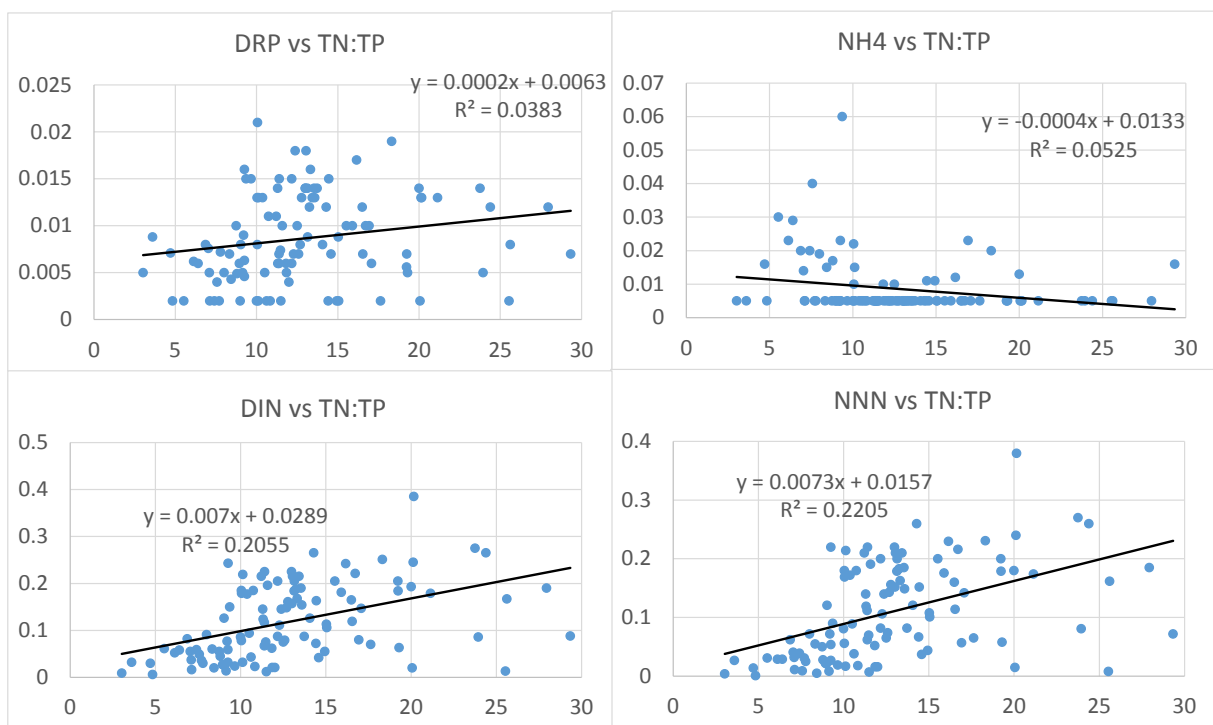


Fig. J4. Whakamaru. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

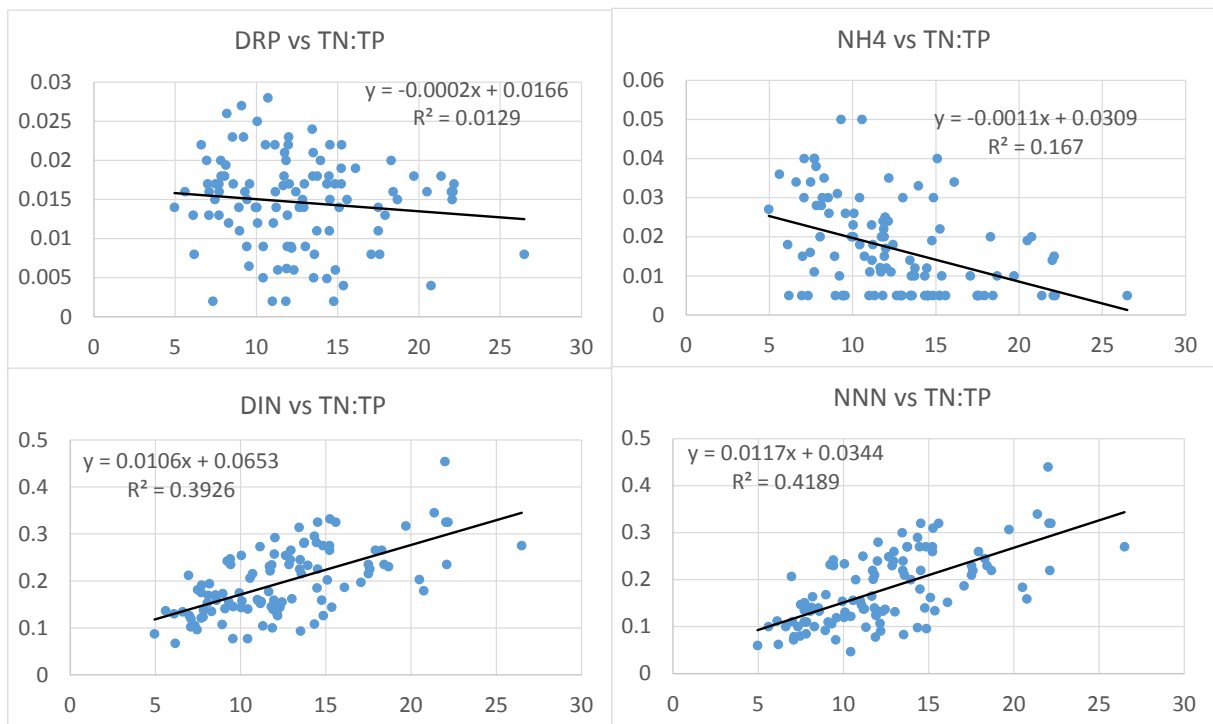


Fig. J5. Waipapa. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

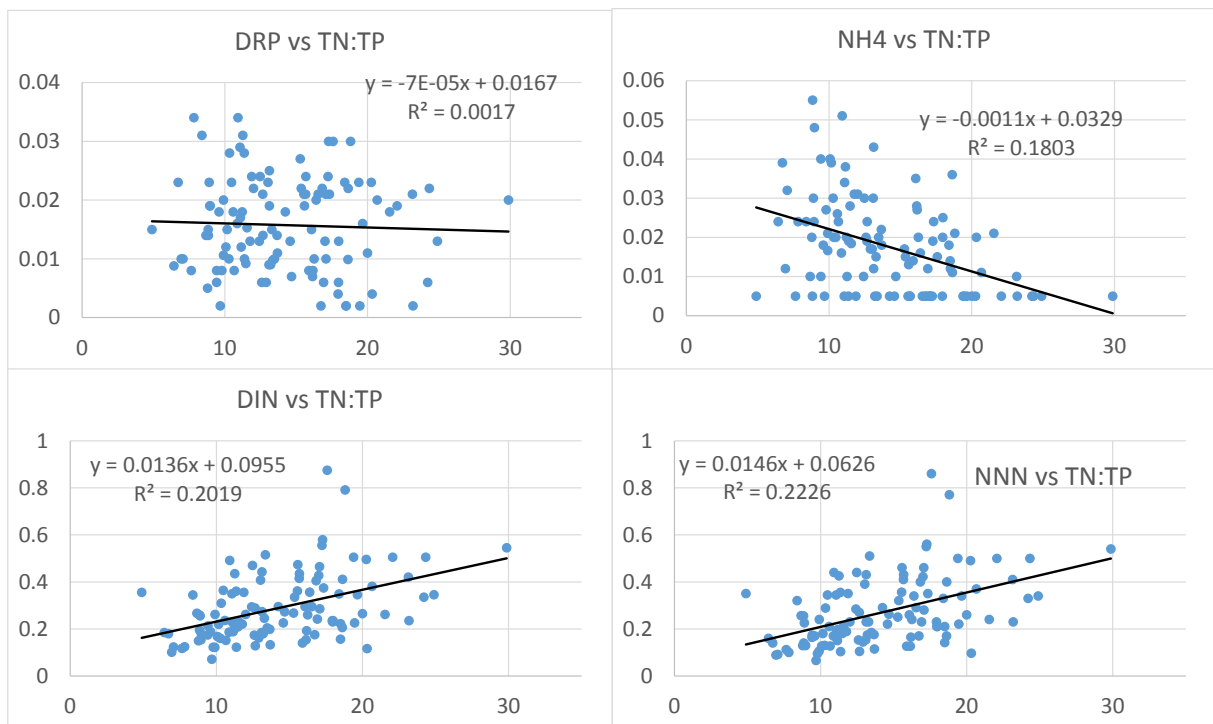


Fig. J6. The Narrows. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

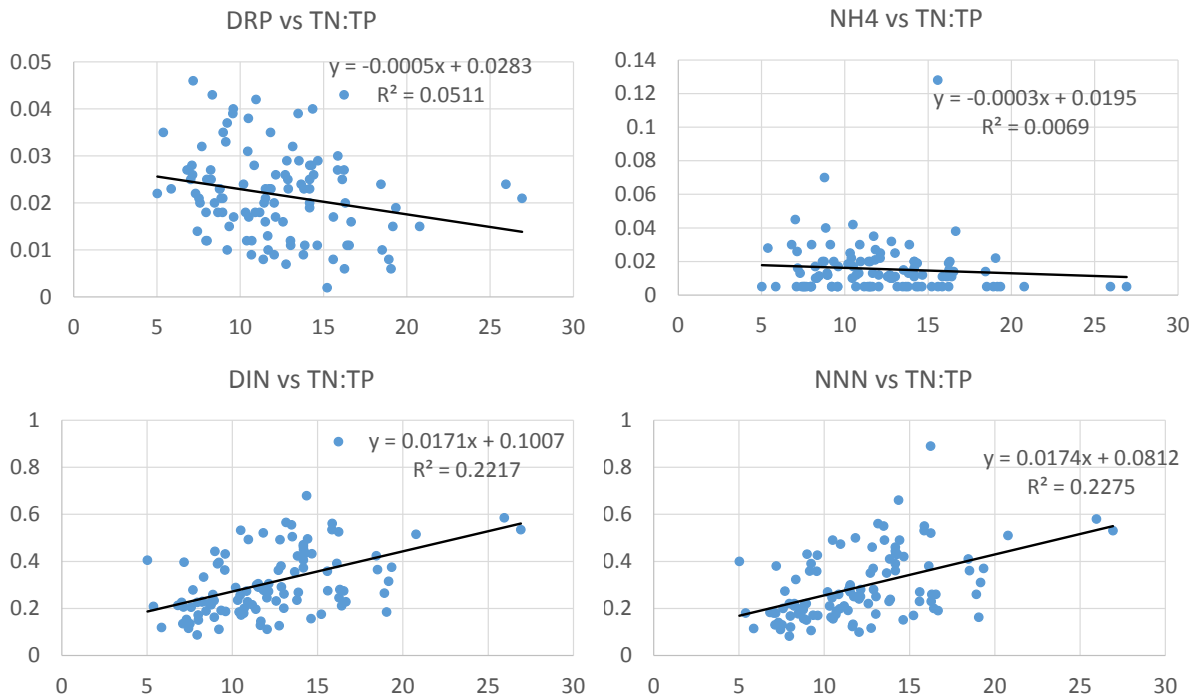


Fig. J7. Horotiu. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

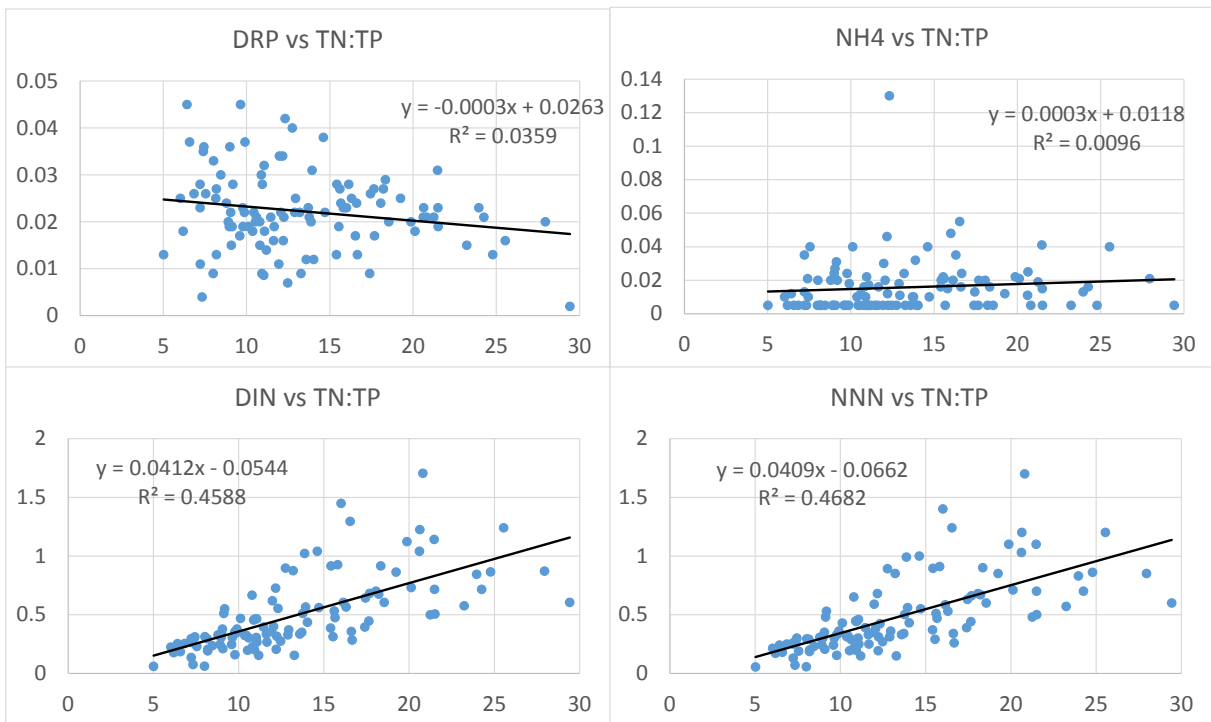


Fig. J8. Huntly. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

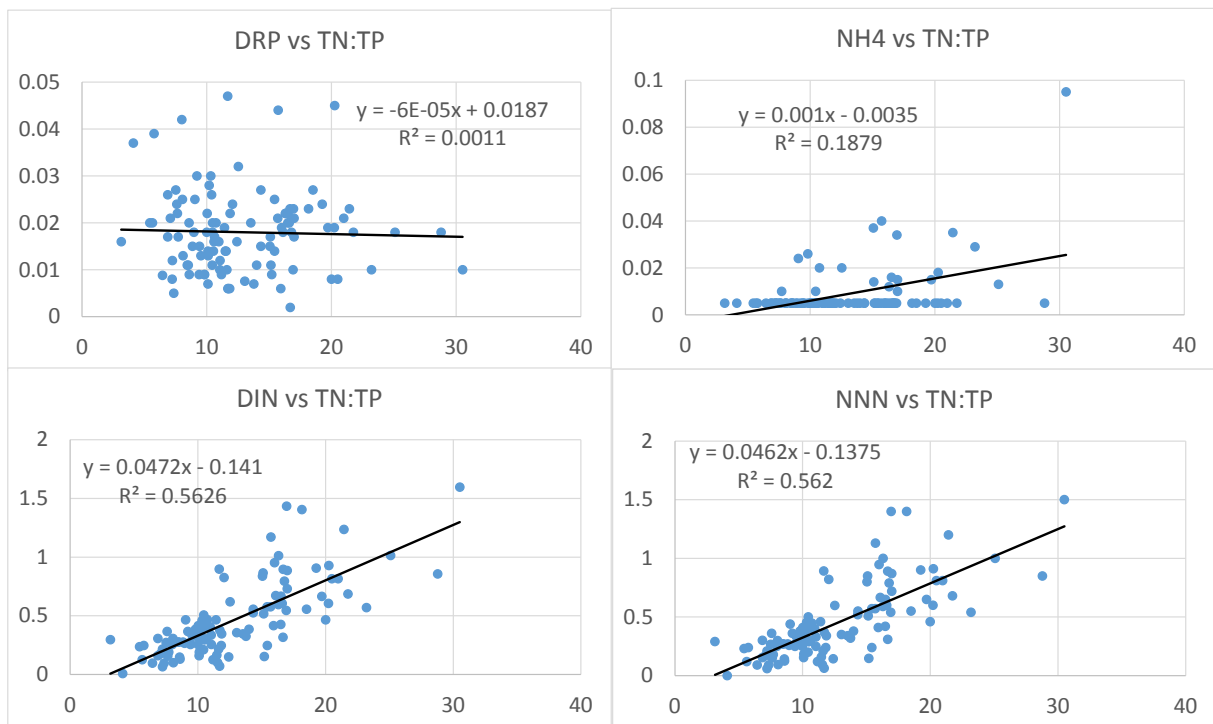


Fig. J9. Mercer. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

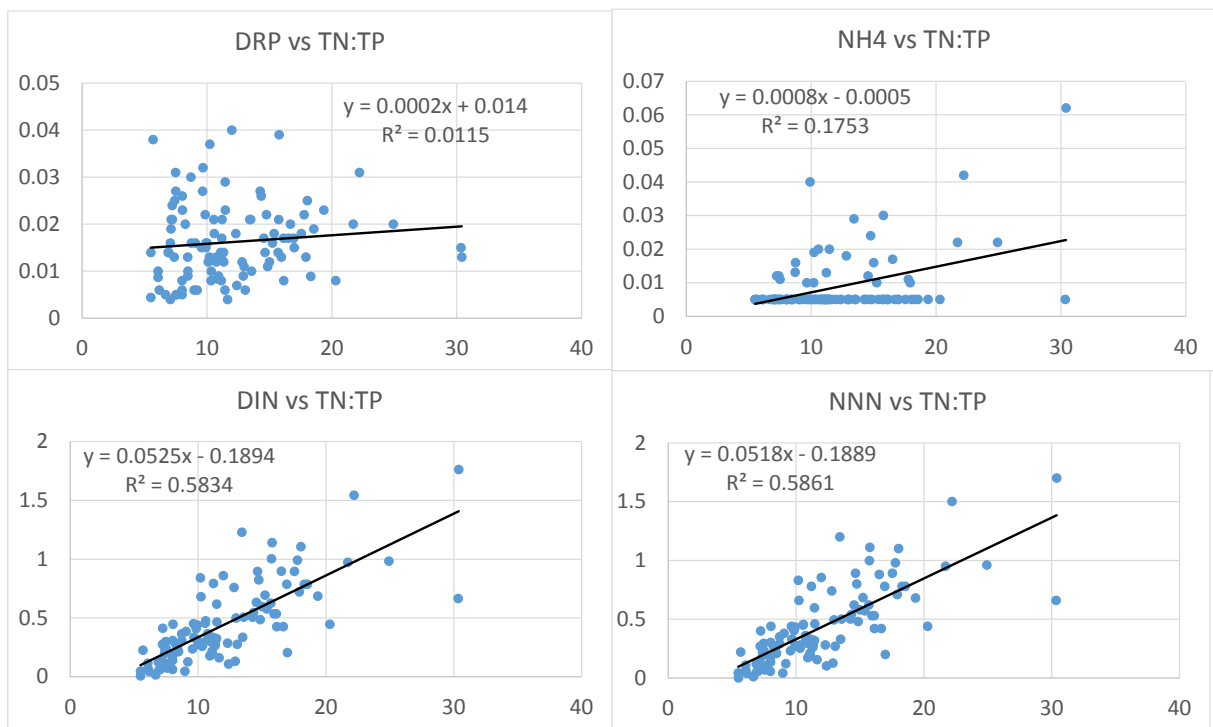


Fig. J10. Tuakau. Various dissolved nutrient against the TN:TP ratio. All data of 2006-2014.

## Appendix K Chlorophyll *a* versus dissolved nutrients, for three different brackets of TN : TP ratio, by station

Data of 2006-2014 (all data, not means or medians). Data of Taupo Gates, Ohaaki, Ohakuri and Whakamaru not plotted. At Taupo Gates, Ohaaki 100% of the chlorophyll *a* data were below the detection limit, at Ohakuri 37% of the chlorophyll *a* data were below the detection limit. Whakamaru chlorophyll *a* data were unreliable.

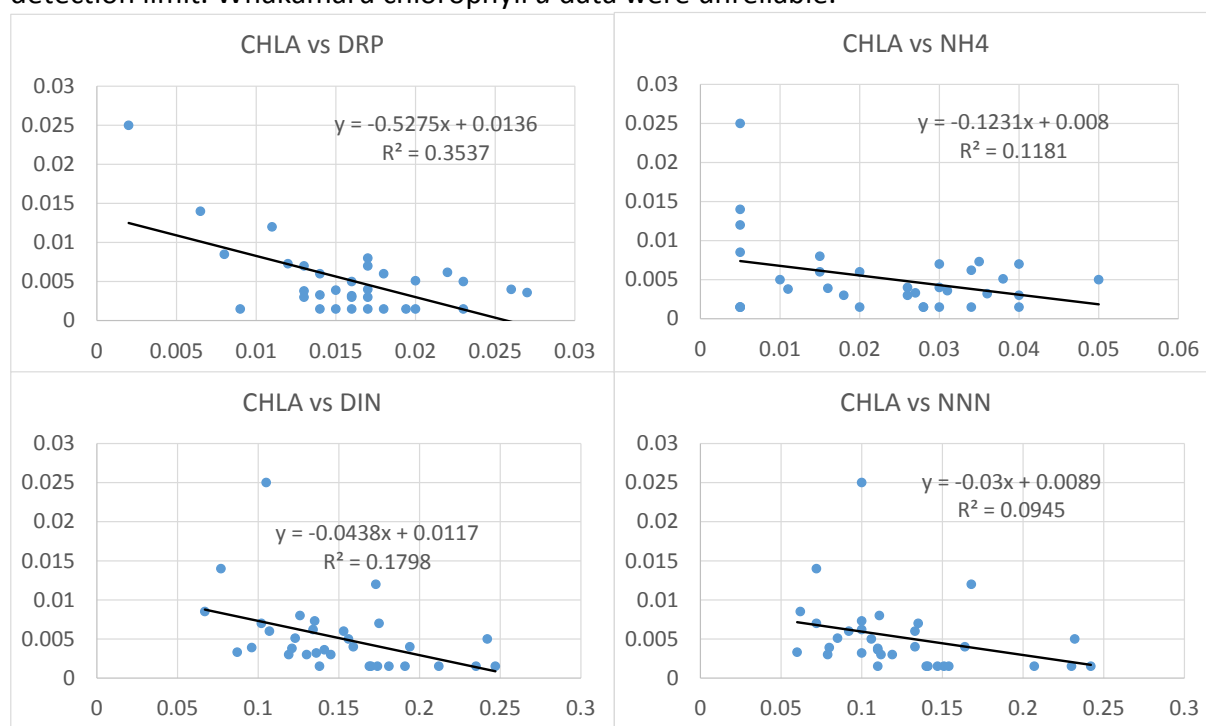


Fig. K1. Waipapa. Data were used only when TN:TP < 10. All data of 2006-2014.

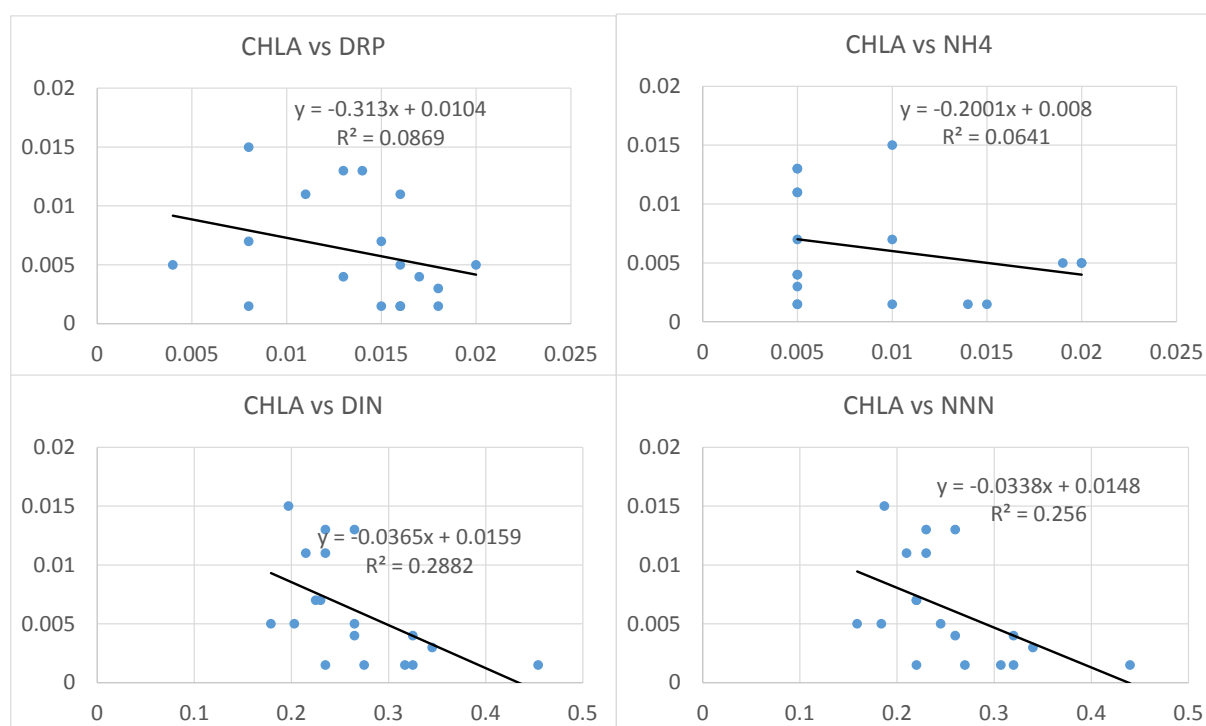


Fig. K2. Waipapa. Data were used only when TN:TP > 17. All data of 2006-2014.

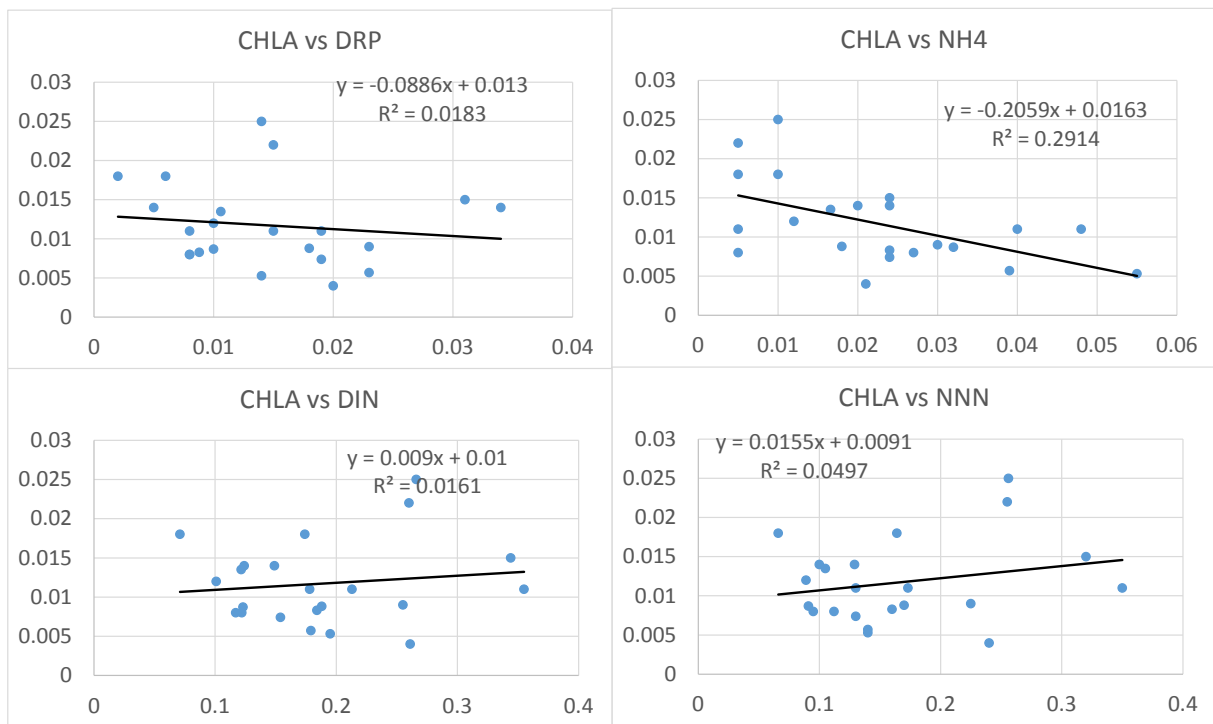


Fig. K3. The Narrows. Data were used only when TN:TP < 10. All data of 2006-2014.

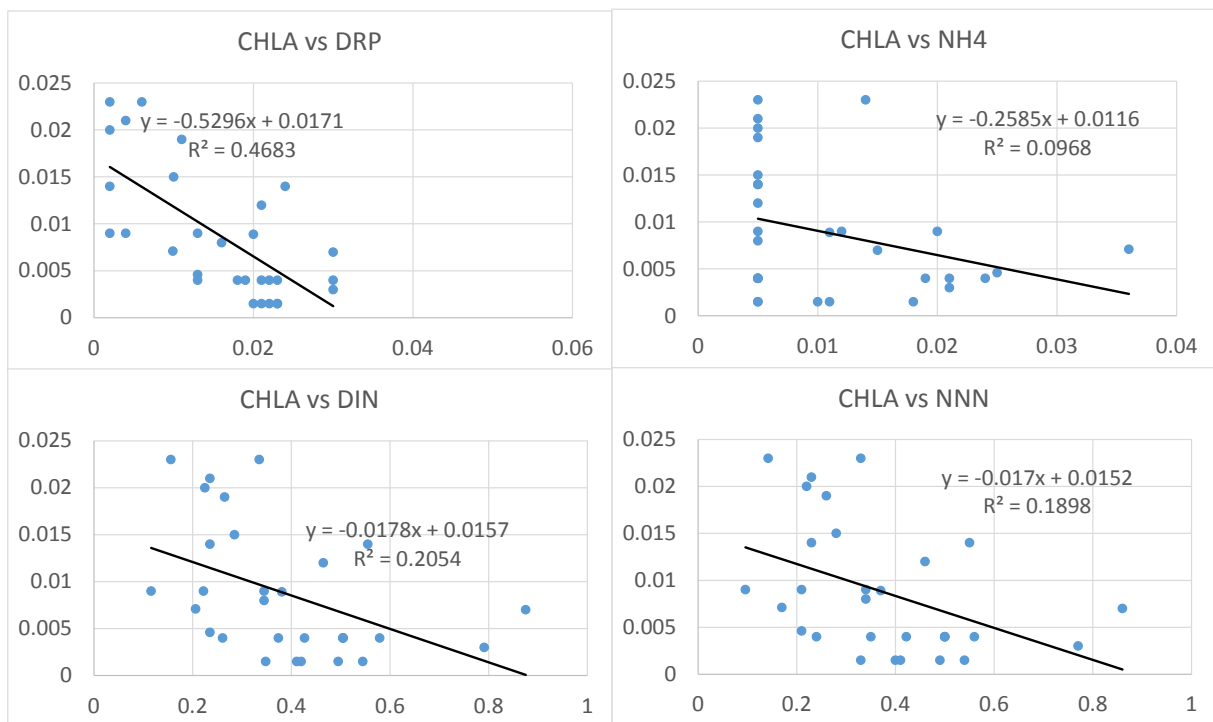


Fig. K4. The Narrows. Data were used only when TN:TP > 17. All data of 2006-2014.



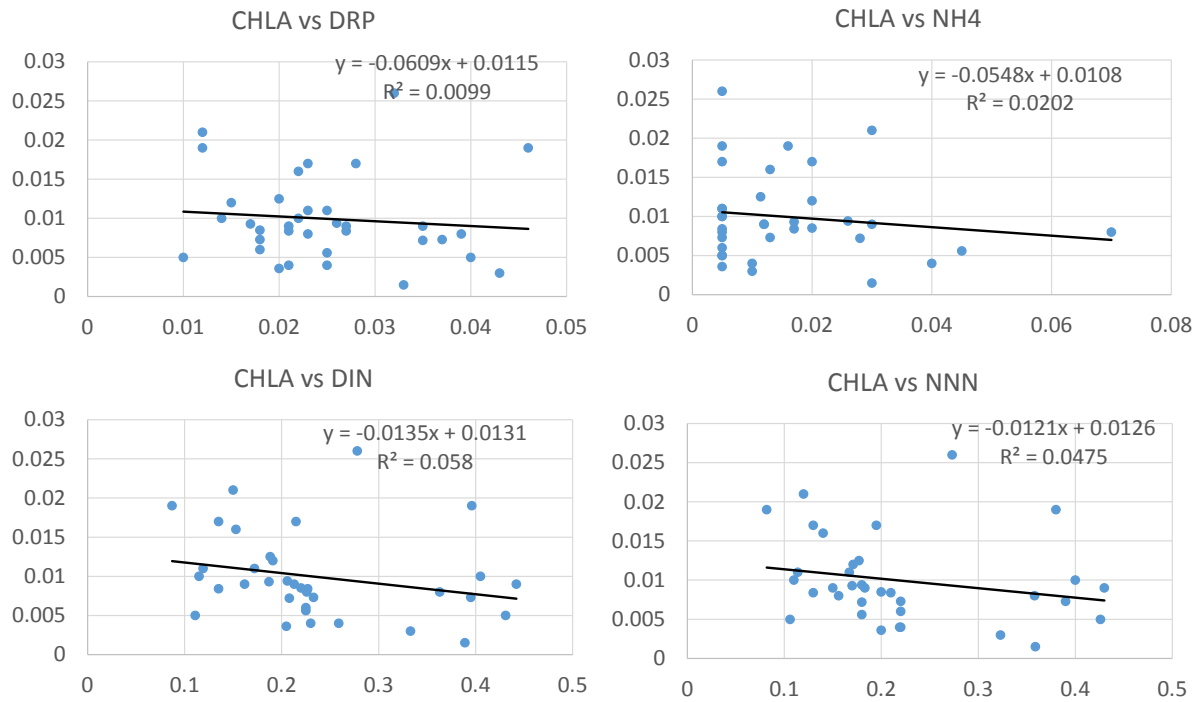


Fig. K5. Horotiu. Data were used only when TN:TP < 10. All data of 2006-2014.

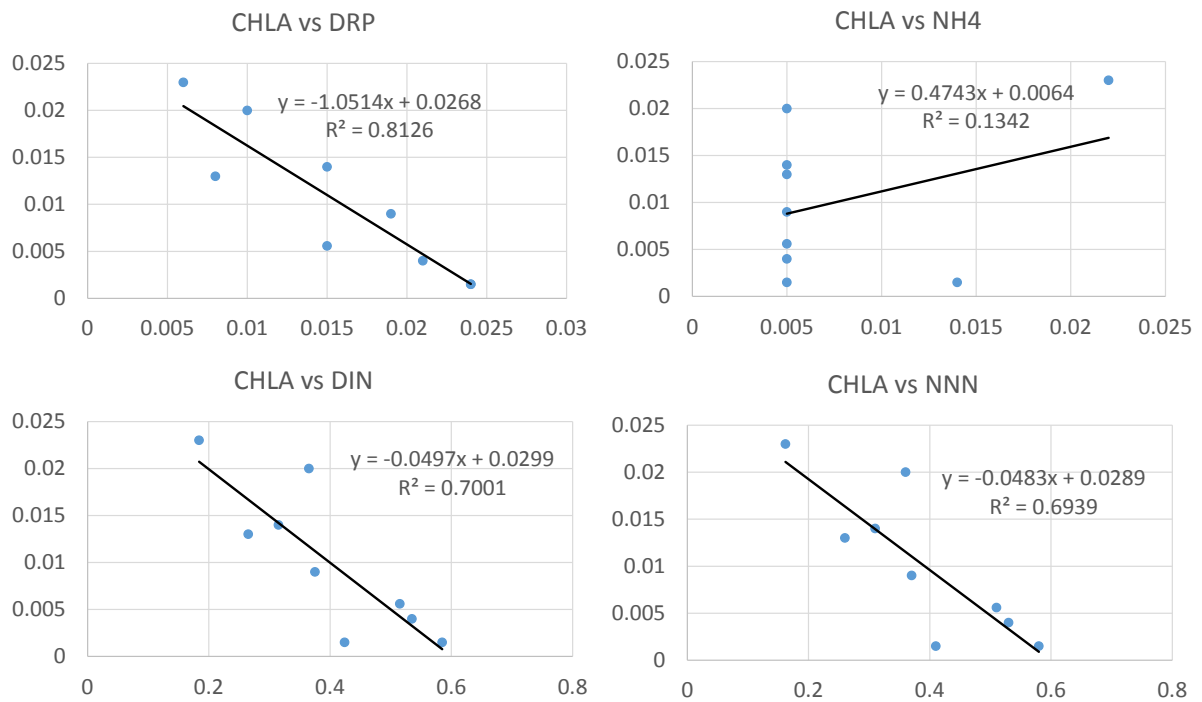


Fig. K6. Horotiu. Data were used only when TN:TP > 17. All data of 2006-2014.

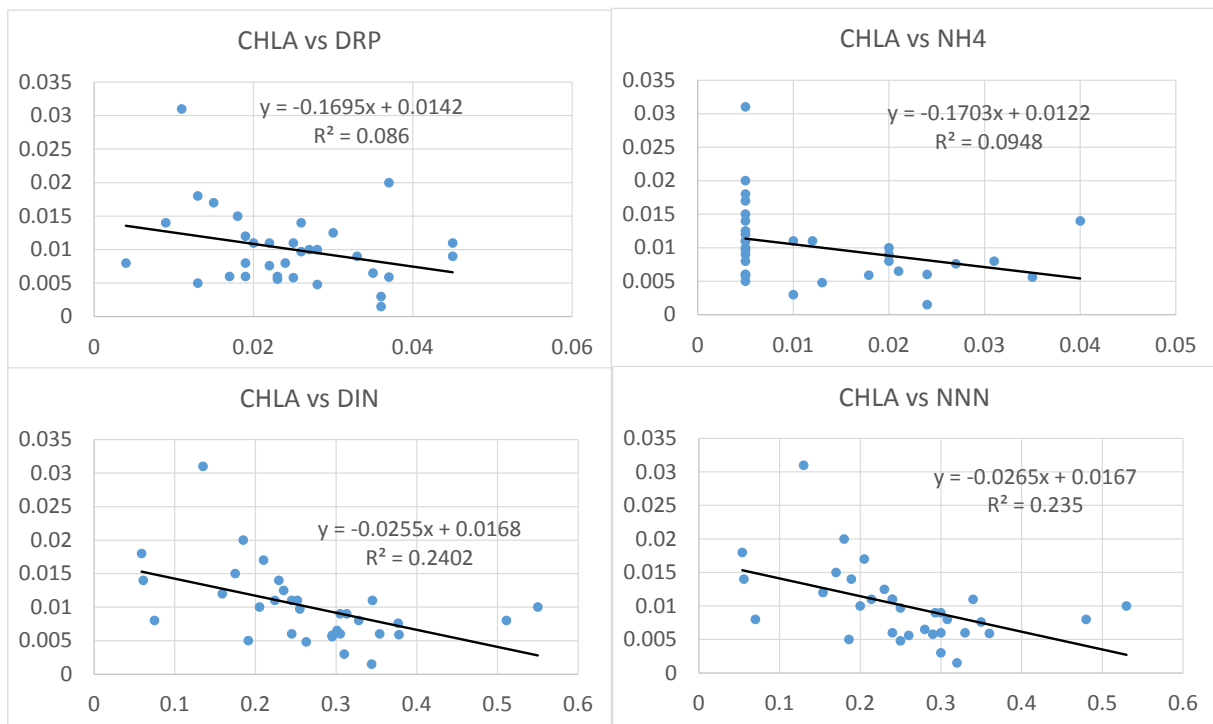


Fig. K7. Huntly. Data were used only when TN:TP < 10. All data of 2006-2014.

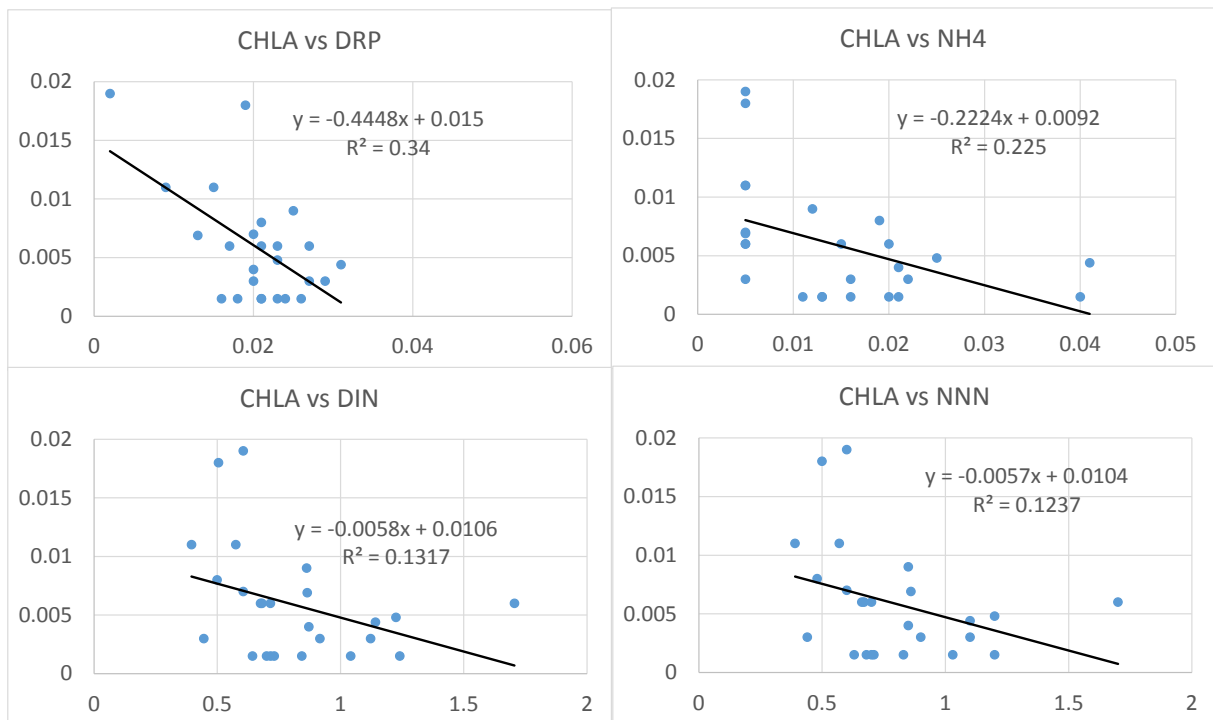


Fig. K8. Huntly. Data were used only when TN:TP > 17. All data of 2006-2014.

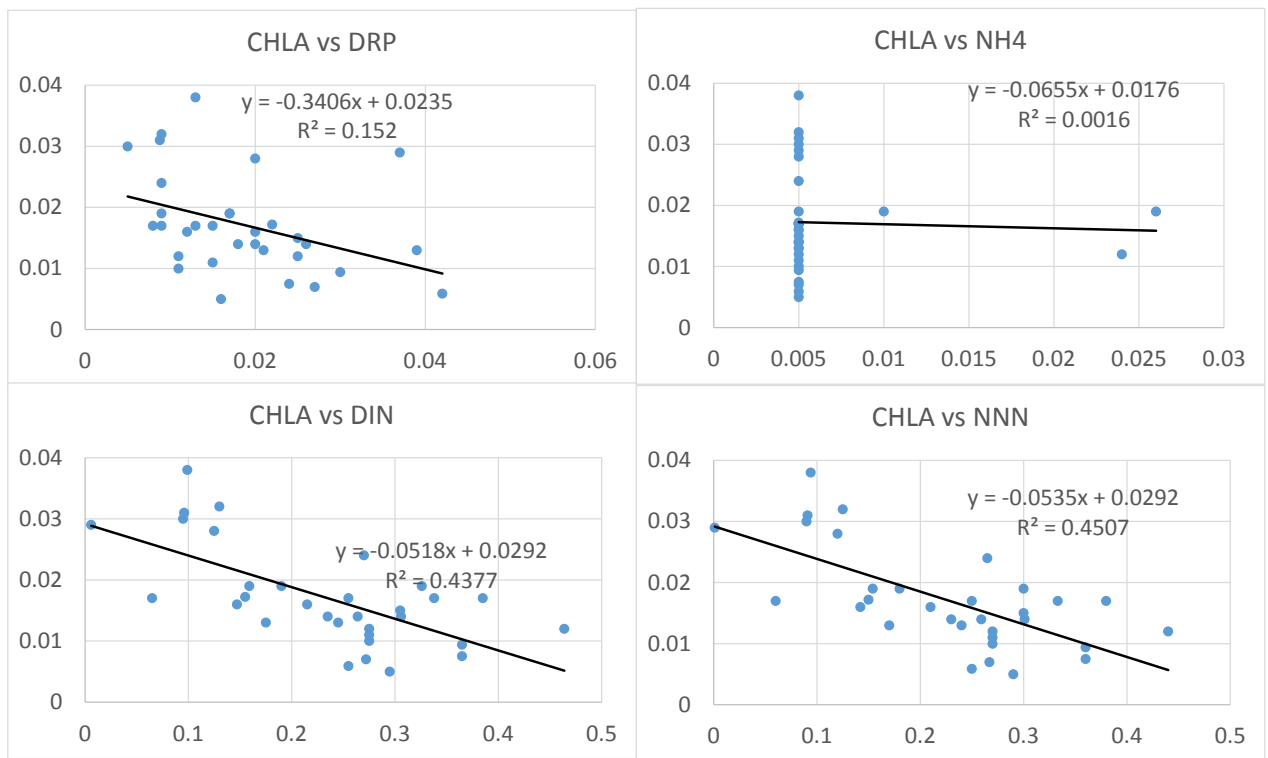


Fig. K9. Mercer. Data were used only when TN:TP < 10. All data of 2006-2014.

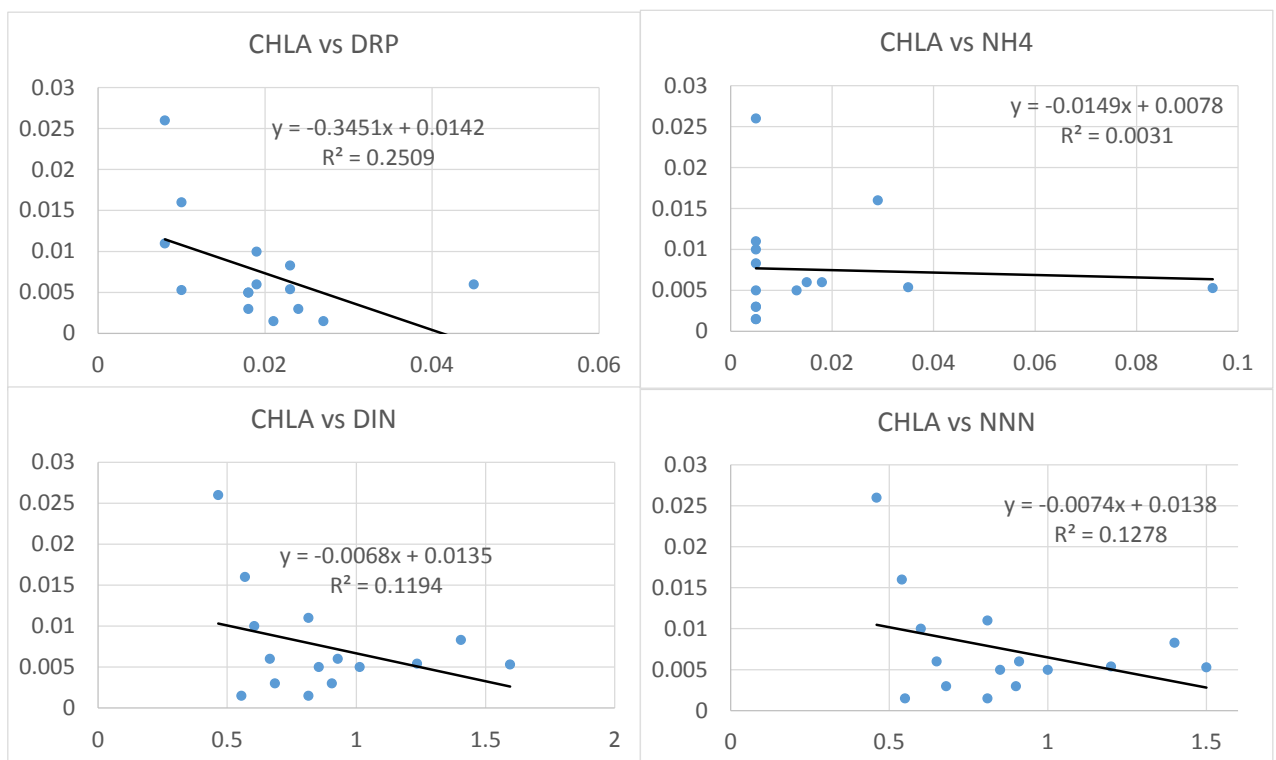


Fig. K10. Mercer. Data were used only when TN:TP > 17. All data of 2006-2014.

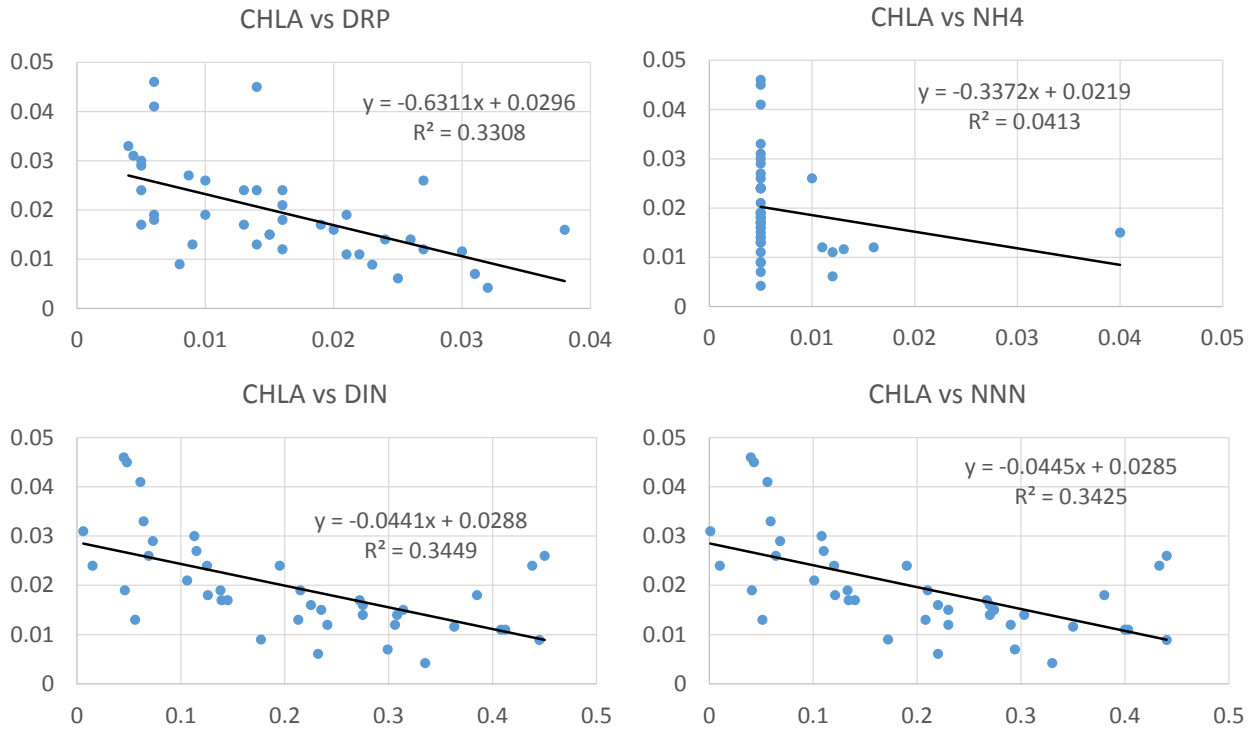


Fig. K10. Tuakau. Data were used only when TN:TP < 10. All data of 2006-2014.

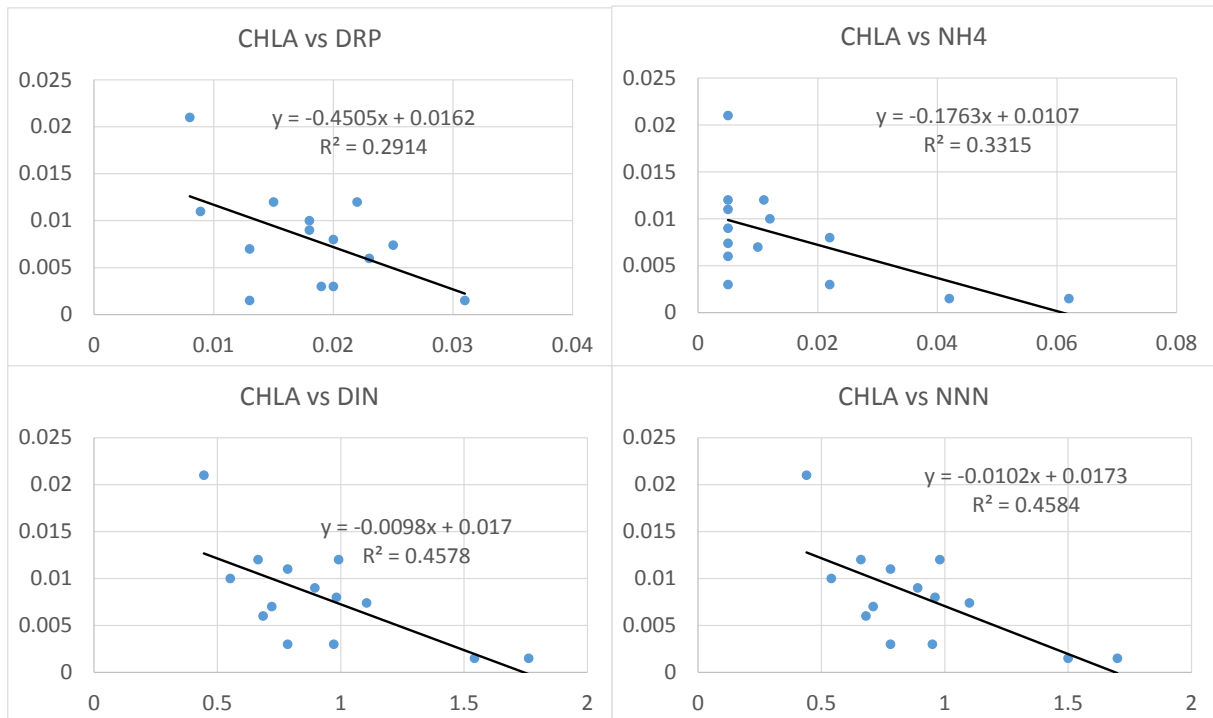


Fig. K11. Tuakau. Data were used only when TN:TP > 17. All data of 2006-2014.

## Appendix L TN versus TP

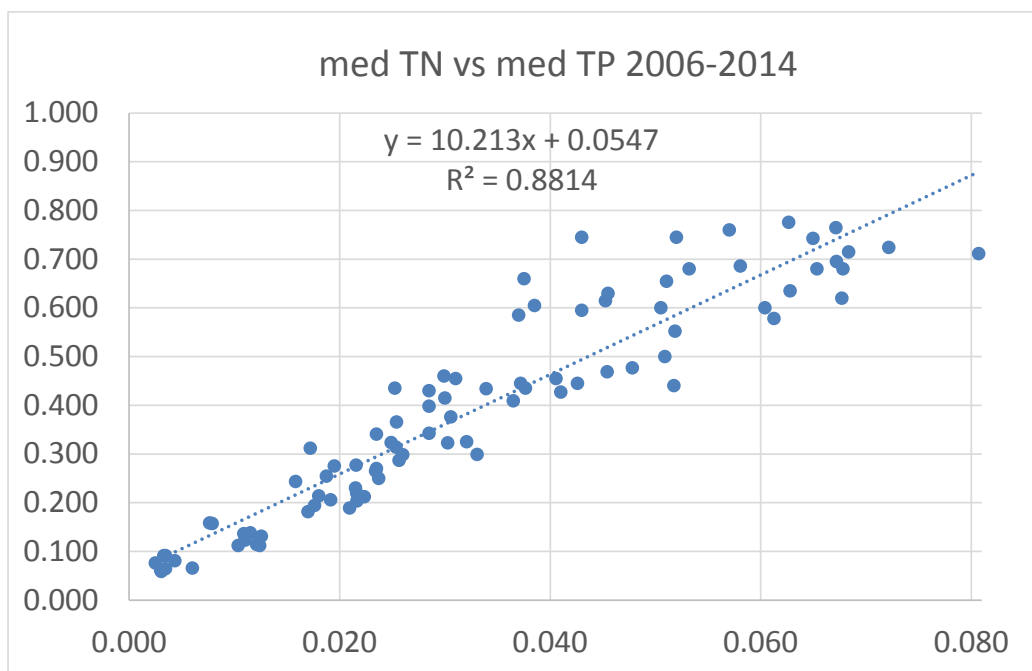


Fig. L1. Median TN against median TP for each year and station, all data of 2006-2014.

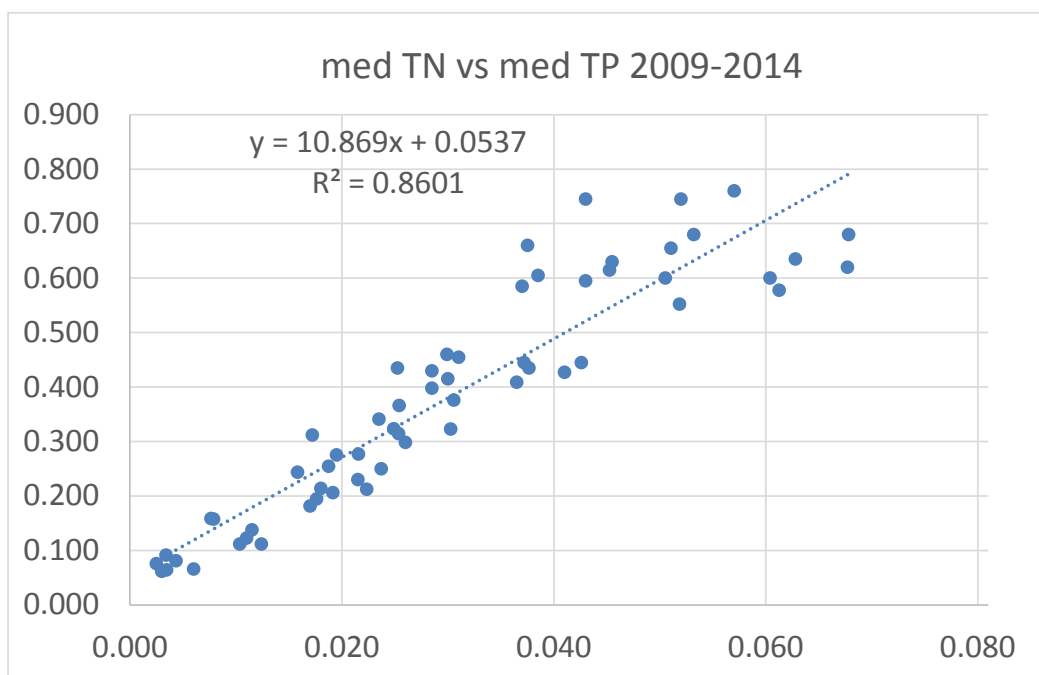


Fig. L2. Median TN against median TP for each year and station, all data of 2009-2014.

## Appendix M Nutrient conditions when chlorophyll *a* is high



Fig. M1. Top left: Minimum, maximum and 95<sup>th</sup> percentile of chlorophyll *a*. The remaining panels show mean nutrient concentrations when chlorophyll *a* > 95<sup>th</sup> percentile ( $n = 6$  to  $7$ , data 2006-2014). Taupo Gates and Ohaaki not included because 100% of chlorophyll *a* data were below detection limit (37% of chlorophyll *a* data of Ohakuri were below the detection limit).

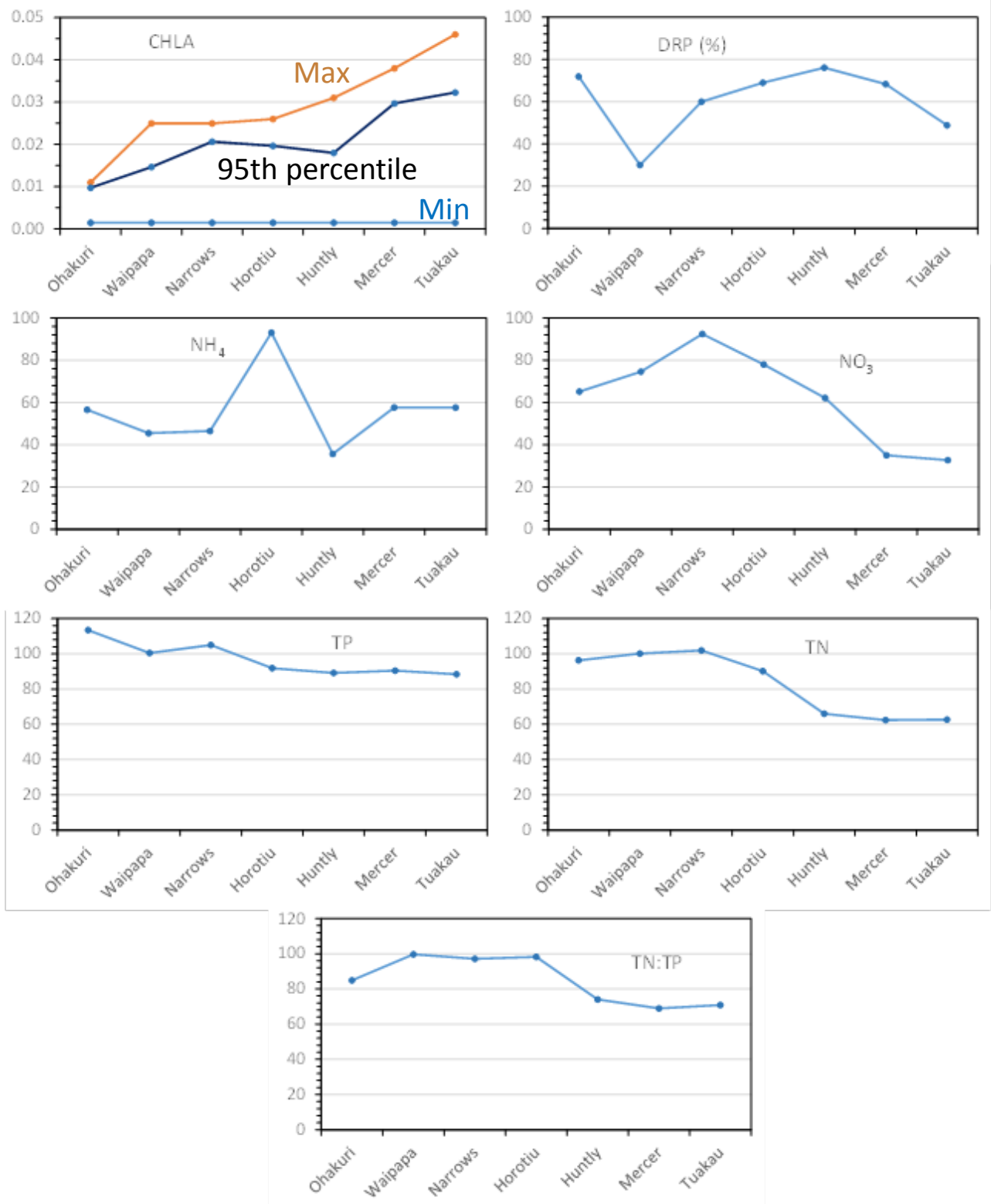


Fig. M2. Nutrient concentrations when chlorophyll *a* is above the 95th percentile, as a % of the mean ( $n = 6$  to  $7$ , data 2006-2014).

## Appendix N Frequency distributions of potential growth limiting conditions

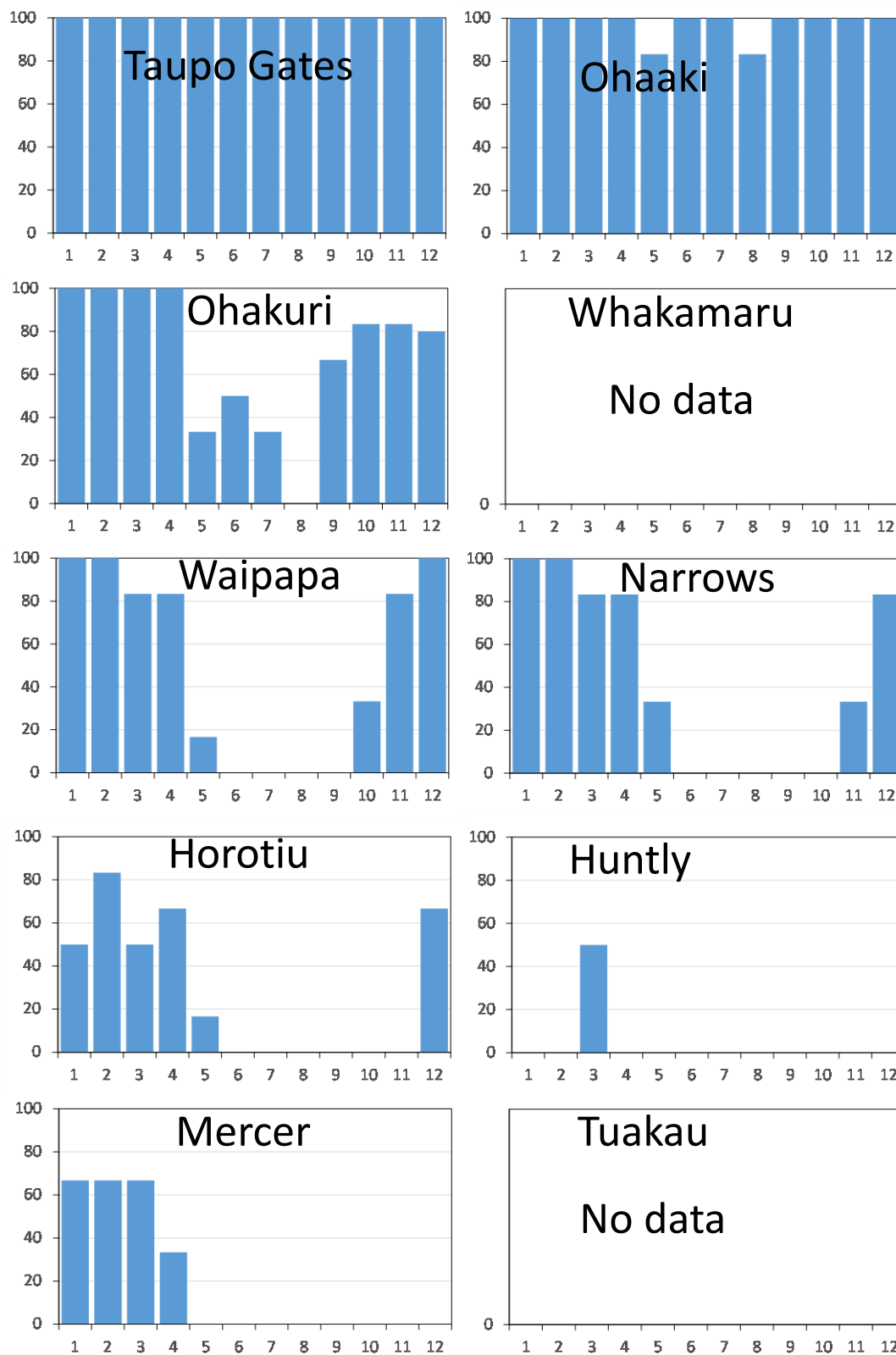


Fig. N1A. Frequency distributions of occurrence of  $\text{NO}_3 < 0.09 \text{ mg L}^{-1}$  by station and month (1990-1995).



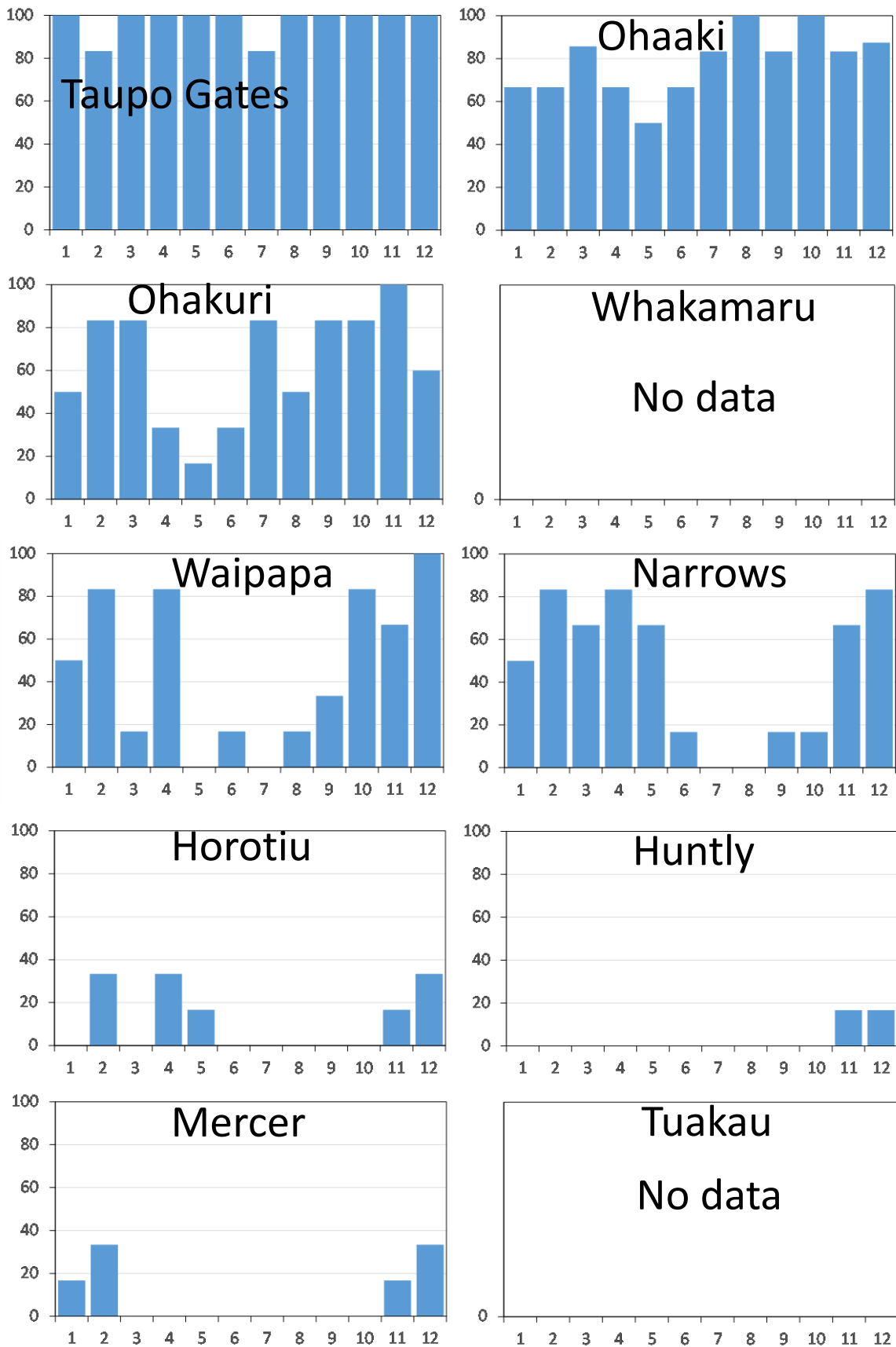


Fig. N1B. Frequency distributions of occurrence of DRP  $<0.012 \text{ mg L}^{-1}$  by station and month (1990-1995).

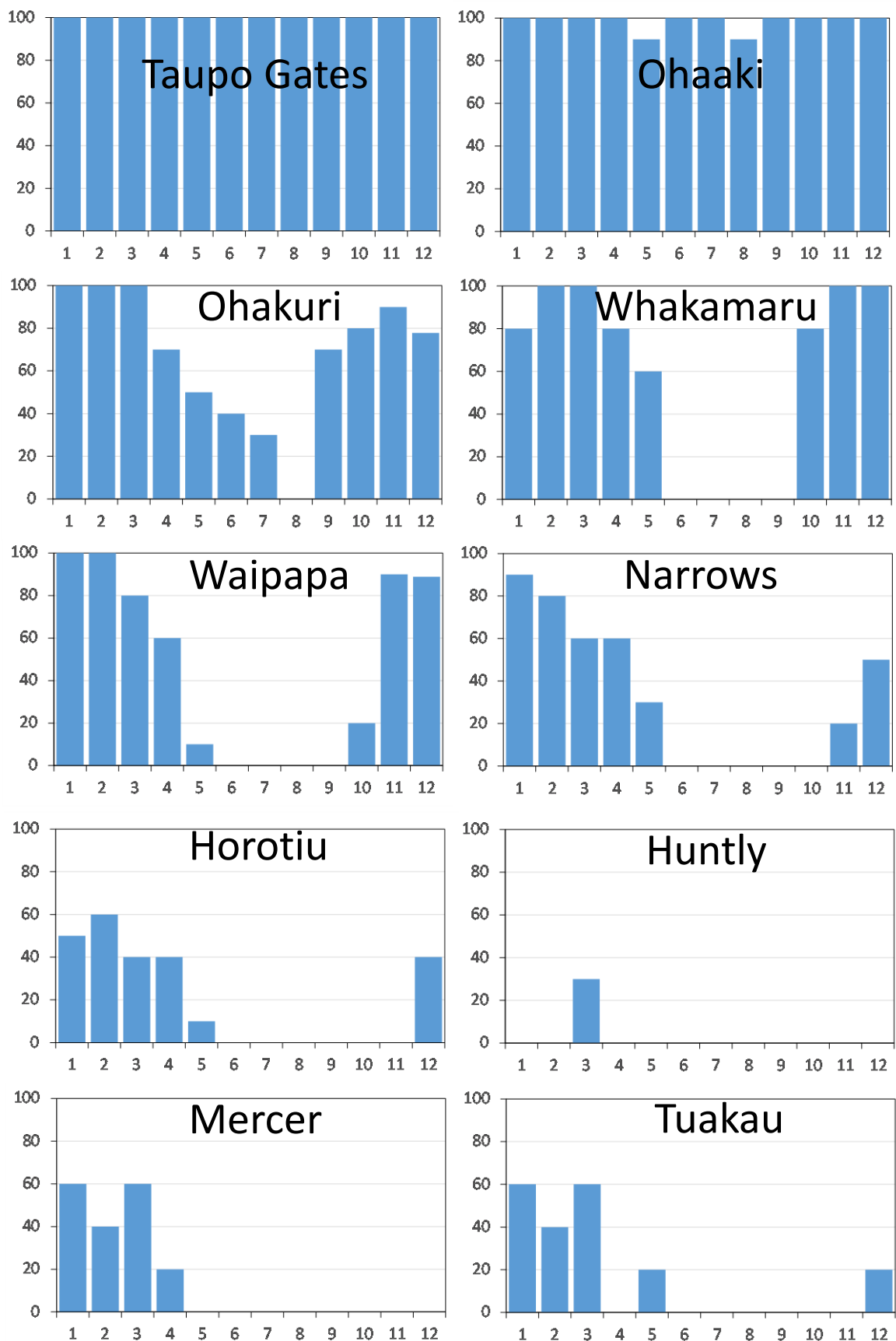


Fig. N1C. Frequency distributions of occurrence of  $\text{NO}_3^- < 0.09 \text{ mg L}^{-1}$  by station and month (1990-1999).

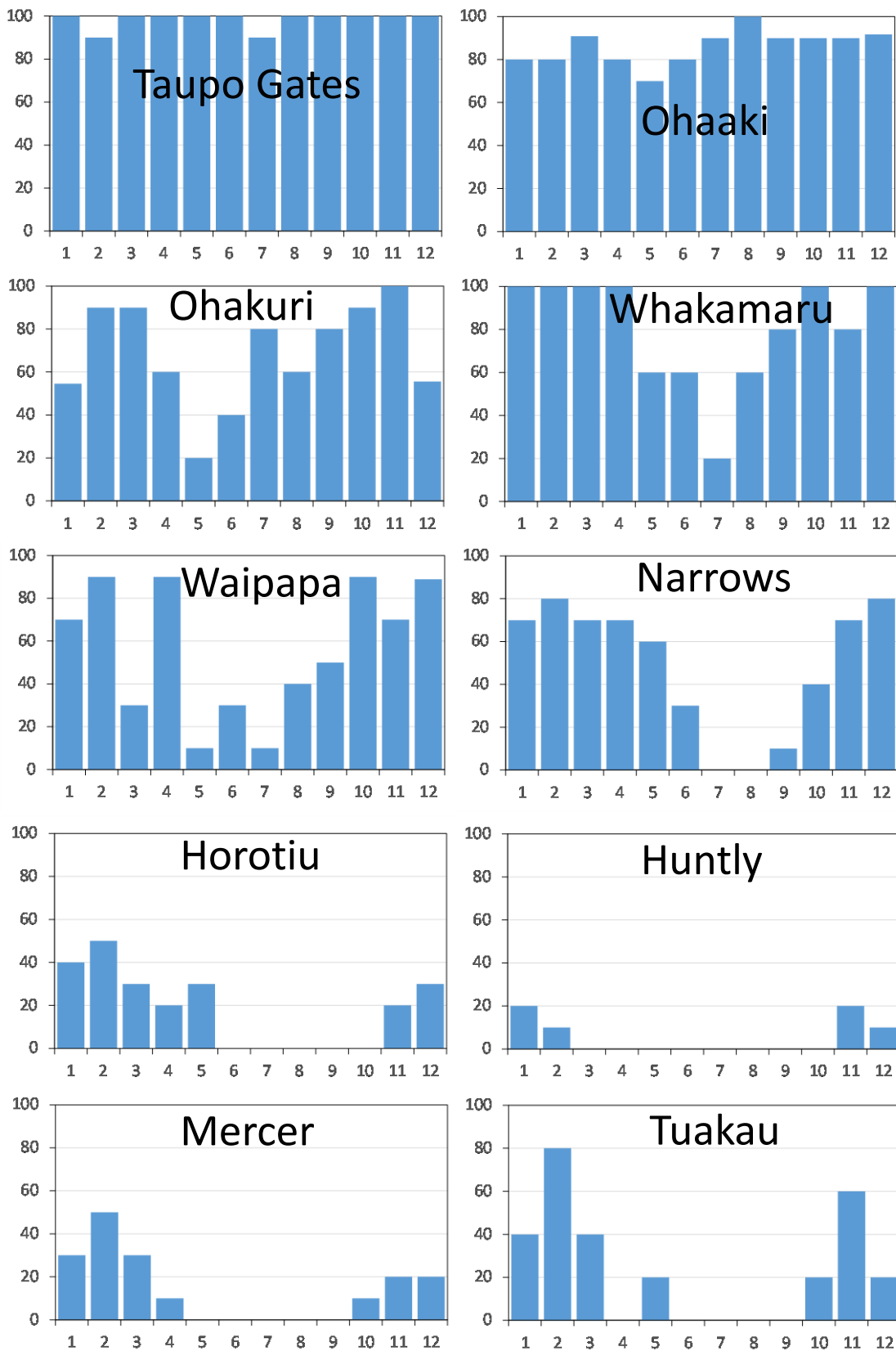


Fig. N1D. Frequency distributions of occurrence of DRP  $<0.012 \text{ mg L}^{-1}$  by station and month (1990-1999).

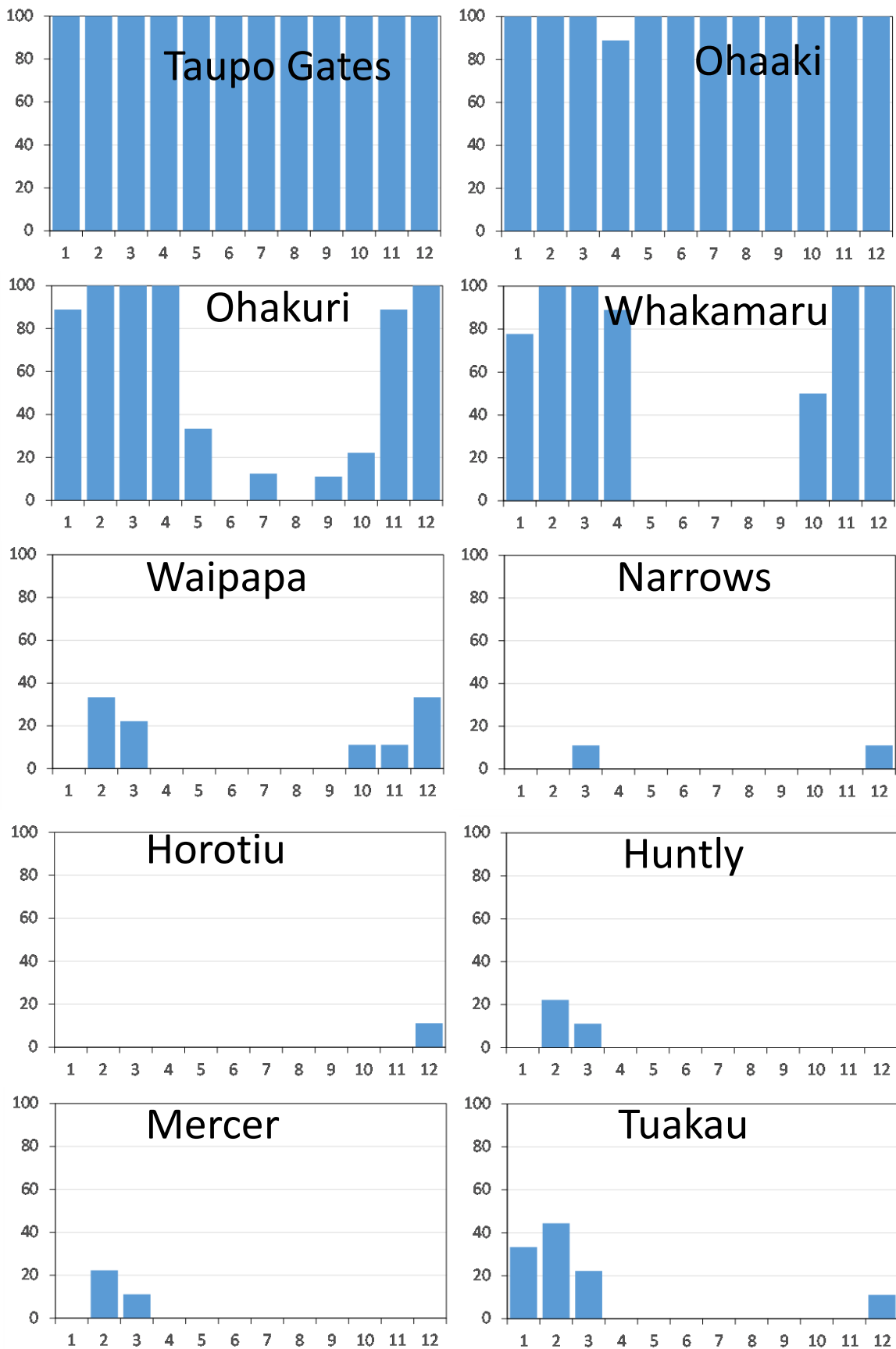


Fig. N1E. Frequency distributions of occurrence of  $\text{NO}_3^- < 0.09 \text{ mg L}^{-1}$  by station and month (2006-2014).

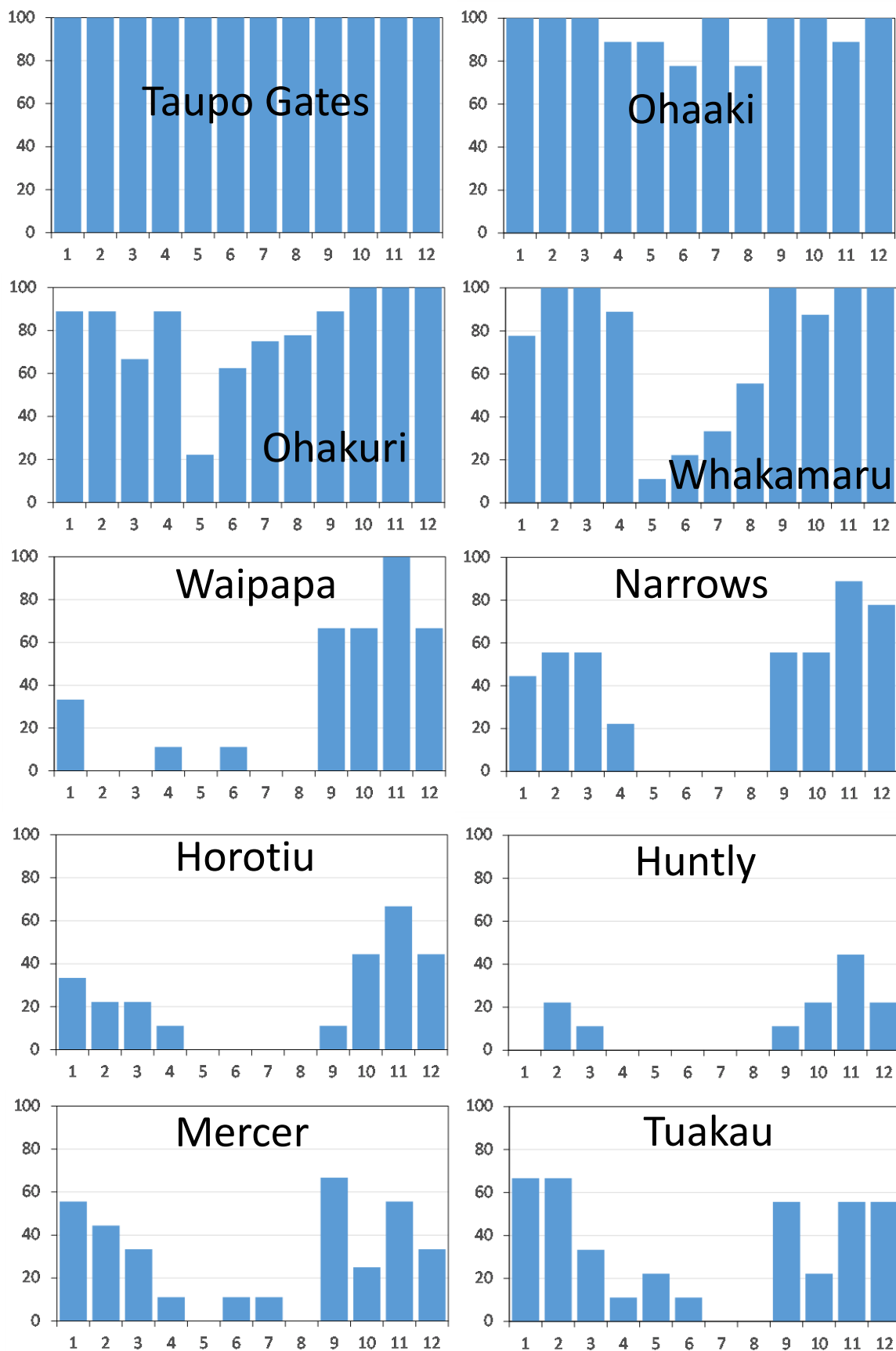


Fig. N1F. Frequency distributions of occurrence of DRP  $<0.012 \text{ mg L}^{-1}$  by station and month (2006-2014).

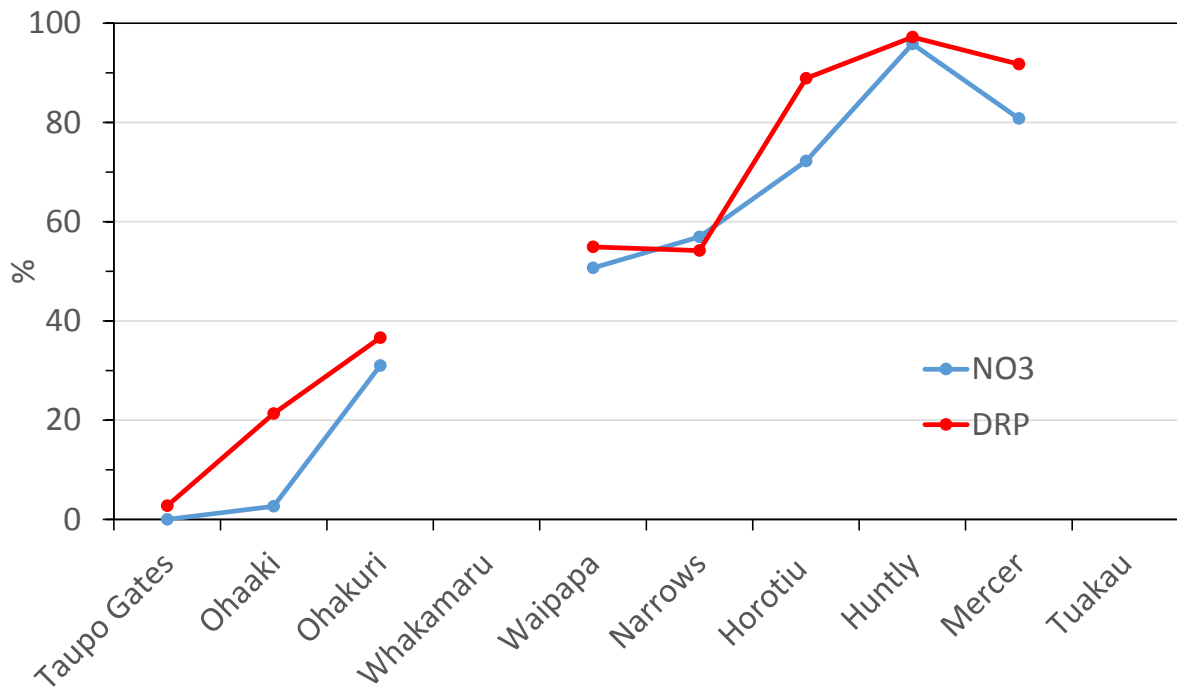


Fig. N2A. Percentage of NO<sub>3</sub> data >0.09 mg L<sup>-1</sup> and DRP data >0.012 mg L<sup>-1</sup> (1990-1995). A comparative indication of how the proportion of the data for which the effect of nutrient availability on algal growth rate was negligible changes between stations. See text for explanations and caveats.

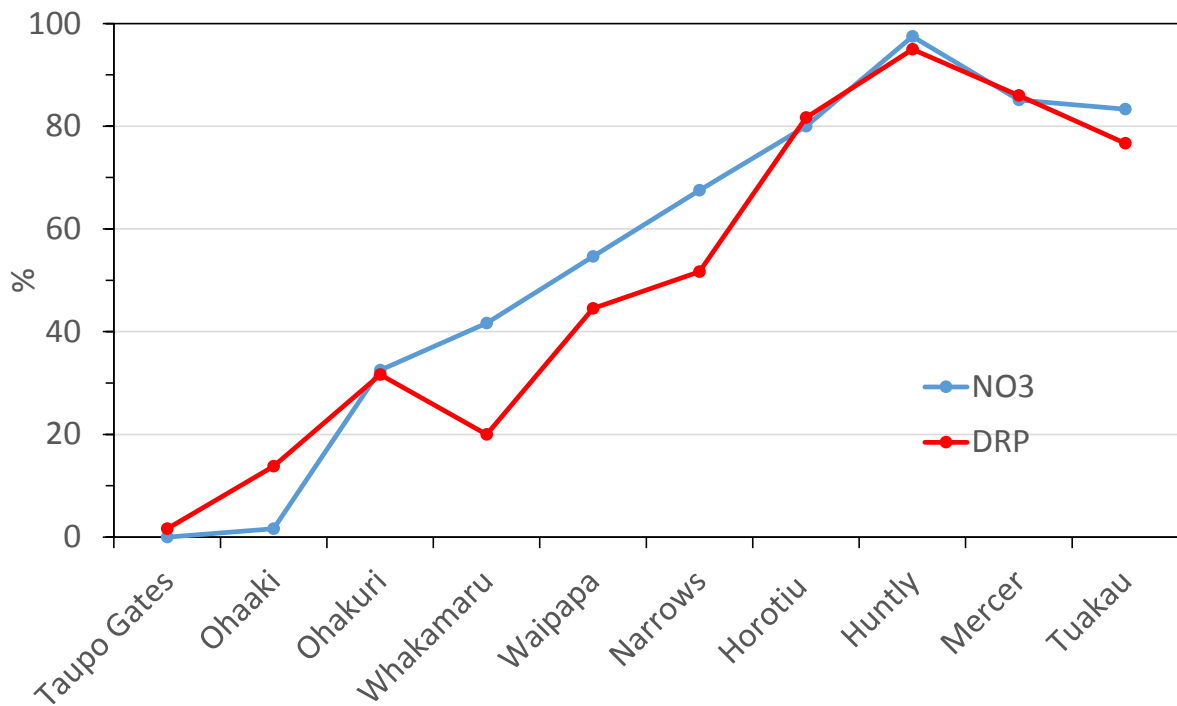


Fig. N2B. Percentage of NO<sub>3</sub> data >0.09 mg L<sup>-1</sup> and DRP data >0.012 mg L<sup>-1</sup> (1990-1999).

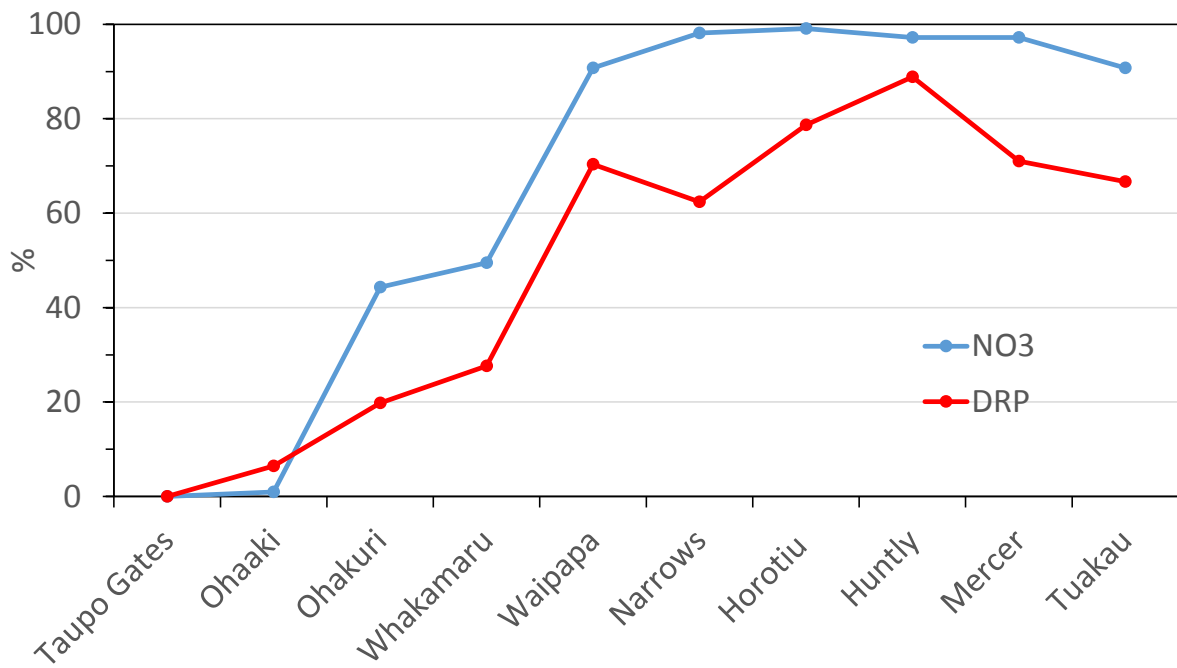


Fig. N2C. Percentage of NO<sub>3</sub> data >0.09 mg L<sup>-1</sup> and DRP data >0.012 mg L<sup>-1</sup> (2006-2014).

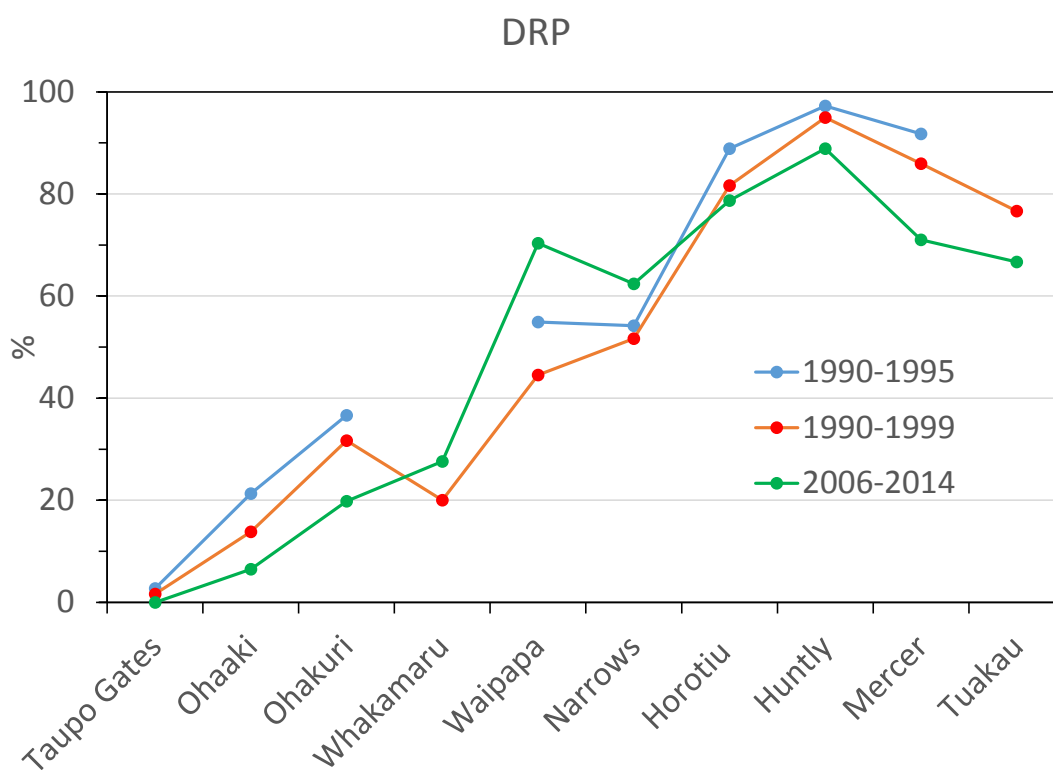
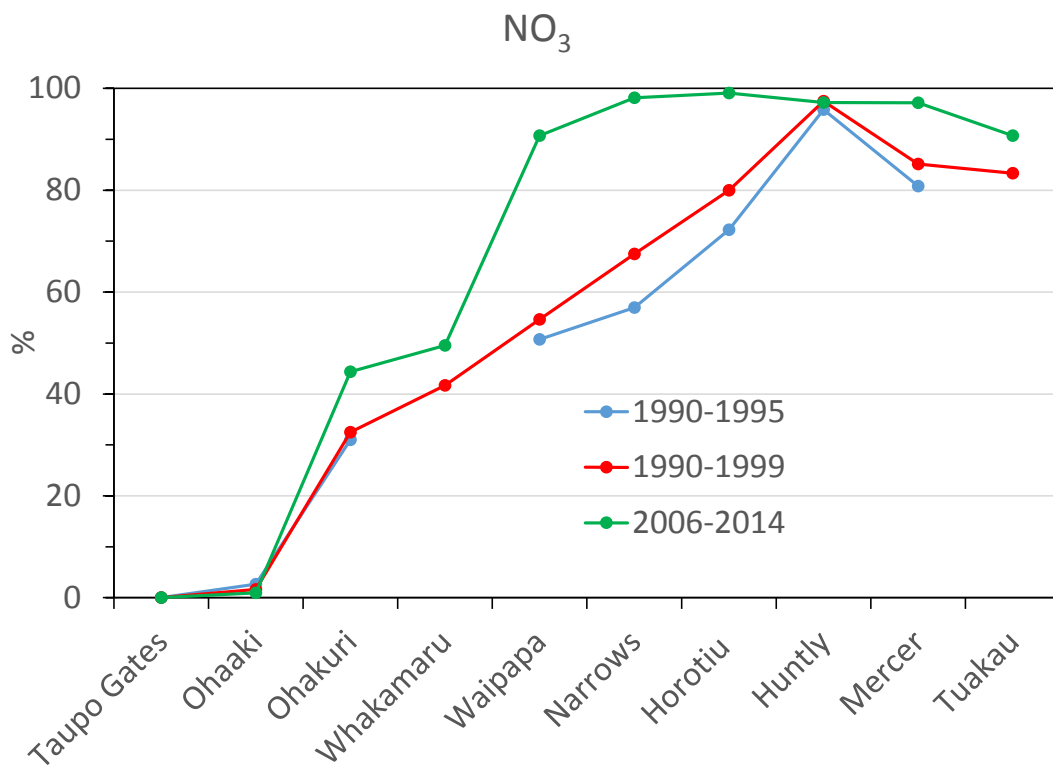


Fig. N2D. Comparisons between three time periods of the proportions of the  $\text{NO}_3$  data  $>0.09 \text{ mg L}^{-1}$  and  $\text{DRP}$  data  $>0.012 \text{ mg L}^{-1}$ .



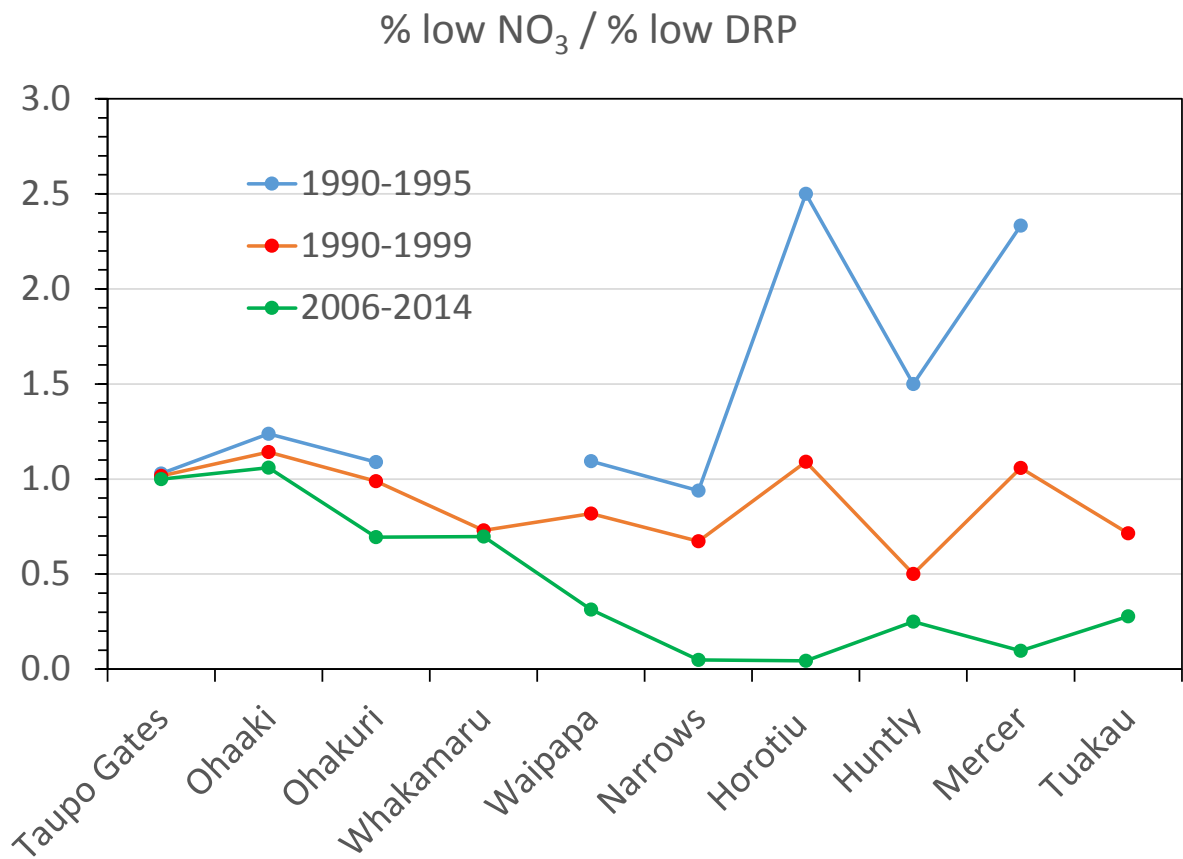


Fig. N2E. The ratio of the proportions of the NO<sub>3</sub> data <0.09 mg L<sup>-1</sup> and DRP data <0.012 mg L<sup>-1</sup>.

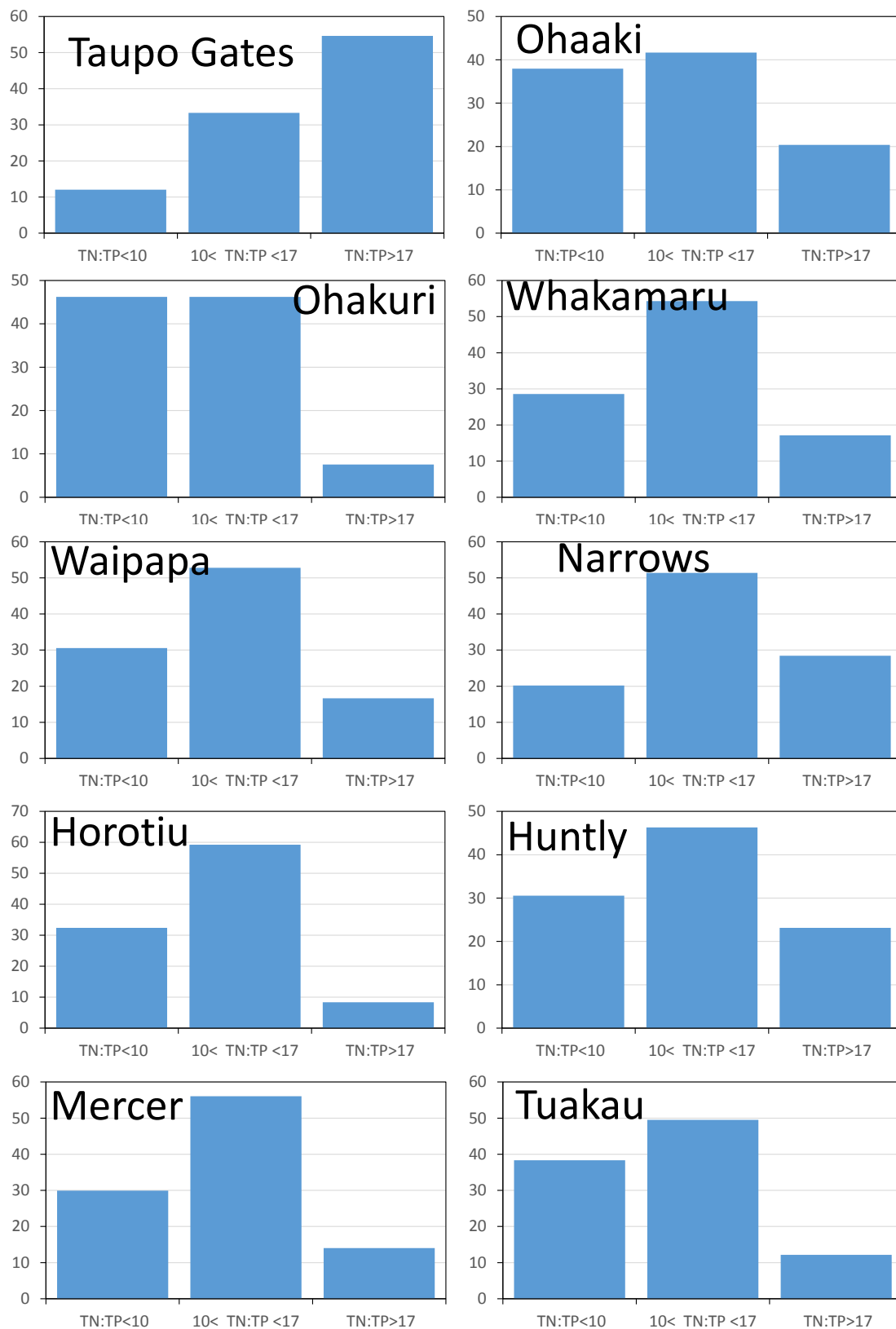


Fig. N3. Percentages of occurrence of three brackets of TN:TP ratios, by station (2006-2014).

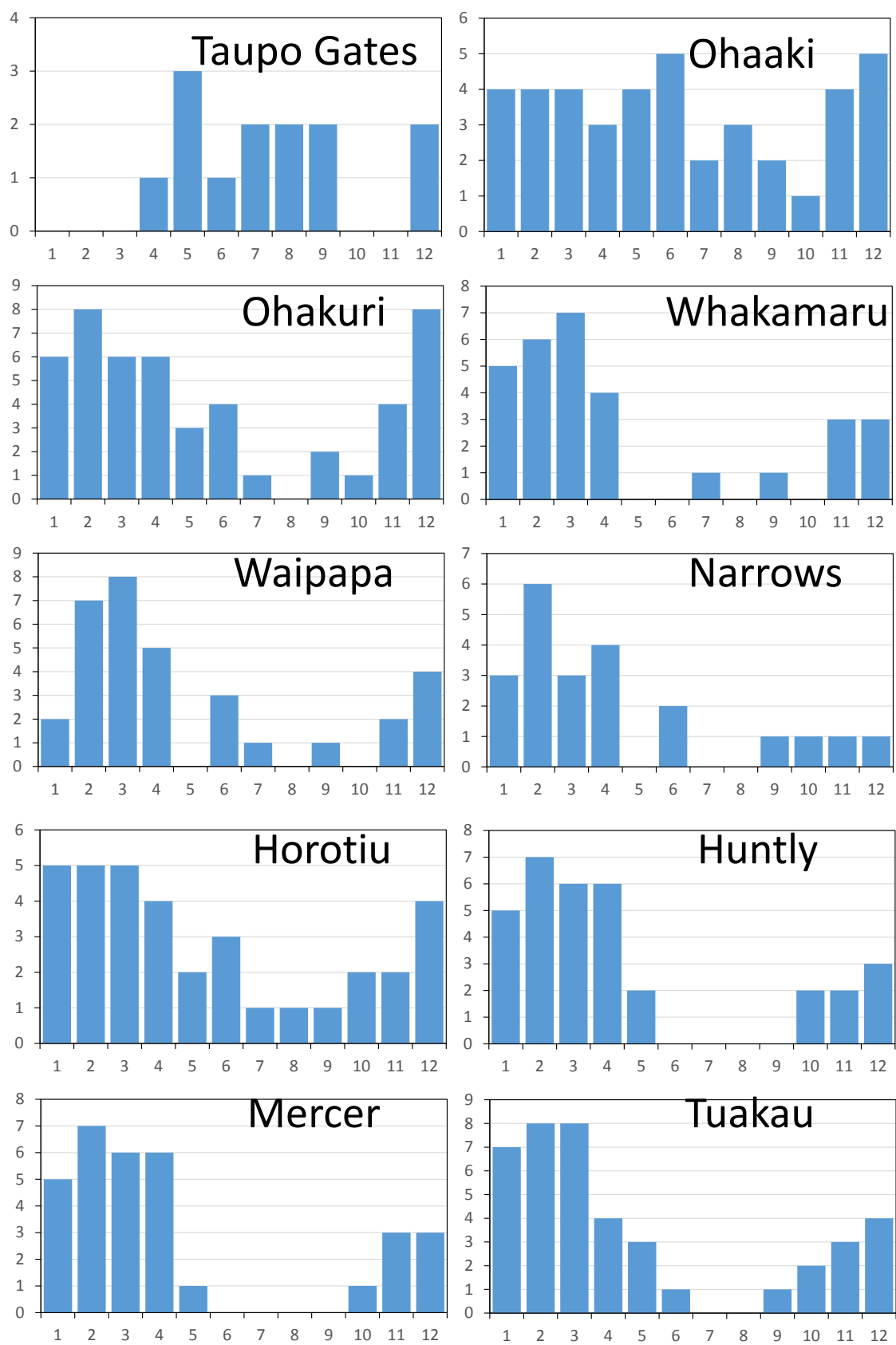


Fig. N4. Frequency distributions of TN:TP < 10, by station and by month (2006-2014).

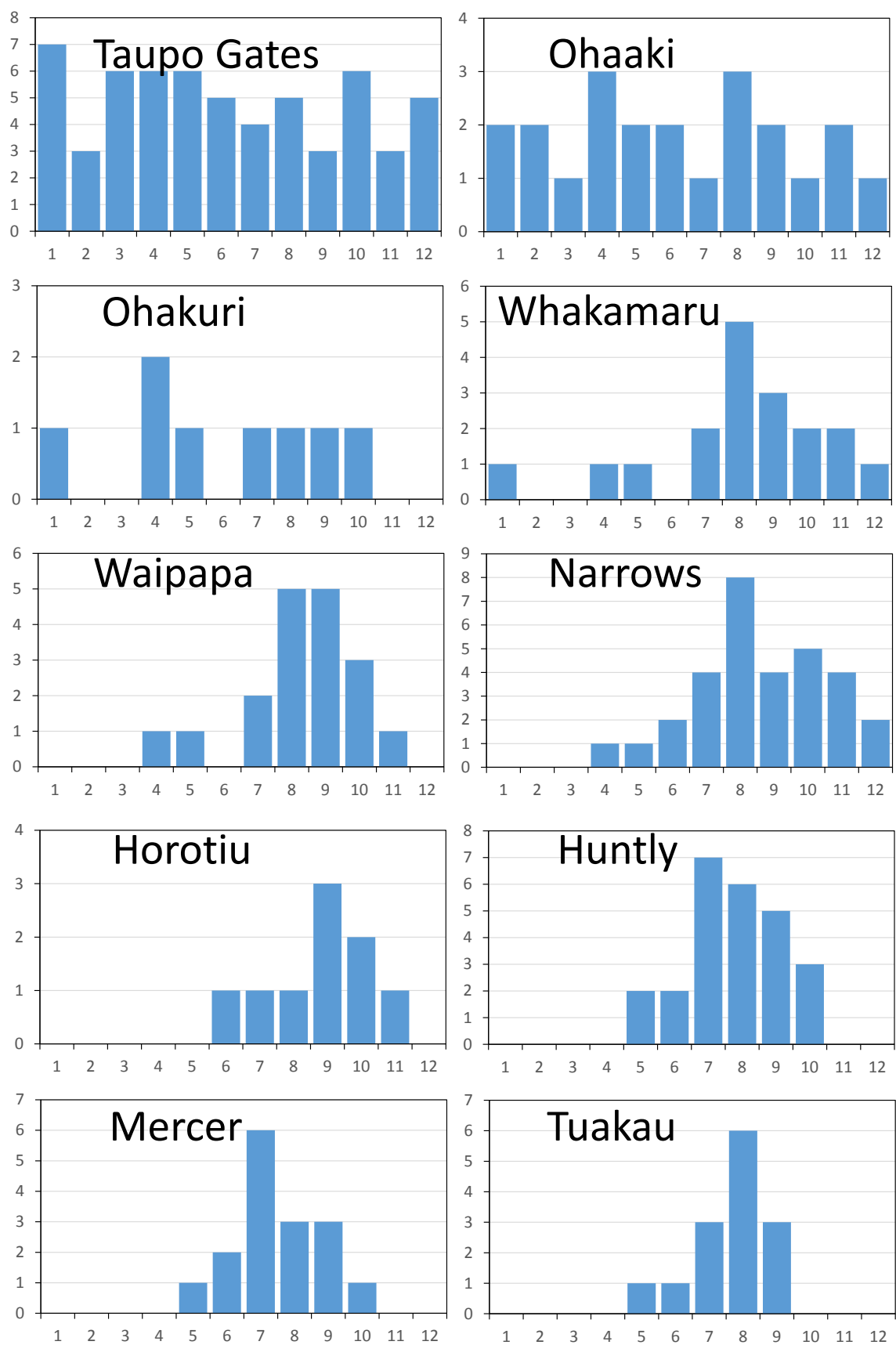


Fig. N5. Frequency distributions of TN:TP > 17, by station and by month (2006-2014).

## Appendix O Proportions of dissolved and particulate nutrients

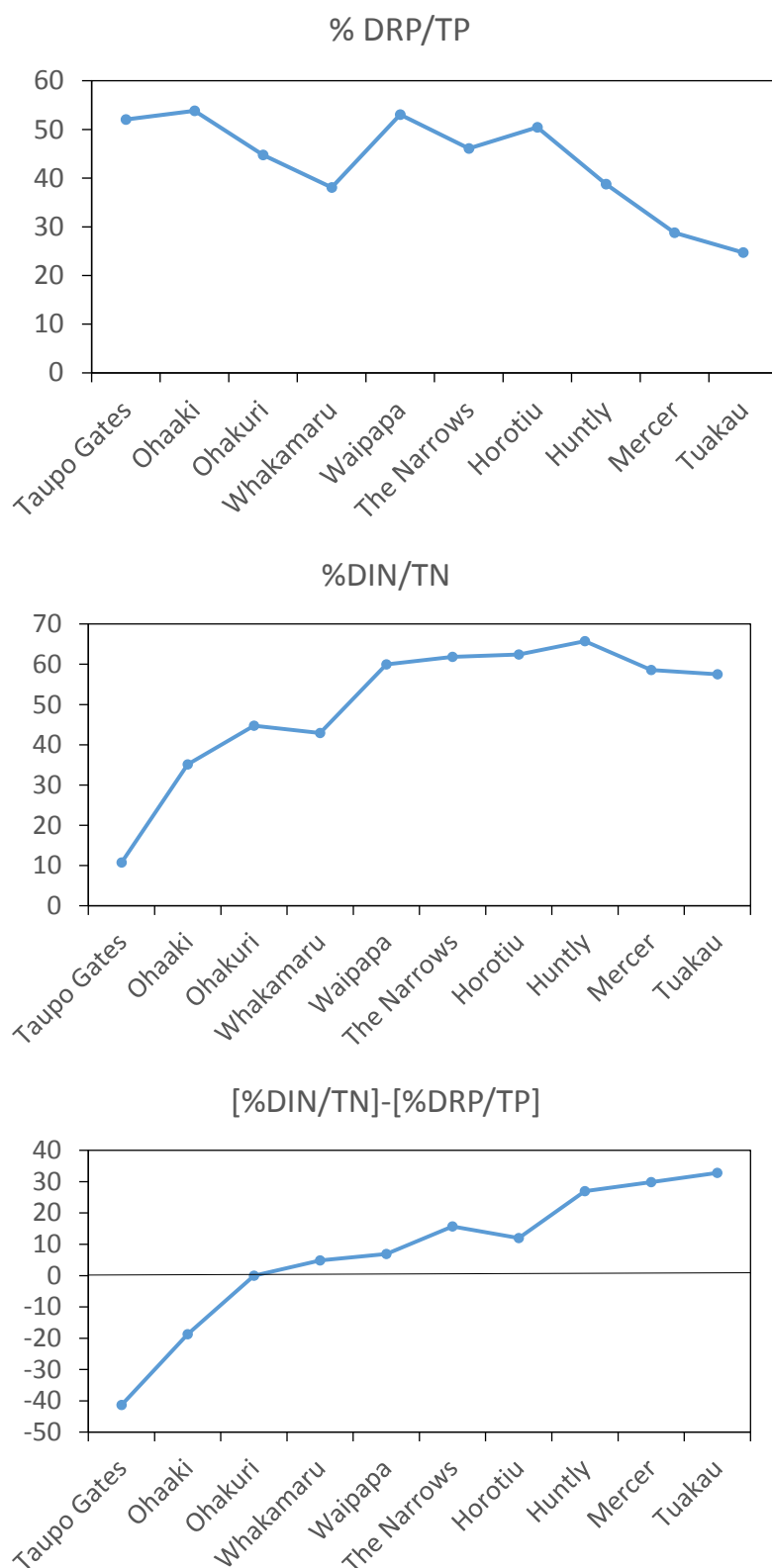


Fig. O1. Mean dissolved inorganic nutrients as a proportion of total nutrients (top two panels), by station, and the difference between the proportions of DIN and DRP (bottom panel) .Data of 2006-2014.

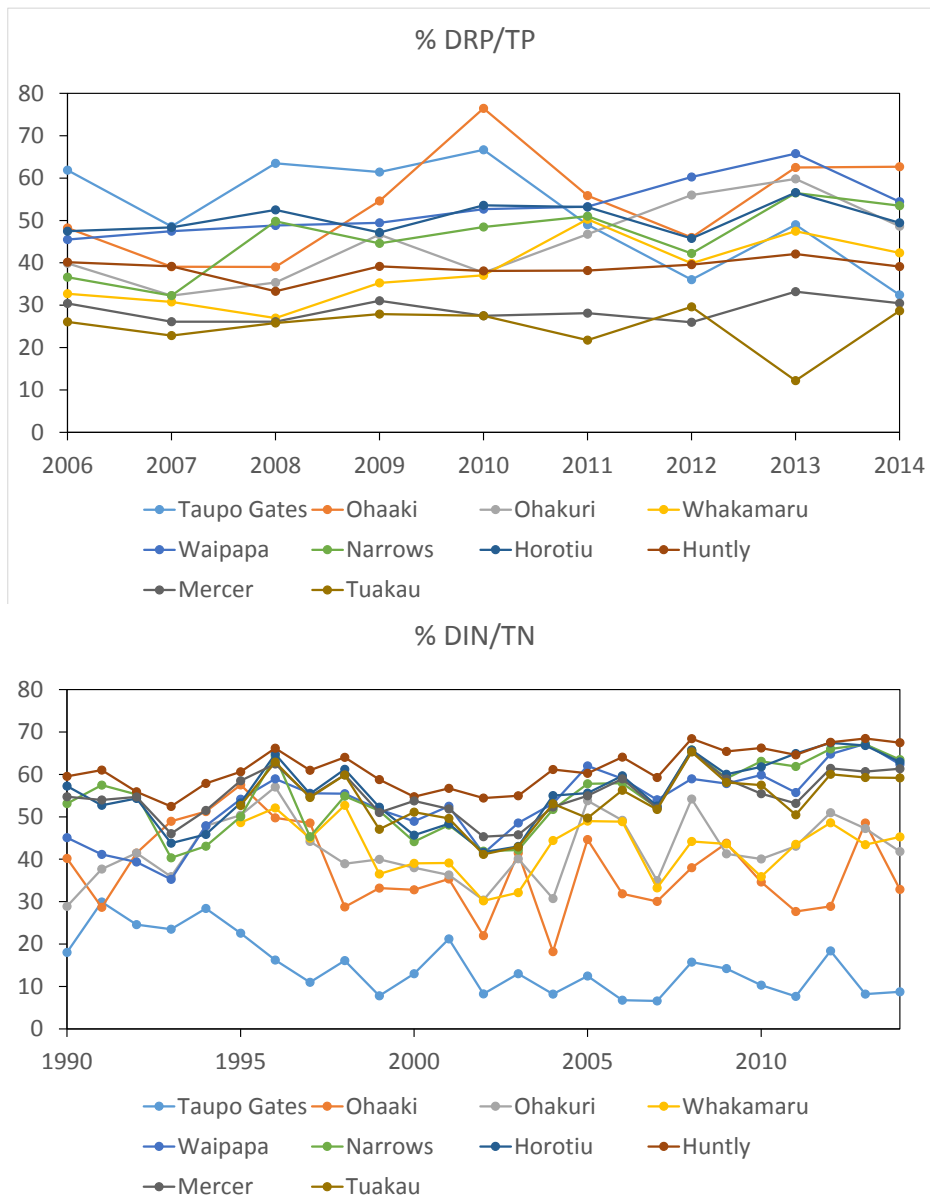


Fig. O2. Time series of dissolved inorganic nutrients as a proportion of total nutrients. Note shorter time scale for DRP.

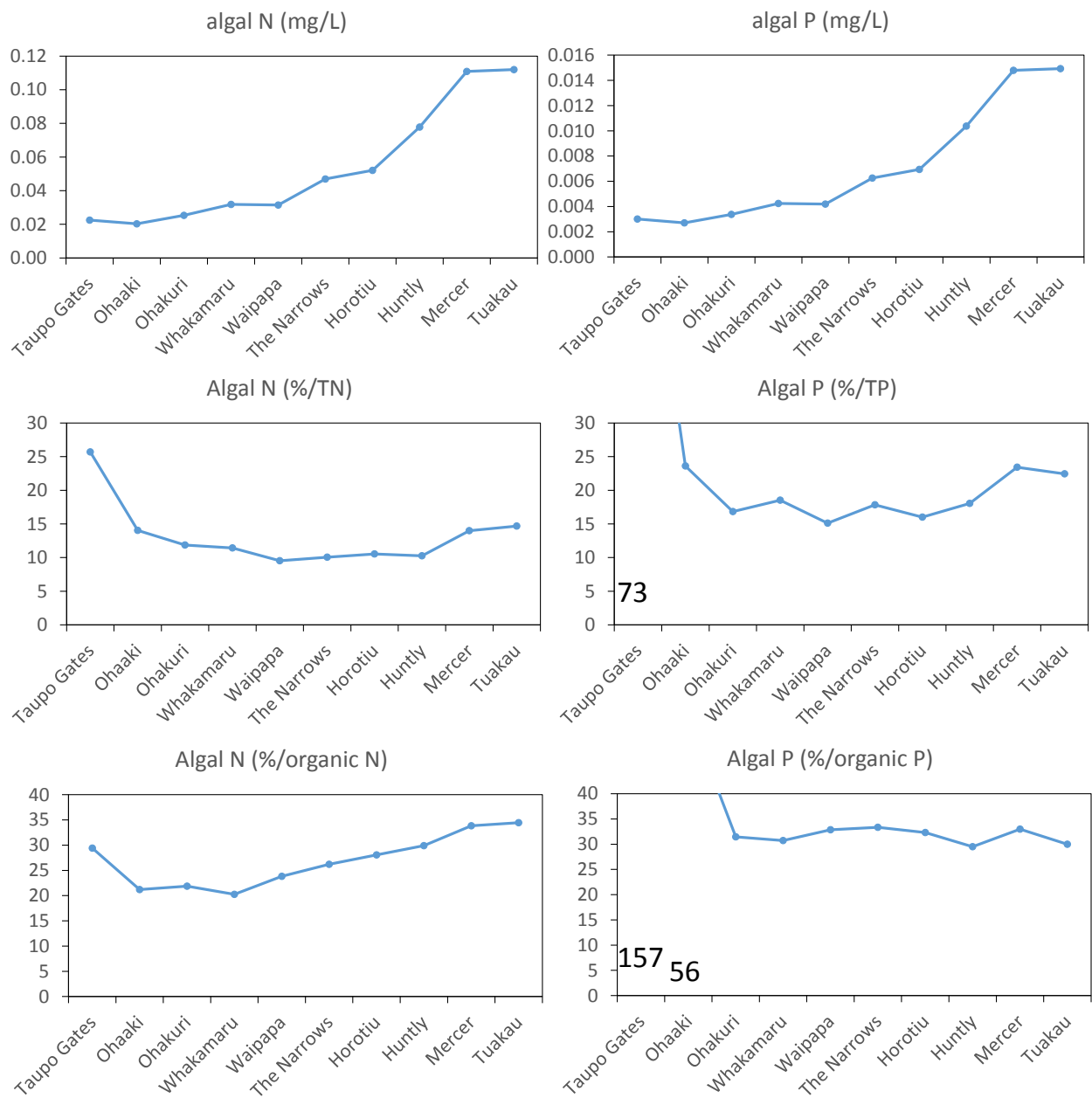


Fig. O3. Particulate nutrients, presumably mostly contained in algal cells, in absolute amounts and as proportions of total nutrients and of organic nutrients. Data of 2006-2014. Percentages of algal P:TP and algal P:organic P at Taupo Gates and Ohaaki that were considered unreliable are given in the plots. See text for explanations (section 3.9).

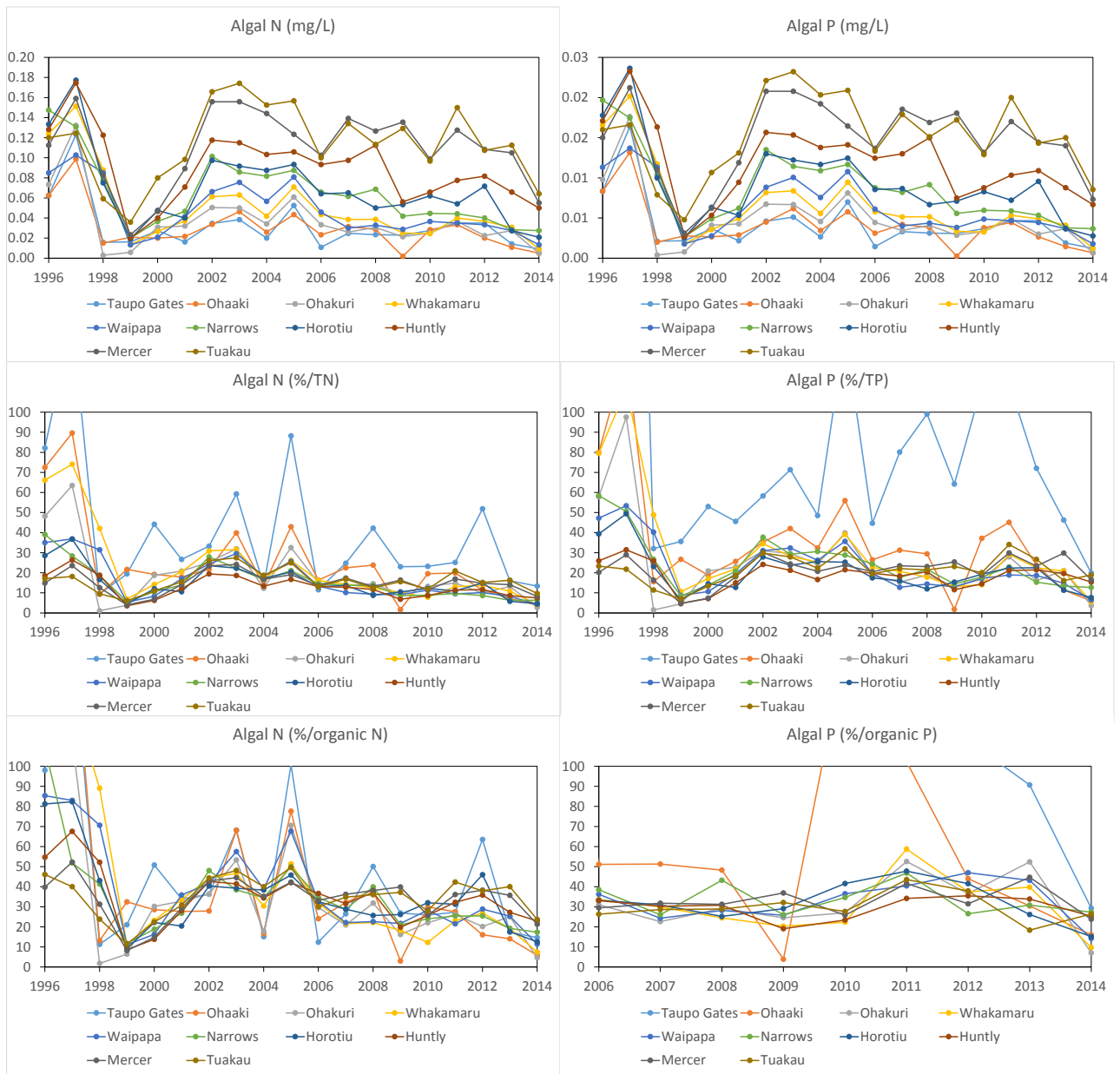


Fig. O4. Time series of particulate nutrients, presumably mostly contained in algal cells, in absolute amounts and as proportions of total nutrients and of organic nutrients. Note different time scales for algal P as a proportion of organic P, because of unreliability of DRP before 2006, from which organic P was estimated by difference with TP.



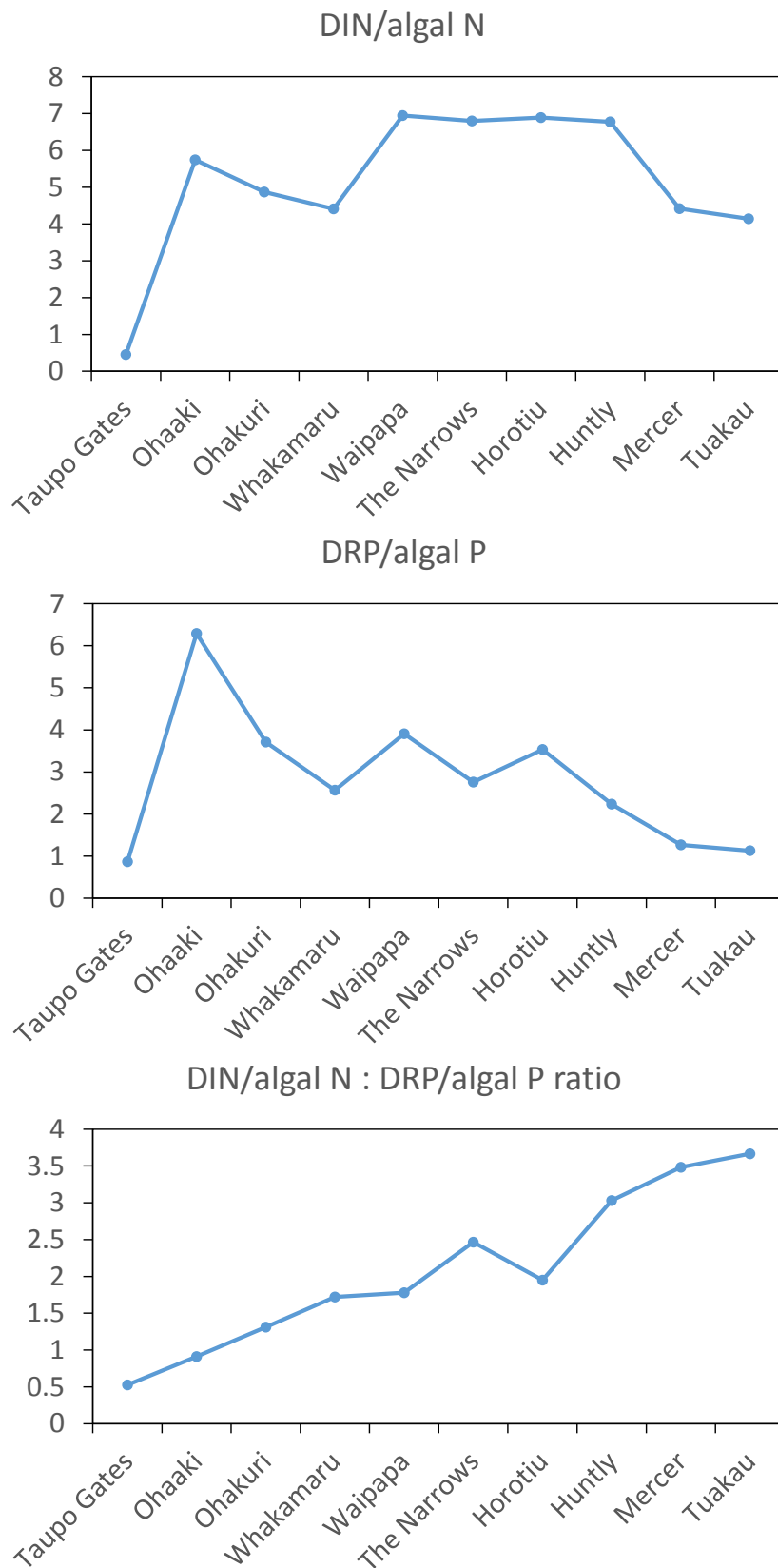


Fig. O5. The amounts of inorganic dissolved nutrients available to algae, relative to nutrients contained in algal cells, and the ratio of these amounts for nitrogen and phosphorus. Data of 2006-2014.

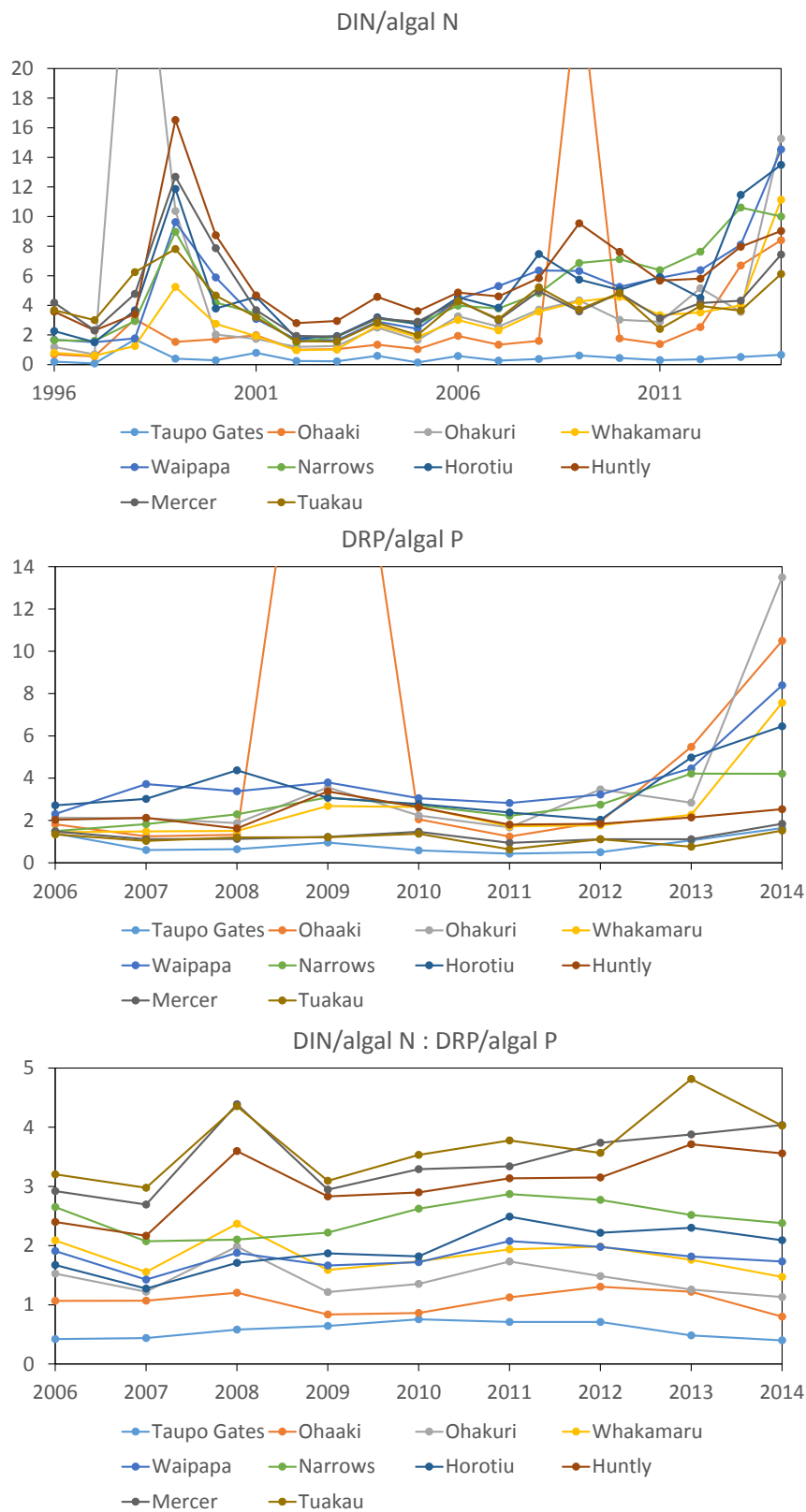


Fig. O6. Time series of availability of dissolved inorganic nutrients, relative to algal N and algal P. Bottom panel: the ratio of the values in the top two panels.

Appendix P National Objectives Framework Numeric Attribute States and relationships between chlorophyll *a* and nutrients in the Waikato River

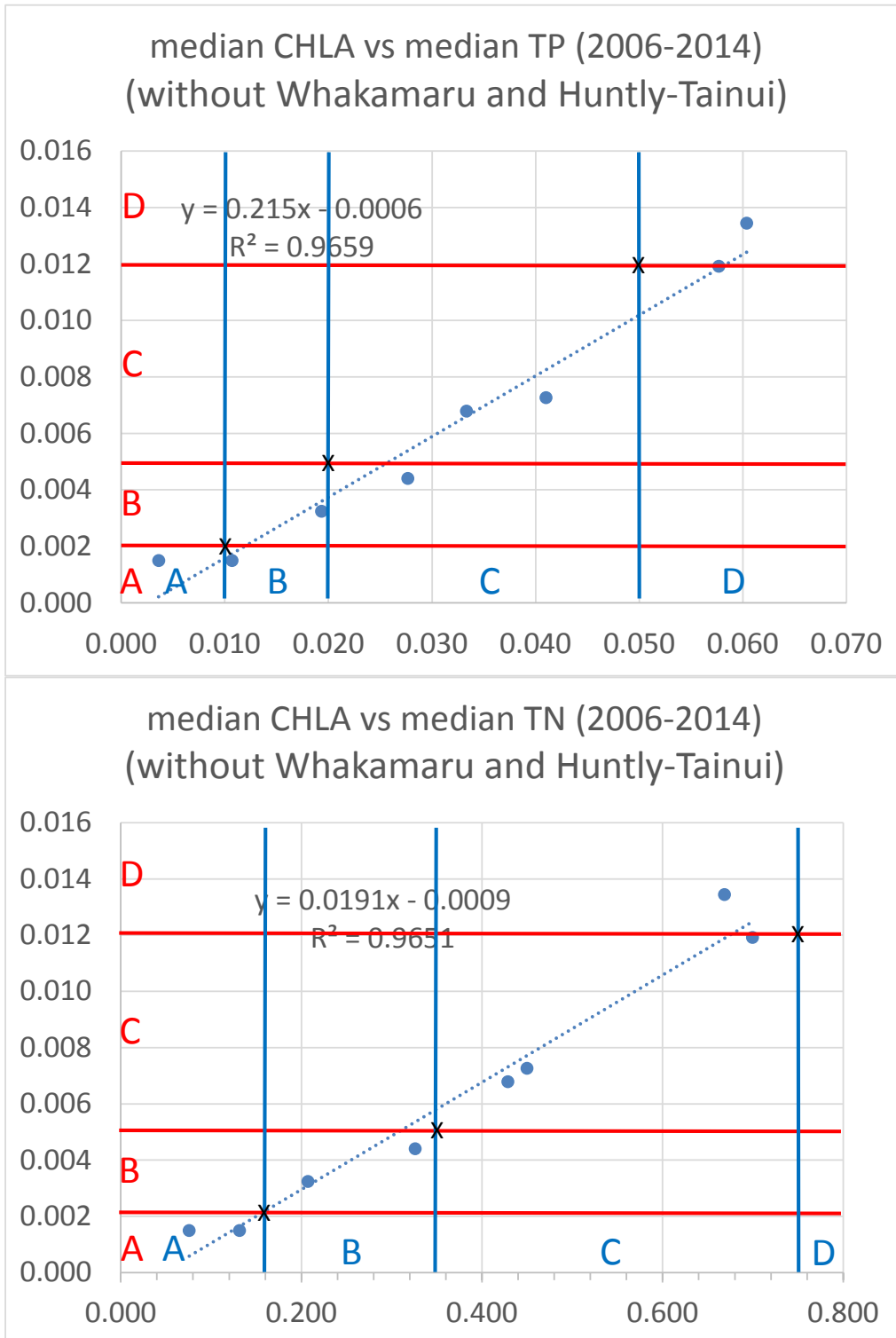


Fig. P1. Boundaries of Attribute States A, B, C and D for chlorophyll *a* (red bars) and TP (top) or TN (bottom) in stratified lakes (blue bars for nutrients), superimposed on the regression of chlorophyll *a* against TP and TN. Annual medians of each station, 2006-2014. X indicates where the boundaries of Attribute States for chlorophyll *a* and TN or TP would be expected to meet.

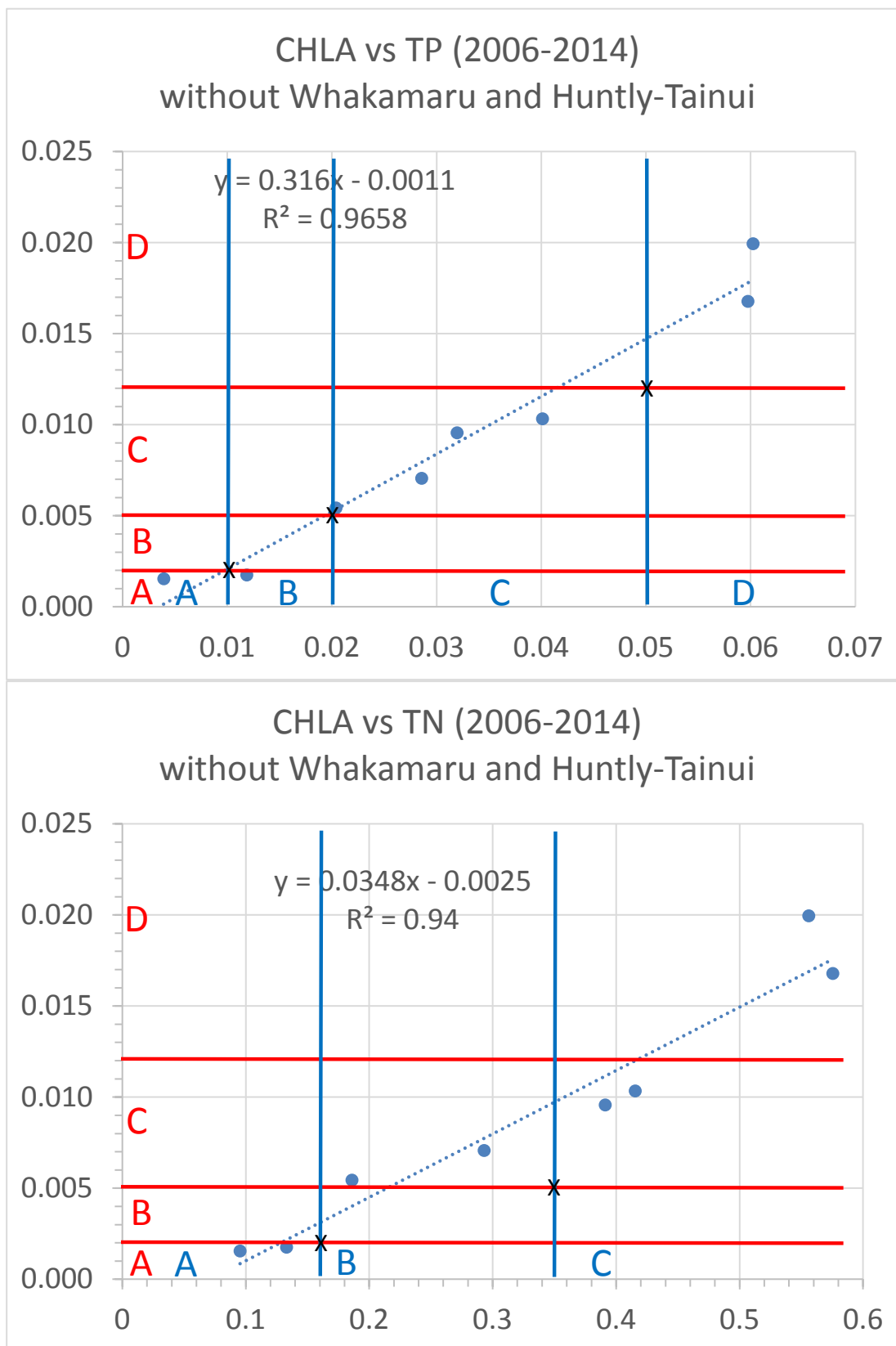


Fig. P2. Boundaries of Attribute States A, B, C and D for chlorophyll *a* (red bars) and TP (top) or TN (bottom) in stratified lakes (blue bars for nutrients), superimposed on the regression of chlorophyll *a* against TP and TN. Growing season means (October-March) of each station, 2006-2014. X indicates where the boundaries of Attribute States for chlorophyll *a* and TN or TP would be expected to meet.

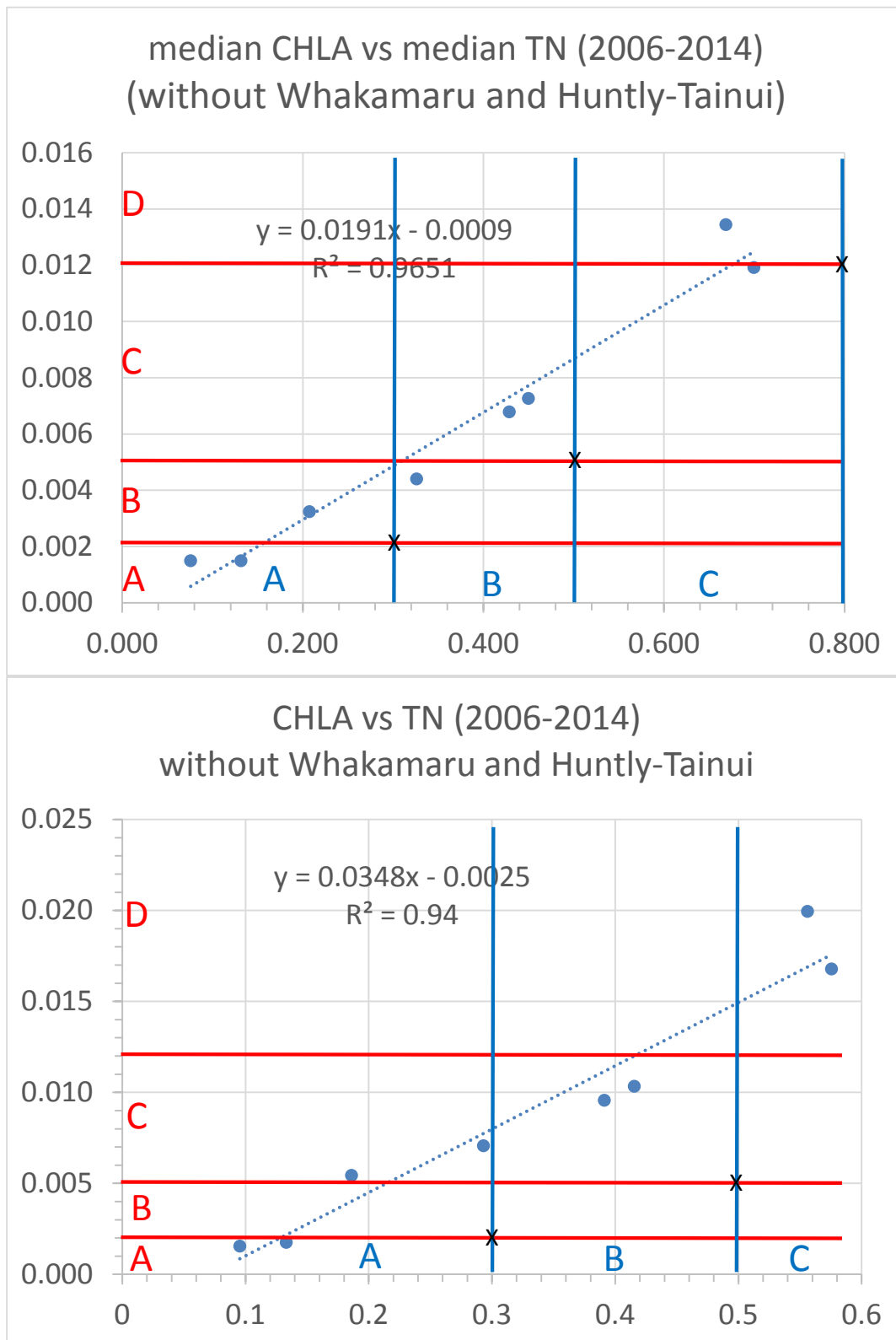


Fig. P3. Boundaries of Attribute States A, B, C and D for chlorophyll *a* (red bars) and TN in polyeutrophic lakes (blue bars), superimposed on the regression of chlorophyll *a*s against TN. Top: Annual medians of each station, Bottom: Growing season means (October-March) of each station. Data of 2006-2014. X indicates where the boundaries of Attribute States for chlorophyll *a* and TN or TP would be expected to meet.

## Appendix Q Predicting chlorophyll *a* from TP and TN

### Fitted Model Plot

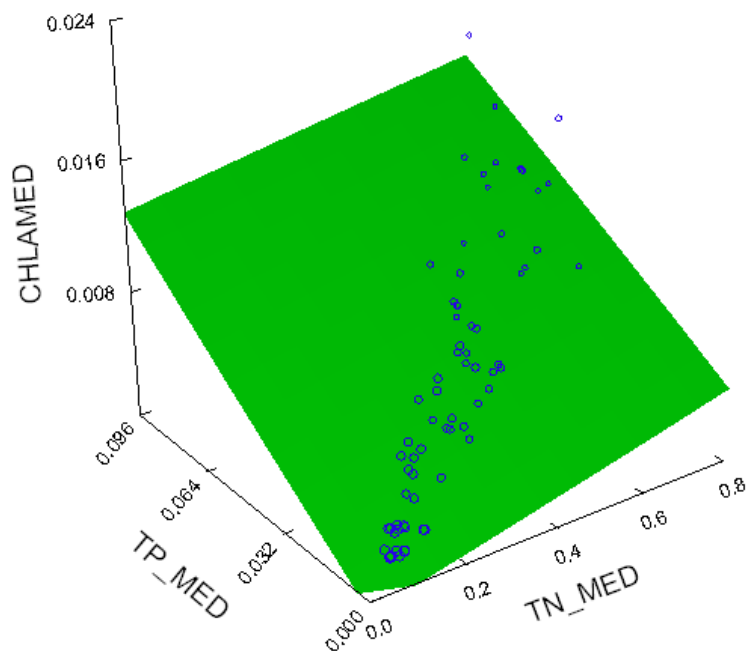


Fig. Q1. Systat output of multiple linear least squares regression of chlorophyll *a* as dependent variable against TN and TP:  $CHLA = -0.001 + 0.140 * TP + 0.006 * TN$ , adjusted  $R^2 = 0.83$ , standard error of the estimate:  $0.002 \text{ mg L}^{-1}$ . The constant was not significantly different from zero but the coefficients for TP and TN were both significant ( $p = 0.000$  and  $p = 0.040$  respectively) in spite of the strong covariation between TN and TP ( $R^2 = 0.88$  for the linear relationship between TN and TP). The standardized coefficient for TP was twice as high as for TN, illustrating the greater effect of variation in TP on chlorophyll *a* concentrations, compared with variability in TN, as can also be seen in the figure. As a result of the strong covariation between TN and TP the data do not cover most of the plane in the figure but are almost in a straight line. Data: untransformed annual medians, 2006-2014, not including Huntly and Whakamaru.

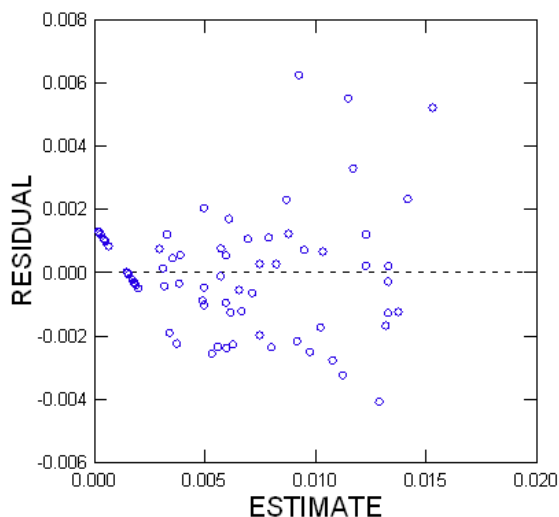


Fig. Q2. Plot of residuals versus predicted values of the results in Fig. Q1.

### Predicted CHLA vs measured CHLA

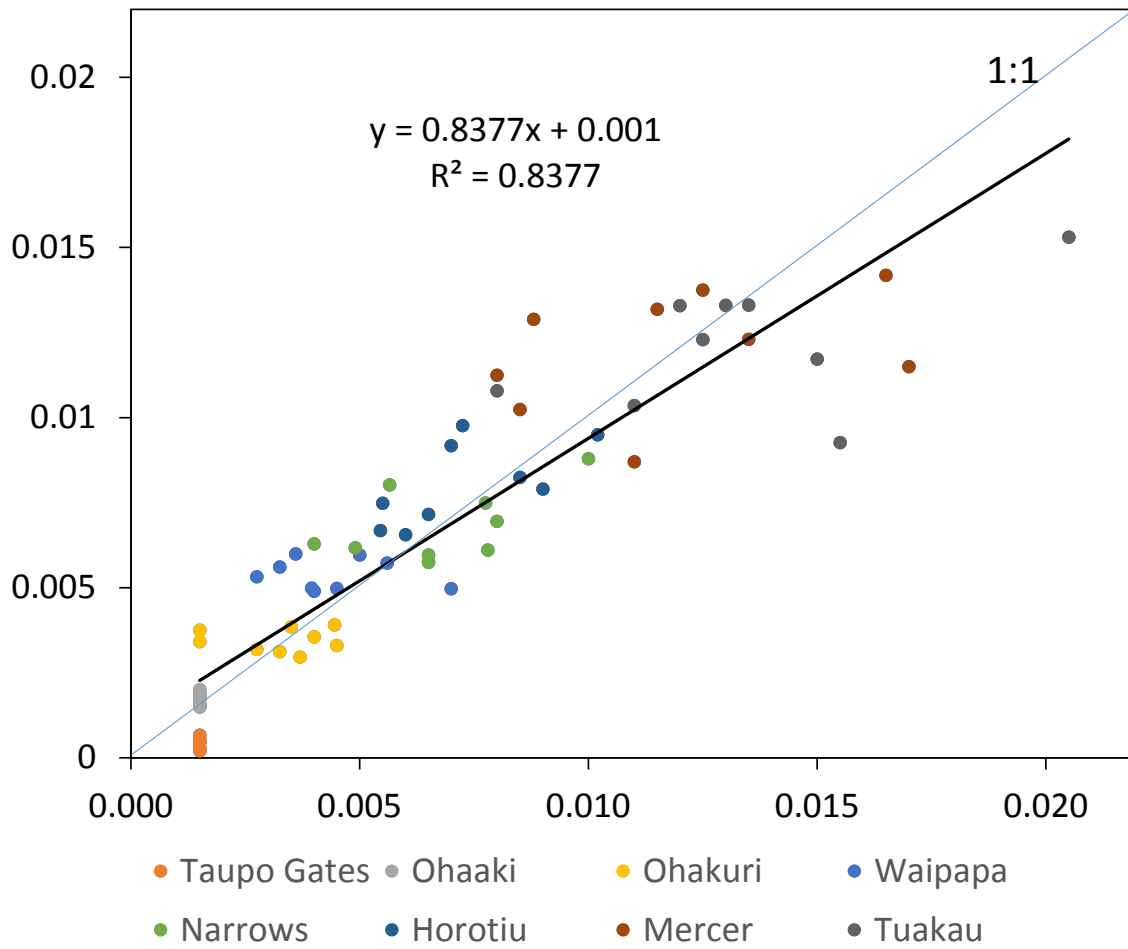


Fig. Q3. Chlorophyll *a* predicted with Eq. 3 against measured chlorophyll *a*. Medians, 2006-2014.