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Testing the generality of the effect of environmental variables on flatfish catch

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While the extraction of fish can have a considerable effect on fish populations, environmental influences such as water quality, habitat degradation and climatic variation can also be influential. Here we assessed the relationship between flatfish catch rates in the Kaipara Harbour and some relevant environmental variables. In the Kaipara Harbour, flatfish catch is largely made up of yellow belly flounder (YBF) that are two and three years old. As the number of cohorts within flatfish catch is quite restricted, the influence of environmental variables can be investigated using commercial catch per unit effort (CPUE) information and environmental variables from when fish were juveniles occupying upper harbour inlets, which are prone to water quality issues and habitat degradation. To conduct this analysis we used water quality data collected by Auckland Council at Shelly Beach since 1992 (temperature, nitrate, dissolved oxygen and ammonia), a range of climatic variables (the Southern Oscillation Index (SOI), Trenberth index Z1, and monthly rainfall), and flatfish catch data. Shelly Beach is the only water quality site in the Kaipara to have a long time series of data; this appears correlated with other sites across the harbour, but is likely to underestimate a correlation between water quality and flatfish catch rates at other sites. After grooming the commercial catch data for errors and selecting only records from vessels that had consistently fished we first examined catch in relation to effort variables within a Generalised Linear Model (GLM). This provided an index of flatfish abundance that could later be correlated with appropriately lagged environmental variables. Next we identified which environmental variables might be influencing flatfish recruitment and abundance by offering them in subsequent GLM runs.

We conducted separate GLMs for each of the months when newly settled YBF are present (August–December). This required averaging the environmental variables for that month from two and three years prior to the flatfish catch used within the model. We also conducted GLMs representing the entire August–December juvenile settlement period, with environmental variables lagged by two, three and the average of two and three years. A number of environmental variables were selected as explaining a small (typically about 2 % for each variable) amount of overall variation within the model (typically about 30% of the variation was explained by any model). Nitrate and SOI were selected by five and three of the eight GLM runs respectively, and generally demonstrated Pearson correlations with the aforementioned index of flatfish abundance of about -0.4 – -0.6. In addition to these analyses, we conducted correlations using additional climatic variables (Trenberth Z4, M2, MZ4) over the entire recorded catch history (i.e. back to 1990) and for both the Kaipara and Manukau Harbours (Manukau CPUE index supplied by T. Kendrick, Trophia). In both the Kaipara and Manukau Harbours the SOI index demonstrated Pearson correlations with flatfish abundance of between -0.29 and -0.58 while linear correlations had R^2 values between 0.09 and 0.34. In the Manukau Harbour alone, Trenberth M2 had a Pearson correlation with flatfish abundance of between -0.38 and -0.63 while linear correlations had R^2 values between 0.15 and 0.40 (depending on the lag used).

The results described here suggest that recruitment of YBF may be correlated with different types of environmental variables. The relationship to nitrate may indicate that the intensification of land–use within the Kaipara has led to a degradation in water quality and habitats that juvenile YBF depend on which may be connected to the long term decline in YBF CPUE. This mechanism was also suggested for a similar and previous analysis conducted for the Manukau Harbour, however, monitoring of benthic macrofauna suggests that at least the central areas of both the Manukau and Kaipara Harbours are not degraded. Alternatively, nitrate may be less influential on YBF CPUE, or even just correlated with another variable that is. For example, regional climate variation was also seen to be related to YBF CPUE through the correlation with the SOI index (both Kaipara and Manukau) and Trenberth

M2 (Manukau only). This climate variation could independently be influencing within harbour nitrate levels as well as YBF CPUE through some other mechanism. Any influence of climate on YBF CPUE is likely to come about during the YBF larval phase, which occurs outside of harbours on the open coast. Specifically, periods of favourable YBF recruitment were observed to coincide with El Niño events, which could suggest that pelagic productivity (and larval survival) is higher on the open coast at these times. El Niño conditions have been scarce over recent years and are unlikely to prevail in the short to medium–term due to the existing Interdecadal Pacific Oscillation phase. Continued monitoring of flatfish CPUE in response to major shifts in climate variability and trends in water quality will confirm the strength of the relationship with these variables and should provide utility in ensuring the continued sustainability of flatfish populations.

1. INTRODUCTION

Many coastal fish species utilise estuarine nursery habitats when they are juveniles (Beck et al. 2001) and thus provide an important function for coastal fisheries. If these critical habitats become degraded through land based influences and their ensuing effect on water quality (Morrison et al. 2009; Morrison et al. 2014a), then recruitment to adult fish populations may be reduced in later years.

The FLA 1 fishery covers the upper half of the North Island and consists of a group of nine flatfish species that are predominantly caught by setnet (Kendrick & Bentley 2012). Within the Kaipara Harbour, the focus of this study, FLA catch is nearly entirely composed of yellow belly flounder (YBF), *Rhombosolea leporina* (Kendrick & Bentley 2012). YBF is a species that exhibits fast growth and a short lifespan (Mutoro 1999); nearly all of the YBF catch is composed of two and three year olds in equal proportion (McKenzie et al. 2013). As such, a species with these life history characteristics should be reasonably resilient to overfishing, yet nearly all of the component fisheries within FLA 1 (including the Kaipara) demonstrate long-term declines (Kendrick & Bentley 2012). When this trend is considered alongside the shallow estuarine habitat occupied by juvenile YBF, it is possible that environmental variables, such as reduced water quality, could be responsible for the long-term trends in the YBF fishery.

In a previous report (McKenzie et al. 2013) we observed relationships between environmental variables (dissolved oxygen, ammonia, and turbidity; when lagged to represent the period when juveniles would have been present) and commercial YBF catch within the Manukau Harbour. This result suggested that water quality, and presumably the influence of land-use practices on water quality, may be negatively affecting the recruitment success of YBF and other flatfish species. Here we assess whether a similar relationship exists for YBF in the Kaipara Harbour, which may suggest a more generic influence of water quality on recruitment success for flatfish populations. To achieve this end, a predecessor project (Appendix 1) has already assessed the water quality time series for the Kaipara, comparing the general representativeness of the one long-term water quality monitoring site (Shelly Beach) with other sites in the Harbour that encompassed potential juvenile YBF habitat (see Appendix 1). Shelly Beach was found to have good utility in predicting most of the water quality variables monitored at the other sites within the Kaipara, providing confidence to continue with the assessment of the relationship between these environmental variables and YBF CPUE.

The specific objective of the present project was to:

1. Assess the influence of environmental variables on FLA catch.

2. METHODS

2.1 YBF catch data, grooming and vessel selection

YBF catch data were extracted from the Ministry for Primary Industries (MPI) database by requesting all trips where FLA 1 quota was landed. Catch data are supplied as a landings file (representing a whole trip, within which multiple fishing events may have occurred) and an effort file (detailing specific information about each fishing event). We first combined these files based on common trip codes, prorating the landed catch weight of FLA across relevant events using the estimate of catch supplied by the fisher. We then constrained this dataset to catches from just the Kaipara Harbour using statistical area (Kaipara Harbour is Statistical Area 044) verified by the reported point of landing. The resulting dataset incorporated two form types (CEL and NCE), however, both report information at the day level, so no adjustments were needed to make them comparable. Catch data were then groomed to identify outlier values (Table 1). If an event reported a catch that was more than 3.5 standard deviations (sd) from the median for that vessel, the entire event was removed. The distribution of effort variables was also assessed and a range of plausible values determined. Where events listed an effort variable outside of these ranges, that value was replaced by the median value for that vessel. Where the median was still outside the plausible range, that value was replaced with "NA", effectively removing that event from subsequent analyses. The ranges set for the effort variables used in this study were: mesh size (effort_width) 80–150 mm; net length 25–2500 m; duration 0–24 hours. This generally resulted in fewer than 2% of observations having an effort variable imputed. However, for the CEL data the mesh size variable had a larger number of missing values, with about 14 000 out of about 90 000 values having a value imputed (Table 1). Data were further constrained so that only events using setnet as their method and targeting FLA or YBF (which are effectively synonymous for the Kaipara Harbour) were retained. Finally a vessel selection was performed, constraining the dataset to 34 vessels that had made at least 15 trips per year for a minimum of four years.

Table 1: The number of events in the data extract used in this study and the various steps that removed events or imputed values for events that remained in the dataset.

	Number of events	Imputations made
Original extract	179 490	
Just Kaipara Harbour	91 991	
Catch less than 3.5 sd from vessel median	91 961	
Mesh size (effort_width) restricted to 80–150 mm	89 976	11 970
Net length restricted to 25–2500 m	89 974	1 384
Fishing duration restricted to 0–24 hours	89 974	565
Fishing year 1996 onwards	75 324	
Fishing method = Setnet	74 337	
Target = FLA or YBF	65 422	
Core vessel selection	26 974	

2.2 Environmental variables

The Shelly Beach water quality dataset was obtained from Auckland Council. Each month water quality sampling was generally conducted across all sites on the same day, however, on some occasions sampling may have been conducted over two or three days. We chose to retain these measurements by performing correlations where we ignored the specific day, and compared water quality measurements if they were taken within the same month. While this dataset extends back until 1991, not all of the variables in the dataset have been recorded consistently over this time. Furthermore, the early parts of the dataset contain more missing values, and only some of the variables measured at Shelly Beach were observed to correlate well with water quality measurements from the other parts of the harbour where juvenile YBF are abundant (Appendix 1). As a result, we chose four water quality variables (temperature (°C), nitrate as N (mg/L), dissolved oxygen (% saturation) and ammonia as N (mg/L)) which have all been recorded consistently since 1992 and were highly correlated across other water quality monitoring sites within the harbour. This dataset still contained some missing values, but data averaging conducted as part of subsequent analyses (see Section 2.3) meant that these missing values did not prohibit further analysis.

We also included a range of climatic variables in our comparisons with YBF CPUE. These included monthly values for: the Southern Oscillation Index (SOI), which is calculated as the atmospheric pressure difference between Tahiti and Darwin and represents the intensity of El Niño or La Niña events in the Pacific Ocean; Trenberth index Z1, the atmospheric pressure difference between Auckland and Christchurch which represents westerly flow in this region; Trenberth index Z4, the atmospheric pressure difference between Raoul and Chatham Islands which represents westerly flow in this region; Trenberth index M2, the atmospheric pressure difference between Hokitika and Chatham Island which represents southerly flow in this region; Trenberth index MZ4, the atmospheric pressure difference between Auckland and New Plymouth which represents southwesterly flow in this region; and total monthly rainfall for the Shelly Beach (Maeretahi weather station). Rainfall data was missing for Shelly Beach from 2001–2002, so for this period rainfall data for the nearest other station (Warkworth) was used. Rainfall at this station had a good relationship to that at Shelly Beach in years where both stations were operating (Pearson correlation coefficient = 0.78).

2.3 Comparison of YBF CPUE and environmental variables

Our approach to this analysis was similar to that of McKenzie et al. (2013). In general this involved producing a standardised YBF CPUE index without considering any environmental variables, and then running a series of generalised linear models (GLM) to identify environmental variables that had a relationship with YBF CPUE. Once a specific variable was identified, it could then be plotted against and correlated with the YBF CPUE index calculated without environmental variables so that the strength of that relationship could be described.

The first component of this analysis was to produce the standardised YBF CPUE index for the Kaipara Harbour. This index was produced using a stepwise GLM with log positive catch (i.e. zero catch events were not included) as the response variable. Covariates offered to the model included, vessel (34 levels), month (12 levels), duration, mesh size, net length and form type (two levels, CEL and NCE), with fishing year (25 levels, 1990–2014) forced as the first term in the model. The stepwise GLM process successively added and removed parameters so that the most explanatory parameters (in terms of overall improvement in model residual deviance) were identified. The process was stopped when the addition of a term did not increase the overall residual deviance by more than 1%.

In order to identify environmental variables which may be important to YBF, we first needed to categorise the period when YBF initially settle as juveniles, and may be most vulnerable to the influence of water quality and other environmental variables. In the present study we identified August to December as the period encompassing the larval and initial juvenile stages (YBF settlement in the Manukau peaks over September and October, Mutoro 1999). Separate GLMs were then conducted for each of these months. However, we also had to consider the correct lag to apply, so that the year in which a YBF cohort were juveniles (represented by adult YBF catch data) was correctly aligned with environmental data for that period. Because YBF catch is approximately half two year old and half three year old fish, for each GLM (representing a specific month) we aligned catch data with the average of environmental variables from two and three years prior to the fishing year in which that catch was made. In addition to these monthly GLMs, we also conducted GLMs representing the entire five month period between August and December. As the combination of months meant there was only one time period to assess (as opposed to five for the monthly GLMs), we were able to address lags of two, three and the average of two and three years without the final number of analyses becoming unwieldy.

Before GLMs were performed the collinearity of explanatory variables was examined. Where variables had a relationship, R, of at least 0.6, one variable was removed, allowing the remaining variable to proxy for it. The remaining environmental variables would then be offered to the GLM (in addition to the fishing effort variables listed above): turbidity, temperature, suspended solids, nitrate, dissolved oxygen, ammonia, phosphorous, SOI, Trenberth Z1, and rainfall. Fishing year was not offered as a covariate to these GLMs; without fishing year present the GLM was free to pick environmental variables as a proxy for the year index (McKenzie et al. 2013).

As described above, where environmental variables were selected by the GLM, plots and correlation coefficients between that variable and the YBF CPUE index (calculated without environmental variables) were produced. Where significant correlations were identified with climatic variables, this increased the scope of analyses that were possible. Unlike water quality data, climatic indices are regional and therefore relevant to FLA 1 fisheries outside of the Kaipara. They have also been collected for a much longer time period, and allowed us to produce correlation plots between climatic indices and YBF CPUE for the full extent of the YBF catch dataset, and to incorporate a comparison with YBF CPUE from the Manukau Harbour (updated index supplied by T. Kendrick, Trophia). We chose the following climate indices as best representing the upper North Island: SOI, Trenberth Z4, Trenberth M2 and Trenberth MZ4.

3. RESULTS

3.1 Kaipara Harbour YBF CPUE (without environmental variables)

The standardisation of Kaipara Harbour YBF CPUE produced an index that explained 32% of variation in the catch dataset, selecting four variables (in addition to fishing year, which was forced), with the majority of the variation explained by the model captured by the vessel that made the YBF catches (Table 2).

Table 2: Variables selected by the stepwise GLM standardisation of setnet catch and effort information (without environmental variables) for the Kaipara Harbour. Table shows improvement in model total R^2. Fishing year forced as first term within the model.

Variable	R^2
Fishing year	0.07
Vessel	0.24
Net length	0.27
Month	0.30
Duration	0.32

This index demonstrated an overall decline since its beginning in 1990, although two major CPUE oscillations occurred within the index over its 25 year history (Figure 1). The CPUE index produced in the present study was very similar to the index produced by T. Kendrick, Trophia; differences in the two indices were mostly due to the choice of core vessels and possibly differences in the data grooming criteria.

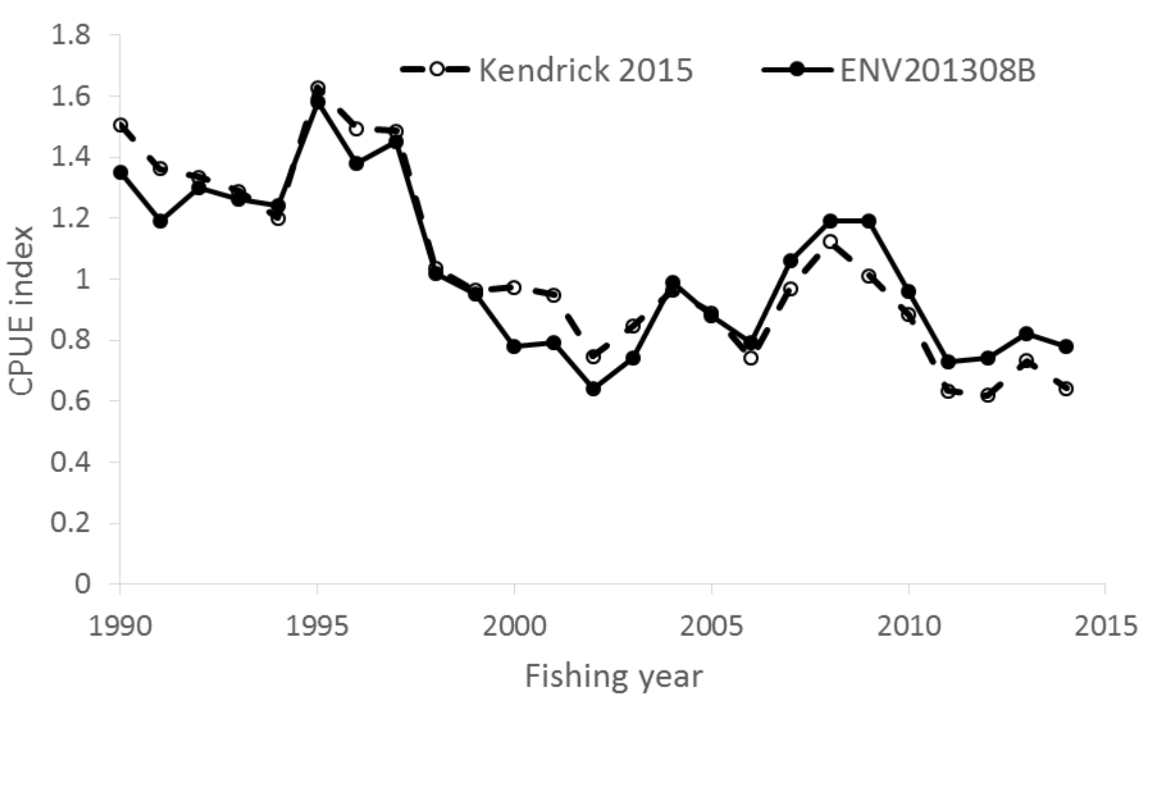

Figure 1: Plot of the Kaipara Harbour standardised YBF CPUE index (calculated without environmental variables) since the 1990 fishing year (index values have an average of 1). Also plotted is the CPUE index as calculated by T. Kendrick, Trophia for MPI. These two indices had a Pearson correlation coefficient of 0.94.

3.2 Environmental correlations with Kaipara YBF CPUE (by month)

When environmental variables corresponding to the month of August (average of two successive years) were offered to the GLM, nitrate was selected as the third variable in the GLM model (Table 3). The August average nitrate concentration showed a negative correlation (Pearson: -0.44) with the base Kaipara YBF CPUE index (Figure 2). Collinearity analysis suggested that nitrate also had some correlation with the SOI index and monthly rainfall (R = 0.5; Appendix 2).

Table 3: Variables selected by the stepwise GLM standardisation of setnet catch and effort information with environmental variables for the Kaipara Harbour for August (values averaged over two consecutive years and lagged to correspond to adult YBF catch). Table shows improvement in model total R^2. Fishing year not offered to model. Selected environmental variables highlighted in grey.

Variable	R^2
Vessel	0.20
Net length	0.23
Nitrate	0.25
Month	0.28
Duration	0.30

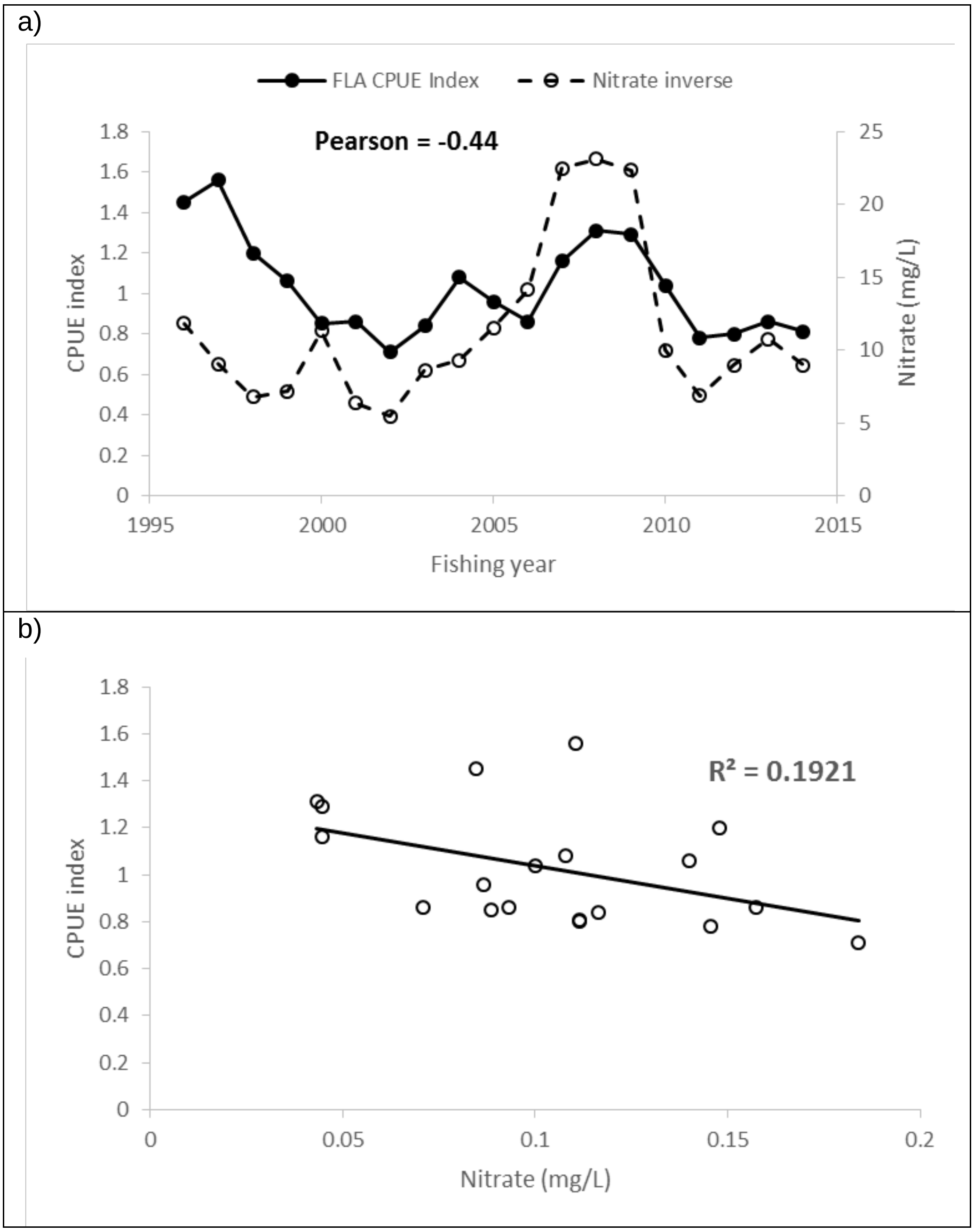

Figure 2: Nitrate concentration (values inversed on plot) for August (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

When environmental variables corresponding to the month of September (average of two successive years) were offered to the GLM, nitrate concentration and dissolved oxygen (DO) % saturation were selected as the fifth and sixth variables in the GLM model (Table 4). The September nitrate concentration and DO % saturation showed negative and positive correlations (Pearson: -0.52 and 0.32 respectively) with the base Kaipara YBF CPUE index respectively (Figures 3 and 4). Collinearity analysis suggested that DO also had some correlation with temperature and monthly rainfall (R = 0.5 and 0.4 respectively; Appendix 2).

Table 4: Variables selected by the stepwise GLM standardisation of setnet catch and effort information with environmental variables for the Kaipara Harbour for September (values averaged over two consecutive years and lagged to correspond to adult YBF catch). Table shows improvement in model total R^2. Fishing year not offered to model. Selected environmental variables highlighted in grey.

Variable	R^2
Vessel	0.20
Net length	0.23
Month	0.25
Duration	0.27
Nitrate	0.29
DO	0.30

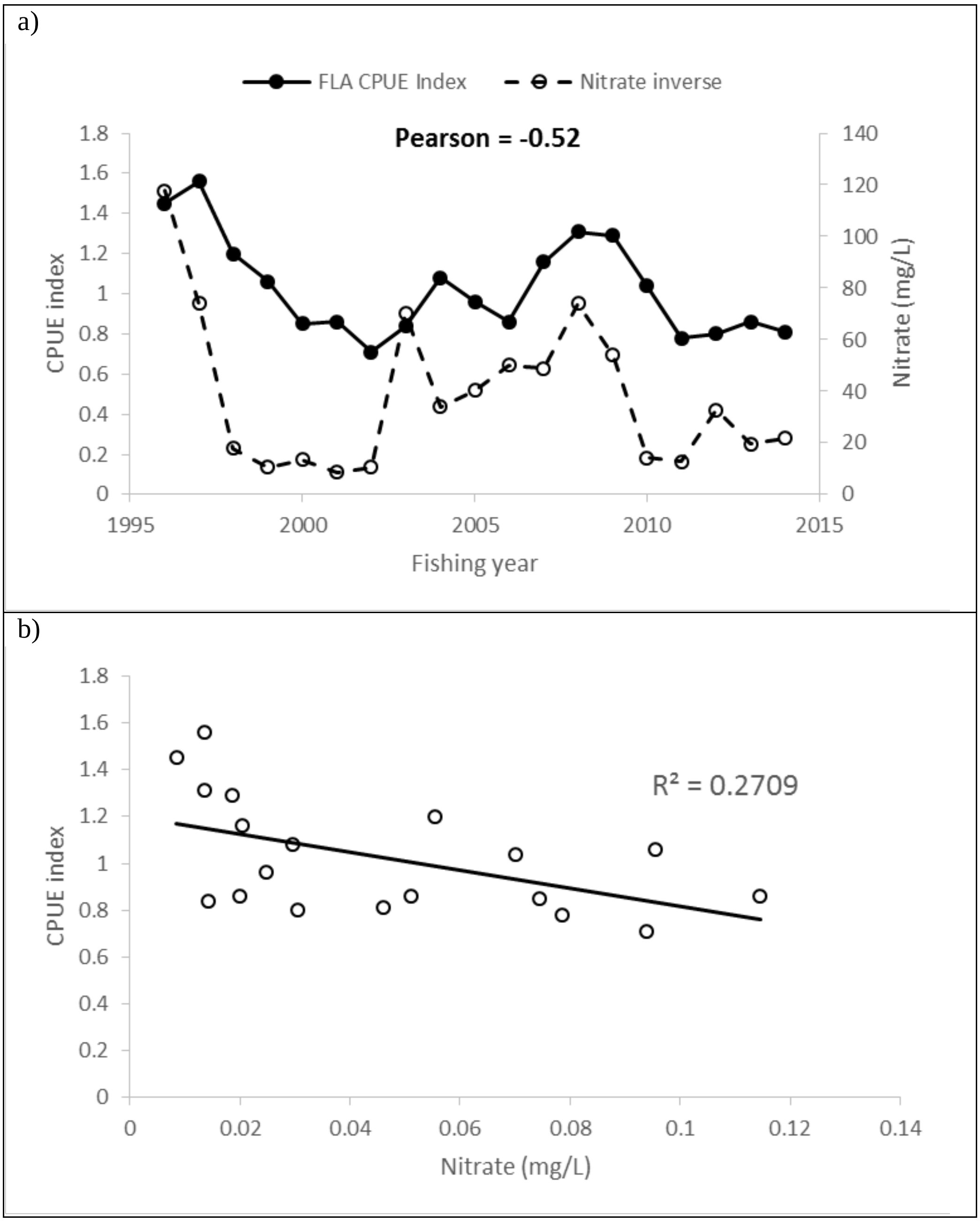

Figure 3: Nitrate concentration (values inversed on plot) for September (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

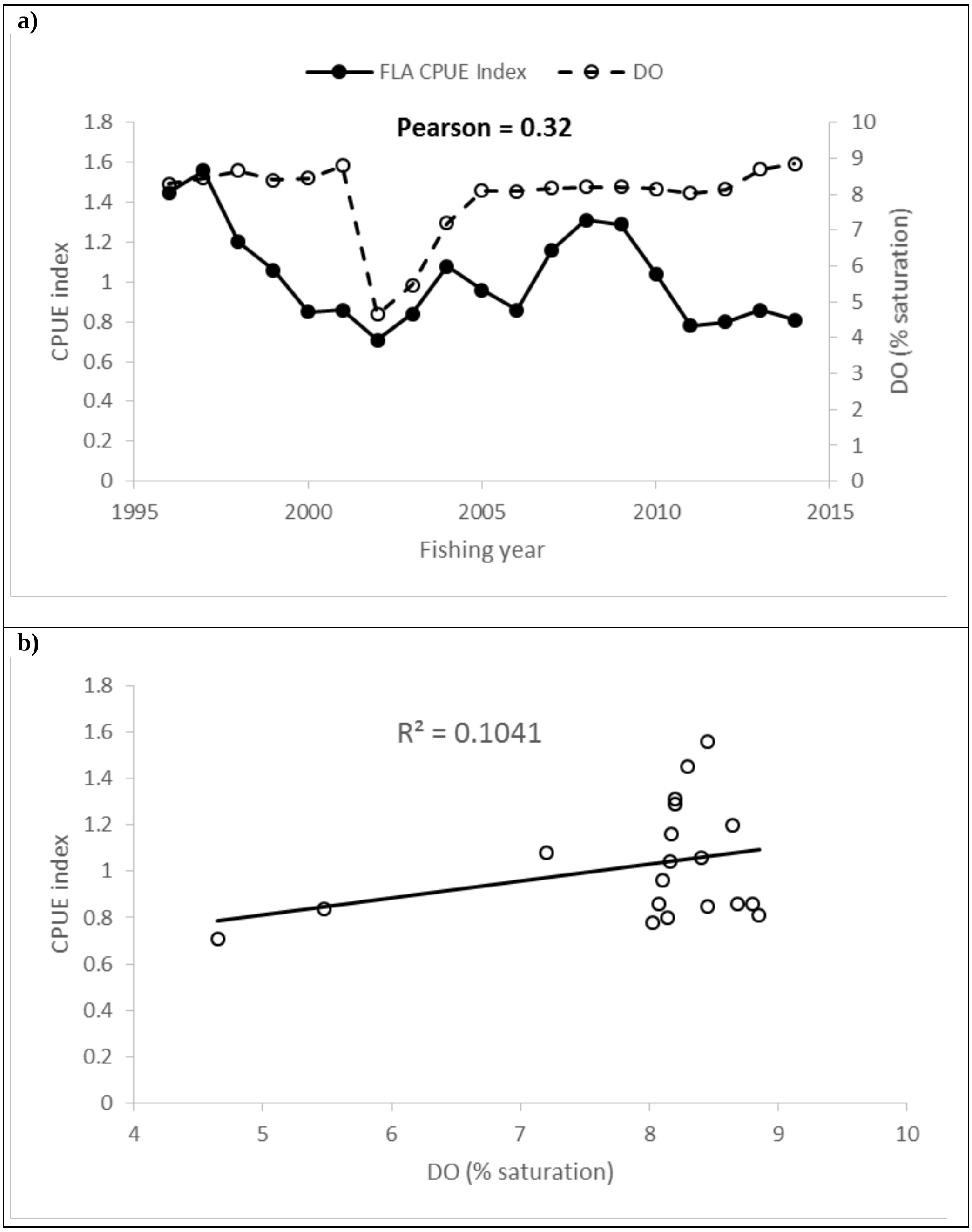

Figure 4: DO % saturation for September (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

When environmental variables corresponding to the month of October (average of two successive years) were offered to the GLM, the SOI index and rainfall were selected as the third and sixth variables in the GLM model (Table 5). The October average SOI index and rainfall showed negative and positive correlations (Pearson: -0.65 and 0.3 respectively) with the base Kaipara YBF CPUE index (Figures 5 and 6). Collinearity analysis suggested that the SOI index had some correlation with ammonia, nitrate, temperature and monthly rainfall (R=0.4;Appendix 2).

Table 5: Variables selected by the stepwise GLM standardisation of setnet catch and effort information with environmental variables for the Kaipara Harbour for October (values averaged over two consecutive years and lagged to correspond to adult YBF catch). Table shows improvement in model total R^2. Fishing year not offered to model. Selected environmental variables highlighted in grey.

Variable	R^2
Vessel	0.20
Net length	0.23
SOI	0.25
Month	0.28
Duration	0.29
Rainfall	0.31

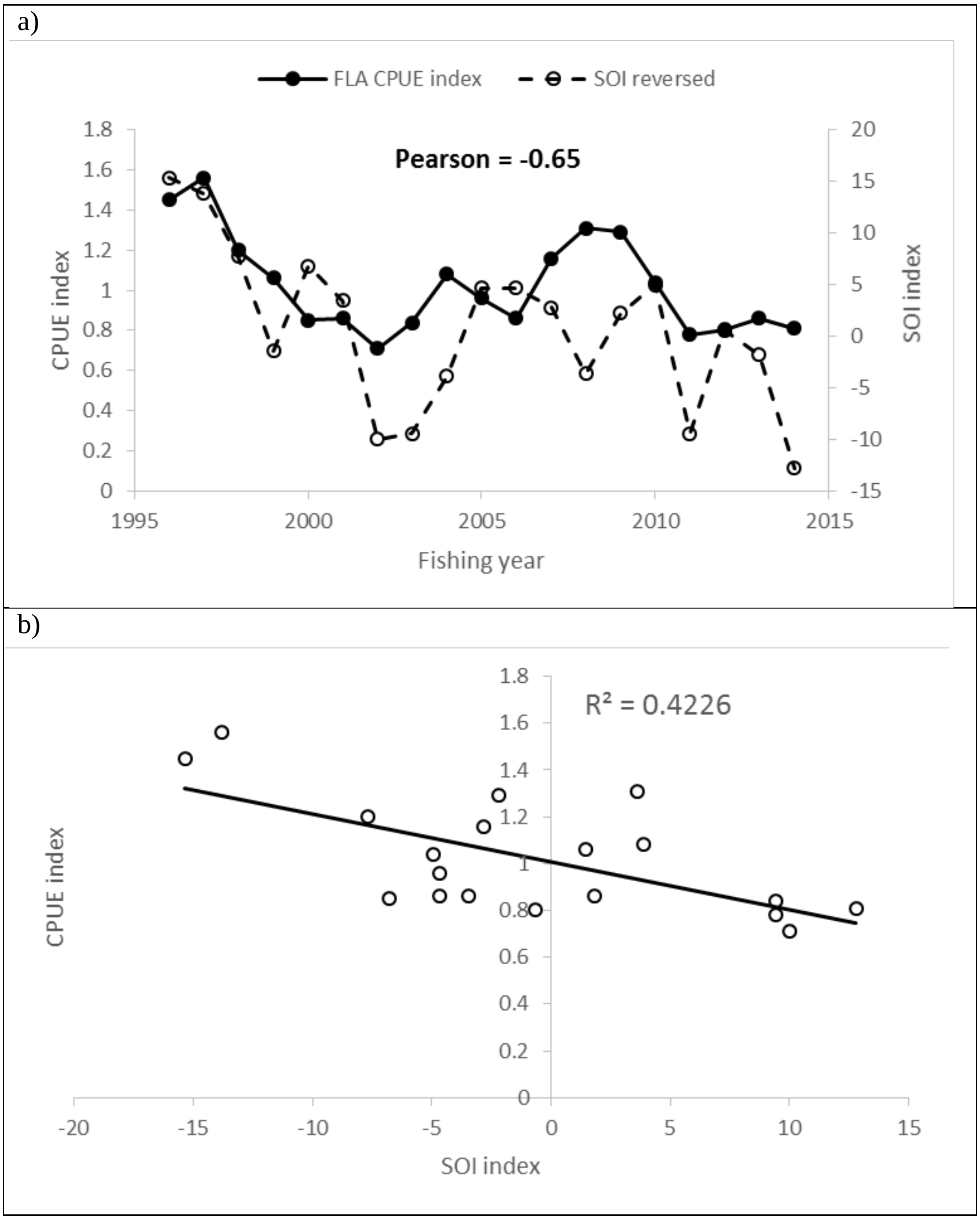

Figure 5: SOI index (sign of values reversed on plot) for October (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

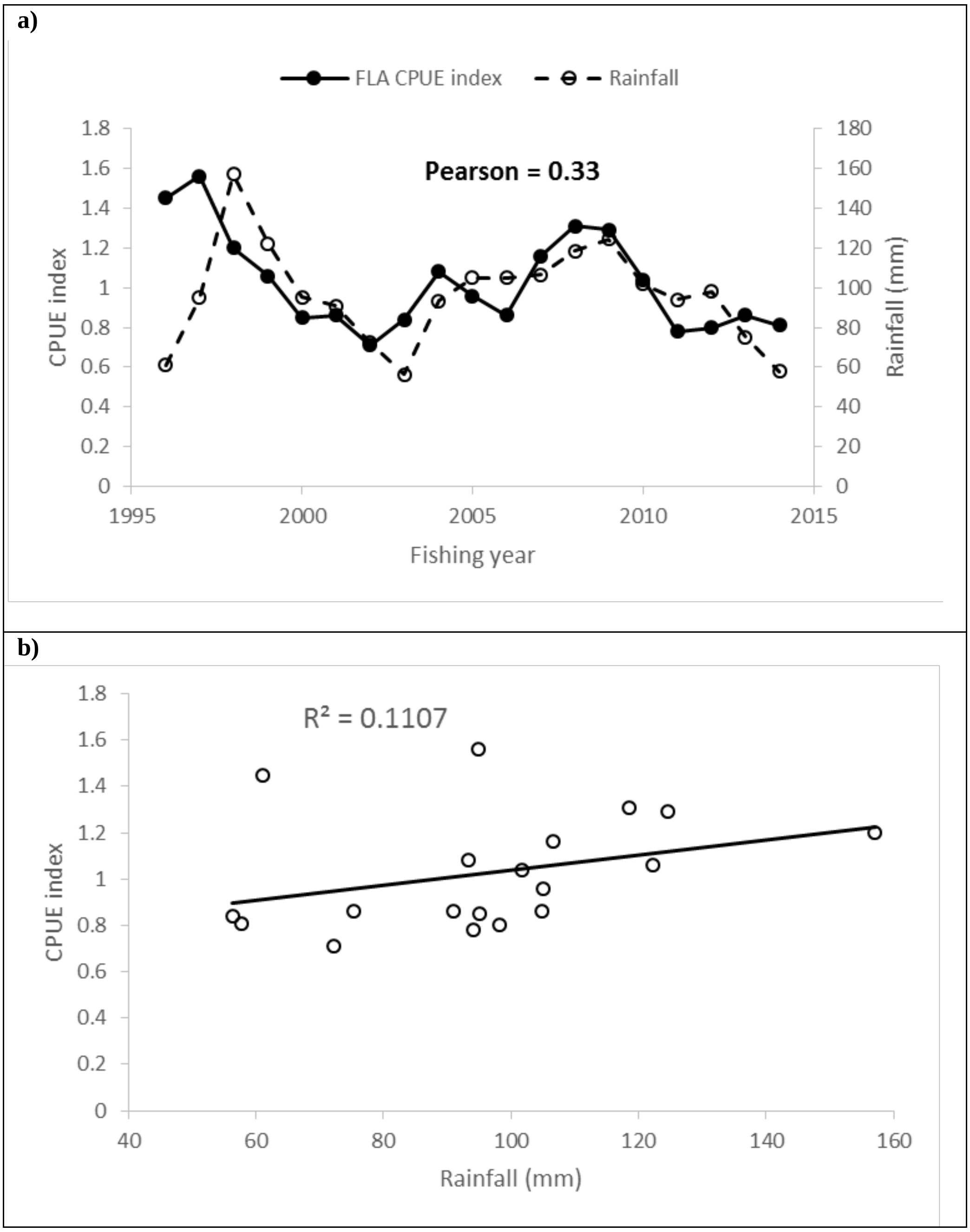

Figure 6: Total rainfall for October (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

When environmental variables corresponding to the month of November (average of two successive years) were offered to the GLM, the SOI index was selected as the fifth variable in the GLM model (Table 6). The November average SOI index showed a negative correlation (Pearson: -0.54) with the base Kaipara YBF CPUE index (Figure 7). Collinearity analysis suggested that the SOI index also had some correlation with temperature (R = 0.4; Appendix 2).

Table 6: Variables selected by the stepwise GLM standardisation of setnet catch and effort information with environmental variables for the Kaipara Harbour for November (values averaged over two consecutive years and lagged to correspond to adult YBF catch). Table shows improvement in model total R^2. Fishing year not offered to model. Selected environmental variables highlighted in grey.

Variable	R^2
Vessel	0.20
Net length	0.23
Month	0.25
Duration	0.27
SOI	0.29

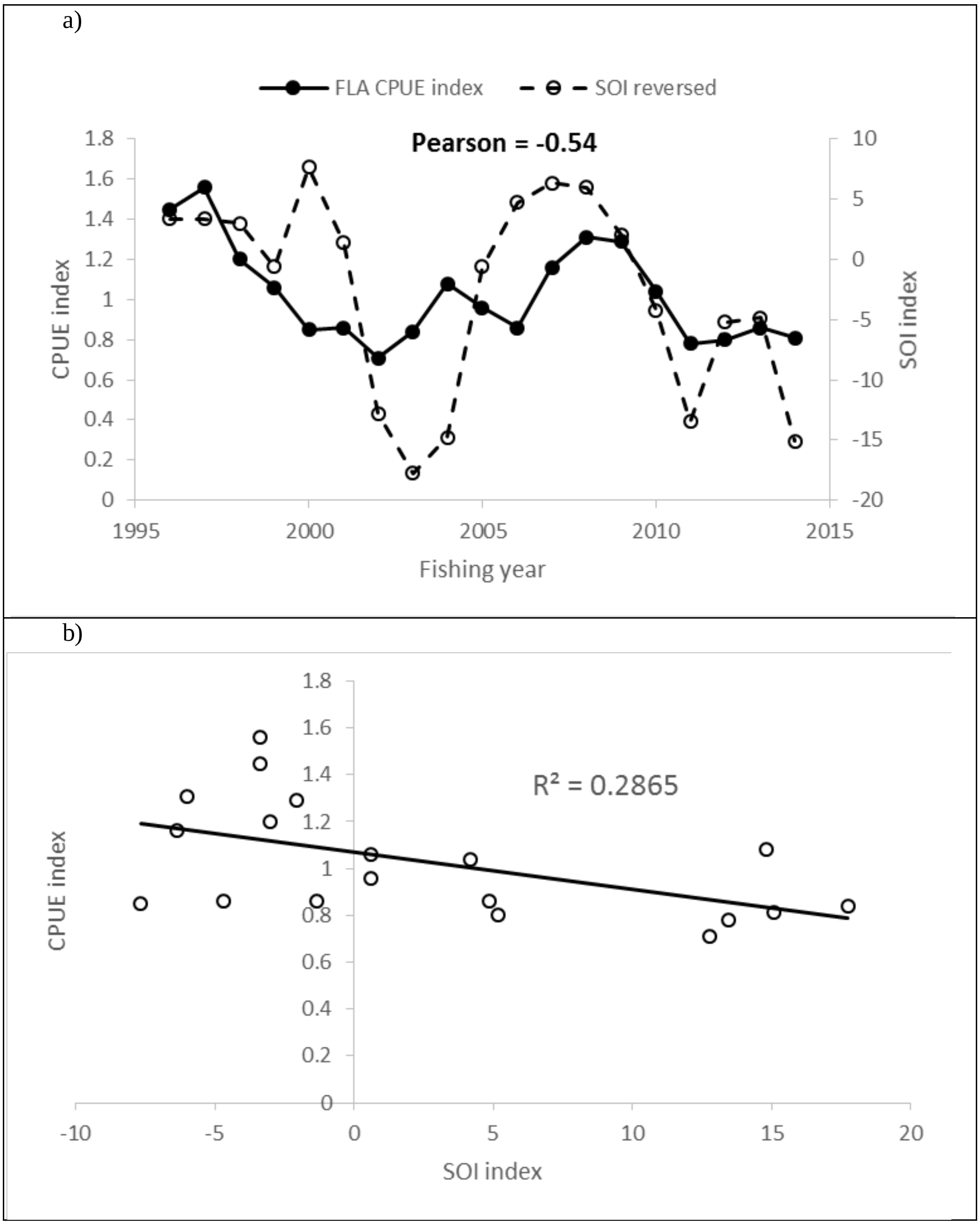

Figure 7: SOI index (sign of values reversed on plot) for November (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

When environmental variables corresponding to the month of December (average of two successive years) were offered to the GLM, water temperature and rainfall were selected as the third and sixth variables in the GLM model (Table 7). The December average water temperature and rainfall showed negative correlations (Pearson: -0.58 and -0.17 respectively) with the base Kaipara YBF CPUE index (Figures 8 and 9). Collinearity analysis suggested that temperature and monthly rainfall also had some correlation with each other (R = 0.4; Appendix 2).

Table 7: Variables selected by the stepwise GLM standardisation of setnet catch and effort information with environmental variables for the Kaipara Harbour for December (values averaged over two consecutive years and lagged to correspond to adult YBF catch). Table shows improvement in model total R^2. Fishing year not offered to model. Selected environmental variables highlighted in grey.

Variable	R^2
Vessel	0.20
Net length	0.23
Temperature	0.26
Month	0.28
Duration	0.30
Rainfall	0.31

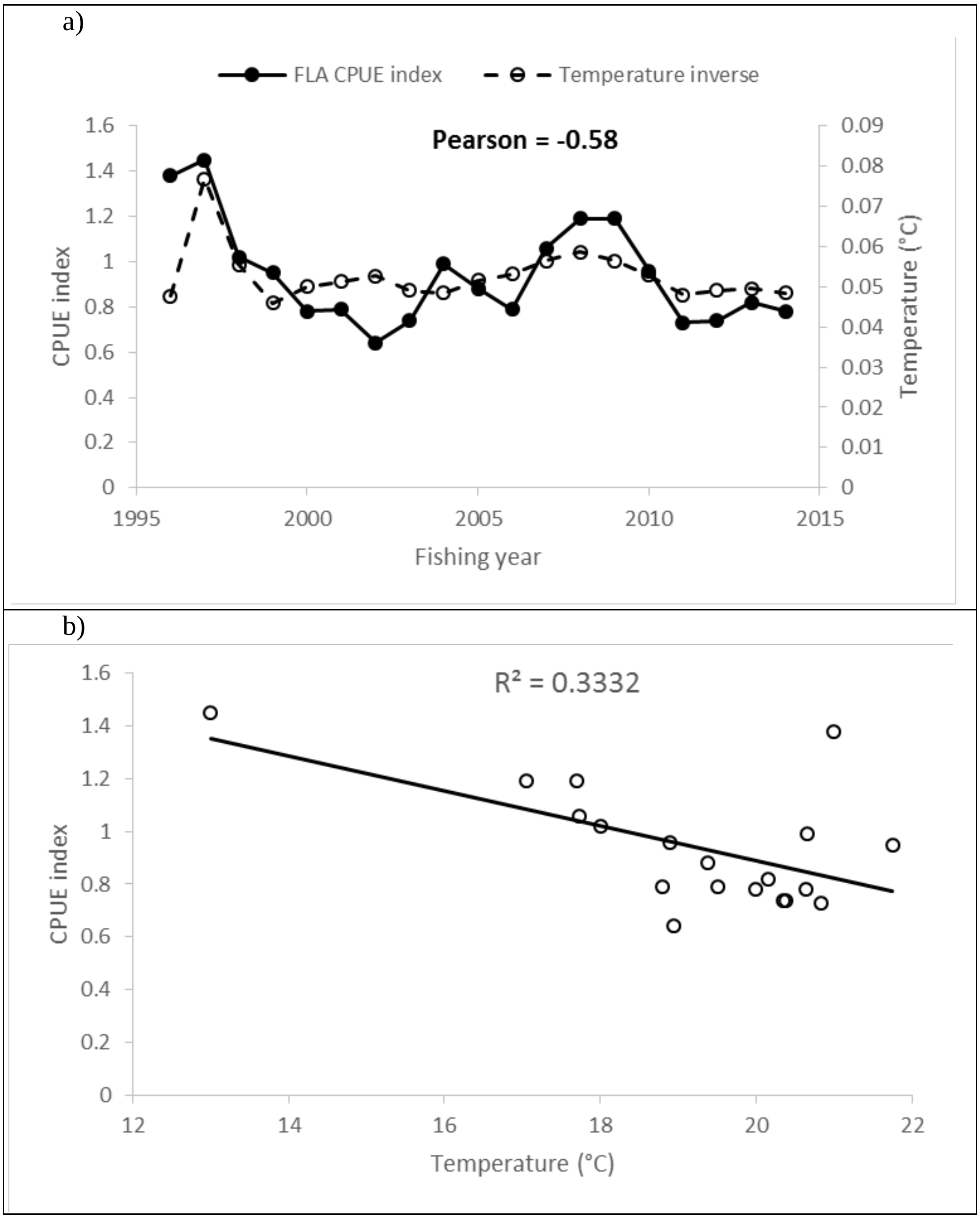

Figure 8: Water temperature (values inversed on plot) in December (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

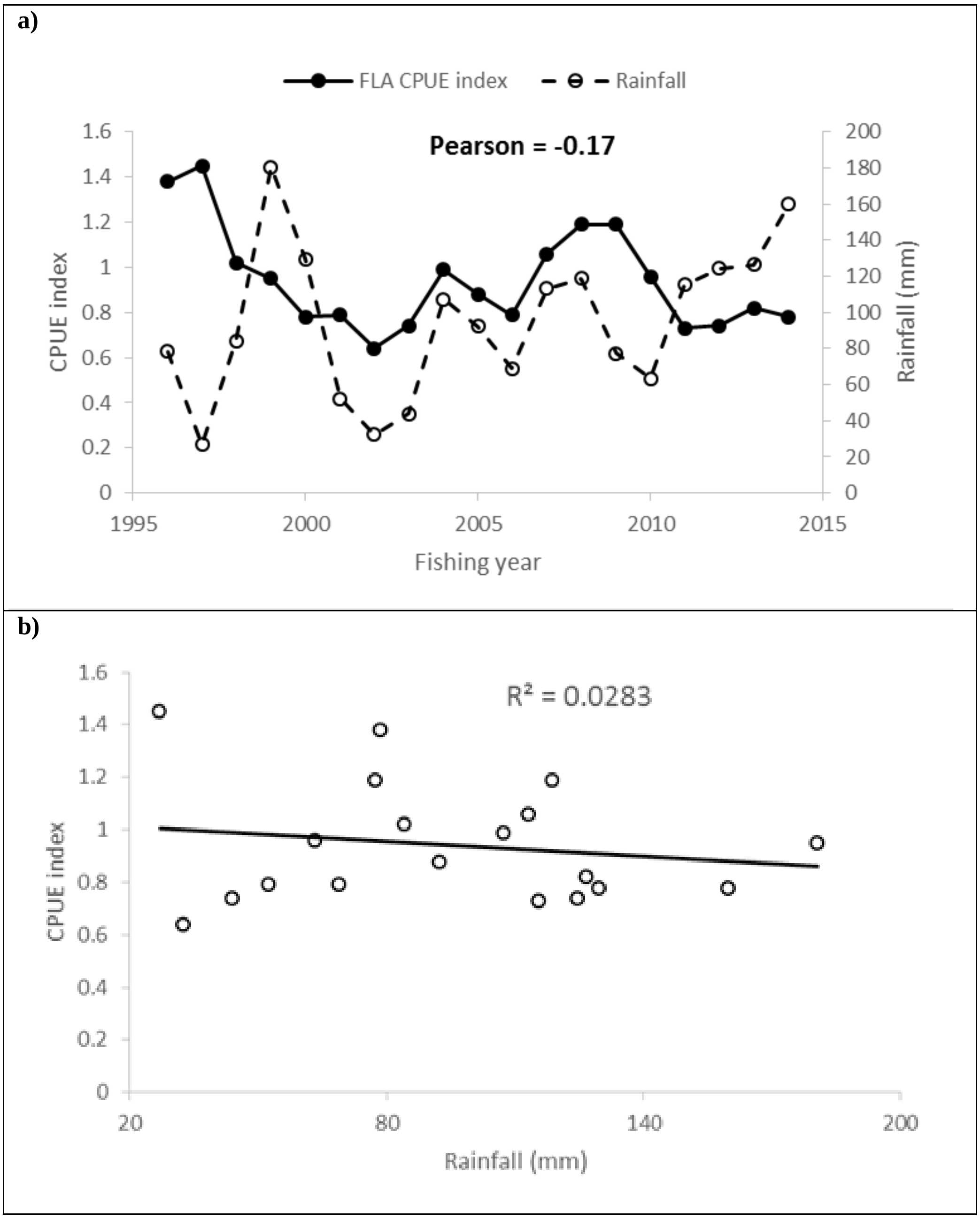

Figure 9: Total rainfall in December (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

3.3 Environmental correlations with Kaipara YBF CPUE (whole juvenile period)

When environmental variables corresponding to the August to December juvenile period (average of two successive years) were offered to the GLM, nitrate concentration was selected as the fifth variable in the GLM model (Table 8). The August to December average nitrate concentration showed a negative correlation (Pearson: -0.42) with the base Kaipara YBF CPUE index (Figure 10).

Table 8: Variables selected by the stepwise GLM standardisation of setnet catch and effort information with environmental variables for the Kaipara Harbour for August-December (values averaged over two consecutive years and lagged to correspond to adult YBF catch). Table shows improvement in model total R^2. Fishing year not offered to model. Selected environmental variables highlighted in grey.

Variable	R^2
Vessel	0.20
Net length	0.23
Month	0.25
Duration	0.27
Nitrate	0.29

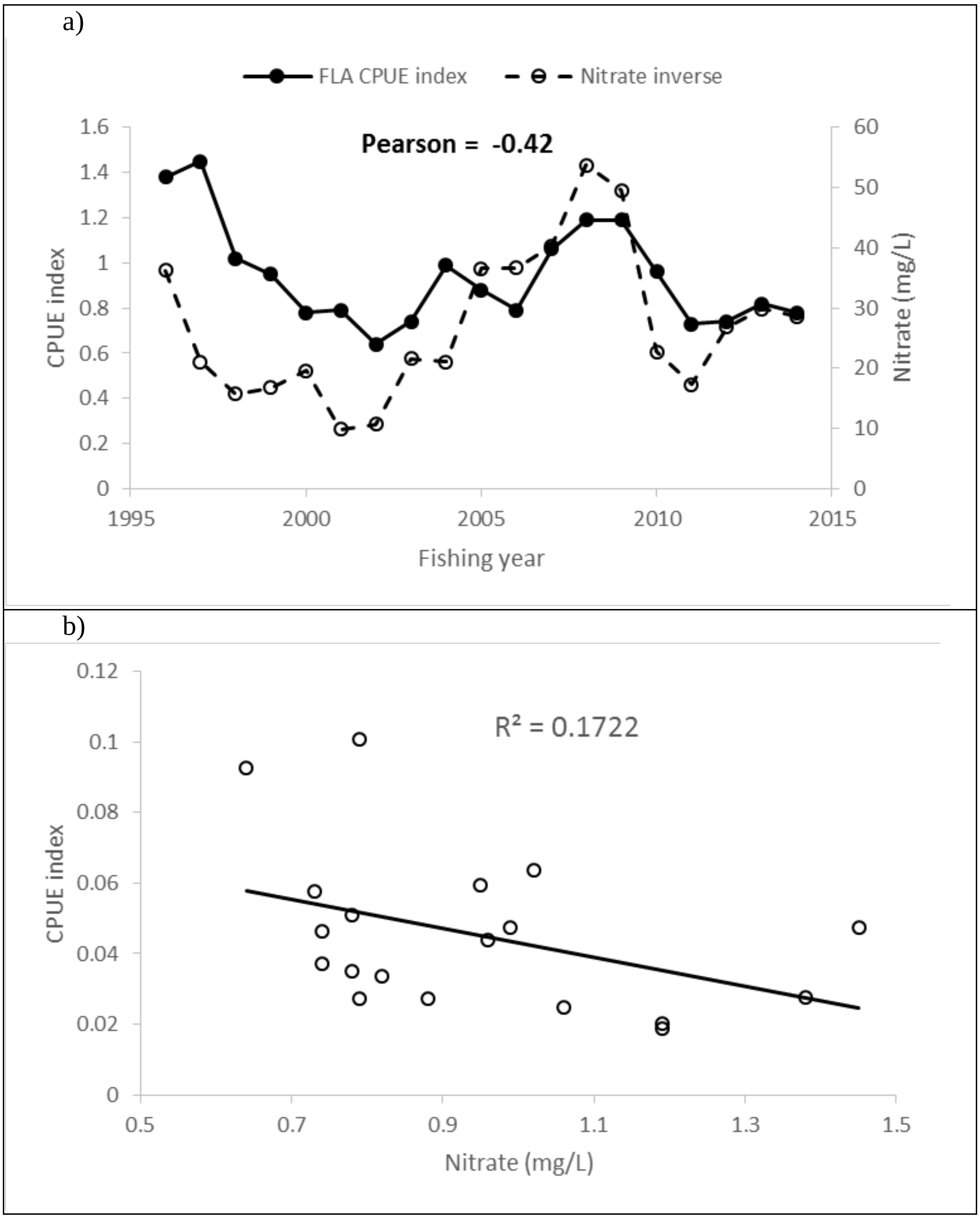

Figure 10: Nitrate (values inversed on plot) for August–December (values averaged over two consecutive years and lagged to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

When environmental variables corresponding to the August to December juvenile period (two year lag only) were offered to the GLM, the SOI index and nitrate concentration were selected as the fifth and sixth variables in the GLM model (Table 9). The August to December average nitrate concentration and SOI index both showed a negative correlation (Pearson: -0.52 and -0.17 respectively) with the base Kaipara YBF CPUE index (Figures 11 and 12). Collinearity analysis suggested that the SOI index and nitrate also had some correlation with each other (R = 0.4; Appendix 2), and the SOI index had a strong correlation with temperature (R = 0.7; Appendix 2).

Table 9: Variables selected by the stepwise GLM standardisation of setnet catch and effort information with environmental variables for the Kaipara Harbour for August–December (lagged by two years to correspond to adult YBF catch). Table shows improvement in model total R^2. Fishing year not offered to model. Selected environmental variables highlighted in grey.

Variable	R^2
Vessel	0.20
Net length	0.23
Month	0.25
Duration	0.27
SOI	0.29
Nitrate	0.30

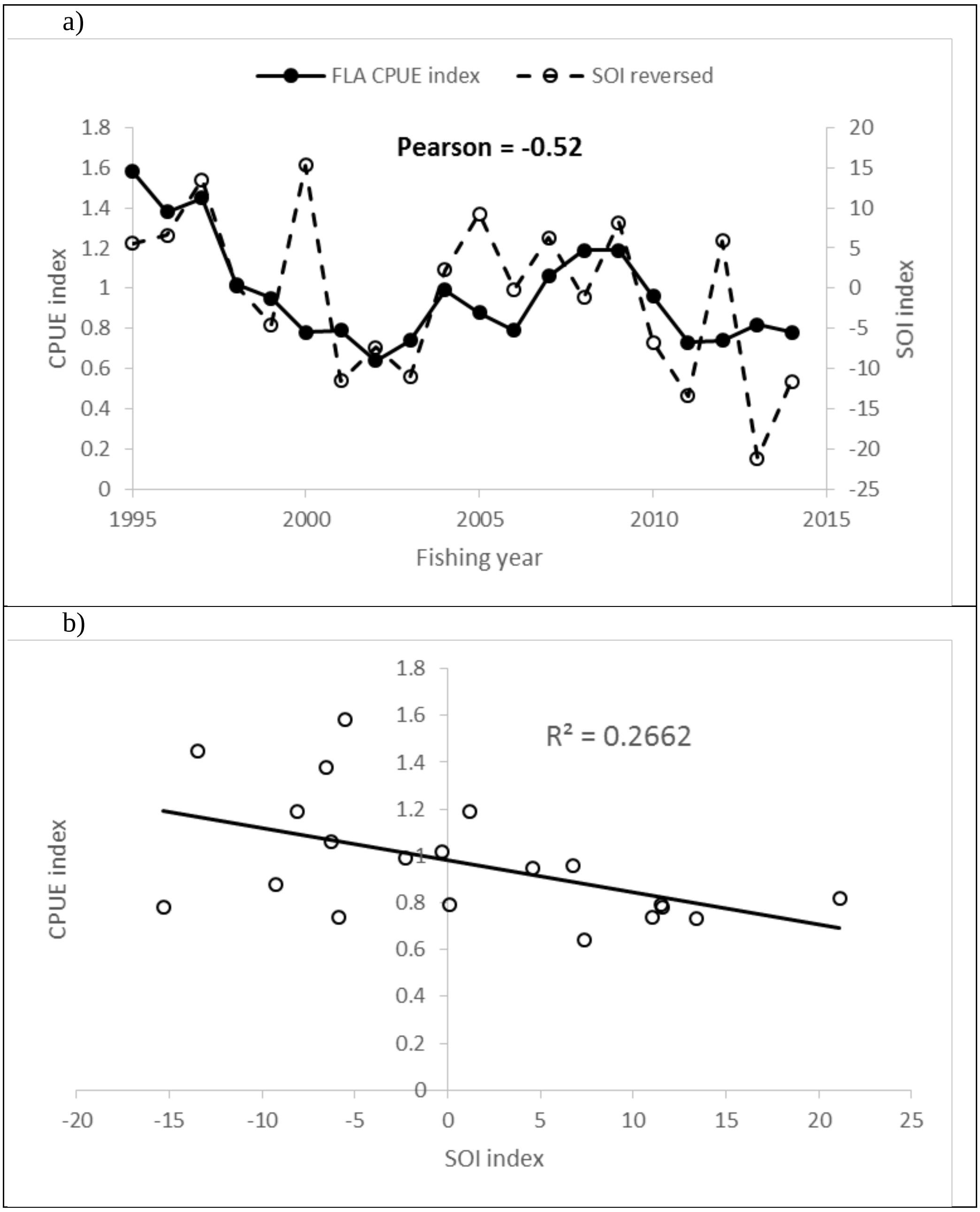

Figure 11: SOI index (sign of values reversed on plot) for August–December (lagged by two years to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

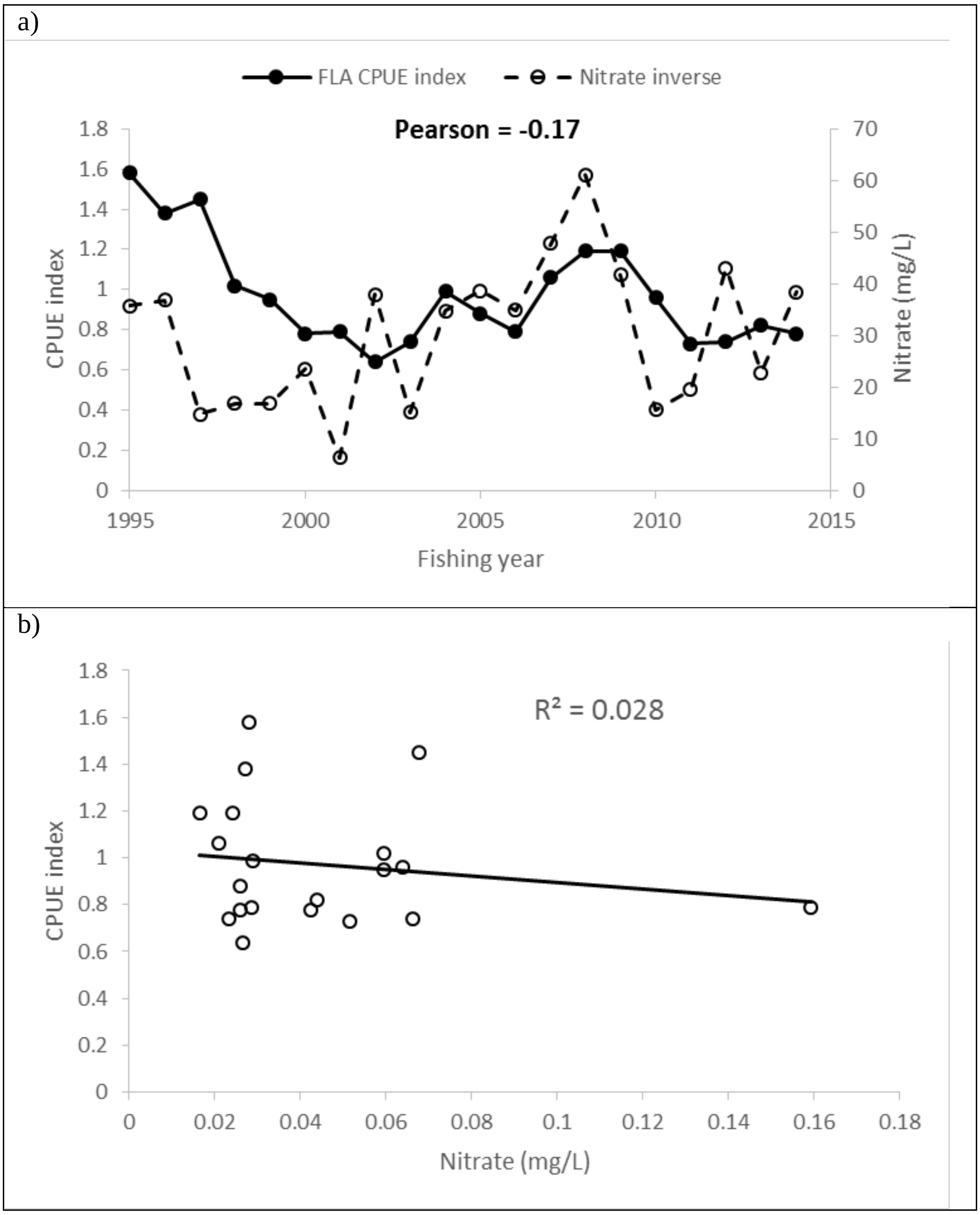

Figure 12: Nitrate (values inversed on plot) for August–December (lagged by two years to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

When environmental variables corresponding to the August to December juvenile period (three year lag only) were offered to the GLM, nitrate concentration was selected as the third variable in the GLM model (Table 10). The August to December average nitrate concentration showed a negative correlation (Pearson: -0.45) with the base Kaipara YBF CPUE index (Figure 13). Collinearity analysis suggested that nitrate also had some correlation with the SOI index (R = 0.4; Appendix 2).

Table 10: Variables selected by the stepwise GLM standardisation of setnet catch and effort information with environmental variables for the Kaipara Harbour for August–December (lagged by three years to correspond to adult YBF catch). Table shows improvement in model total R^2. Fishing year not offered to model. Selected environmental variables highlighted in grey.

Variable	R^2
Vessel	0.20
Net length	0.23
Nitrate	0.25
Month	0.28
Duration	0.30

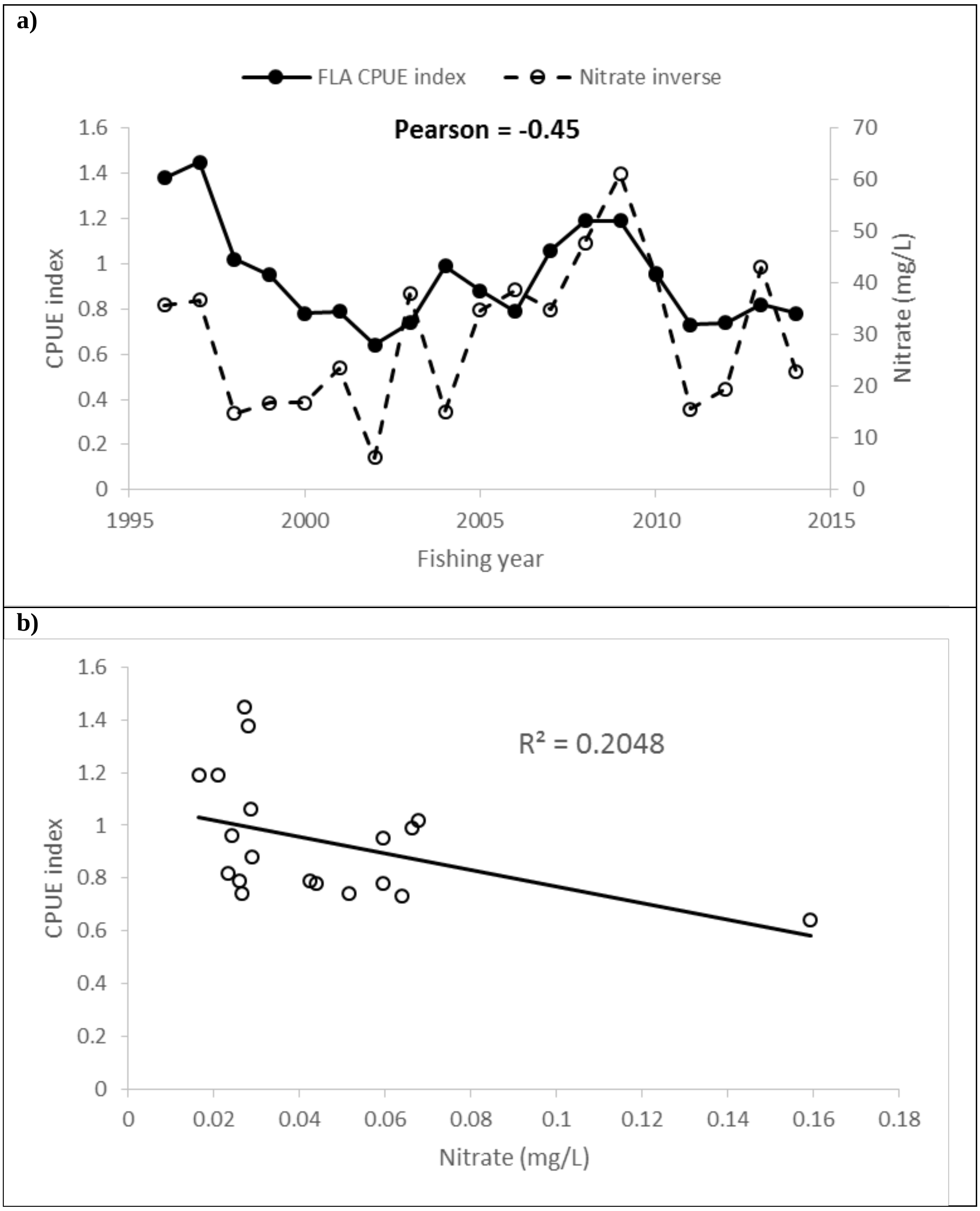

Figure 13: Nitrate (values inversed on plot) for August–December (lagged by three years to correspond to adult YBF catch) against base YBF CPUE for the Kaipara Harbour (a), and corresponding linear regression (b).

3.4 Climatic correlations with entire Kaipara and Manukau YBF CPUE time series

When climatic indices were correlated with the complete base YBF CPUE index (i.e. 1990–2014) for both the Kaipara and Manukau Harbour, reasonable negative correlations (Pearson coefficients > 0.4) were recorded for SOI in the Kaipara Harbour, and were also evident in the Manukau Harbour (Table 11; Figures 14–15). In addition, Trenberth index M2 also expressed a reasonable negative correlation with the base YBF CPUE index for the Manukau Harbour (Table 11; Figure 16). These correlations were performed using the average of environmental variables from the whole August–December juvenile period lagged by two or three years as well as averaging environmental variables from this juvenile period over two consecutive years and lagged appropriately. In the interest of brevity only plots for the two and three year average are presented.

Table 11: Coefficients of correlation (Pearson correlation and R^2 for linear regression) between the Kaipara and Manukau Harbour base YBF CPUE indices and various climatic indices relevant to the upper North Island. Climate index values used in these comparisons are the average of the August–December period (i.e. the time when newly settled YBF exist) within an individual year (and lagged by two or three years to match adult YBF catch) or the average of this same period from two consecutive years (with appropriate lag applied to match adult YBF catch). Values in bold are represented in Figures 14–16.

		Kaipara				Manukau			
		SOI	Z4	M2	MZ4	SOI	Z4	M2	MZ4
2 and 3 year lag average	Pearson	**-0.58**	-0.10	-0.30	0.19	**-0.41**	-0.26	**-0.63**	0.32
	R^2	0.34	0.01	0.09	0.04	0.16	0.07	0.40	0.10
2 year lag	Pearson	-0.47	-0.04	-0.20	0.09	-0.30	-0.11	-0.38	0.19
	R^2	0.22	0.00	0.04	0.01	0.09	0.01	0.15	0.04
3 year lag	Pearson	-0.38	-0.08	-0.18	0.14	-0.29	-0.18	-0.43	0.18
	R^2	0.14	0.01	0.03	0.02	0.09	0.03	0.18	0.03

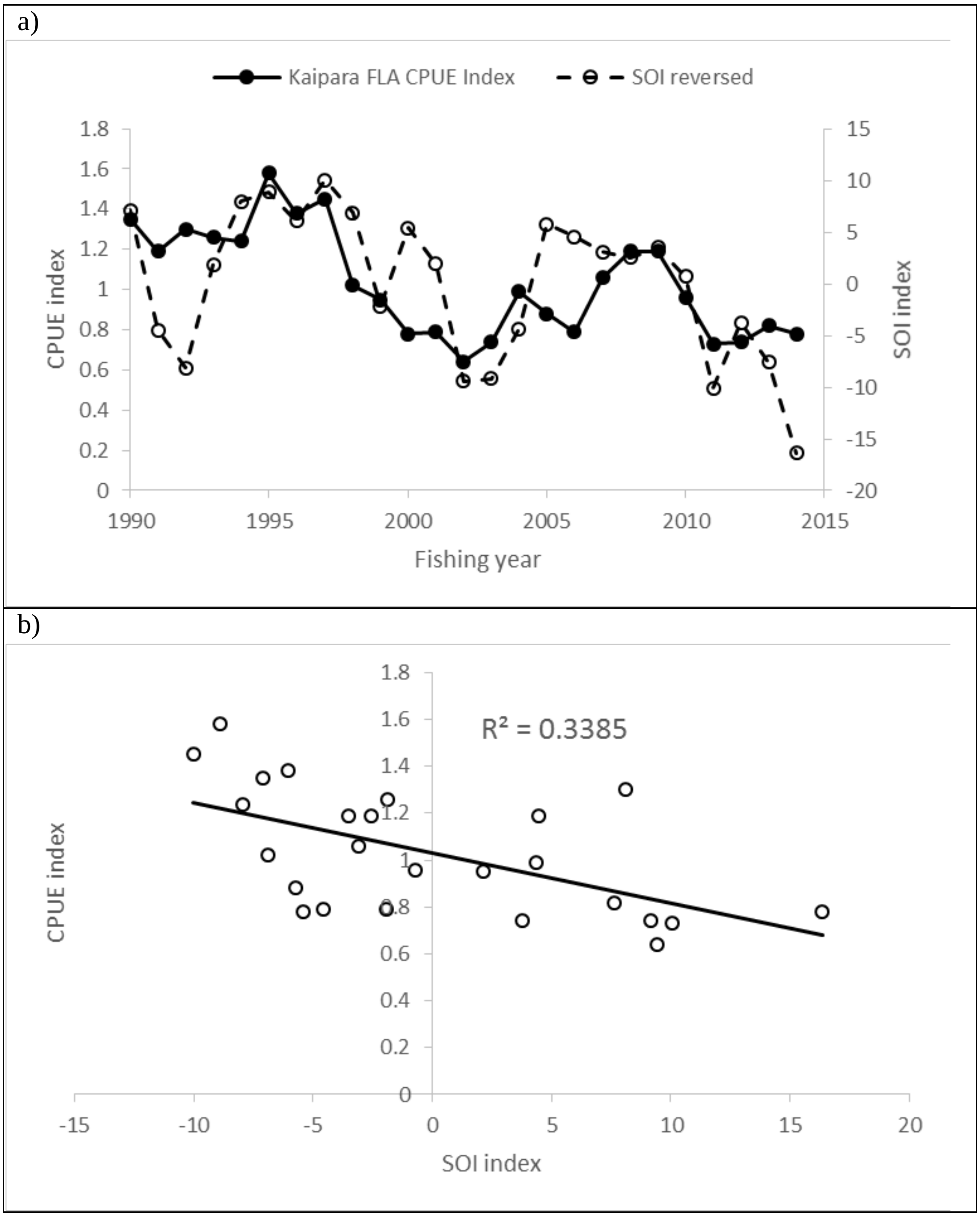

Figure 14: SOI index (sign of values reversed on plot) during August–December averaged over two consecutive years and lagged to correspond to adult YBF catch against the base YBF CPUE index for all years that are available for the Kaipara Harbour (a), and corresponding linear regression (b).

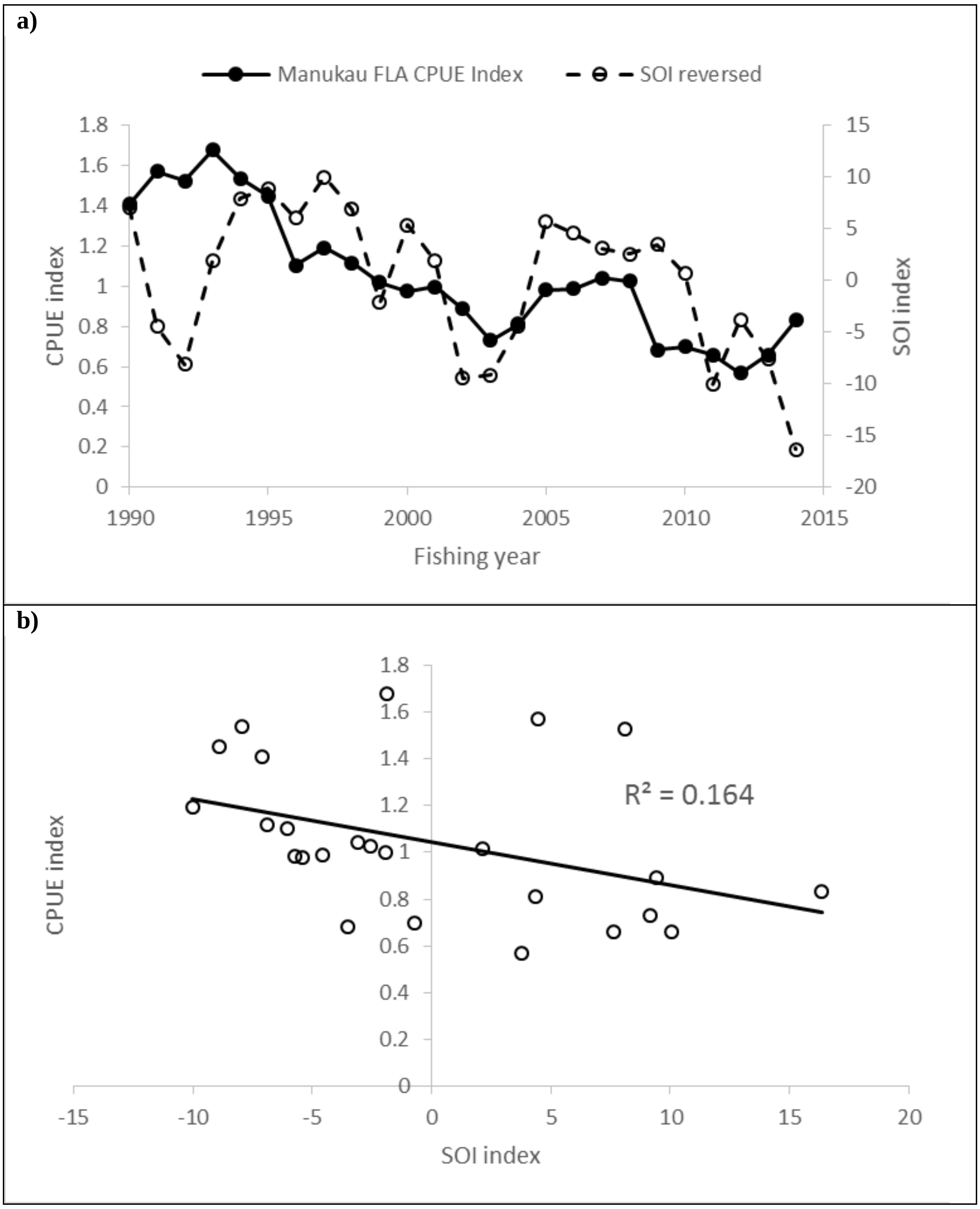

Figure 15: SOI index (sign of values reversed on plot) during August–December averaged over two consecutive years and lagged to correspond to adult YBF catch against the base YBF CPUE index for all years that are available for the Manukau Harbour (a), and corresponding linear regression (b).

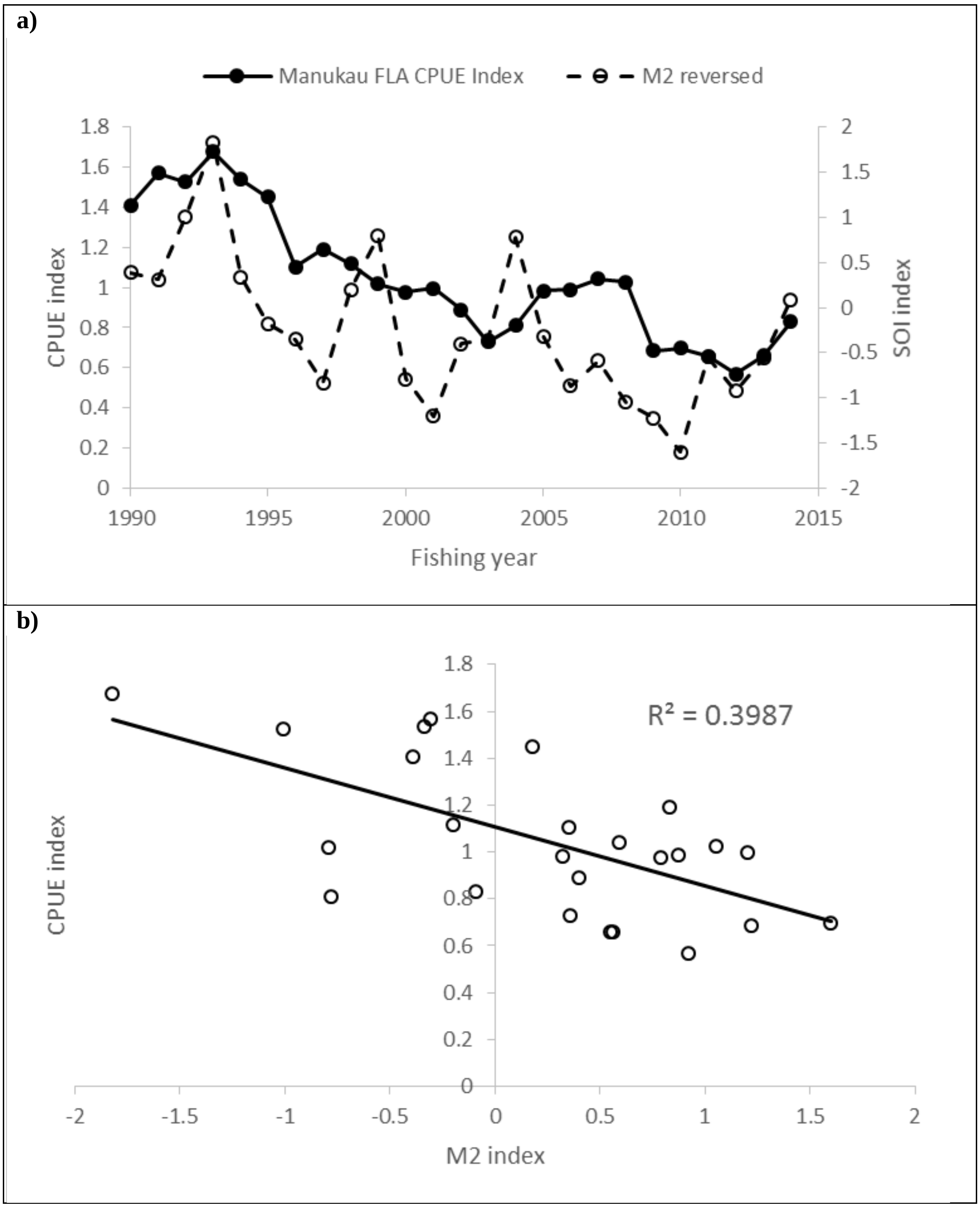

Figure 16: Trenberth M2 index (sign of values reversed on plot) during August–December averaged over two consecutive years and lagged to correspond to adult YBF catch against the base YBF CPUE index for all years that are available for the Manukau Harbour (a), and corresponding linear regression (b).

4. DISCUSSION

YBF offers a unique opportunity to relate commercial catch data with environmental variables because of the restricted number of cohorts within the YBF fishery. Usually information such as year class strength indices derived from fishery independent surveys (e.g. Dunn et al. 2009) would be required to understand the influence of environmental variables on fish abundance. Despite the utility provided by the fast growth and short lifespan of YBF, the fishery still contains two cohorts and the period when YBF settle into estuarine habitats covers multiple months. As such, here we conducted correlations across multiple combinations of environmental variables and catch data. Overall these different permutations suggested that a range of environmental variables may be influencing YBF recruitment success, although environmental variables generally only explained about 2% of GLM model variation. The variables that appeared most often were nitrate concentration and the SOI index, with these variables also often bearing some correlation with each other and also with other climatic variables such as monthly rainfall and temperature. It is important to note that correlations, such as those conducted here, cannot by themselves establish causality. Related variables not included in analyses could be what YBF recruitment is actually responding to. For example, while we demonstrate some relationship between YBF CPUE and nitrate, it is unclear if this merely reflects a relationship of YBF CPUE with other variables that were or were not incorporated in our analysis (Dunn et al. 2009). For example, a variety of variables are often linked to patterns in fish recruitment including temperature, salinity, oxygen, turbulence and advection (reviewed by Ottersen et al. 2004).

The impacts of high nutrient concentrations on estuarine ecosystems are well known. Nutrients such as nitrate, often derived from changes in land–use practise, can lead to eutrophication resulting in a range of effects that are potentially detrimental to fish including: increased algal production, a reduced euphotic zone, hypoxia, and ultimately changes in species distribution and diversity (see Morrison et al. 2009 and references within). The long-term declining trend in YBF CPUE within the Kaipara, could therefore be indicative of a more eutrophied and generally degraded marine environment that is not as supportive to juvenile YBF during vulnerable early life stages (resulting in reduced recruitment). This matches the pattern of long–term intensification of land–use and increased sedimentation that has occurred within the Kaipara Harbour catchment (Swales et al. 2011. Gibbs et al. 2012, Morrison et al. 2014b). Short–term monitoring of intertidal benthic macrofauna within the southern Kaipara, however, suggests that these communities are in a relatively healthy state (Hailes & Hewitt 2012). The health of these more central harbour locations, however, may not necessarily be a good indicator of the health of the inlets that juvenile YBF utilise (in the Manukau Harbour inlets generally have poor benthic macrofauna community health while central harbour locations remain healthy (Greenfield et al. 2013)).

The existence of correlations between climatic variables and YBF CPUE from both the Kaipara and Manukau Harbours seen in the present study suggests that regional scale climate forcing is of relevance to YBF recruitment success in general, even if the strength and relationship to specific climate indices does vary between the two harbours. In a previous study conducted specifically for the Manukau Harbour (McKenzie et al. 2013) climate variables were also offered to a GLM model of YBF CPUE but not selected. If that model had been afforded the longer time series available here (17 compared to 25 years), climatic variables may have also been selected. In terms of an explanation of why correlations occurred with climatic variables, it is often assumed that larval survival and recruitment success are greater when climate conditions promote increased pelagic community productivity (see references within Dunn et al. 2009). As YBF spawn outside of the Kaipara Harbour on the open coast (Mutoro 1999), the relationship between YBF catch and the SOI index seen in the present study may reflect a response of YBF larvae to pelagic community productivity on the open west coast shelf. Specifically, under SOI negative (El Niño) conditions southwesterly winds are more common, which could potentially induce upwelling and make nutrient rich bottom water available for surface production. To our knowledge, no oceanographic studies have been conducted on the northern North Island west coast shelf, so it is not possible to confirm if this situation occurs or not. If this situation was true, however, then the selection of other environmental variables within the GLMs (e.g. temperature monthly rainfall and nitrate) could merely reflect their relationship to regional climate variation as opposed to any explanatory mechanism. Alternative explanations connected to climate variation also exist, however. For example, reduced temperatures expected under El Niño conditions could be prefered by YBF larvae, certain climatic driven processes may interact with the catchment and within harbour circulation patterns promoting sedimentation and eutrophication to the detriment of juvenile YBF, and climate conditions could alter the ability of YBF post-larvae to enter and successfully settle within the Kaipara Harbour itself.

5. MANAGEMENT IMPLICATIONS

While climate variation and the general health of the Kaipara Harbour are not able to be controlled by fisheries management, understanding how they influence fishery catch has great utility. In particular, understanding future trends in both climate and Kaipara Harbour health could be important considerations for YBF extraction levels.

With regard to harbour health, Auckland Council initiated an intertidal benthic community monitoring programme in 2009. In the future this programme will have utility in documenting harbour-wide degradation if it were to occur, but may not be that relevant to the upper reaches which are the locations that juvenile YBF inhabit, and which are also prone to degradation. Nonetheless, future investigations of YBF CPUE should consider incorporating this benthic community data once a reasonable time series has been established.

With regard to climate variations, it is unclear how climate change will affect the prevalence of SOI negative conditions (Cai et al. 2014, 2015), which appear to promote increased YBF CPUE. In the medium to short–term, however, it is likely that SOI negative conditions (which are favourable for YBF recruitment) will continue to remain less prevalent; SOI cycles are modulated by Interdecadal Pacific Oscillation (IPO), which has been in a phase that favours SOI positive conditions since about 1998 (Salinger et al. 2001). Continuing to monitor YBF CPUE, especially in response to any major shifts in climatic variables, would therefore be a prudent approach to ensuring the continued sustainability of YBF catch.

6. ACKNOWLEDGMENTS

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APPENDIX 1: Final Research Progress Report for ENV201308-A "Investigating the feasibility of establishing a relationship between flatfish catch and environmental variables"

FORM 4

CONTENT AND FORMAT OF THE
PROGRESS REPORT

Date:	10 October 2014
Research Provider:	National Institute of Water and Atmospheric Research
Project Code:	ENV2013-08A
Project Title:	Investigating the feasibility of establishing a relationship between flatfish catch and environmental variables
Principle Investigator:	Darren Parsons
Authors:	Darren Parsons, Richard Bian, Jeremy McKenzie
Project Start Date:	1 July 2014
Expected Project End Date:	31 October 2014

Research Progress Report for ENV2013-08A as of 10/10/2014, by Darren Parsons

EXECUTIVE SUMMARY

For some fish species important habitats, such as nurseries, are a fundamental requirement to maintaining population productivity. Previous research has suggested that flatfish catch in the Manukau Harbour is related to the water quality within the harbour when the relevant cohorts of fish would have been juveniles. Auckland Council and Northland Regional Council also monitor water quality from 16 sites within the Kaipara Harbour, but have only done so since 2009. At Shelly Beach, however, water quality has been recorded since 1991. The objective of this project is to assess water quality data sets from the Kaipara Harbour, to see if they have utility to perform a correlation with commercial flatfish catch, similar to that conducted for the Manukau Harbour. Water quality data was provided by Auckland Council and Northland Regional Council. Datasets were merged, constrained to the relevant period (2009-2014), and obvious outlier data points (i.e. those well beyond the normal range of variability) were removed after conducting preliminary plots. For each site we correlated each of the nine water quality variables with the same variable recorded at Shelly Beach. Water quality recordings across all 16 sites were not always conducted on the same day, but were considered comparable if from the same month. For each of these plots we also produced Pearson's product-moment correlation coefficients and performed tests of whether the slope of the regression line was different from 0. We then limited the specific correlations we considered as relevant by qualitatively identifying regions important to juvenile (< 150 mm total length) yellow belly flounder using abundance data from a series of beach seine surveys conducted by NIWA. This led to the identification of three regions, which corresponded to five water quality sites. For each of these sites we made an interpretation of the utility of Shelly Beach to predict relevant water quality variables at that particular site. For dissolved oxygen, water temperature, nitrate and ammonia Shelly Beach was a very good or good predictor across all three regions identified above. For turbidity, suspended solids and soluble phosphorous the Shelly Beach site provided some predictive capacity within the region closest to Shelly Beach, but this capacity was diminished in the other regions. In a previous study of the Manukau Harbour dissolved oxygen, ammonia, and turbidity were identified as being correlated with flatfish catch. If that were also true for the Kaipara Harbour then the assessment of water quality data for the Kaipara Harbour conducted here suggests that the long-term water quality time series

recorded at Shelly Beach should also have utility in correlating flatfish catch with environmental variables.

OBJECTIVES

Overall objective

To determine if there is a relationship between changing environmental variables and flatfish abundance in the Kaipara Harbour.

Objective for this report

1. Explore Kaipara Harbour environmental data to determine its representativeness

INTRODUCTION

Many coastal fish species utilise estuarine nursery habitats when they are juveniles (Beck et al. 2001) and thus provide an important function for coastal fisheries. If these critical habitats become degraded (Morrison et al. 2009; Morrison et al. 2014), then recruitment to adult fish populations may be reduced in later years. In a previous report (McKenzie et al. 2013) we observed relationships between environmental variables (dissolved oxygen, ammonia, and turbidity; when lagged to represent the period when juveniles would have been present) and commercial yellow belly flounder (*Rhombosolea leporina*) (YBF) catch within the Manukau Harbour. This result suggested that water quality, and presumably the influence of land-use practises on water quality, may be negatively affecting the recruitment success of YBF and other flatfish species. Here we propose to assess whether a similar investigation could be undertaken for YBF in the Kaipara Harbour. If a similar relationship is shown this would suggest a more generic influence of water quality on recruitment success for flatfish populations. With this in mind the overall objective here is to determine if there is a relationship between changing environmental variables and flatfish abundance in the Kaipara Harbour.

An environmental time series is required to investigate the influence of environmental variables on YBF catch in the Kaipara Harbour. Auckland Council and Northland Regional Council routinely collect environmental information from 16 sites spread around the Kaipara Harbour (Fig. 1). These data include: turbidity, water temperature, suspended solids, nitrate, ammonia, dissolved oxygen, total phosphorus, dissolved phosphorus, and Enterococci. For 15 of these sites, however, that time series has limited utility as it only dates back to 2009 (compared to the time series for flatfish[1] catch in the Kaipara Harbour which dates back to 1989). One site (Shelly Beach) provides significantly more capacity for comparison with flatfish catch data as it began in 1991. It is unknown, however, if the Shelly Beach site is generally representative of environmental conditions in all Kaipara harbour regions of high juvenile YBF abundance. This is an important consideration, because it is possible that the survival of juvenile YBF and the subsequent influence this may have on adult abundance and catch may be determined by environmental conditions in other parts of the harbour. In this report we compare the environmental time series at Shelly Beach with 14 other sites that are monitored within the Kaipara Harbour for the period when all sites were monitored (2009 onwards). Actually establishing the relationship between YBF catch and environmental variables would be conducted as a follow on project dependent on the level of feasibility determined in this project.

METHODS & RESULTS

Water quality data sets were obtained from Auckland Council and Northland Regional Council and merged. There have been a number of changes in the variables recorded by the councils, so we ensured that only the variables that were available over the entire time series at Shelly Beach (from

[1] Note: greater than 95% of the commercial flounder catch in the Kaipara harbour is YBF (McKenzie et al. 2013)

1991) were included in the merged dataset. This merged dataset was then constrained to the period between May 2009 and April 2014 i.e. from when the councils expanded their water quality monitoring network until now.

Each month water quality sampling was generally conducted across all sites on the same day, however, on some occasions sampling may have been conducted over two or three days. We chose to retain these measurements by performing correlations where we ignored the specific day, and compared water quality measurements if they were taken within the same month. For each site we plotted each water quality variable against the same variable for the Shelly Beach site (our primary site of interest due to the much longer time series that exists at this location). These initial plots revealed that the water quality dataset contained a small number of outlier data points. We removed obvious outliers from the dataset before re-plotting the data (Fig. 2). We also conducted Pearson's product-moment linear correlations; the regression lines from this correlation, the correlation coefficients, and tests of whether the slope of these regressions differed from 0 are reported on each plot within Fig. 2.

Not all of the sites where water quality data are collected within the Kaipara Harbour are necessarily representative of locations where juvenile yellow belly flounder are present in any abundance. We therefore sought to limit the specific correlations we considered as relevant by qualitatively identifying regions important to juvenile (< 150 mm total length) YBF using abundance data from a series of beach seine surveys conducted by NIWA (Fig. 3; M. Morrison and M. Francis unpubl. data). From this data we identified three regions as likely being important to juvenile YBF, which eliminated 10 water quality sites. Correlation coefficients and P values for the remaining five sites (across the three regions identified) are presented in Table 1. To aid with interpretation we have shaded cells based on how well the Shelly Beach site performed as a predictor. This interpretation was largely based on the correlation coefficients and P values, but also included a subjective component (Table 1).

DISCUSSION

For three water quality variables (dissolved oxygen, water temperature, and nitrate) Shelly Beach appeared to serve as a very good predictor across the three regions identified as being important to juvenile YBF within the Kaipara Harbour. For these variables, correlation coefficients were always very high (> 0.8). For the other six variables Shelly Beach appeared to have at least some utility as a predictor of water quality, except for predicting Enterococci, which was highly variable. The best performing of these other variables was ammonia, for which the Shelly Beach site provided good predictive capacity for all three of the yellow belly flounder regions. For turbidity, suspended solids and soluble phosphorous the Shelly Beach site provided some predictive capacity within the South Kaipara region, but this was diminished in the regions further away from Shelly Beach.

In the previous study of the Manukau Harbour the environmental variables that were correlated with commercial flatfish catch were dissolved oxygen, ammonia, and turbidity (McKenzie et al. 2013). The correlations that we conducted here suggest that Shelly Beach has a differing level of predictive capacity for these variables within relevant parts of the Kaipara Harbour. For dissolved oxygen the predictive capacity is very good ($r \geq 0.86$) across all of the regions identified as being important to juvenile YBF. For ammonia the predictive capacity is good ($r \geq 0.7$) within three of the above regions. For turbidity the predictive capacity is good ($r = 0.72$) within one of the above regions and poor ($r \leq 0.54$) within the remaining two regions.

RECOMMENDATIONS

The correlations of water quality variables from sites around the Kaipara Harbour conducted here suggest that the long term data set for Shelly Beach has utility for performing an analysis of commercial YBF catch and environmental variables. We therefore recommend that the second stage of this project be undertaken and the long term water quality data set at Shelly Beach (specifically: dissolved oxygen; ammonia; turbidity; temperature; nitrate) be incorporated into a catch per unit effort analysis for YBF in the Kaipara Harbour. This outcome of this analysis, however, will be influenced by two assumptions that need to be considered, but are difficult to fully assess at this stage. They relate to: (1) the environmental variables that juvenile YBF respond to, specifically in the Kaipara Harbour, and (2) the regions within the Kaipara Harbour that juvenile yellow belly flounder actually utilise. With regard to specific environmental variables, it is not possible to ascertain in advance which environmental variables will be important to YBF. If they are the same as for our previous analysis in the Manukau Harbour (McKenzie et al. 2013) then Shelly Beach has good utility. With regard to juvenile YBF distribution within the Kaipara, we have incorporated the best information available. Some uncertainty remains, however, as overall these beach seine surveys captured a relatively low number of juvenile YBF. If the northern and northeastern parts of the Kaipara Harbour are actually also important to YBF this would reduce the utility of Shelly Beach (correlations were generally poor in these areas for most water quality variables).

ACKNOWLEDGEMENTS

Thanks to Auckland Council (Jarrod Walker) and Northland Regional Council (Richard Griffiths) for providing water quality data sets and Mark Morrison and Malcolm Francis for providing juvenile yellow bellyflounder beach seine data and useful discussion therein.

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PUBLICATIONS

There are no other publications currently associated with this project.

DATA MANAGEMENT

All data are held on a secure server that is regularly backed up and all data will be ultimately stored on Ministry databases.

Table 1: Correlation between Kaipara Harbour council sampling sites with Shelly Beach for nine water quality variables from May 2009 to April 2014. Sites are ordered from closest (Makarau Estuary) to farthest (Hargeaves Basin) from Shelly Beach. Vertical lines separate water quality sampling sites into three regions that correspond to areas where juvenile yellow belly flounder are abundant (see Fig. 3 for more detail). Correlation coefficients refer to Pearson's product-moment correlations and P values refer to tests of whether the slope of that line included 0. Dark grey cells: interpreted as Shelly Beach having definite utility for predicting that variable for that site (Pearson's r usually > 0.6 and often > 0.8, correlation not determined by high leverage points); Light grey cells: interpreted as Shelly Beach having some utility for predicting that variable for that site (Pearson's r usually > 0.5, potential for high leverage points to influence the strength of the correlation). Where no correlation coefficients or P values are listed that variable was not measured at that site.

Yellow belly flounder Region	**South Kaipara**		**Tauhoa**	**Oruawharo**	
Water quality site	*Makarau Estuary*	*Kaipara River*	*Hoteo River Mouth*	*Oruawharo River*	*Hargreaves Basin*
Dissolved Oxygen	r = 0.9 P<0.01	r=0.96 P<0.01	r=0.92 P<0.01	r=0.86 P<0.01	r=0.87 P<0.01
Ammonia	r=0.79 P<0.01	r=0.87 P<0.01	r=0.7 P<0.01	r=0.6 P<0.01	r=0.76 P<0.01
Turbidity	r=0.54 P<0.01	r=0.72 P<0.01	r=0.42 P<0.01	r=0.36 P=0.01	r=0.42 P<0.01
Temperature	r=0.98 P<0.01	r=0.99 P<0.01	r=0.98 P<0.01	r=0.98 P<0.01	r=0.98 P<0.01
Suspended solids	r=0.48 P<0.01	r=0.69 P<0.01	r=0.46 P<0.01		
Nitrate	r=0.85 P<0.01	r=0.9 P<0.01	r=0.8 P<0.01	r=0.81 P<0.01	r=0.81 P<0.01
Total Phosphorous	r=0.46 P<0.01	r=0.41 P=0.03	r=0.36 P<0.01	r=0.57 P<0.01	r=0.33 P=0.03
Soluble Phosphorous	r=0.4 P<0.01	r=0.6 P<0.01	r=0.49 P<0.01	r=0.45 P<0.01	r=0.39 P<0.01
Enterococci	r=0.34 P=0.01	r=0.38 P=0.05	r=0.48 P<0.01	r=0.56 P<0.01	r=0.65 P<0.01

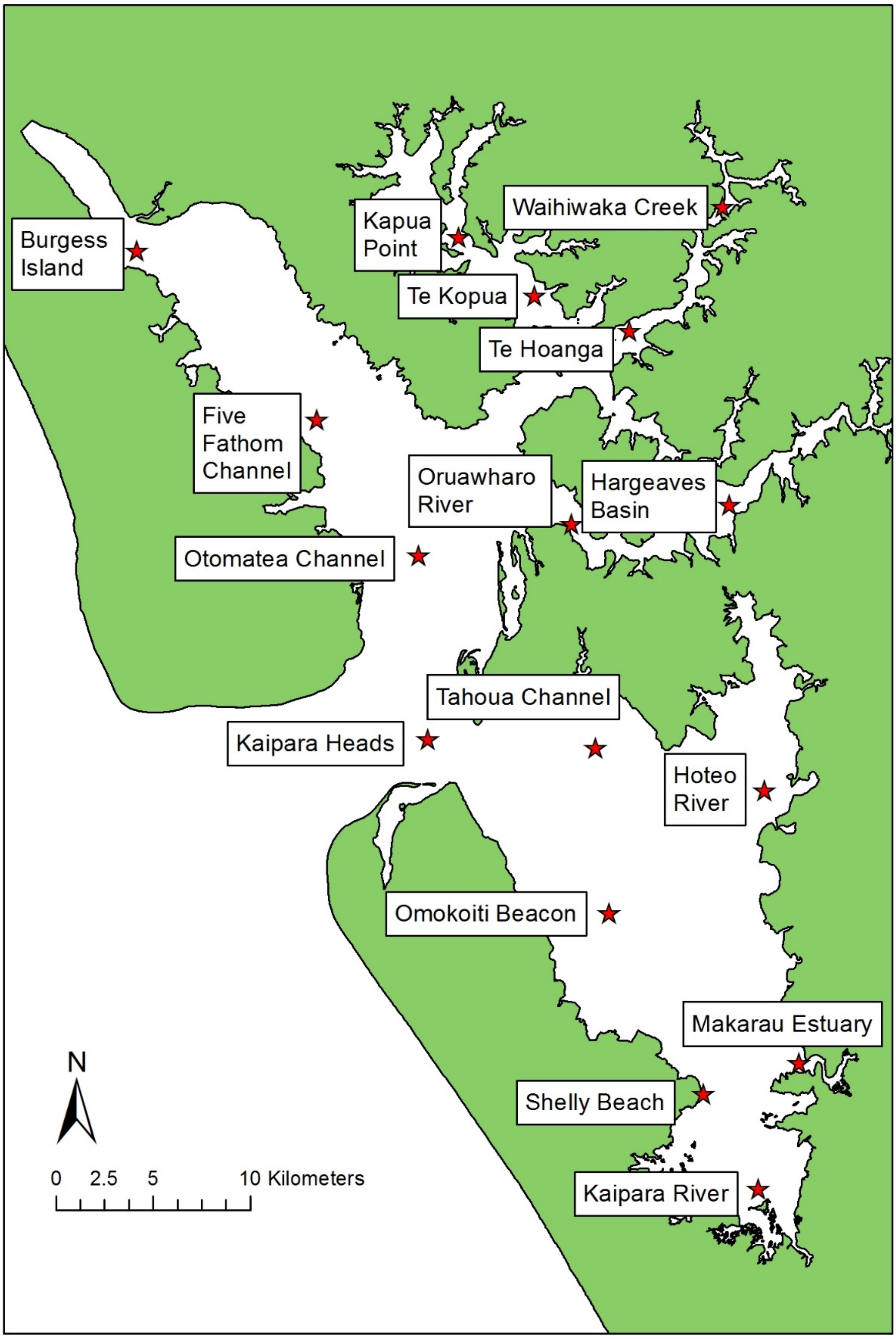


Fig. 1: Map of the Kaipara Harbour and the locations where Auckland Council and the Northland Regional Council collect water quality samples. Note the location of Shelly Beach to the south.

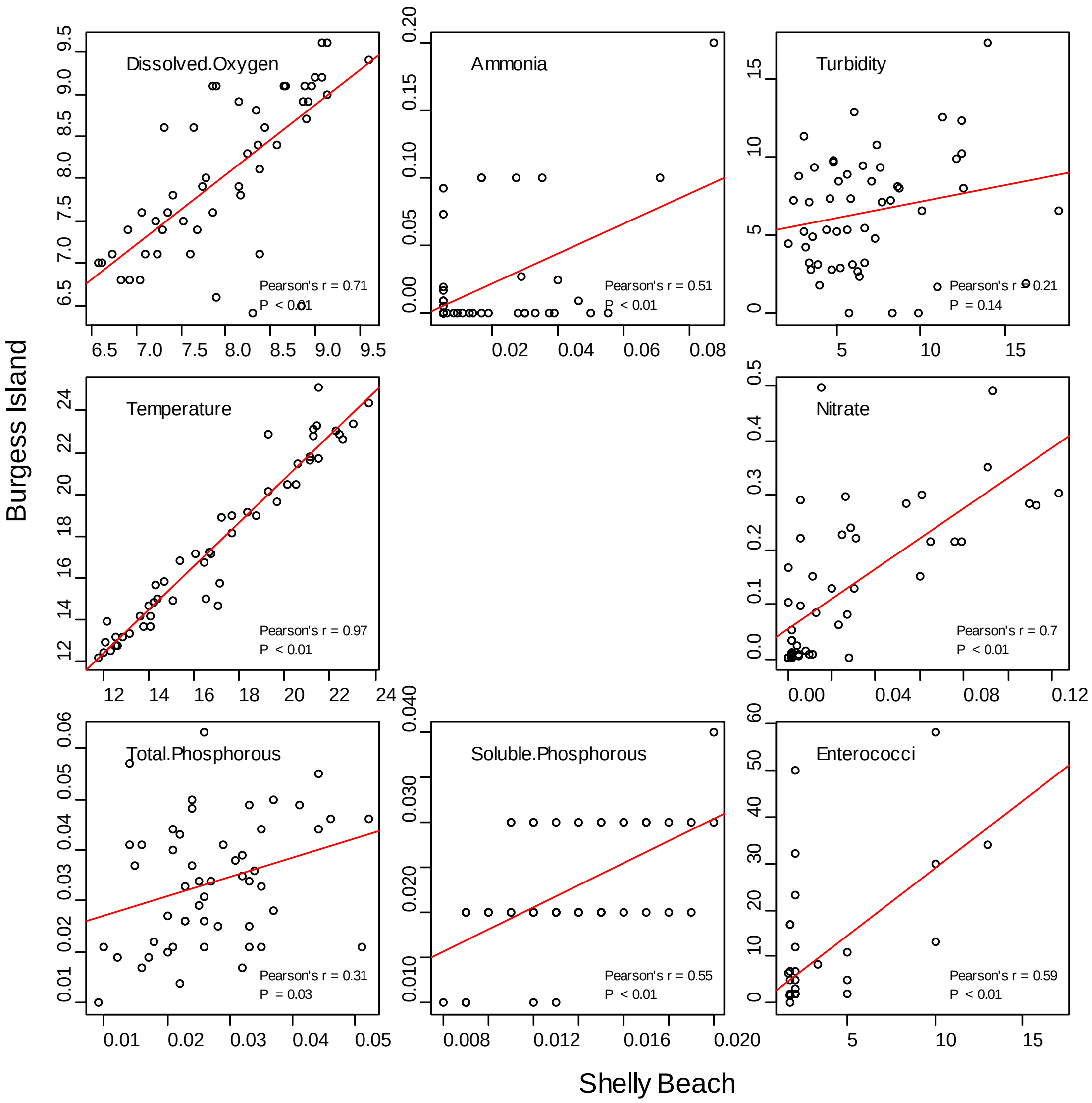


Fig. 2: Correlation between Kaipara Harbour council sampling sites and Shelly Beach for nine water quality variables from May 2009 to April 2014. The Shelly Beach site is always represented on the horizontal axis and the other site used in the comparison is on the vertical axis. Correlation lines and coefficients refer to Pearson's product-moment correlations and P values refer to tests of whether the slope of that line included 0. Where a plot is missing, that variable was not measured for that site.

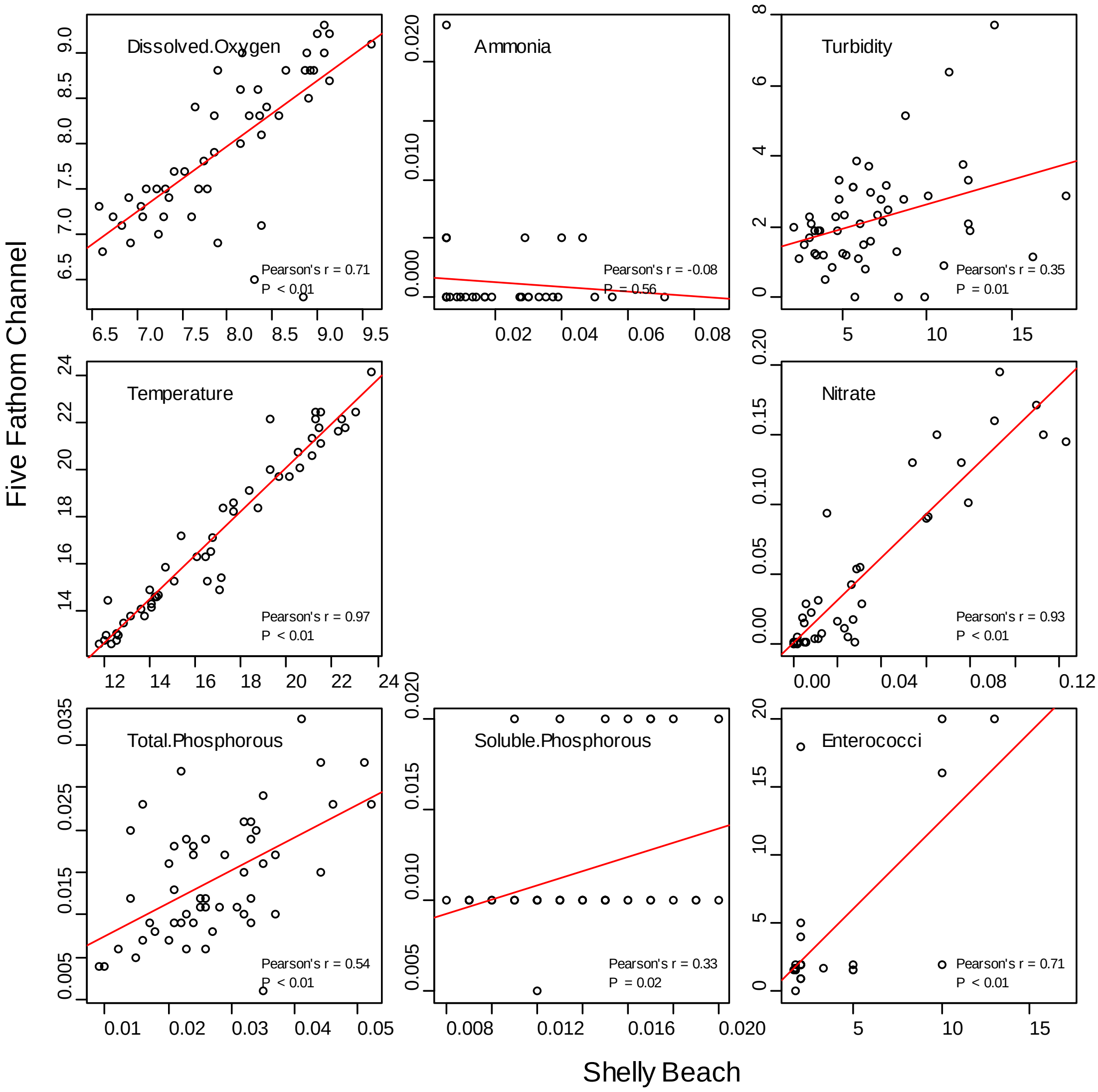
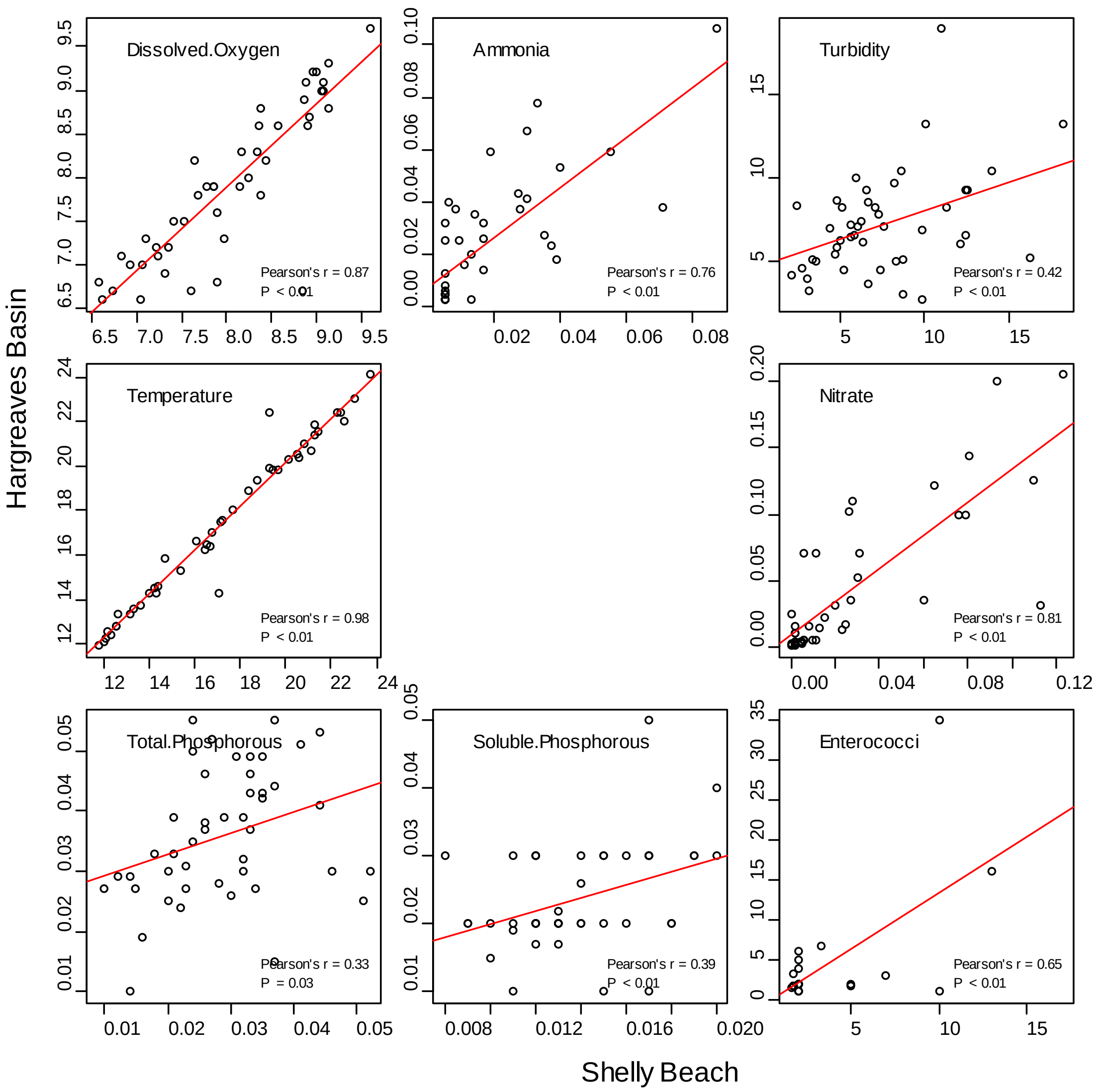


Fig. 2 continued



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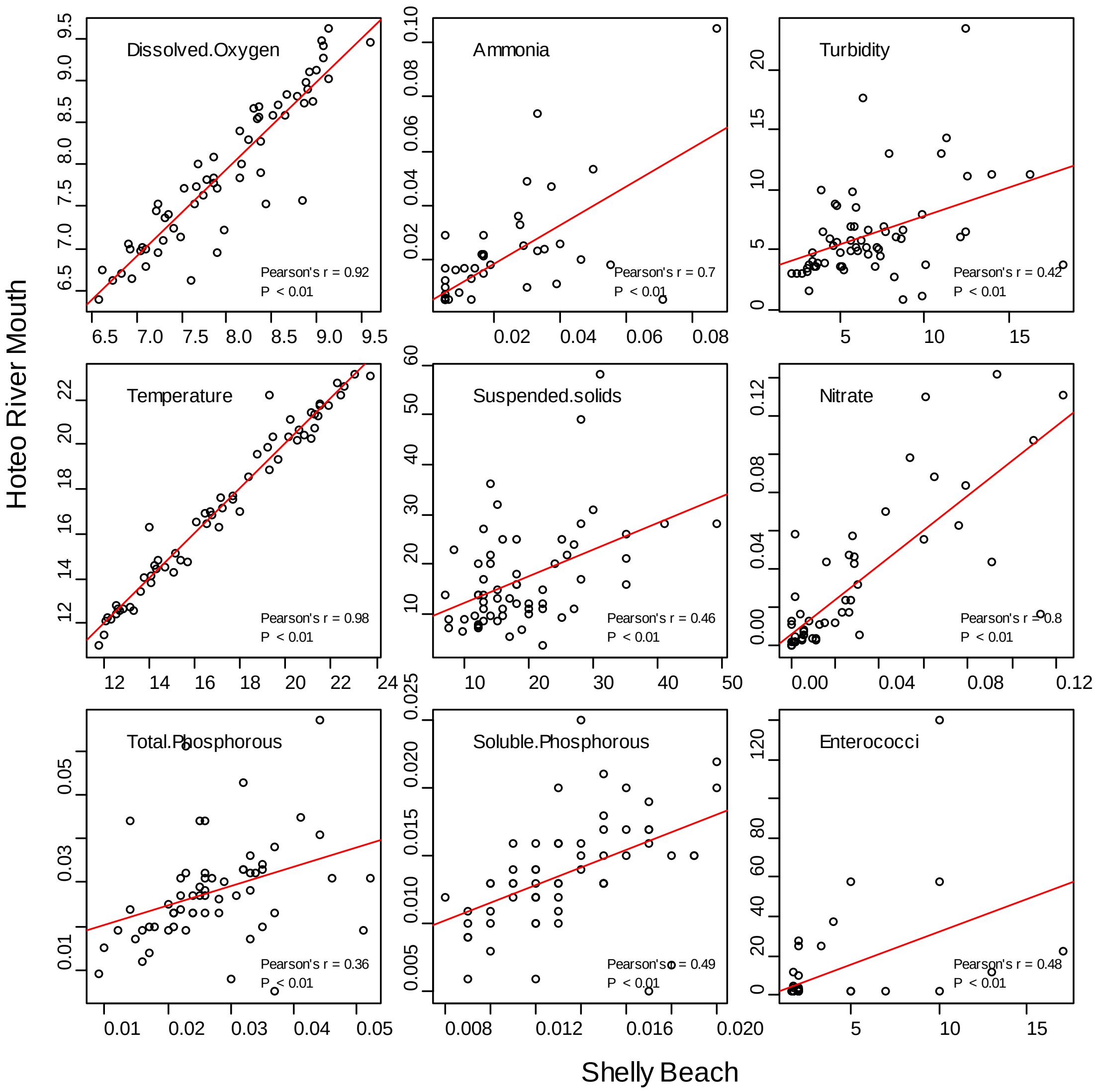

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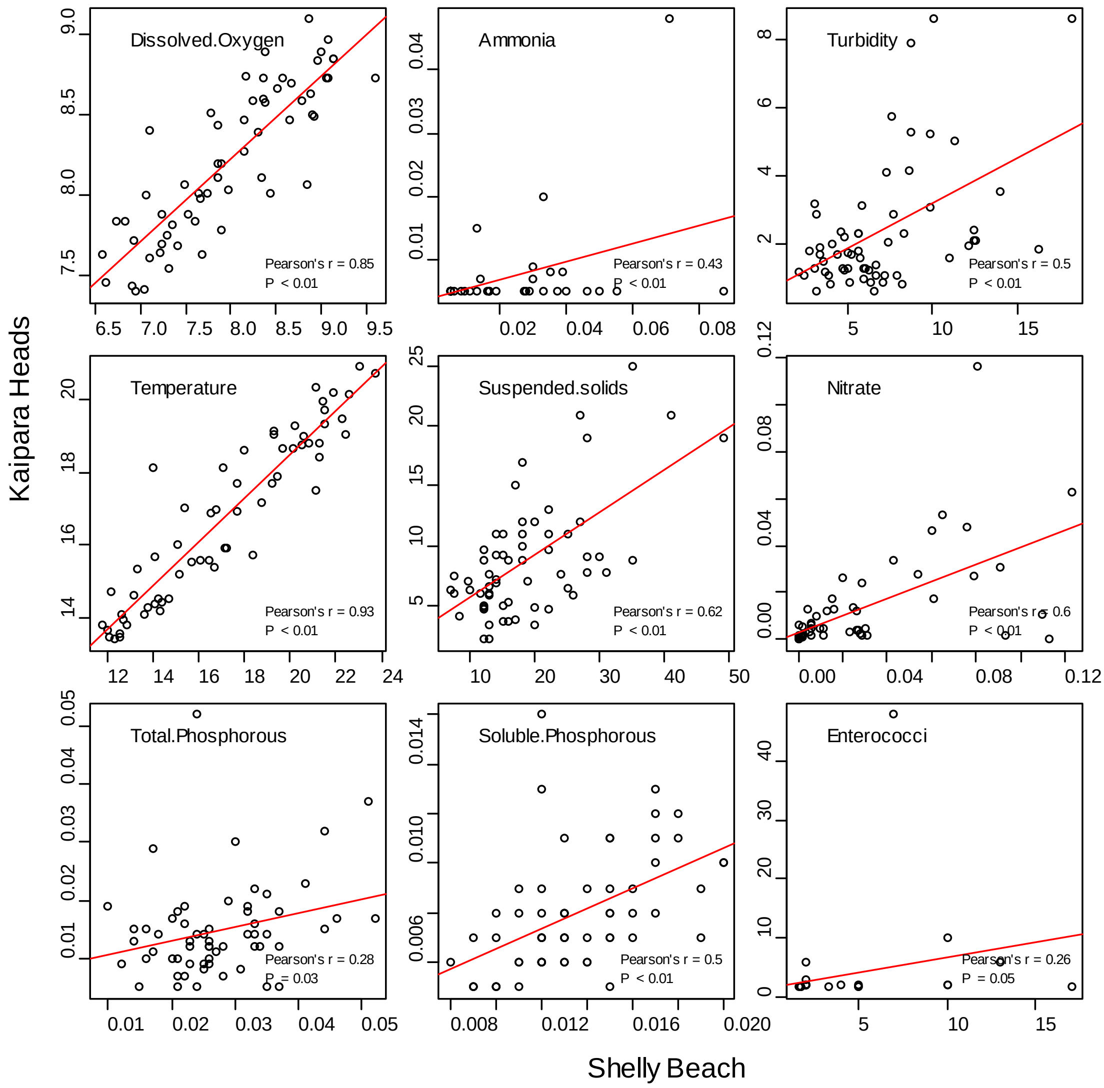

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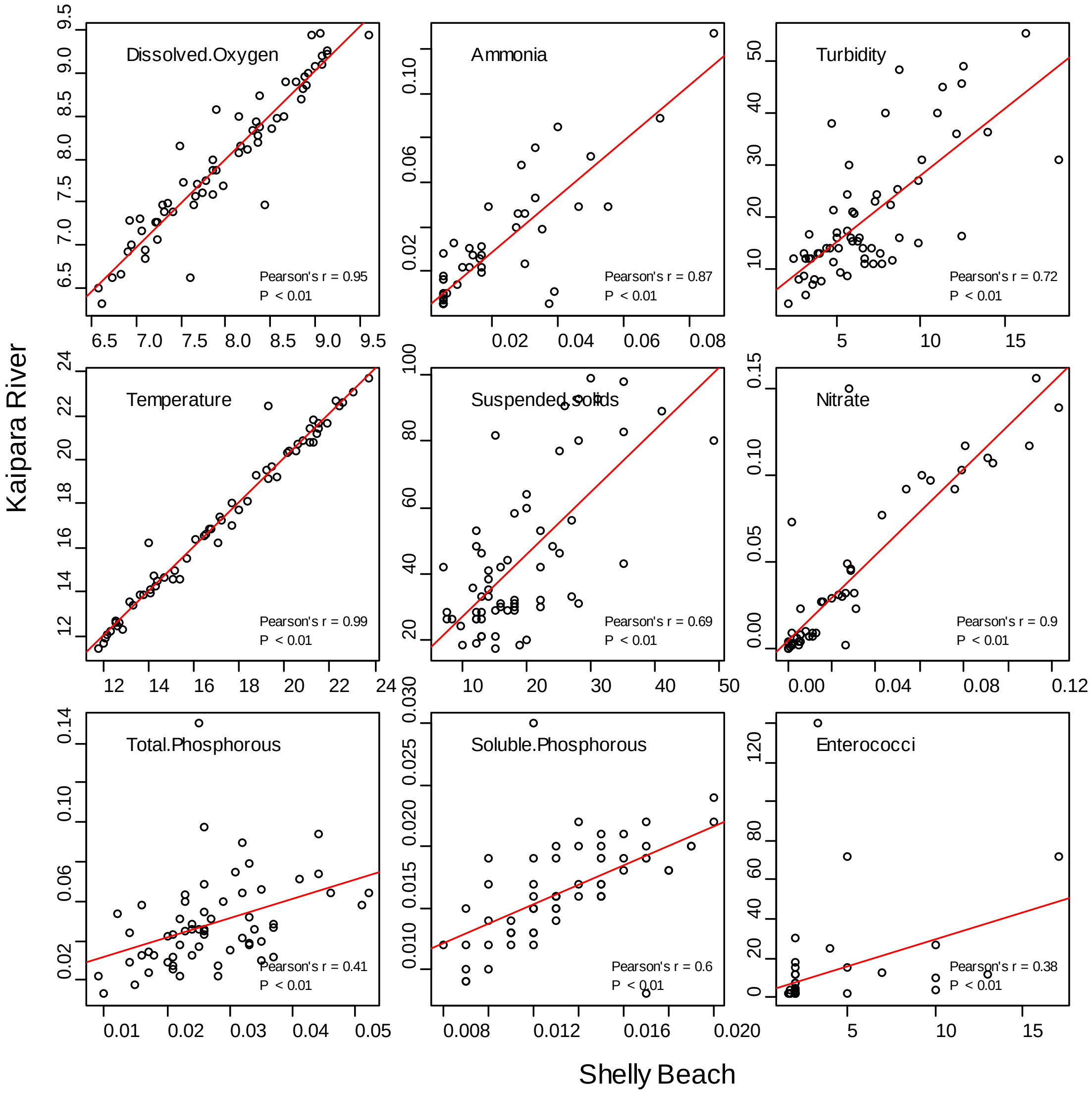

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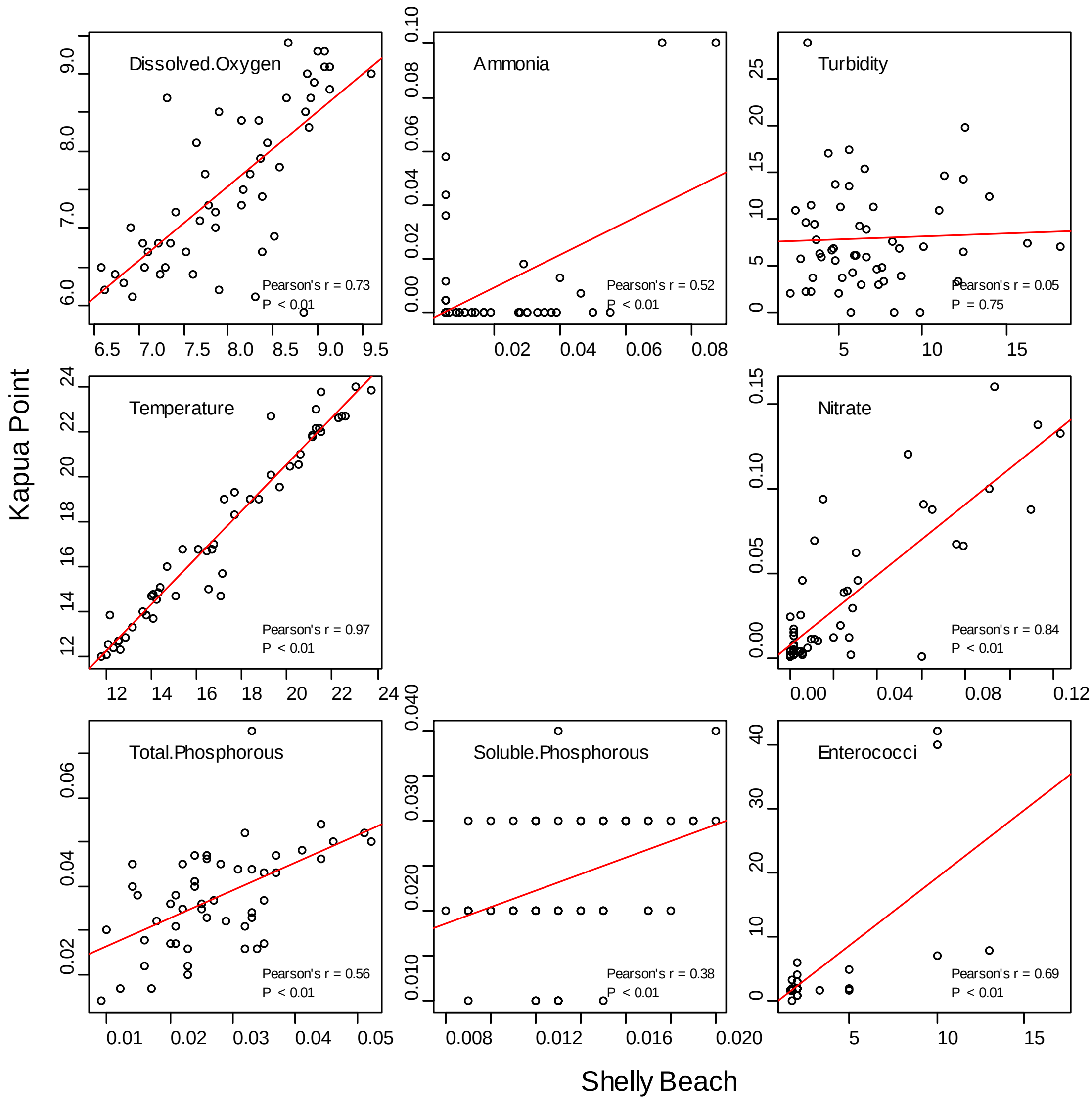

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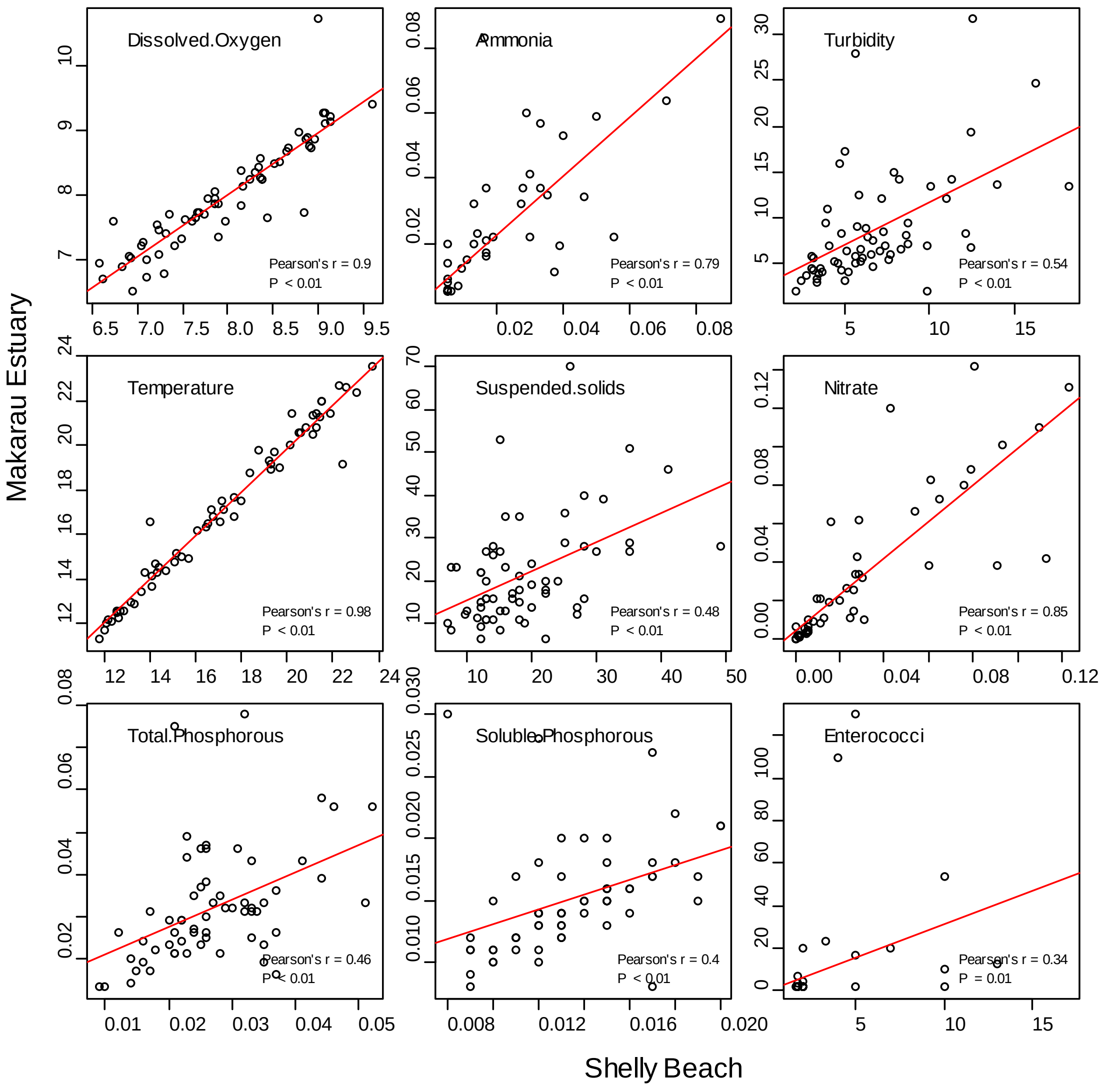

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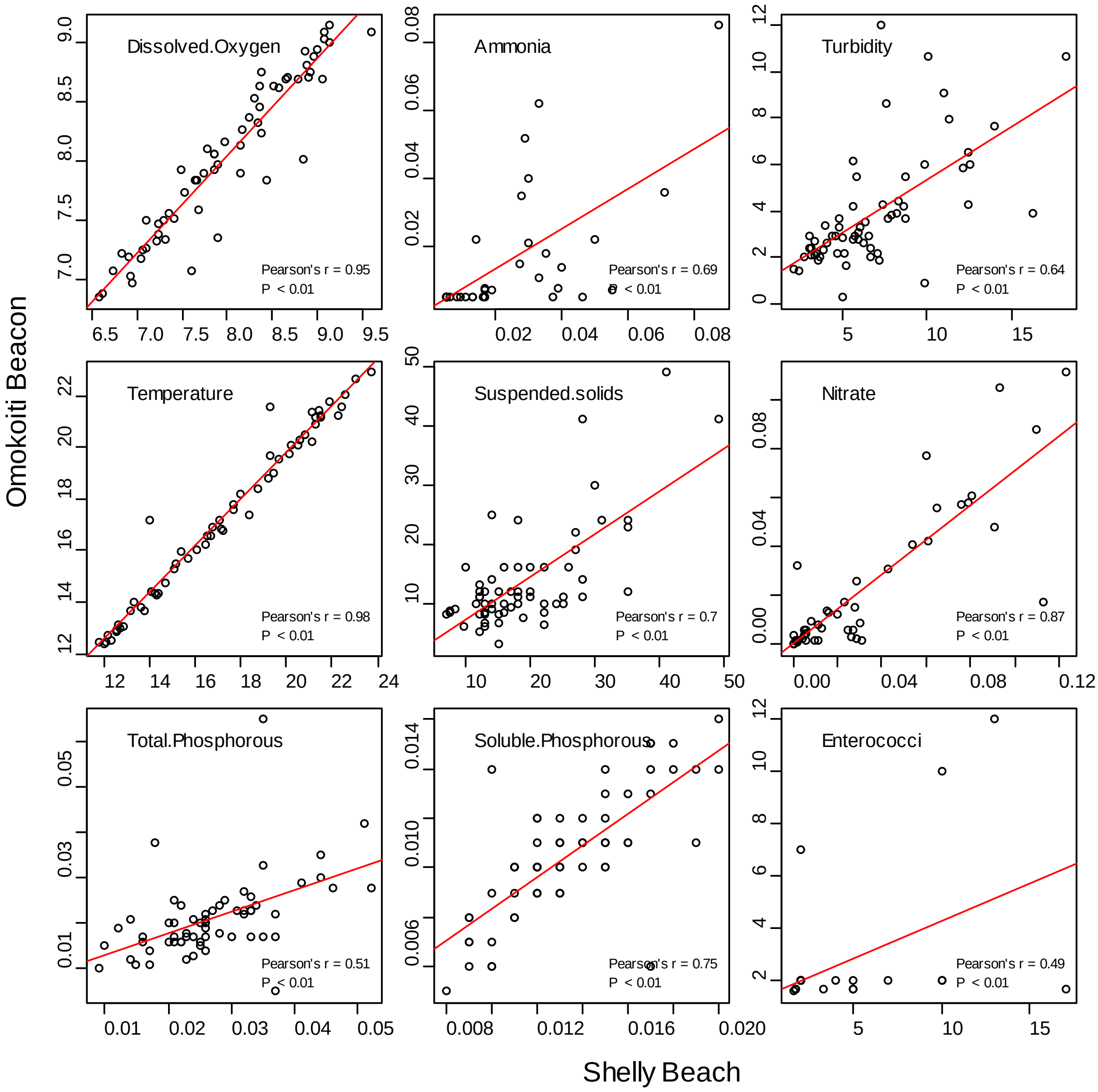

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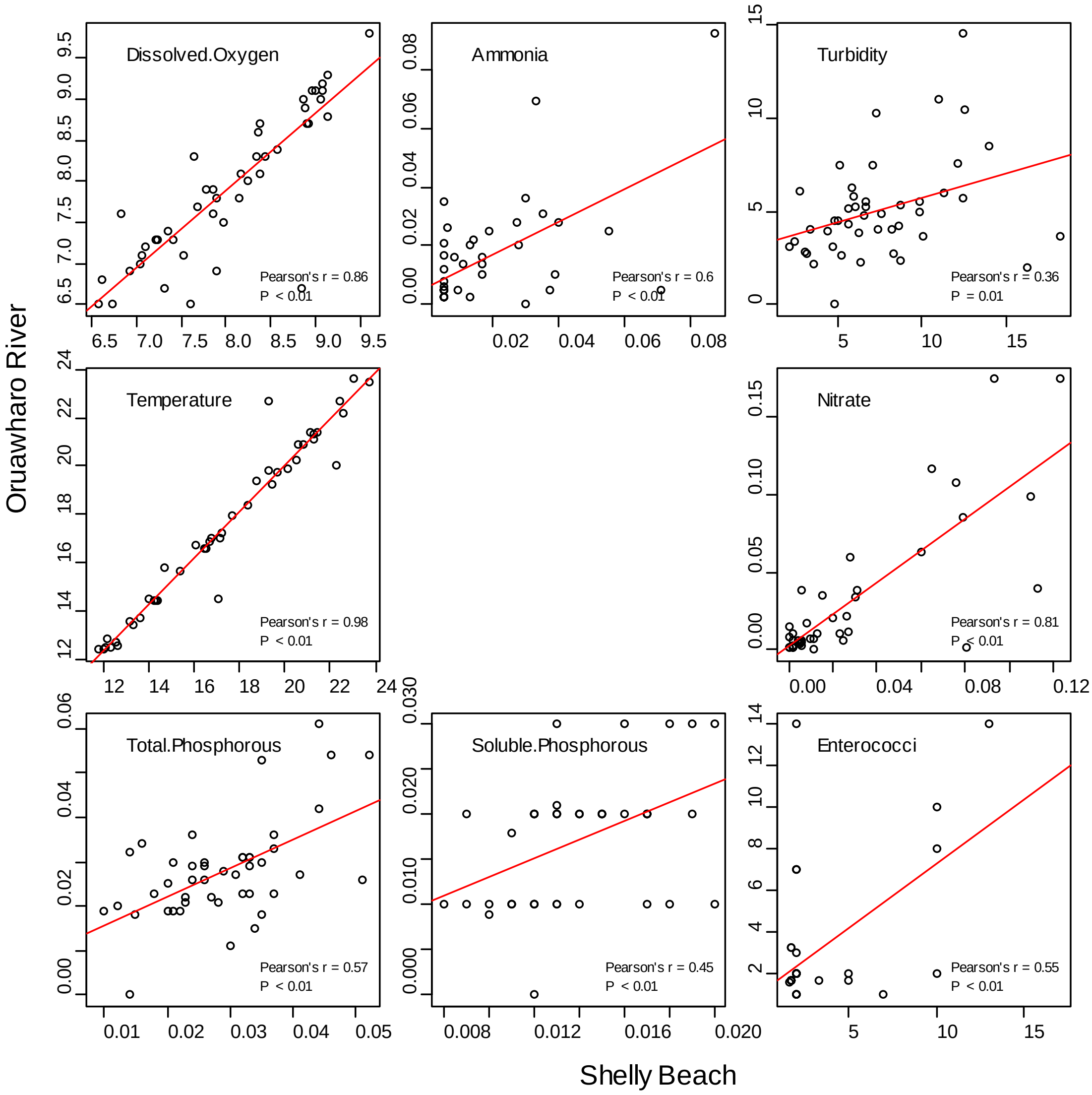

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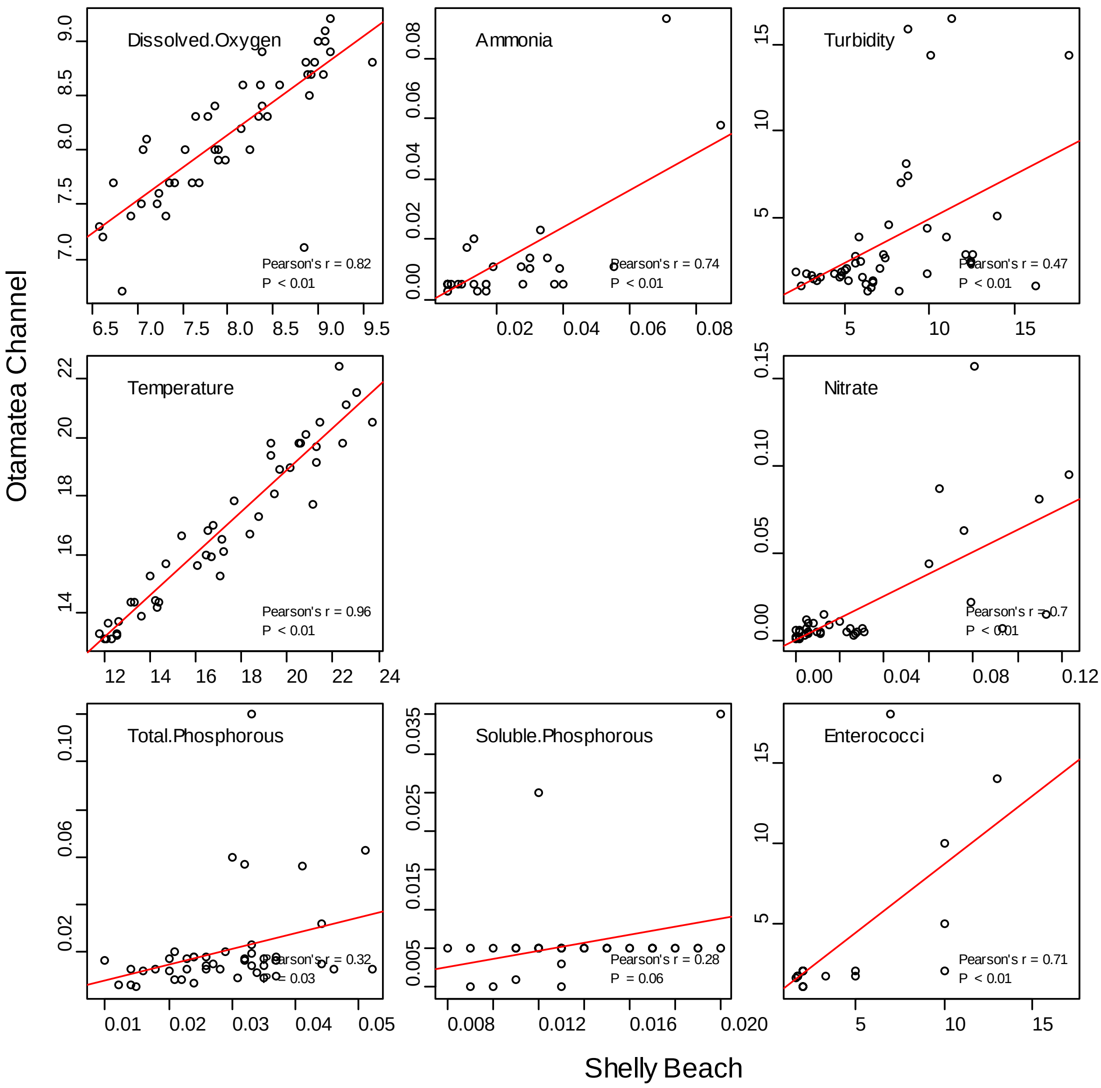

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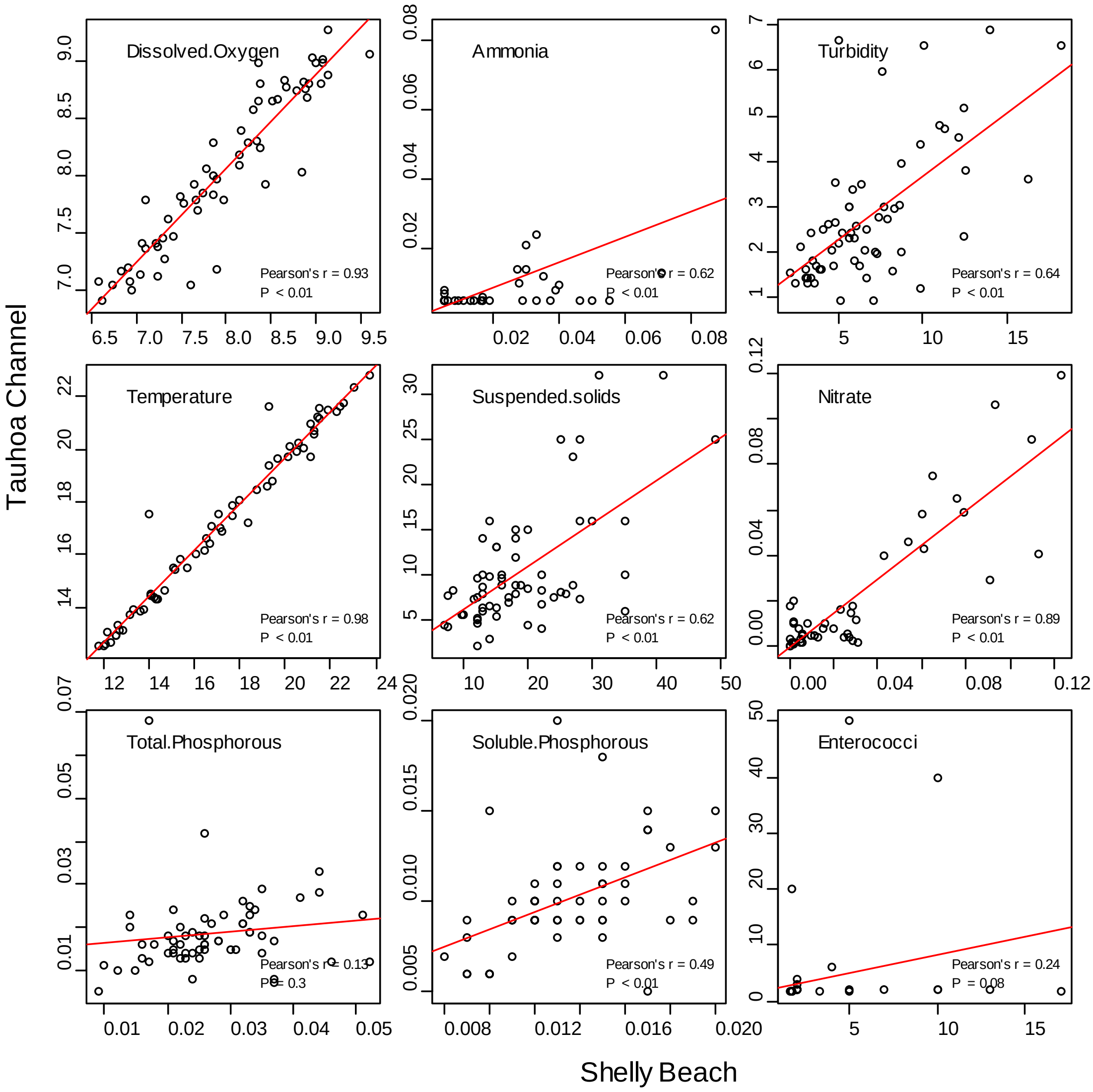

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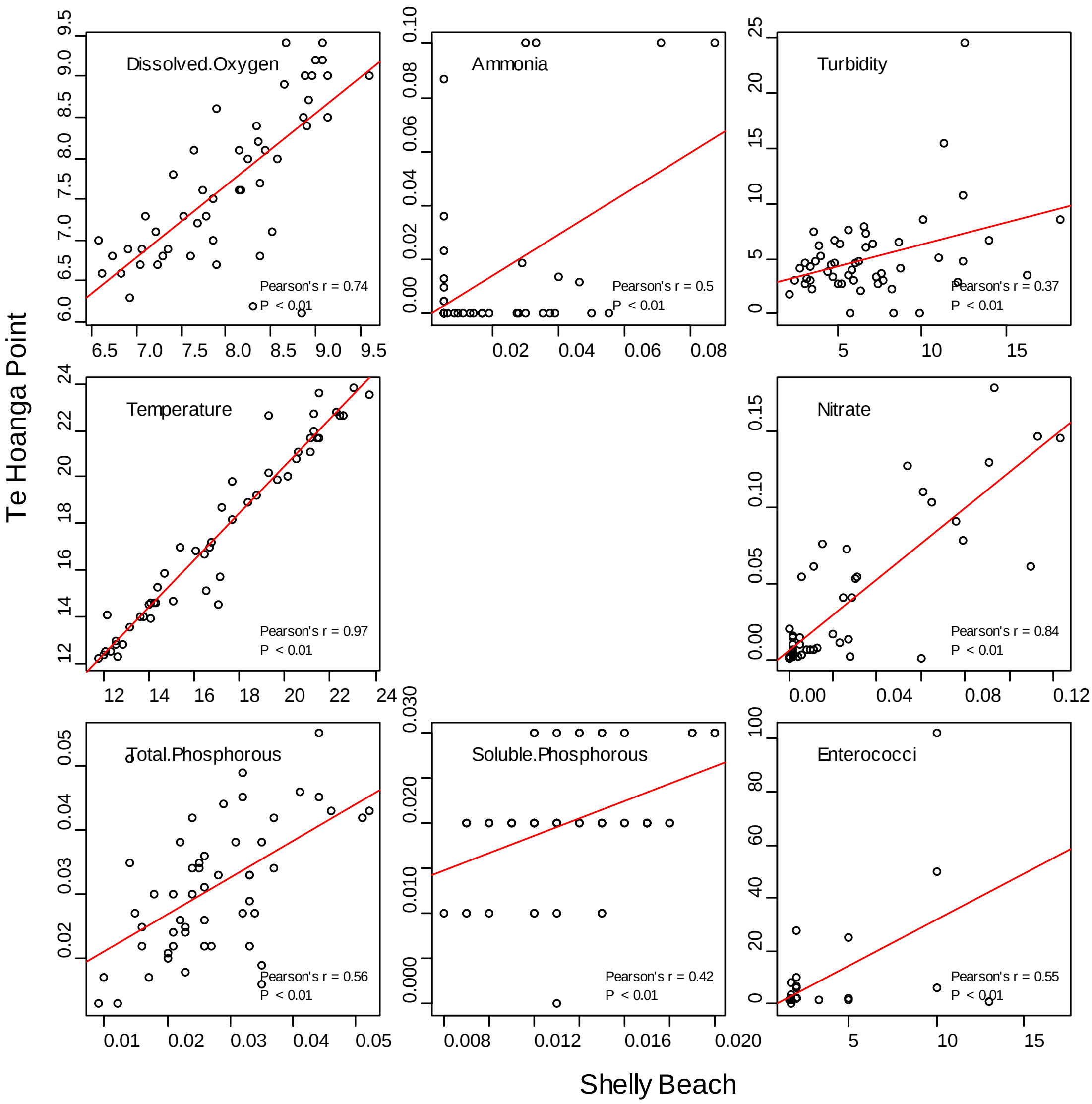

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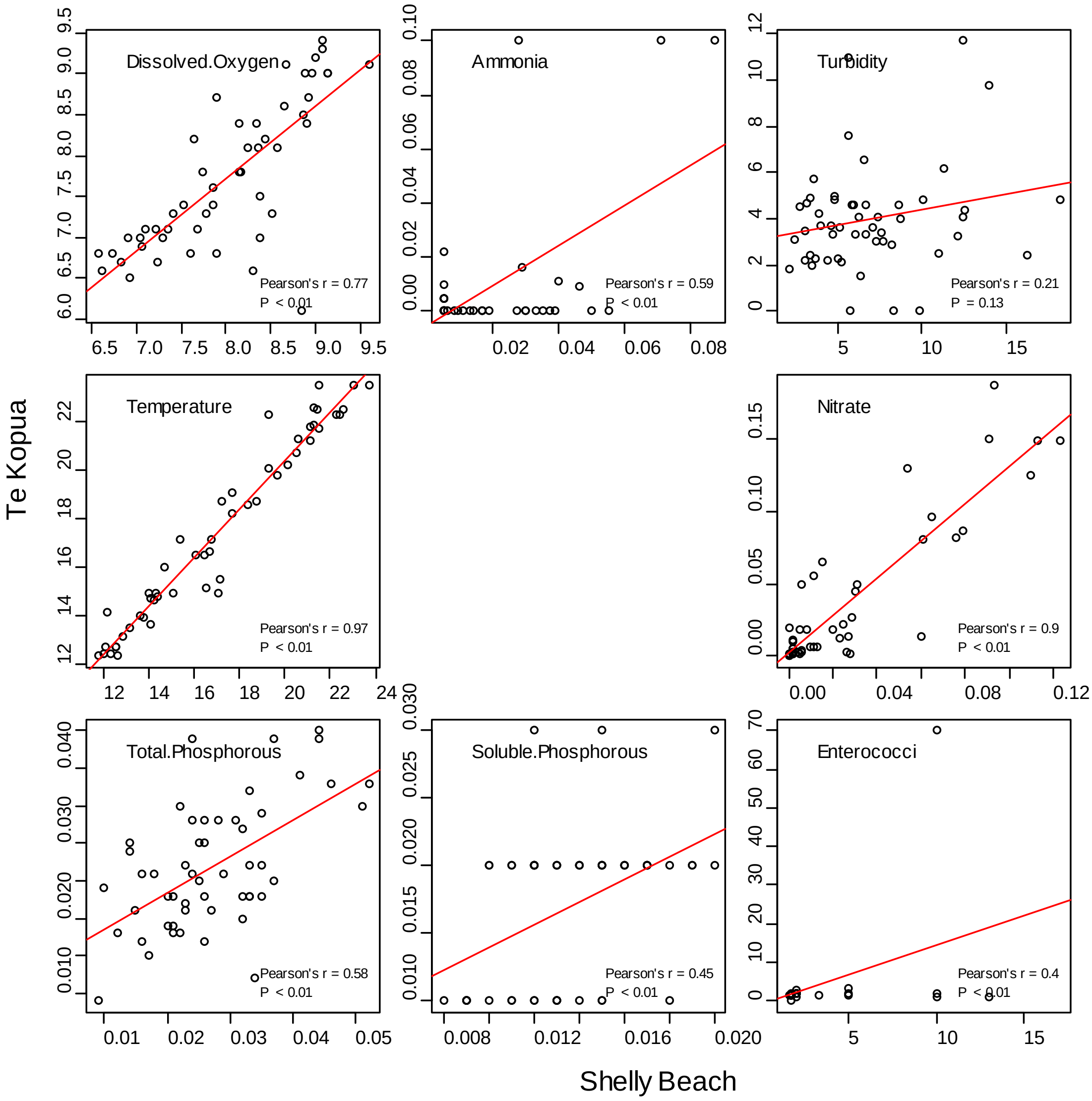

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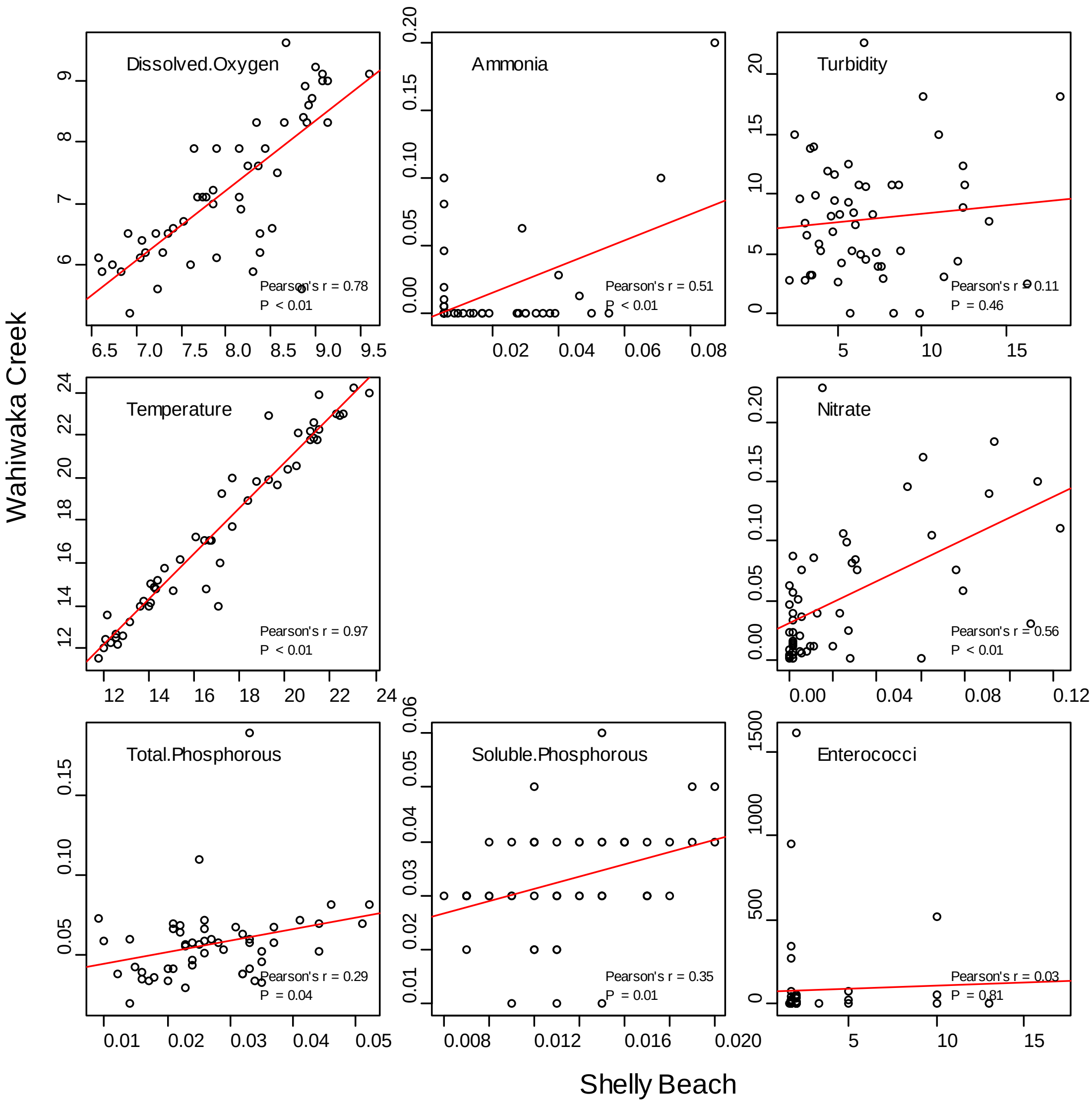

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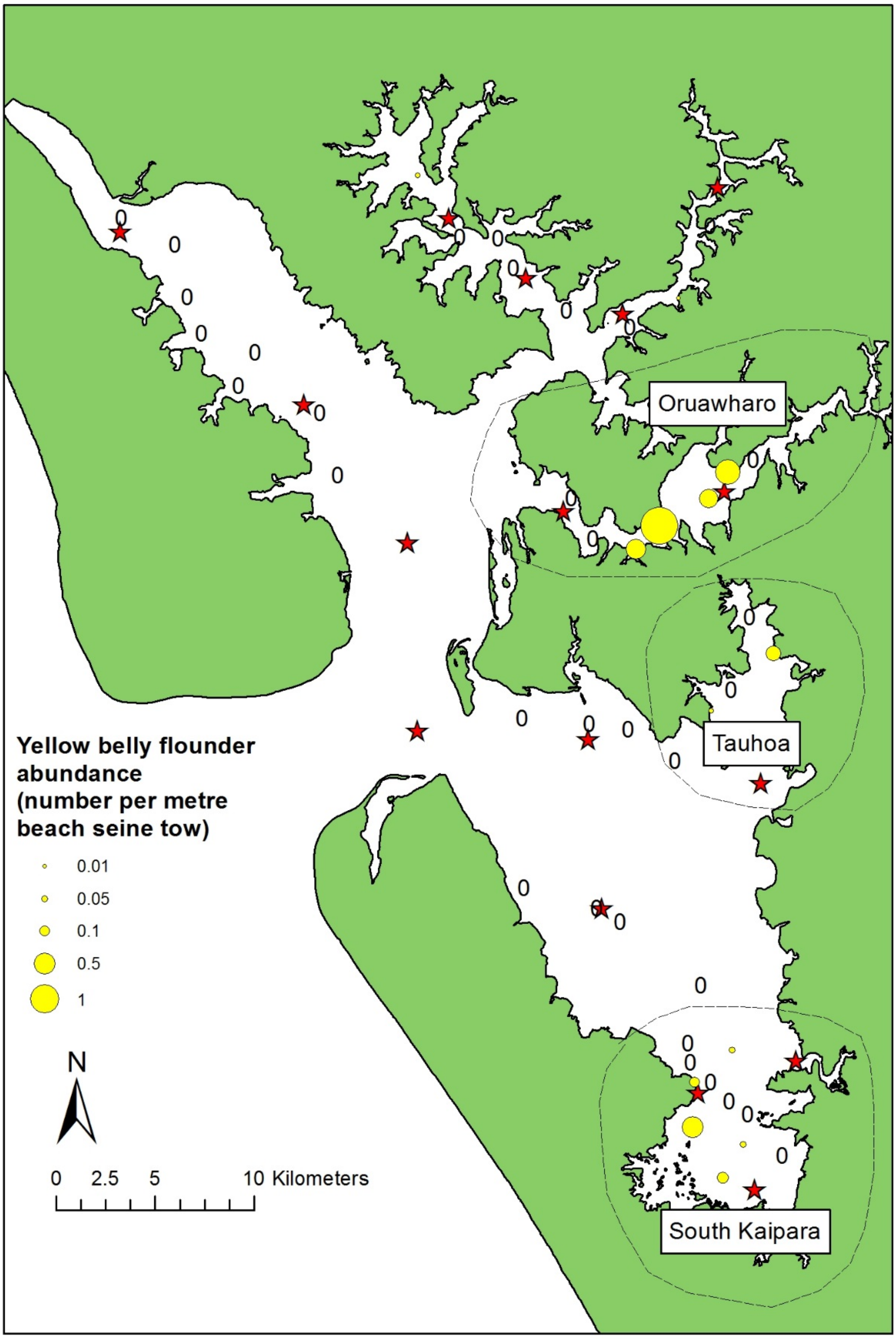
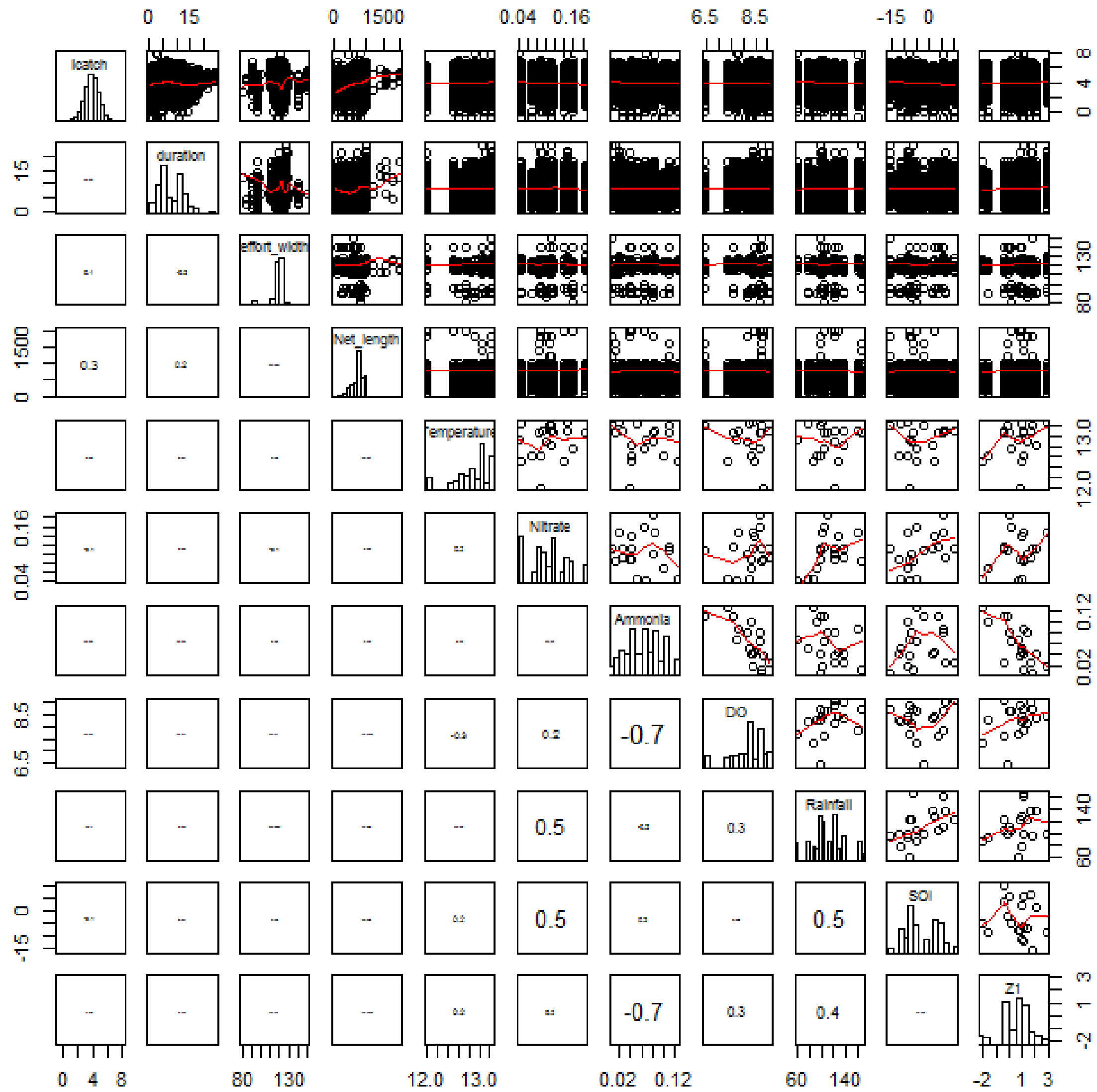


Fig. 3: Map of the Kaipara Harbour showing council water quality sampling sites (red stars) and yellow belly flounder abundance (yellow bubbles; M. Morrison and M. Francis, NIWA, unpubl. data). 0's represent a sampling event where no juvenile YBF were caught. Dashed lines and labels represent three regions identified as being important to juvenile (< 150 mm total length) yellow belly flounder. These regions are also presented in Table 1.

APPENDIX 2: Collinearity plots for continuous explanatory variables (listed in sections 2.2 and 2.3) offered to the different GLMs used to investigate the influence of environmental variables on YBF catch.

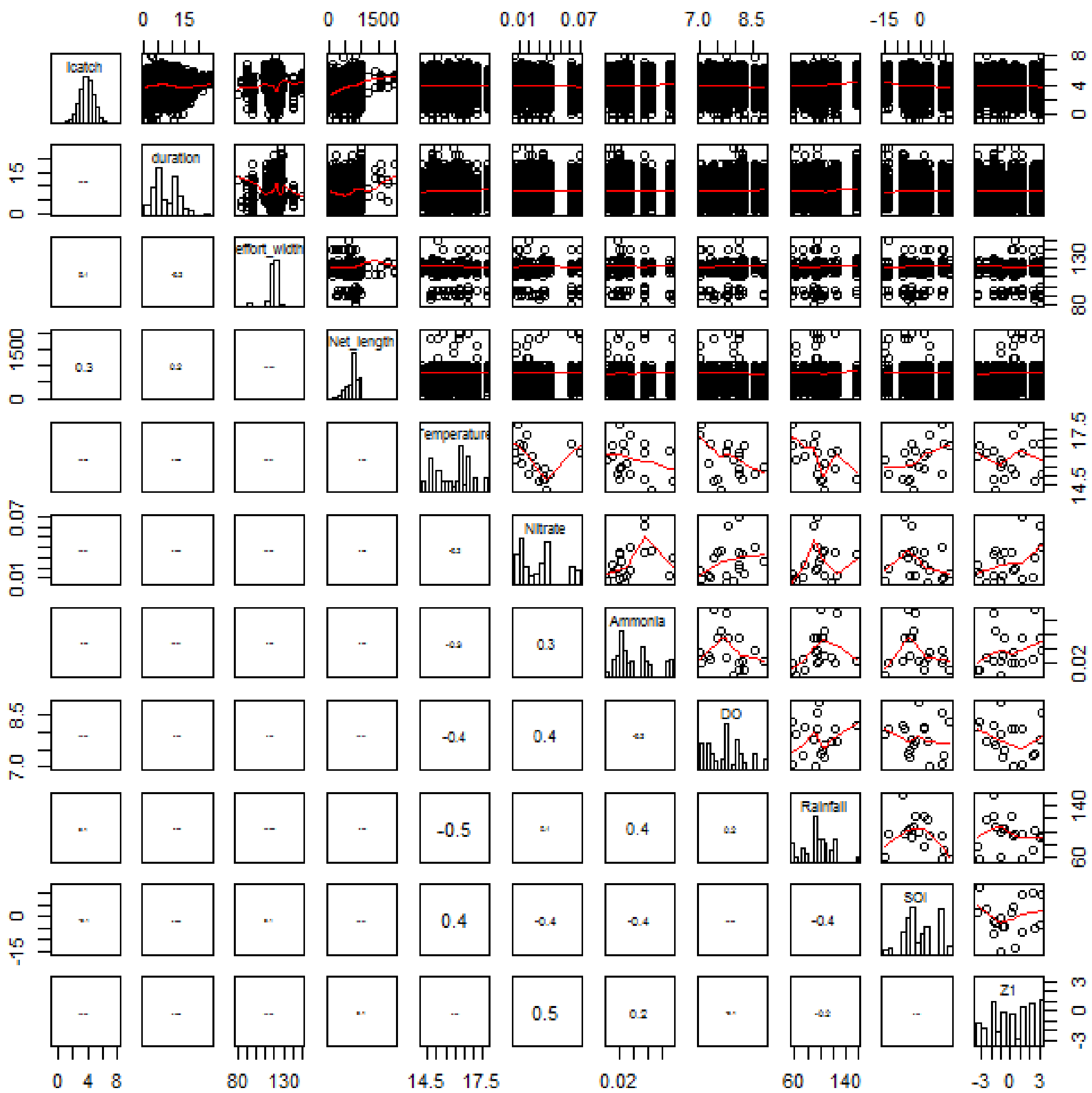
Each panel plot lists histograms of each variable in the panels along the diagonal axis (lcatch = the log of the weight (kg) of FLA caught in a fishing event; effort_width = the mesh size (mm) of the net used in each fishing event). Correlation plots (loess smoothers in red) for each combination of these variables are located in the panels above the diagonal and correlation coefficients (R values) corresponding to each correlation plot are located in the panels below the diagonal. In these panels the size of the correlation coefficient is also indicated by the font size. Where correlations were large (R ≥0.6) one of the variables was removed.

August GLM

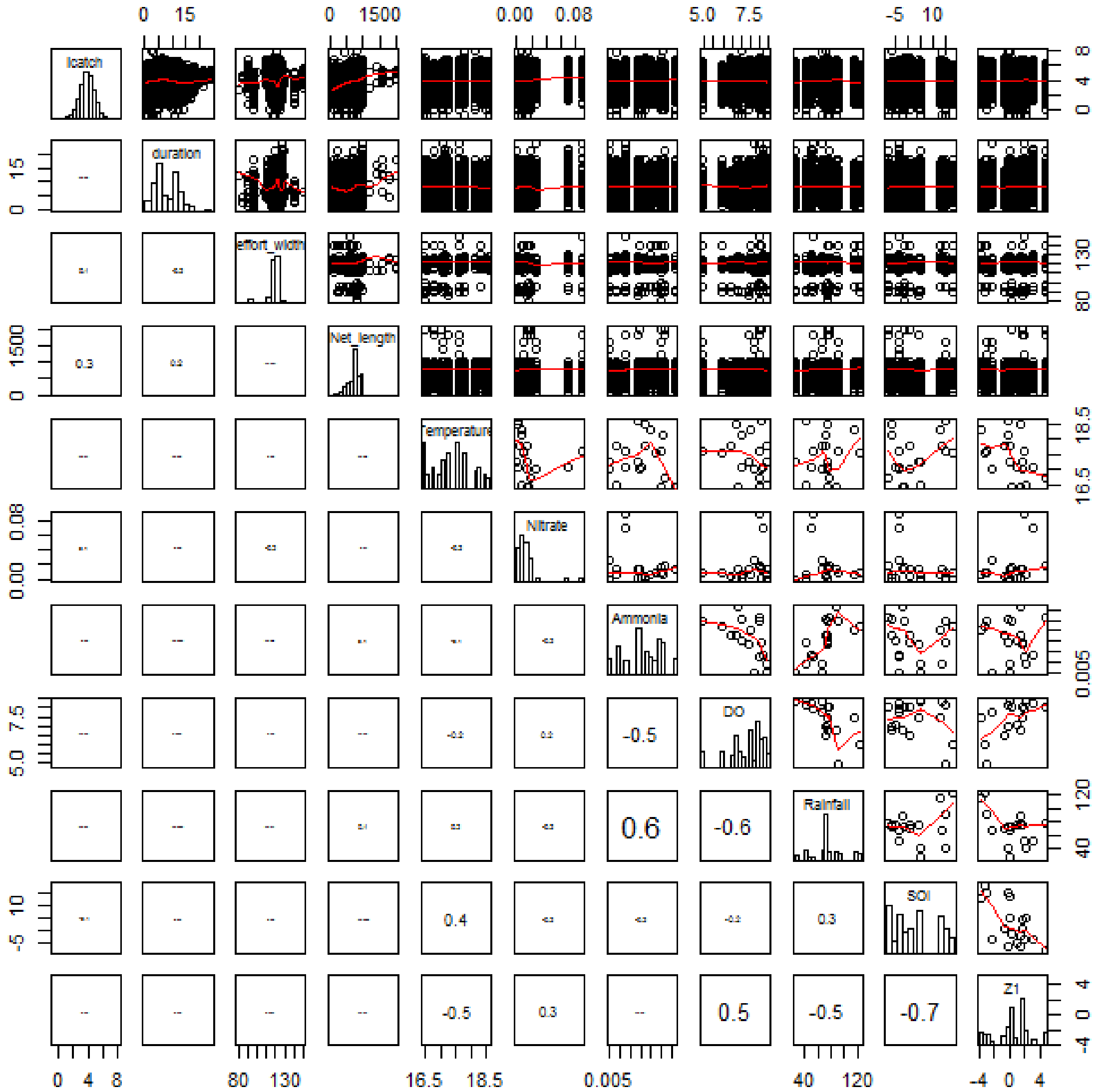


September GLM

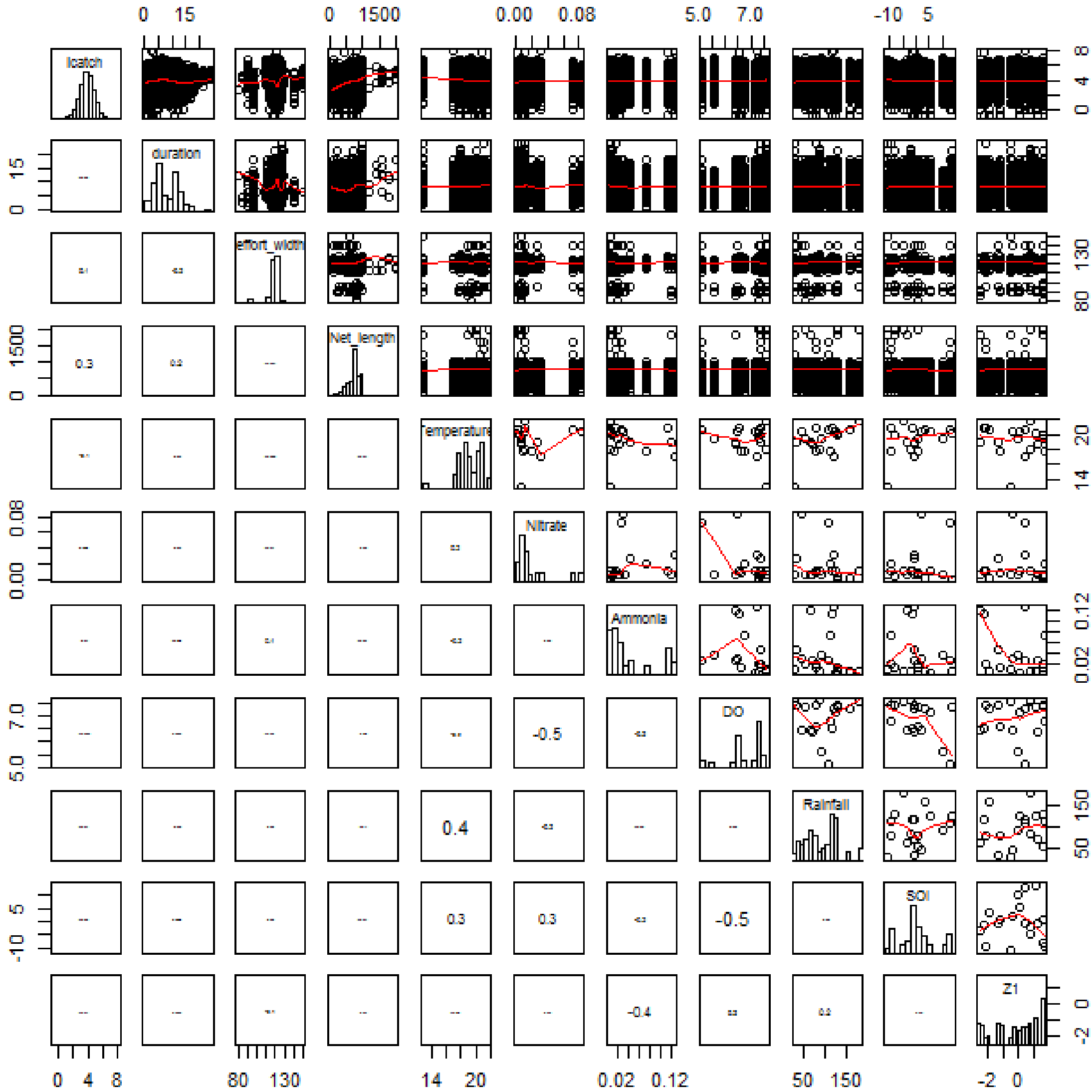
October GLM


lcatch
duration
effort_width
Net_length
Temperature
Nitrate
Ammonia
DO
Rainfall
SOI
Z1
0.3
-0.4
0.4
-0.5
0.4
0.5
0.3
0.4
-0.4
0.2

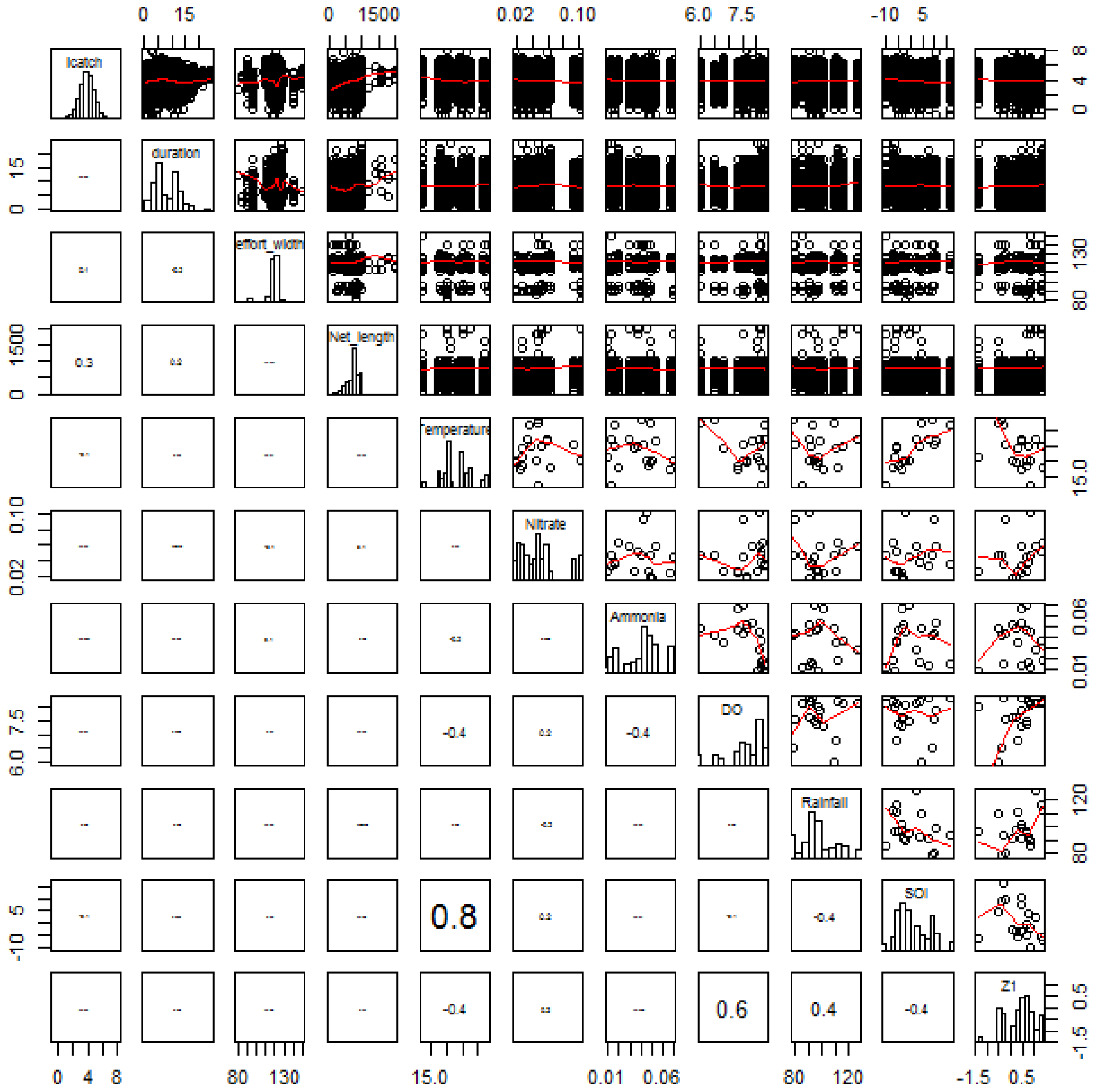
November GLM



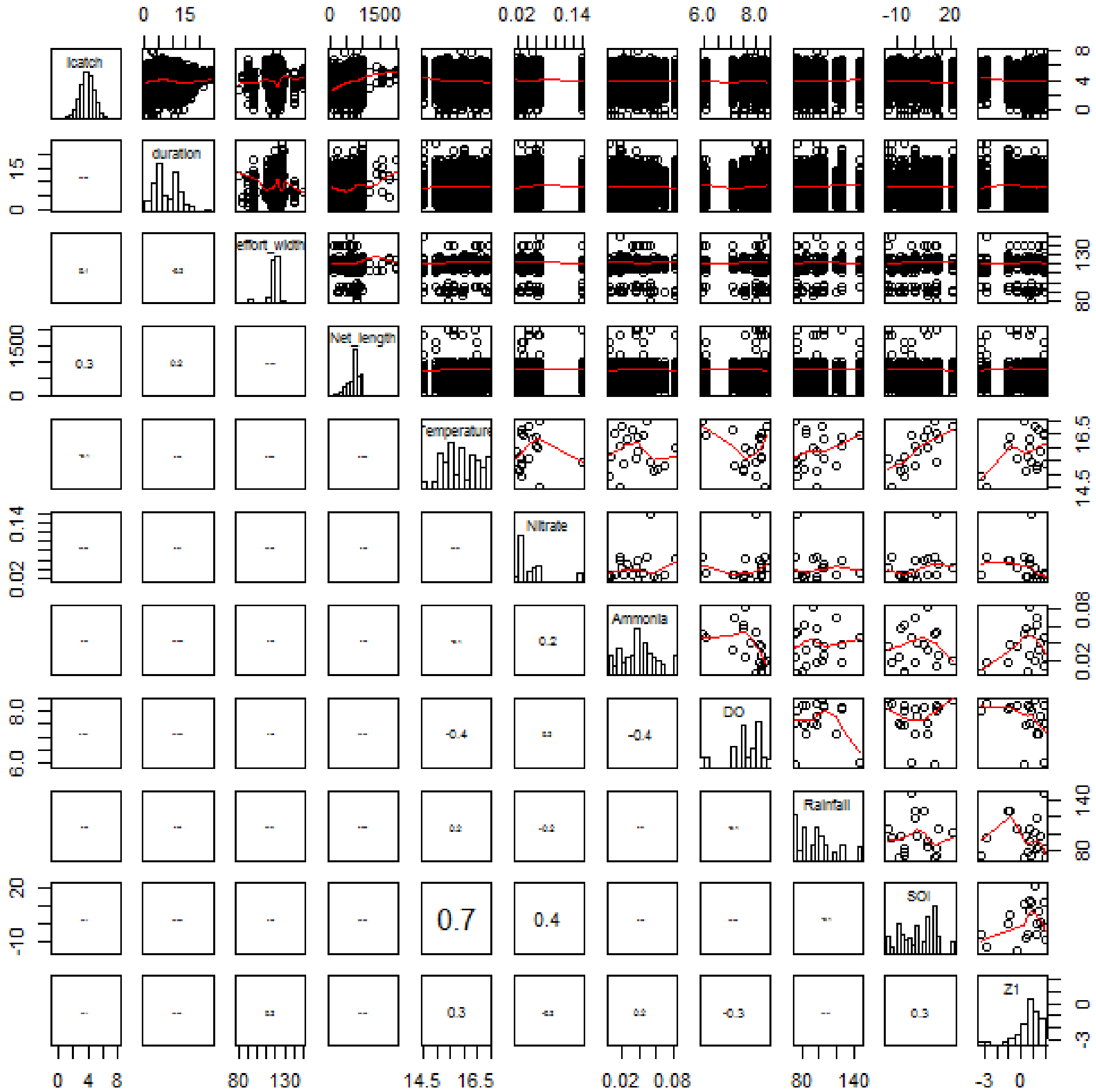
December GLM



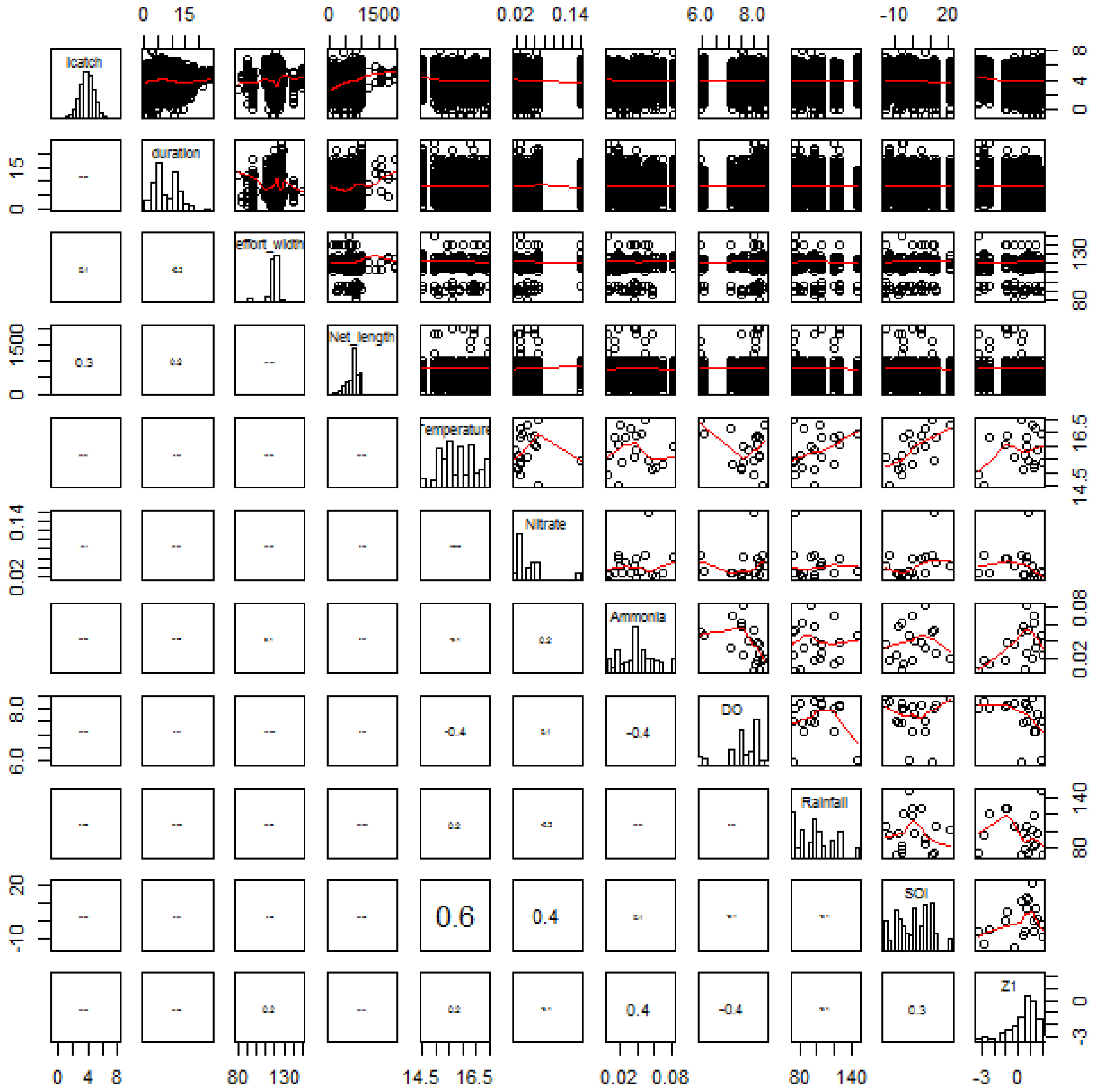
GLM for whole juvenile period, two and three year lag average



GLM for whole juvenile period, just two year lag



GLM for whole juvenile period, just three year lag



APPENDIX 3: Description of relevant Auckland Council Water Quality Variables (text provided by Jarrod Walker, Auckland Council).

Water Temperature
Water bodies generally show seasonal patterns in temperature that are correlated with air temperature. Heat transfer between the atmosphere and water surface primarily influences water temperatures of large water masses. Stream temperatures, in the absence of industrial discharges of heated water, are primarily regulated by the extent of riparian vegetation shading of the waterway. In catchments developed for urban uses or intensive agriculture, riparian vegetation has generally been removed to ameliorate flooding problems or maximise land use and as a result stream temperatures tend to be elevated. Shallow coastal saline water temperatures are most commonly influenced by water passage on incoming tides over intertidal sediments that have been warmed by the sun, resulting in an increase in water temperature. Lake water colour can also influence water temperature, because incident radiation is absorbed to a greater extent by darker water bodies resulting in an increase in water temperature.

Elevated water temperature can influence aquatic biota in the following ways:
(i) Community structure in compromised waterways may be dominated by thermotolerant species that can survive fluctuations in temperature, particularly those experienced in summer.
(ii) An increase in water temperature results in a reduction in the dissolved oxygen-carrying capacity of the water. This may be critical for sensitive organisms particularly where saturation levels are already reduced (see next section).

Dissolved Oxygen
Dissolved oxygen saturation (DO %sat.) gives a direct measure for the assessment of a waterway's ability to support aquatic life and is therefore one of the more important water quality parameters measured in our surveys. However where low saturation levels occur there is often a multiplicity of possible causes.

DO (% sat.) levels show natural fluctuations both diurnally (throughout the day) and seasonally. Diurnal changes are caused predominantly by the respiratory activities of aquatic biota, particularly plants. Seasonal variations mainly follow changes in temperature, which are inversely related to oxygen solubility.

Dissolved oxygen levels around 5 mg/L are known to be stressful to sensitive aquatic biota. This concentration equates to a DO (% sat.) of 40%–60% at the range of temperatures commonly found in Auckland waterways. If low DO (% sat.) levels persist for any extended period of time some organisms that cannot move away may die. Ultimately the diversity of aquatic biota may be reduced to include only those species tolerant of low DO (% sat.).

Amelioration of low DO (% sat.) levels can be achieved by a reduction of point source and non-point source runoff by the modification of land use practices. Riparian vegetation has a role to play in filtering out diffuse sources of oxygen-demanding substances in rural and urban runoff, reducing temperatures and restricting in-stream plant growth by shading. Urbanised areas have the potential to reduce the input of oxygen demanding substances by utilising various stormwater treatment initiatives. In terms of point source inputs, ARC rural and industrial pollution abatement activities are designed to eliminate unauthorised discharges and control authorised discharges of contaminants to a level that can be assimilated by the water body concerned.

In catchments with agricultural development, substantial volumes of stream water are abstracted for irrigation purposes. Consequently DO (% sat.) levels may be further compromised by discharges of pollutants during the summer when the stream assimilation capacity is reduced by such abstractions.

Supersaturation of water is not unusual where aquatic plants in the form of macrophytes, periphyton or free-floating algae are abundant. During the hours of daylight the release of oxygen during photosynthesis augments the transfer of oxygen through the surface of the waterbody by diffusion. The negative side to the presence of these plants is the consumption of oxygen at night (i.e. by respiration), which can lead to serious oxygen depletion and subsequent effects on other biota. Depression in DO (% sat.) levels caused by this phenomenon is usually greatest in the early hours of the morning.

Turbidity
Turbidity is a measure of the degree to which light is scattered in water by suspended particles and colloidal materials. Samples are analysed in the laboratory using a meter and the results are given as nephelometric turbidity units (NTU). When turbidity levels are high, light penetration is reduced, thereby limiting the ability of aquatic plants (algae and macrophytes) to photosynthesise (i.e. a reduction in the so-called euphotic depth). Organisms that are visually oriented may have difficulty locating and catching prey in turbid water and the fine suspended material that is characteristic of turbid water may detrimentally affect gill structures of aquatic organisms.

Suspended Solids (also called non-filterable residue)
Suspended solids (SS) is a measurement of the suspended material in the water column, including plankton, non-living organic material, silica, clay and silt. High SS levels reduce light penetration and provide media for pollutants to attach to, resulting in a reduction in water quality for a variety of uses, such as horticulture, irrigation, stock water supply, and recreational and ecological functions. Under the appropriate conditions the suspended material can settle out as sediment thereby causing further problems, such as smothering of biota.

SS burdens to waterways can be reduced in a variety of ways depending on the type of land use concerned:
• In rural catchments riparian zone management provide an effective filter for diffuse sources of SS and reduces streambed and bank scouring by dissipating the energy of floodwaters.
Preventing stock access to stream beds and banks is a useful mitigation tool for reducing excessive SS.
• In urban and industrial areas SS can be reduced through the implementation of storm water control measures. The period when land is being urbanised has the greatest potential to mobilise sediments to waterways. ARC Environment has produced urban earthworks guidelines to minimise SS runoff from exposed erodible soils.

Ammonia
Ammoniacal nitrogen is a macro-nutrient but is considered in general water quality evaluations in terms of its toxicity to many aquatic animals. Ammonia occurs in a number of waste products, which if discharged to the environment can result in elevated ammonia levels. Ammonia is reported as a combination of un-ionised ammonia (NH_3) and the ammonium ion (NH_4+). At normal pH values the latter form predominates. Un-ionised ammonia is the more toxic form to aquatic life. The toxicity of ammonia is very dependent on water temperature, salinity and pH. Regulatory agencies, such as the ARC Environment, have tended to rely on overseas criteria such as those promulgated by the USEPA. The ARC has commissioned studies on Auckland freshwater biota, which corroborate that USEPA criteria are appropriate.

Ammonia toxicity for given pH and temperature combination can be calculated using a mathematical equation. As a generalisation a chronic or long term exposure limit of 0.77 mg/L is appropriate for sensitive freshwater organisms under ambient conditions. In saline waters ammonia toxicity is influenced by salinity in addition to pH and temperature. The chronic exposure limit for sensitive saline organisms under ambient conditions is 2.3 mg/L.

Long term or chronic effects on biota include the limitation of species that can survive in the waterway to those tolerant of ammonia. In addition sublethal effects, such as disruption of feeding patterns and removal of food sources, reduction of reproductive viability and restricted recruitment of juvenile organisms in response to long term exposure to ammonia, have been documented by the USEPA.

In catchments with intensive farming practices ammonia rich wastewaters can come from several sources. Potential causes of diffuse input include rainfall on areas adjacent to waterways that have been grazed, had spray irrigated with wastewater or had fertilisers such as ammonia urea applied to them recently. Rural point sources include race runoff, oxidation pond discharges, silage leachate, or raw wastes when disposal systems break down or are not used as intended.

Nitrate
Nitrate is the end product of the breakdown (oxidation) of ammonia through the intermediate step of nitrite by microbial decomposition. It is not particularly toxic to aquatic life. Water for use as potable supply is limited to 10 mg/L on public health grounds. In terms of crop irrigation water requirements with higher nitrate levels could be seen as an advantage saving on fertiliser costs. For stock drinking water requirements the recommended limit is 100 mg/L.

Sources of nitrate in aquatic systems are similar to those discussed for ammonia. Nitrate is poorly bound to the soil and is therefore highly mobile. It is readily leached into local groundwater systems, particularly under high rainfall events. In winter when ground conditions become saturated the capacity of the soil to assimilate waste is reduced, resulting in elevated nitrate levels in runoff.

Nitrate is an important plant nutrient (which is generally non-limiting), which in conjunction with sufficient available phosphorus can lead to proliferation of aquatic plants (algae and macrophytes). Respiration of aquatic plants at night can lead to reductions in dissolved oxygen to the point that other aquatic organisms may become stressed or killed. Photosynthetic activity of aquatic plants also leads to elevated stream pH, which has an effect on the toxicity of other contaminants in the water such as ammonia.

Total Phosphorus
Total phosphorus is a measure of all the phosphorus present in the sample and includes the soluble (bioavailable) fraction that is adsorbed onto sediment particles and present in the form of algae and other organic matter. The Lake Managers Handbook defines lake trophic status in terms of average annual total phosphorus level as follows:
Total Phosphorus (mg/L) Trophic status
<0.01 Ultra-oligotrophic (ultra-low enrichment)
0.01–0.02 Oligotrophic (very low enrichment)
0.02–0.05 Mesotrophic (medium enrichment_
>0.05 Eutrophic (highly enriched)

Dissolved Reactive Phosphorus (soluble reactive phosphorus)
Dissolved reactive phosphorus (DRP) is considered to be the bioavailable fraction of phosphorus and is an important as an indicator of water quality. It is frequently cited as the nutrient limiting the proliferation of algae and other aquatic plants in New Zealand waterways. Levels required to stimulate in stream plant growth are reportedly as low as 0.01 mg/L.