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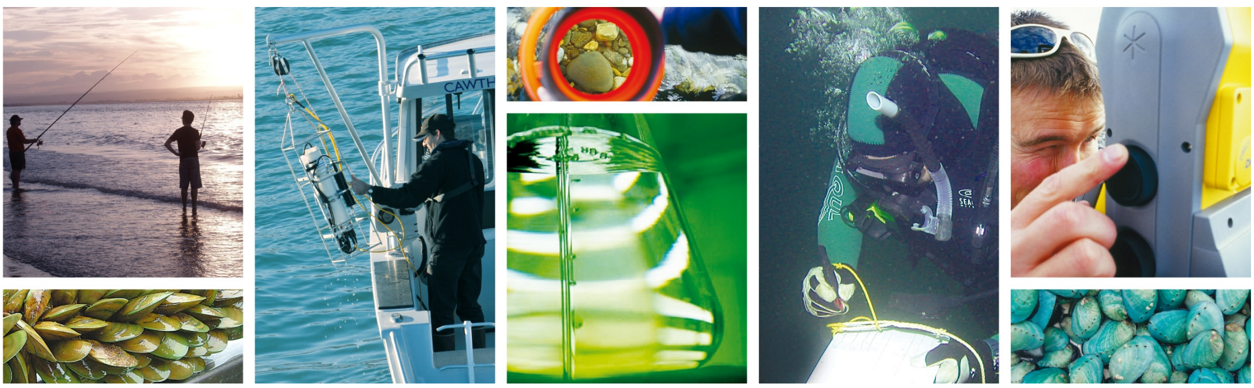
Temporal Variability in Ecosystem Metabolism of Rivers in the Manawatu-Wanganui Region



RESEARCH BASED SOLUTIONS

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Temporal Variability in Ecosystem Metabolism of Rivers in the Manawatu-Wanganui Region

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Prepared for

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EXECUTIVE SUMMARY

A one-off measurement of the daily change in dissolved oxygen in the lower Manawatu River in 2007 indicated that this river has incredibly high rates of ecosystem metabolism (primary production and ecosystem respiration) that are indicative of very poor ecosystem health. An assessment of the lower Rangitikei River on the same day suggested this river had poor ecosystem health due to high rates of ecosystem respiration. Horizons Regional Council has been collecting continuous records of dissolved oxygen (DO) at five sites throughout the region since 2005, which can be used to calculate ecosystem metabolism. The aim of this study was to determine if the Manawatu River consistently has measurements indicative of poor health and how this compares with other rivers in the region.

We calculated ecosystem metabolism using DO data from five sites seasonally from winter 2006 to autumn 2008. The sites were Manawatu at Hopelands, Manawatu at Teachers College, Mangatainoka at Pahiatua Town Bridge, Rangitikei at Mangaweka and Rangitikei at Onepuhi. The sites varied in their intensity of catchment land use ranging from 58% native vegetation in the catchment for the Rangitikei at Mangaweka to 10% native vegetation for the Manawatu at Hopelands. Dissolved oxygen data generally displayed characteristic daily patterns at most sites. However, we had concerns with the accuracy of the data, particularly in August 2007, where night-time DO values did not drop below 100% saturation at all sites. To address these concerns we corrected the data, but uncertainties involved with the correction mean that less confidence can be placed on metabolism values calculated from corrected data.

Rates of gross primary production (GPP) were low at Rangitikei at Onepuhi and Manawatu at Teachers College and indicative of healthy conditions according to broad guidelines on interpretation of these measures. GPP was low to moderate at Rangitikei at Mangaweka and Mangatainoka at Pahiatua and indicative of healthy to satisfactory conditions. In contrast, GPP was consistently high at Manawatu at Hopelands and indicative of poor ecosystem health.

Rates of ecosystem respiration (ER) were generally moderate to high at all sites and indicative of satisfactory to poor ecosystem health.

The balance between GPP and ER indicated that these sites generally were relying on some organic matter from upstream or the surrounding catchment to support the rates of ER that were recorded. The only exception to this was Manawatu at Hopelands during winter when rates of GPP were two times higher than rates of ER and in-stream production (*i.e.* periphyton and phytoplankton) may have been supporting the entire food web. The P/R ratios provided no indication of poor ecosystem health at any of the other sites, suggesting that this indicator may not be a particularly sensitive measure of large river health.

As expected there were distinct seasonal patterns in the ecosystem metabolism measurements with most sites displaying higher values in the warmer months. However, given the concerns with the accuracy of some of the dissolved oxygen data, it was difficult to confirm a significant difference in the seasonal patterns among sites. The Manawatu at Hopelands site had a greater seasonal range in GPP and ER than the remaining four sites.

Based on the results of this study, it is apparent that parts of the Manawatu River (*i.e*. Manawatu at Hopelands) consistently had metabolic rates indicative of poor ecosystem health. In contrast, parts of the Rangitikei River (*i.e*. Rangitikei at Onepuhi) had consistently satisfactory to good ecosystem health. Metabolism measurements at the remaining three sites indicated good to moderate ecosystem health depending on season.

Continuous monitoring of DO concentration provides the opportunity to calculate rates of ecosystem metabolism that can be used to assess ecosystem health. The accuracy of the metabolism calculations is heavily dependent on the accuracy of the raw DO data. Therefore, we recommend regular checks and calibration of the DO monitoring equipment. As more data becomes available it would be useful to compare results from the Manawatu-Wanganui Region with measurements from similar large rivers to determine if the broad guidelines used in this study to interpret the metabolism measurements are appropriate for large rivers generally. Furthermore, it would be useful to compare measures of ecosystem metabolism to traditional water quality, biomonitoring or periphyton assessments to determine whether functional indicators could provide suitable surrogate measures of ecosystem health for large river systems where other measures can not be undertaken. It would also be useful to determine the feasibility of developing an automated river metabolism calculator so real-time metabolism measurements could be displayed on the Horizons website along with the raw DO data.

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1. INTRODUCTION

River health assessment has traditionally concentrated on structural measurements related to abundance and community composition of macroinvertebrates and other stream life. However, it is increasingly recognised that a complete assessment of river health requires information on both structural and functional components of the ecosystem (Young *et al.* 2008). Functional components refer to the rates of key ecosystem processes. Ecosystem metabolism – the combination of primary productivity (photosynthesis) and ecosystem respiration – is a measure of the main factors controlling dissolved oxygen dynamics in rivers and indicates how much organic carbon is produced and consumed in river systems. Recent research has shown that ecosystem metabolism is a useful indicator of river ecosystem health and can be measured by monitoring the daily changes in oxygen concentration at a site (Fellows *et al*. 2006; Young *et al*. 2008). Dissolved oxygen concentrations rise during the day time when sunlight facilitates photosynthesis, and then decline during the night when only respiration is occurring. The size of the daily fluctuations depends on the amount of photosynthesis and respiration occurring within the river and also the flux of oxygen through the river surface. Sites with very high rates of primary production will normally be characterised by a riverbed covered with a high biomass of periphyton (algae and other slimes growing on the substrate) or other aquatic plants that are not limited by shading, or a lack of nutrients. Sites with high rates of ecosystem respiration are normally characterised by large inputs of organic matter from point-source discharges of sewage/waste water, or large diffuse inputs from sources such as agricultural runoff and deciduous tree leaves. High biomasses of algae and other aquatic plants are also often associated with high rates of ecosystem respiration.

In the past, limitations of dissolved oxygen (DO) probes and logging equipment, as well as knowledge of the temporal and spatial variability associated with river metabolism, have acted as barriers to the routine use of ecosystem metabolism as a form of ecosystem health assessment. However, recent development of optical DO probes have made it possible to deploy equipment for long periods, supposedly without the need for regular calibration. There is also a rapidly growing amount of literature reporting rates of ecosystem metabolism of streams, and to a lesser degree large rivers, in New Zealand and abroad (Uehlinger 2006; Gawne *et al.* 2007; Young *et al.* 2008; Collier *et al.* 2009; Young & Collier 2009). This has enabled a better understanding of natural variability in ecosystem metabolism. Horizons Regional Council has deployed dissolved oxygen loggers on a continuous basis in a selection of rivers since 2005. This data set provides the opportunity to investigate spatial and temporal variability in ecosystem metabolism and to demonstrate the additional value that can be extracted from the continuous DO data.

Ecosystem processes, such as ecosystem metabolism, are effected by upstream activities but can also be influenced by local impacts such as point-source discharges and riparian vegetation clearance (Gücker *et al.* 2006; Von Schiller *et al.* 2008). As such, different reaches in a large river can have different rates of metabolism. By comparing rates of metabolism among different reaches of a river system and also among rivers with differing land-use intensities, it is possible to comment on the pressures potentially influencing river metabolism at any one location.

Ecosystem metabolism varies seasonally in relation to temperature, river flow and light availability (Uehlinger 2006). Seasonal variation and flow must be accounted for when establishing and assessing ecosystem health in relation to reference conditions. Based on trends observed in smaller rivers, we would expect metabolic rates to be higher in the warmer months and lower immediately after high flows due to scouring and/or flushing of organic matter from the system. Ecosystem metabolism can also vary on a smaller temporal scale, *i.e.* on a weekly basis, due to weather conditions. For example, clouds reduce the intensity of light reaching the river which can result in lower gross primary productivity (Young & Huryn 1996).

In this report we investigate the temporal variability in ecosystem metabolism at five sites on large rivers in the Manawatu-Wanganui Region characterised by a range of land-use intensities. This information will improve our understanding of temporal variability in metabolism rates that are likely to be encountered in Manawatu and Rangitikei Rivers and the potential effects of land-use on this variability. We also compare the metabolism rates with existing guidelines on what represents good and poor ecosystem health.

2. METHODS

Environmental data was investigated for five sites located on rivers throughout the Manawatu-Wanganui Region. The sites were located on large rivers with catchments subject to a range of land-use intensities and varying geologies (Figure 1, Table 1).

Table 1. Catchment characteristics of the sites on five rivers in the Manawatu-Wanganui Region.

Site	Northing	Easting	Order	% Native vegetation	% Urban area	% Pastoral land*	Predicted N load (g m^{-3})
Rangitikei at Mangaweka	2750300	6151300	7	57.90	0.98	45.4	0.698
Rangitikei at Onepuhi	2720100	6122200	7	49.91	1.19	52.6	0.785
Manawatu at Hopelands	2761500	6089800	6	10.11	2.60	85.3	1.232
Manawatu at Teachers College	2733100	6089200	7	21.97	2.50	75.0	1.123
Mangatainoka at Pahiatua	2750100	6080200	6	21.76	2.86	45.4	1.143

*data provided by Horizons.

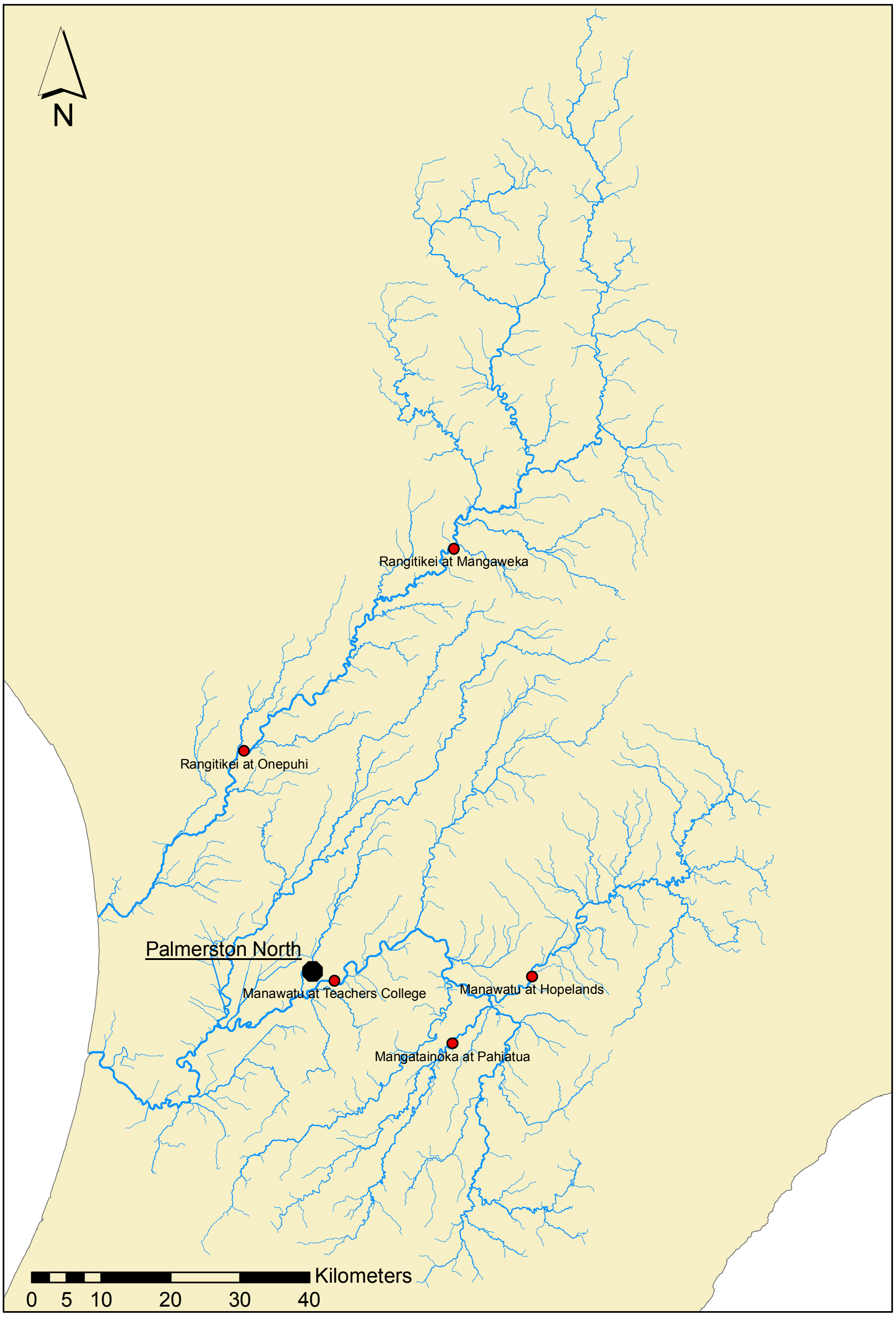

Figure 1. Map showing location of the five sampling sites.

Data supplied by Horizons Regional Council included average water depth, flow, temperature and dissolved oxygen (DO) values. The latter was comprised of 15-minute measurements of DO saturation collected using optical DO loggers. Graphs of the full range of data available at each site between February 2006 and May 2008 were inspected to identify gaps in the data sets and to choose suitable times to calculate metabolism *i.e.* times of relatively stable flow. Periods chosen for metabolic calculations were 21-25 August 2006 (winter), 19-23 November 2006 (spring), 18-22 February 2007 (summer), 7-11 May 2007 (autumn), 21-25 August 2007 (winter), 19-23 November 2007 (spring), 19-23 February 2008 (summer) and 19-23 May 2008 (autumn). For each date, metabolic estimates were calculated with DO data from midday to the following midday.

Before analysis, random noise in the data set was removed/reduced by applying a moving average smooth with an interval of five measurements. Metabolism values were then calculated using the RiverMetabolismEstimator spreadsheet model (Version 1.2) developed by Young & Knight (2005). This model uses the following approach to calculate metabolism values. Mean daily ecosystem respiration (ER) and the reaeration coefficient (k) were determined using the night time regression method (Owens 1974), which uses only data collected in the dark (<2 µmol m^{-2} s^{-1}). Light data were not available for the sites, so the night time period was determined by examining the oxygen data. Night time typically is the period between the fastest recorded reduction in oxygen concentration (dusk) and the highest recorded oxygen deficit (difference between the oxygen concentration at saturation and the observed concentration in the water) which occurs at dawn. The rate of change of oxygen concentration over short intervals during the night was regressed against the oxygen deficit to yield:

$$dO/dt = ER + kD \qquad (1)$$

where dO/dt is the rate of change of oxygen concentration (g m^{-3} s^{-1}), ER is the ecosystem respiration rate (g O_2 m^{-3} s^{-1}), k is the reaeration coefficient (s^{-1}), and D is the oxygen deficit (g m^{-3}). The slope of the regression line estimates k and the y-intercept estimates ER (Kosinski 1984).

The reaeration coefficient and ecosystem respiration rate obtained were then used to determine gross photosynthetic rate over the sampling interval using:

$$GPP_t = dO/dt + ER - kD \qquad (2)$$

where GPP_t is the gross photosynthetic rate (g O_2 m^{-3} s^{-1}) over time interval (t). To compensate for daily temperature fluctuation, ER is assumed to double with a 10°C increase in temperature (Phinney & McIntire 1965) while the reaeration rate is assumed to increase by 2.41% per degree (Kilpatrick *et al.* 1989). Daily gross primary production (GPP, g O_2 m^{-3} s^{-1}) was estimated as the integral of all temperature-corrected photosynthetic rates during daylight (Wiley *et al.* 1990).

This analysis gave values of production and respiration per unit volume. An areal estimate was obtained by multiplying the volume-based estimates by average reach depth (m) which allowed comparison among stations with different depths.

Problems associated with the raw DO data were evident at some sites on some occasions. On these occasions DO values did not fall below 100% saturation at any time over the 24 hour sampling period. We consider that it is physically impossible for a site with high productivity, leading to greater than 100% DO saturation during the day, to not have equally high rates of respiration which would reduce the dissolved oxygen concentration to below 100% saturation at dawn. The DO probes appear to have been recording artificially high values either due to insufficient calibration or technical failure. In these situations we corrected the oxygen data by subtracting a sufficient proportion to ensure that concentrations were below 100% saturation at dawn. Corrections of between 10-30% were required at times. Estimates of metabolism on these occasions were calculated using this corrected data. It is possible that the DO measurements were still too high after correction, however we have no way of knowing how much more to correct the data.

Gross Primary Productivity and ER data were log-transformed to meet the assumptions of normality for statistical analysis. An analysis of variance (ANOVA) to test for similarity among sites and over time was conducted in Systat Version 10.

3. RESULTS

3.1. Dissolved oxygen data

Very high values for DO saturation were observed at the Manawatu at Hopelands site (Table 2). Supersaturation of dissolved oxygen (>100% DO) was evident at all sites, while DO minima were very low at times and well below the dissolved oxygen saturation standards proposed in the Horizons One Plan to protect ecosystem health.

As mentioned previously, DO concentrations at some sites at some times were consistently supersaturated even at night time, suggesting that the DO probes were recording artificially high values (Figure 2). This was particularly evident in August 2007 (Figure 2).

Table 2. Range in temperature and dissolved oxygen data at the five study sites.

Site	Temp Min	Temp Max	% DO Min	% DO Max
Manawatu at Hopelands	6.31	25.83	40.02	332.02
Manawatu at Teachers College	6.9	24.8	41.93	125.07
Mangatainoka at Pahiatua	6.28	24.04	43.14	119.57
Rangitikei at Mangaweka	3.9	23.5	66.01	147.27
Rangitikei at Onepuhi	4.69	25.23	47.12	145.17

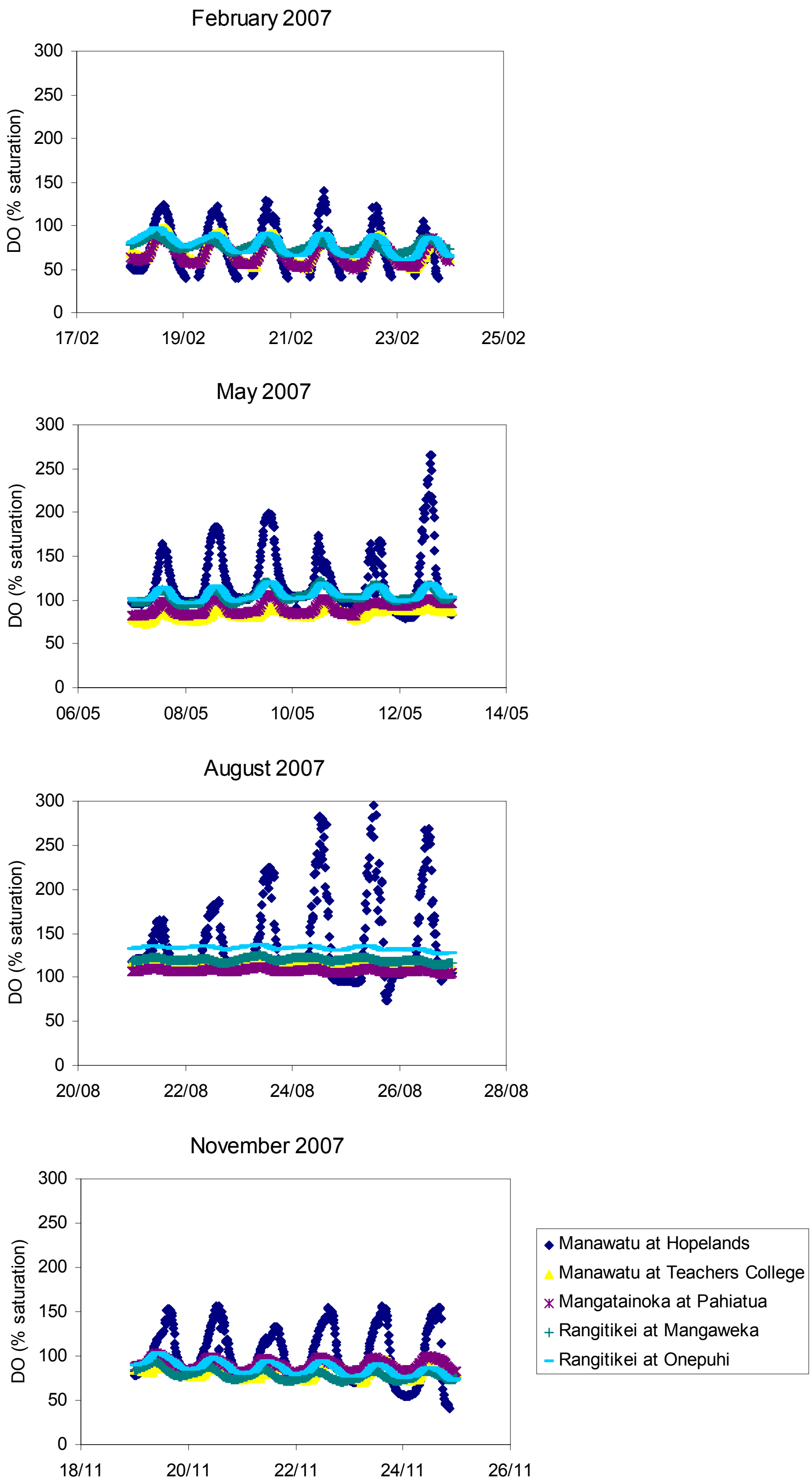

Figure 2. Graphs showing the five-daily range in dissolved oxygen data used in metabolic calculations for each of the five study sites for part of the study period.

3.2. Ecosystem metabolism

3.2.1. Gross primary productivity

Rates of GPP ranged from 0.15 g O_2 m^{-2} d^{-1} (Rangitikei at Onepuhi in winter) to 119.71 g O_2 m^{-2} d^{-1} (Manawatu at Hopelands in winter). GPP was generally low throughout the study period in the Rangitikei at Onepuhi and indicative of healthy conditions according to the criteria suggested by Young *et al*. (2008). The only exception at this site was during summer 2008 when measurements indicated satisfactory health. In contrast, GPP was consistently high in the Manawatu at Hopelands and indicative of poor ecosystem health throughout 2007 (Figure 3). Rates of GPP indicated satisfactory to healthy conditions at the remaining three study sites – Manawatu at Teachers College, Mangatainoka at Pahiatua, and Rangitikei at Mangaweka. GPP was lowest in winter and highest in summer at all sites, except Manawatu at Hopelands. At all sites the difference between minimum GPP and maximum GPP recorded over the 24-month study period averaged 9.9 g O_2 m^{-2} d^{-1}, except at Manawatu at Hopelands where the range was 117.3 g O_2 m^{-2} d^{-1}.

An analysis of variance showed a significant difference in GPP among study sites ($F_{(4, 160)} = 116.80$, $p < 0.001$) and over time ($F_{(7, 160)} = 25.86$, $p < 0.001$). However, a significant interaction between the effects of site and time showed that the difference among sites varied with time ($F_{(28,160)} = 12.67$, $p < 0.001$); *i.e.* sites had different seasonal trends. Repetition of the analysis with the exclusion of Manawatu at Hopelands data (because GPP appeared to vary significantly at this site compared to others) showed the same trends as the previous analysis, suggesting that all study sites have significantly different GPP over time.

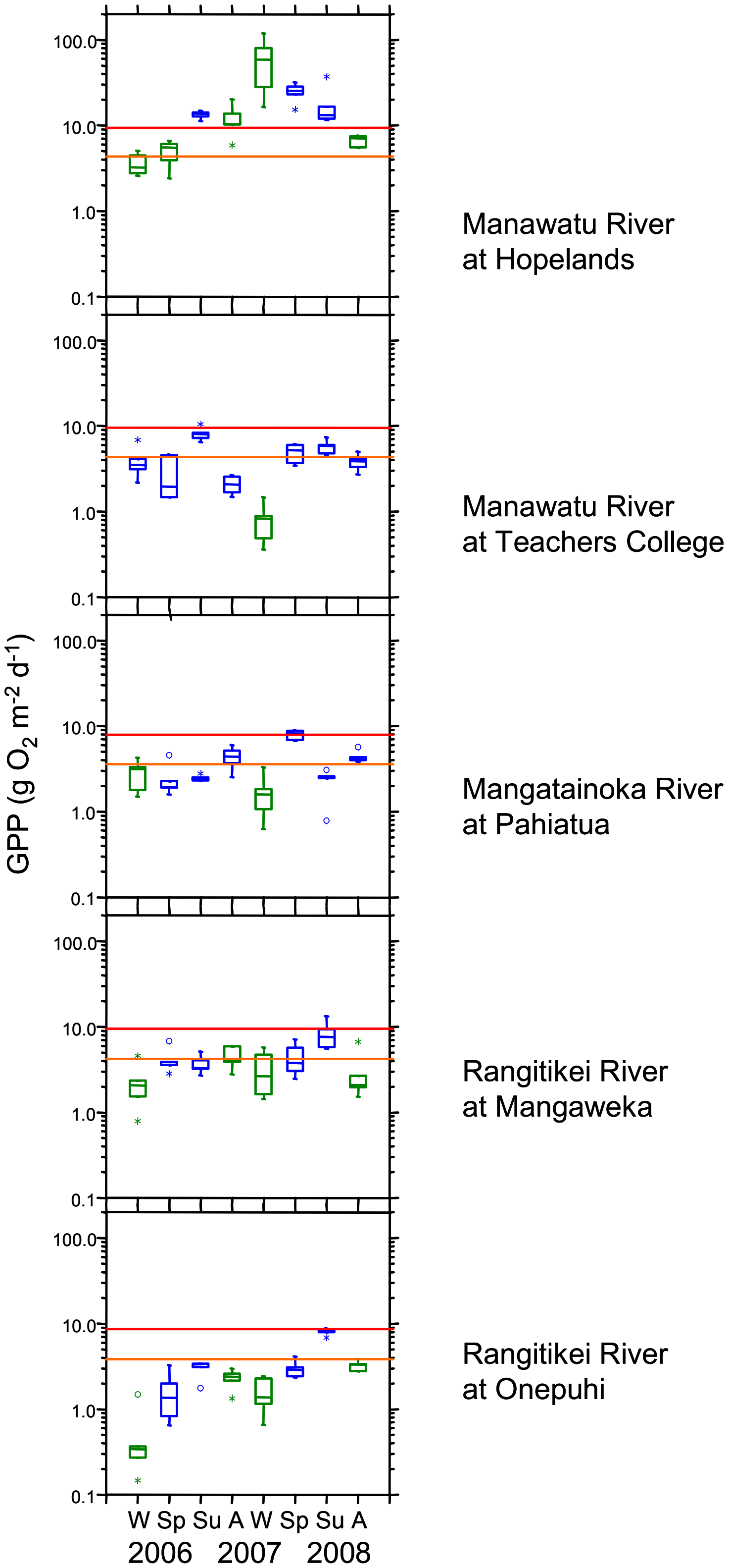

Figure 3. Rates of gross primary production (GPP) for five study sites on rivers in the Manawatu-Wanganui Region. Box plots show the median, upper and lower quartiles and range of values. Green boxes indicate GPP calculated using corrected data. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al.* (2008): below the orange line is 'healthy', above the orange line is 'satisfactory' and above the red line is 'poor'. Note *Y* axis is on a $\log_{10}$-scale.

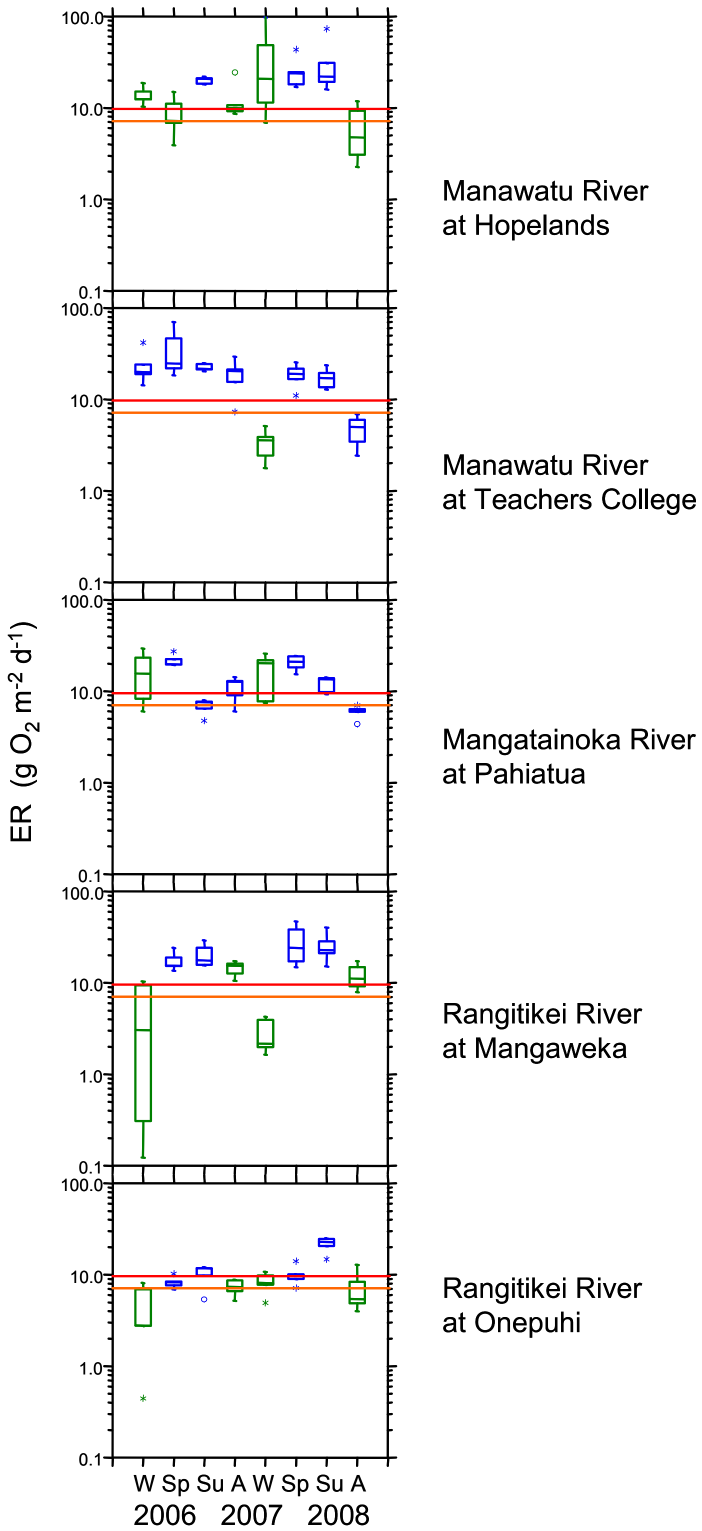

Figure 4. Rates of ecosystem respiration (ER) for five study sites on rivers in the Manawatu-Wanganui Region. Box plots show the median, upper and lower quartiles and range of values. Green boxes indicate ER calculated using corrected data. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al*. (2008): below the orange line is 'healthy', above the orange line is 'satisfactory' and above red line is 'poor'. Note *Y* axis is on a $\log_{10}$-scale.

3.2.2. Ecosystem respiration

Rates of ER ranged from 0.12 g O_2 m^{-2} d^{-1} (Rangitikei at Mangaweka in winter) to 97.99 g O_2 m^{-2} d^{-1} (Manawatu at Hopelands in winter). ER was generally high throughout the study period at Manawatu at Hopelands and indicative of poor ecosystem health (Figure 4). Similarly, both Manawatu at Teachers College and Rangitikei at Mangaweka had high rates of ER indicative of poor ecosystem health, except in winter. Mangatainoka at Pahiatua had moderate to high rates of ER indicating satisfactory to poor condition. Rangitikei at Onepuhi had generally moderate rates of ER, but still had some high values during the warmer months indicating poor ecosystem health. The difference between minimum ER and maximum ER recorded over the 24-month study period ranged from 25 g O_2 m^{-2} d^{-1} at Rangitikei at Onepuhi up to 95.7 g O_2 m^{-2} d^{-1}at Manawatu at Hopelands.

As with GPP, an analysis of variance showed that ER was different among sites ($F_{(4, 160)} = 11.25$, $p < 0.001$) and over time ($F_{(7, 160)} = 19.65$, $p < 0.001$) and there was a significant interaction ($F_{(28,160)} = 7.96$, $p < 0.001$), suggesting the difference between sites varied with season.

3.2.3. P/R ratio

The balance between GPP and ER is a useful measure of the sources of energy driving a stream ecosystem. If GPP equals or exceeds ER then organic matter produced within the system (*e.g.* periphyton biomass) is probably supporting the food chain, whereas if ER greatly exceeds GPP then organic matter from upstream or the surrounding catchment is being used to maintain the ecosystem (*e.g.* allochthonous inputs). The ratio of GPP:ER (or P/R) ranged from 0.05 (Rangitikei at Onepuhi in winter) to 2.8 (Manawatu at Hopelands in winter). These values are all within the range expected for healthy river systems, except for the higher values recorded in winter 2007 and autumn 2008 at Manawatu at Hopelands which were indicative of satisfactory conditions (Figure 5). The P/R ratios indicated that these sites generally were relying on organic matter from upstream or the surrounding catchment to support the food chain, although the relatively high ratios at Manawatu at Hopelands and Rangitikei at Mangaweka indicate that algae probably contributed significantly to the food chain at times.

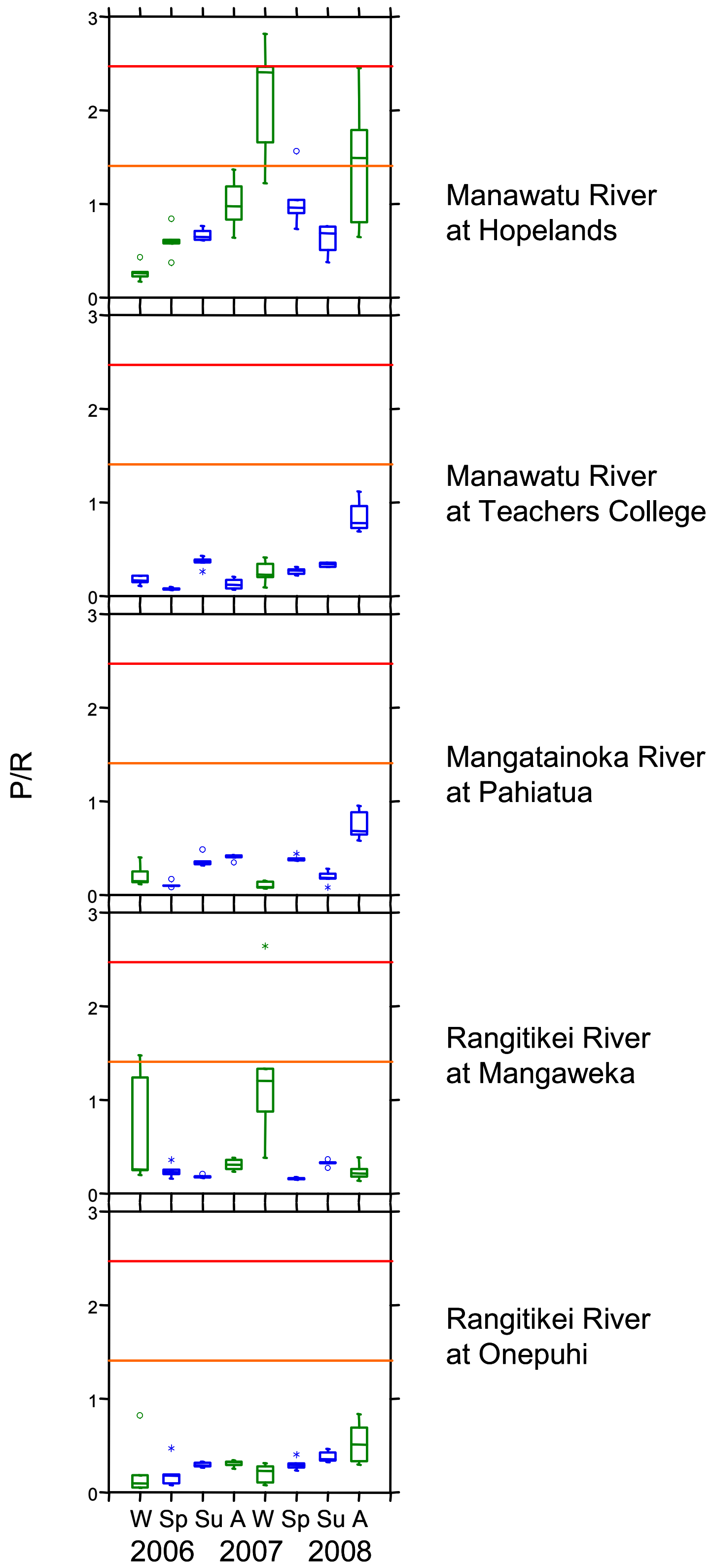

Figure 5. The ratio of GPP to ER for five study sites on rivers in the Manawatu-Wanganui Region. Box plots show the median, upper and lower quartiles and range of values. Green boxes indicate P/R calculated using corrected data. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al*. (2008): below the orange line is 'healthy', above the orange line is 'satisfactory' and above red line is 'poor'.

3.2.4. Assessing ecosystem health

Preferably, local sites representing best attainable condition should be used to determine reference condition for assessing ecosystem health, rather than the broad guidelines used above (Young *et al.* 2006). None of the study sites appear suitable to represent reference condition based on land-use pressures (*e.g.* percent native vegetation). For example, a recent survey identified 60% vegetation cover as a potential threshold for change in the response in ecosystem metabolism in New Zealand streams (Clapcott *et al.* in review). However, there was weak evidence of a relationship between catchment land use and ecosystem metabolism in Manawatu Rivers. The Rangitikei at Onepuhi had consistently lower GPP and ER compared to other sites, associated with relatively low pressure values (*i.e.* relatively high native vegetation cover and low predicted nitrogen load). In contrast, Manawatu at Hopelands had relatively high GPP and ER, associated with relatively high pressure values. There were insufficient data to statistically test these relationships. However, Rangitikei at Onepuhi could be used to represent 'best attainable' condition for large rivers of the Manawatu region based on consistently low ecosystem metabolism measures during the study period. In comparison to average annual values for Rangitikei at Onepuhi, rates of GPP and ER suggest that Manawatu at Hopelands has poor ecosystem health and the remaining three sites have satisfactory ecosystem health for most of the year (Figure 6).

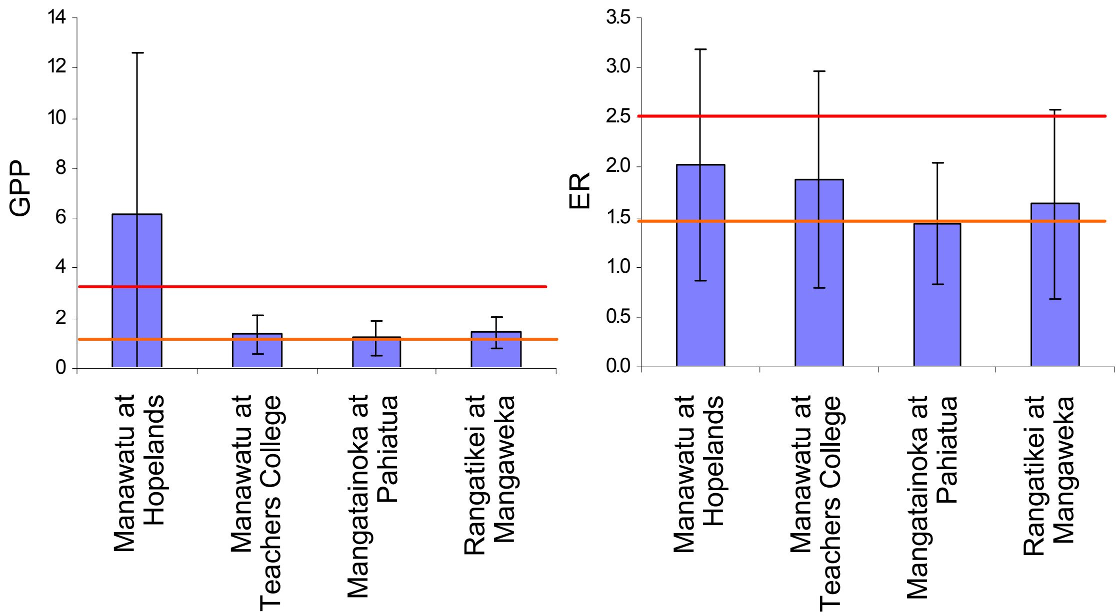

Figure 6. Ratio of rates of GPP and ER (g O_2 m^{-2} d^{-1}) for four sites on rivers in the Manawatu-Wanganui Region compared to Rangitikei at Onepuhi. Bars show annual means and standard deviations. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al*. (2008): below the orange line is 'healthy', above the orange line is 'satisfactory' and above red line is 'poor'.

3.3. Comparison with independent data

In late November 2007, metabolism was calculated for an additional site on the Manawatu (at Opiki) and Rangitikei (at Bulls Bridge) rivers as part of a national study (Collier *et al.* 2009). The measurements from the present study are within the range of those values observed by Collier *et al*. (2009) but considerably less than the GPP and ER values calculated for the Manawatu River at Opiki (Figure 7).

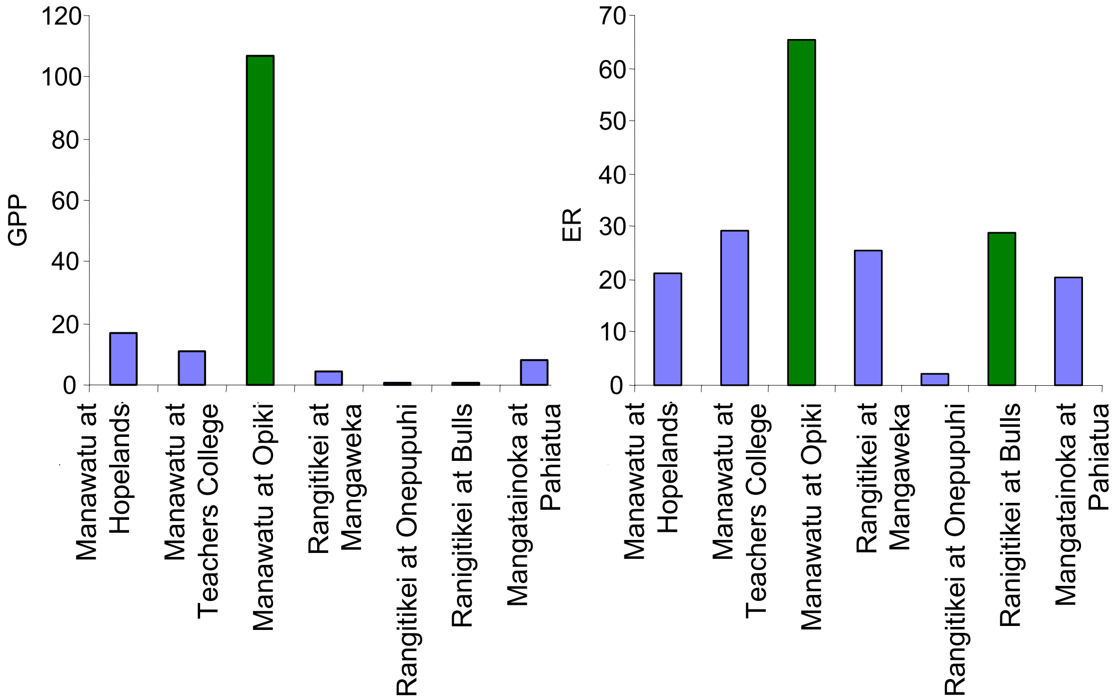

Figure 7. Rates of GPP and ER (g O_2 m^{-2} d^{-1}) for seven sites on rivers in the Manawatu-Wanganui Region on 27 November 2007. Green bars indicate sites measured as part of another study.

3.4. Comparison with water quality data

A comparison of metabolic rates with water quality data collected from the study sites showed distinct relationships between GPP and black disk clarity, DRP, NH_4-N, NO_3-N and POM. Similarly, relationships were also detected between ER and DRP, NO_3-N, POM and temperature (Table 3). These simple correlations support the concept that light intensity is an important controlling factor for rates of GPP, whereas temperature is the dominant driver of ER. Similarly, there appears to be a strong coupling between GPP and ER evident in the way they both respond to increasing nutrient availability.

Table 3. Pearson's correlation coefficients for metabolic variables and water quality metrics for data from five sites on rivers in the Manawatu-Wanganui Region during the study period August 2006 to May 2008. Values in bold highlight significant relationships (P <0.01).

	N	*ER*	*GPP*	*P/R*
Black disk clarity	26	0.155	**0.335**	0.034
Conductivity	28	-0.118	-0.139	-0.109
Dissolved oxygen	38	**-0.309**	**-0.579**	**-0.553**
Dissolved reactive phosphorus (DRP)	40	**0.347**	**0.786**	**0.646**
E. coli	32	0.022	-0.183	-0.167
Ammonia (NH_4-N)	35	0.063	**0.626**	**0.627**
Nitrates (NO_3-N)	23	**0.453**	**0.557**	**0.577**
pH	32	0.085	0.039	-0.045
Particulate organic matter (POM)	24	**0.342**	**0.629**	**0.482**
Suspended solids (SS)	16	0.104	0.020	-0.108
Temperature	40	**0.281**	0.022	**-0.205**
Total nitrogen (TN)	40	0.130	0.188	0.096
Total phosphorus (TP)	40	0.171	0.067	-0.067
Turbidity	40	-0.078	-0.068	-0.110

4. DISCUSSION

The metabolism measurements indicate that the five sites examined in this study cover a gradient of river health. During the study period, Manawatu at Hopelands had consistently high rates of GPP and ER. While they were not as high as rates observed in the lower reaches of the Manawatu by Collier *et al*. (2009), rates of GPP and ER consistently indicated that the health of this stretch of the river was poor. This 'poor' classification was based on comparison with broad guidelines for interpreting metabolism results (Young *et al*. 2008) as well as when compared to an approximate regional 'best attainable condition' site (*i.e.* Rangitikei at Onepuhi).

High rates of GPP and ER are indicative of poor ecosystem health because they show that a river system has an unbalanced food web. High rates of ER are associated with an abundance of allochthonous inputs from sewerage, agricultural fertilisers, urban run-off, or other sources of high carbon and nutrient loads (Young & Huryn 1999; Gücker *et al.* 2006). High ER is also often associated with high in-stream temperatures (Acuña *et al.* 2004; Roberts *et al.* 2007), due to seasonal variability or reduced flow during drought events or the over-allocation of in-stream or ground waters. The direct cause of high ER is likely to be a stimulation of excessive organic matter breakdown by microbial communities as well as respiration by an increased periphyton and phytoplankton biomass. Likewise, high GPP at an ecosystem level is due to an increased biomass of periphyton and/or phytoplankton whose growth is stimulated by warm temperatures and nutrient availability. High GPP also often correlates to higher light levels due to season or the clearance of riparian vegetation (Bunn *et al.* 1999).

Manawatu at Hopelands had the highest land-use pressure in terms of predicted nitrogen loading (Table 1) and percentage of native vegetation remaining (10%) and would be expected to be the least healthy of the study sites. In contrast, Rangitikei at Onepuhi had relatively low land-use pressure with approximately 50% native vegetation cover in the catchment and low predicted nitrogen loading (Table 1). It had consistently low rates of GPP and ER and was classified as healthy in terms of GPP rates and mostly satisfactory in terms of ER rates when compared to guideline values based on other reference sites. However, other land-use impacts within the catchment, such as point-source impacts, reduce its suitability as a long-term reference site. Preferably a reference site would have greater than 60% native vegetation cover, low-intensity land development in the remaining 40% of the catchment and no or limited point-source impacts.

The Rangitikei at Mangaweka had the least land-use pressure (58% native vegetation) and as such we would expect this site to be the healthiest of the five sites. However, this was not the case based on our assessment of metabolism data. Our results suggest that local environmental variables, such as naturally high levels of dissolved reactive phosphorous in the upper catchment, and/or human impacts, such as the Taihape sewerage treatment discharge, are likely to be contributing to the relatively high rates of metabolism observed at Rangitikei at Mangaweka.

Most sites had higher metabolic rates in the warmer months as expected. Seasonal variability influenced the assessment of ecosystem health when compared to the broad guideline values. For example, rates of GPP in the Mangatainoka at Pahiatua indicated good health in summer and winter, satisfactory health in autumn, and poor health in spring. We expected the most marked divergence from healthy conditions to occur during summer and autumn when low flows, warm temperatures, plentiful sunlight and the accumulation of algal biomass combine to produce high rates of metabolism, although changes in flow which influence accumulation of algal biomass are not necessarily associated with particular seasons. Therefore these results are particularly interesting. However, caution needs to be applied to this comparison across seasons because problems with the raw DO data may confound the comparison. Even after data correction, the metabolic rates may have been under/over estimates of the true metabolic rates at these times.

The most impacted site in terms of land-use intensity defined by native vegetation cover and predicted nitrogen load (*i.e.* Manawatu at Hopelands) had a much higher annual range in metabolism measures than the remaining sites. This supports the suggestion that human disturbance can lead to increased temporal variability in ecosystem functions, which is indicative of decreased stability/resilience of the ecosystem (Rapport *et al.* 1998). For example, dramatic changes over time in food supplies or water quality may make it hard for organisms to adapt or recover from disturbances such as floods. However, again the problems with the raw DO data limit the strength of such conclusions.

In conclusion, a range in ecosystem health was evident for Manawatu and Rangitikei Rivers from August 2006 to May 2008 based on the assessment of ecosystem metabolism.

Metabolism appeared to have a relationship with land use and with water quality parameters. Additional pressures and/or disturbances that were examined in this study can also influence the response of metabolism, such as point-source inputs. Point-source discharges in the sample reach can affect metabolism more than diffuse land-use effects (Authors, unpublished data). It would be interesting to determine whether sites that did not respond to seasonal trends as predicted had local disturbances and/or environmental variables (*e.g.* algal blooms) that were related to metabolic variables.

5. RECOMMENDATIONS

1. Calculate metabolism for ongoing DO data to establish inter-annual seasonal trends and provide more robust data for analysis of relationships between metabolism and environmental data (particularly flow).
2. Compare metabolism estimates with similar large rivers from a national dataset as it becomes available and/or establish a local regional reference site.
3. Establish a data quality assurance methodology that includes the regular calibration of equipment and data checking. Consider deploying two DO loggers at a site for a short time to cross-validate data. A single spot measurement is not sufficient for calibration.
4. Consider establishing several sites upstream and downstream of known land use and point-source impacts to establish the effects of each on ecosystem health (*e.g.* Manawatu upstream of Dannevirke STP (the Hopelands site is downstream of Dannevirke by several kilometres) lower Mangatainoka, lower Manawatu, lower Rangitikei, Hautapu River upstream and downstream of Taihape sewage).

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Appendix 1. Daily metabolism estimates from sites on five rivers in the Manawatu-Wanganui Region. Calculations with low R^2 values (<0.4) are in red and should be treated with caution. Corrected refers to whether DO data needed to be corrected before metabolism calculation – see methods section.

Season	Date	Depth	ER	GPP	PR	*k*	*R2*	Corrected
Manawatu River at Hopelands								
Winter	21/08/2006	0.98	15.00	2.58	0.17	8.74	0.84	Yes
Winter	22/08/2006	0.99	18.70	5.07	0.27	16.40	0.90	Yes
Winter	23/08/2006	0.93	10.32	4.45	0.43	9.77	0.92	Yes
Winter	24/08/2006	0.90	12.47	3.24	0.26	11.77	0.99	Yes
Winter	25/08/2006	0.93	12.42	2.77	0.22	8.68	0.97	Yes
Spring	19/11/2006	0.91	7.22	6.08	0.84	14.39	0.78	Yes
Spring	20/11/2006	0.87	3.90	2.40	0.62	5.72	0.78	Yes
Spring	21/11/2006	0.84	6.82	3.92	0.58	6.19	0.72	Yes
Spring	22/11/2006	0.81	11.08	6.63	0.60	12.53	0.94	Yes
Spring	23/11/2006	0.80	14.95	5.55	0.37	11.92	0.93	Yes
Summer	18/02/2007	0.57	18.07	13.85	0.77	5.29	0.95	No
Summer	19/02/2007	0.57	20.98	14.89	0.71	6.71	0.84	No
Summer	20/02/2007	0.57	20.76	12.72	0.61	5.91	0.89	No
Summer	21/02/2007	0.56	18.29	11.27	0.62	5.39	0.66	No
Summer	22/02/2007	0.56	22.01	14.22	0.65	5.77	0.97	No
Autumn	7/05/2007	0.61	10.68	10.41	0.98	7.82	0.98	Yes
Autumn	8/05/2007	0.60	10.01	13.70	1.37	9.84	0.97	Yes
Autumn	9/05/2007	0.60	8.62	10.21	1.19	8.89	0.99	Yes
Autumn	10/05/2007	0.60	9.17	5.86	0.64	5.53	0.87	Yes
Autumn	11/05/2007	0.60	24.36	20.27	0.83	11.22	0.91	Yes
Winter	21/08/2007	1.03	6.87	16.51	2.40	10.55	0.65	Yes
Winter	22/08/2007	0.97	11.43	28.14	2.46	11.70	0.72	Yes
Winter	23/08/2007	0.92	20.96	59.00	2.82	21.43	0.91	Yes
Winter	24/08/2007	0.88	48.31	79.99	1.66	24.75	0.91	Yes
Winter	25/08/2007	0.85	97.99	119.71	1.22	23.18	0.87	Yes
Spring	19/11/2007	0.66	18.12	28.29	1.56	14.76	0.97	No
Spring	20/11/2007	0.64	16.99	15.30	0.90	10.60	0.97	No
Spring	21/11/2007	0.63	24.37	25.41	1.04	14.53	0.97	No
Spring	22/11/2007	0.62	23.90	22.94	0.96	11.30	0.92	No
Spring	23/11/2007	0.61	43.42	31.81	0.73	12.95	0.98	No
Summer	17/02/2008	0.57	15.86	11.97	0.76	5.52	0.82	No
Summer	18/02/2008	0.53	21.90	16.66	0.76	8.44	0.75	No
Summer	19/02/2008	0.51	19.27	13.26	0.69	7.08	0.75	No
Summer	20/02/2008	0.50	30.85	11.61	0.38	15.33	0.66	No
Summer	21/02/2008	0.49	73.11	37.12	0.51	28.24	0.93	No
Autumn	19/05/2008	0.65	3.08	5.49	1.79	7.31	0.99	Yes
Autumn	20/05/2008	0.64	2.25	5.53	2.45	7.95	0.98	Yes
Autumn	21/05/2008	0.64	4.76	7.10	1.49	8.81	0.98	Yes
Autumn	22/05/2008	0.65	9.28	7.44	0.80	5.91	0.95	Yes
Autumn	23/05/2008	0.65	11.85	7.64	0.65	6.71	0.96	Yes

Season	Date	Depth	ER	GPP	PR	*k*	*R*2	Corrected
Manawatu River at Teachers College								
Winter	21/08/2006	2.02	24.04	3.52	0.15	4.99	0.13	No
Winter	23/08/2006	1.88	14.28	3.13	0.22	5.83	0.18	No
Winter	24/08/2006	1.76	19.95	2.19	0.11	9.17	0.67	No
Winter	25/08/2006	1.75	41.71	6.89	0.17	12.15	0.51	No
Winter	26/08/2006	2.25	18.85	4.10	0.22	5.14	0.33	No
Spring	19/11/2006	2.79	21.72	1.47	0.07	3.73	0.66	No
Spring	20/11/2006	2.15	18.37	1.48	0.08	3.39	0.38	No
Spring	26/11/2006	2.10	46.35	4.52	0.10	9.00	0.64	No
Spring	25/11/2006	2.00	24.68	1.97	0.08	4.76	0.25	No
Spring	24/11/2006	2.73	70.03	4.66	0.07	11.75	0.75	No
Summer	18/02/2007	1.02	24.31	10.45	0.43	4.30	0.92	No
Summer	19/02/2007	1.01	21.30	8.32	0.39	3.66	0.92	No
Summer	20/02/2007	1.01	21.50	8.10	0.38	3.32	0.83	No
Summer	21/02/2007	1.00	20.30	7.23	0.36	3.42	0.73	No
Summer	22/02/2007	1.00	24.87	6.47	0.26	4.14	0.82	No
Autumn	7/05/2007	1.14	29.41	2.09	0.07	10.97	0.29	No
Autumn	8/05/2007	1.13	21.26	2.57	0.12	9.22	0.42	No
Autumn	9/05/2007	1.10	15.49	2.68	0.17	7.07	0.34	No
Autumn	10/05/2007	1.11	7.28	1.49	0.20	3.15	0.14	No
Autumn	11/05/2007	1.62	20.55	1.68	0.08	9.02	0.59	No
Winter	21/08/2007	1.15	2.43	0.83	0.34	4.54	0.73	Yes
Winter	22/08/2007	1.17	3.57	1.48	0.41	7.43	0.67	Yes
Winter	23/08/2007	1.19	1.77	0.36	0.20	3.36	0.41	Yes
Winter	24/08/2007	1.22	3.87	0.89	0.23	4.18	0.18	Yes
Winter	25/08/2007	1.24	5.13	0.48	0.09	5.41	0.13	Yes
Spring	19/11/2007	1.30	11.02	2.64	0.24	3.01	0.24	No
Spring	20/11/2007	1.26	16.69	2.93	0.18	4.52	0.82	No
Spring	21/11/2007	1.23	19.11	4.23	0.22	5.33	0.26	No
Spring	22/11/2007	1.20	25.48	5.00	0.20	8.23	0.73	No
Spring	23/11/2007	1.18	21.56	5.20	0.24	6.88	0.59	No
Summer	19/02/2008	1.09	12.84	4.55	0.35	5.27	0.85	No
Summer	20/02/2008	1.04	13.53	4.79	0.35	4.18	0.91	No
Summer	21/02/2008	1.01	19.31	5.98	0.31	5.22	0.80	No
Summer	22/02/2008	0.98	23.73	7.40	0.31	6.91	0.41	No
Summer	23/02/2008	0.97	17.17	5.91	0.34	3.83	0.73	No
Autumn	20/05/2008	1.12	2.43	2.72	1.12	4.59	0.94	No
Autumn	21/05/2008	1.11	3.46	3.32	0.96	5.52	0.94	No
Autumn	22/05/2008	1.10	4.98	3.89	0.78	5.36	0.96	No
Autumn	23/05/2008	1.11	5.99	4.13	0.69	4.65	0.95	No
Autumn	24/05/2008	1.26	6.91	5.00	0.72	5.34	0.92	No

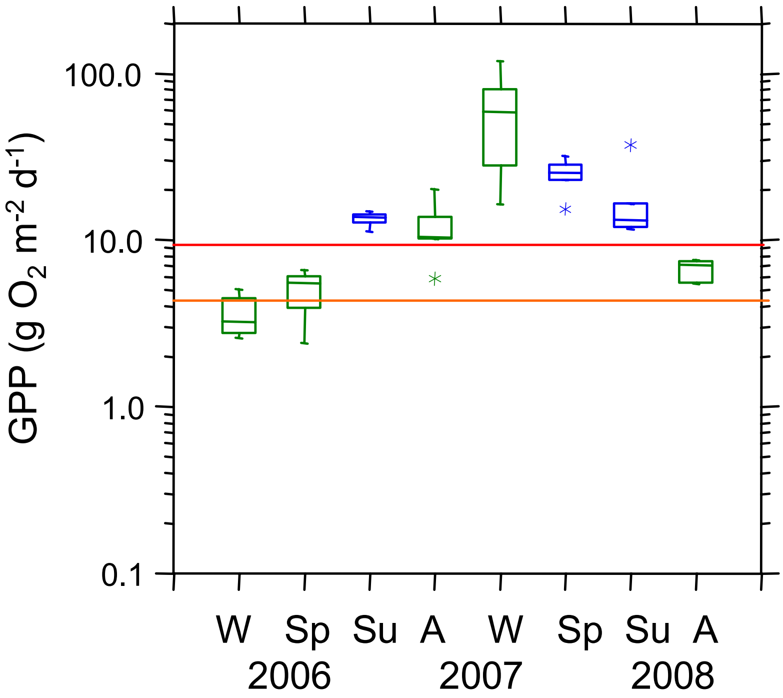
Season	Date	Depth	ER	GPP	PR	*k*	*R*2	Corrected
Mangatainoka River at Pahiatua								
Winter	21/08/2006	1.09	29.24	4.27	0.15	17.67	0.87	Yes
Winter	23/08/2006	0.93	8.22	3.30	0.40	12.29	0.83	Yes
Winter	24/08/2006	0.86	6.06	1.49	0.25	6.56	0.83	Yes
Winter	25/08/2006	0.85	15.62	1.79	0.11	12.69	0.85	Yes
Winter	26/08/2006	1.41	23.14	3.16	0.14	11.45	0.76	Yes
Spring	19/11/2006	1.52	27.12	4.56	0.17	8.88	0.79	No
Spring	20/11/2006	1.13	19.63	1.92	0.10	10.84	0.81	No
Spring	21/11/2006	0.99	19.76	1.60	0.08	10.83	0.77	No
Spring	22/11/2006	0.91	19.44	1.92	0.10	10.54	0.78	No
Spring	23/11/2006	0.90	22.34	2.27	0.10	11.32	0.84	No
Summer	18/02/2007	0.36	7.96	2.78	0.35	3.80	0.57	No
Summer	19/02/2007	0.35	6.49	2.32	0.36	2.96	0.51	No
Summer	20/02/2007	0.34	7.62	2.50	0.33	3.45	0.58	No
Summer	21/02/2007	0.34	4.76	2.31	0.49	1.69	0.61	No
Summer	22/02/2007	0.33	7.70	2.42	0.31	3.68	0.48	No
Autumn	7/05/2007	0.56	12.70	4.40	0.35	11.50	0.98	No
Autumn	8/05/2007	0.52	12.90	5.18	0.40	14.26	0.88	No
Autumn	9/05/2007	0.49	9.00	3.70	0.41	10.19	0.94	No
Autumn	10/05/2007	0.62	14.23	6.02	0.42	12.79	0.92	No
Autumn	11/05/2007	0.96	6.05	2.54	0.42	8.48	0.83	No
Winter	21/08/2007	0.89	25.89	1.83	0.07	23.63	0.88	Yes
Winter	22/08/2007	0.84	21.86	3.29	0.15	22.54	0.77	Yes
Winter	23/08/2007	0.80	20.25	1.60	0.08	21.18	0.82	Yes
Winter	24/08/2007	0.76	7.73	1.07	0.14	7.29	0.53	Yes
Winter	25/08/2007	0.73	7.46	0.63	0.08	7.65	0.56	Yes
Spring	19/11/2007	0.61	15.40	6.75	0.44	13.51	0.88	No
Spring	20/11/2007	0.58	24.01	8.82	0.37	19.72	0.88	No
Spring	21/11/2007	0.55	18.24	6.85	0.38	15.28	0.89	No
Spring	22/11/2007	0.53	24.30	8.96	0.37	22.01	0.97	No
Spring	23/11/2007	0.51	20.97	8.20	0.39	20.47	0.87	No
Summer	19/02/2008	0.43	14.19	2.46	0.17	8.27	0.89	No
Summer	20/02/2008	0.39	9.25	2.59	0.28	5.24	0.90	No
Summer	21/02/2008	0.35	9.82	0.78	0.08	7.49	0.96	No
Summer	22/02/2008	0.31	13.57	3.06	0.23	9.72	0.91	No
Summer	23/02/2008	0.29	13.89	2.51	0.18	10.45	0.58	No
Autumn	19/05/2008	0.46	5.96	5.67	0.95	15.83	0.94	No
Autumn	20/05/2008	0.45	4.36	3.85	0.88	12.59	0.97	No
Autumn	21/05/2008	0.45	6.22	4.00	0.64	11.04	0.96	No
Autumn	22/05/2008	0.44	6.99	4.07	0.58	10.44	0.97	No
Autumn	23/05/2008	0.43	6.35	4.33	0.68	13.61	0.89	No

Season	Date	Depth	ER	GPP	PR	*k*	*R*2	Corrected
Rangitikei River at Mangaweka								
Winter	20/08/2006	1.19	10.43	2.07	0.20	10.75	0.93	Yes
Winter	21/08/2006	1.19	9.42	2.35	0.25	7.69	0.65	Yes
Winter	23/08/2006	1.13	0.31	4.58	14.83	9.77	0.95	Yes
Winter	24/08/2006	1.10	0.12	1.54	12.42	6.91	0.88	Yes
Winter	25/08/2006	1.18	3.06	0.79	0.26	5.60	0.85	Yes
Spring	20/11/2006	1.10	19.06	6.82	0.36	14.59	0.83	No
Spring	21/11/2006	1.02	15.45	3.57	0.23	12.49	0.90	No
Spring	22/11/2006	0.97	13.67	2.83	0.21	10.76	0.73	No
Spring	23/11/2006	0.93	24.28	3.91	0.16	14.70	0.90	No
Spring	25/11/2006	0.92	15.29	3.90	0.26	9.52	0.88	No
Summer	18/02/2007	0.66	15.55	2.71	0.17	8.23	0.82	No
Summer	19/02/2007	0.65	17.72	3.24	0.18	8.44	0.72	No
Summer	20/02/2007	0.65	15.72	3.30	0.21	6.69	0.80	No
Summer	21/02/2007	0.65	24.26	4.05	0.17	11.02	0.86	No
Summer	22/02/2007	0.65	29.26	5.19	0.18	12.29	0.80	No
Autumn	7/05/2007	0.72	17.38	4.10	0.24	10.62	0.97	Yes
Autumn	8/05/2007	0.70	15.44	5.94	0.38	10.29	0.97	Yes
Autumn	9/05/2007	0.69	16.38	5.89	0.36	14.53	0.99	Yes
Autumn	10/05/2007	0.68	10.60	2.80	0.26	9.88	0.97	Yes
Autumn	11/05/2007	0.69	12.72	3.90	0.31	10.13	0.98	Yes
Winter	21/08/2007	1.15	1.64	1.44	0.87	15.60	0.75	Yes
Winter	22/08/2007	1.10	3.92	4.72	1.20	10.85	0.64	Yes
Winter	23/08/2007	1.06	2.18	5.77	2.64	28.72	0.83	Yes
Winter	24/08/2007	1.03	1.99	2.65	1.33	12.68	0.91	Yes
Winter	25/08/2007	1.00	4.26	1.64	0.38	19.26	0.75	Yes
Spring	19/11/2007	0.79	17.26	3.06	0.18	8.84	0.80	No
Spring	20/11/2007	0.78	14.90	2.47	0.17	6.70	0.75	No
Spring	21/11/2007	0.76	24.20	3.79	0.16	10.02	0.80	No
Spring	22/11/2007	0.75	38.40	5.70	0.15	16.37	0.80	No
Spring	23/11/2007	0.74	47.22	7.14	0.15	20.90	0.84	No
Summer	19/02/2008	0.62	40.54	13.40	0.33	27.37	0.89	No
Summer	20/02/2008	0.61	15.27	5.59	0.37	9.32	0.76	No
Summer	21/02/2008	0.60	28.52	9.31	0.33	18.56	0.87	No
Summer	22/02/2008	0.60	23.03	7.69	0.33	16.35	0.95	No
Summer	23/02/2008	0.60	21.22	5.82	0.27	13.54	0.86	No
Autumn	19/05/2008	0.77	17.33	6.70	0.39	27.35	0.91	Yes
Autumn	20/05/2008	0.76	7.95	2.09	0.26	11.22	0.49	Yes
Autumn	21/05/2008	0.76	9.17	1.97	0.21	10.44	0.90	Yes
Autumn	22/05/2008	0.75	14.87	2.68	0.18	15.67	0.85	Yes
Autumn	23/05/2008	0.76	11.17	1.53	0.14	9.70	0.80	Yes

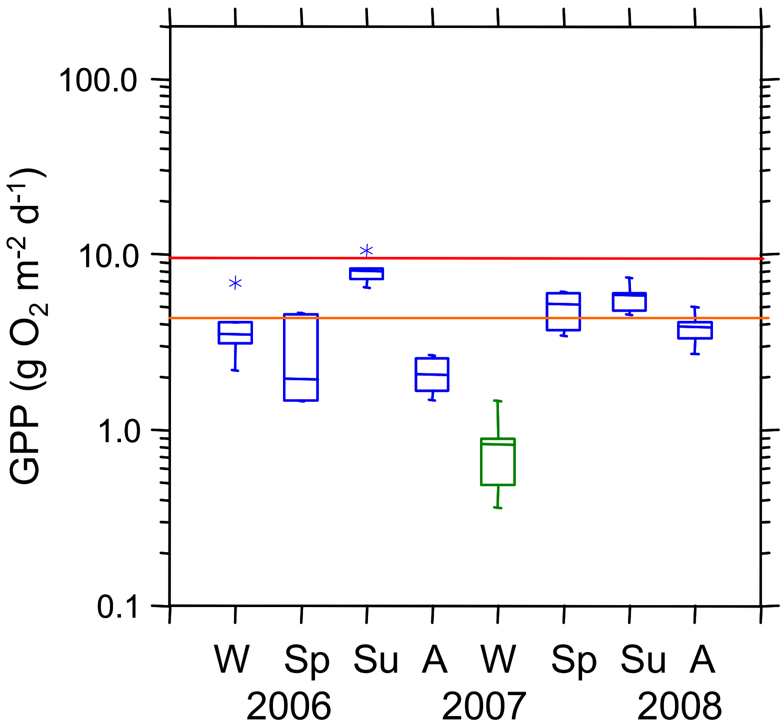
CAWTHRON

Season	Date	Depth	ER	GPP	PR	*k*	*R*2	Corrected
Rangitikei River at Onepuhi								
Winter	18/08/2006	0.71	2.78	0.27	0.10	8.88	0.70	Yes
Winter	19/08/2006	0.67	6.93	0.34	0.05	11.45	0.83	Yes
Winter	21/08/2006	0.78	8.15	1.49	0.18	9.66	0.88	Yes
Winter	24/08/2006	0.66	0.44	0.37	0.82	9.75	0.79	Yes
Winter	25/08/2006	0.68	2.80	0.15	0.05	8.73	0.84	Yes
Spring	19/11/2006	1.01	6.95	3.28	0.47	13.74	0.65	No
Spring	20/11/2006	0.70	7.63	1.37	0.18	12.15	0.96	No
Spring	21/11/2006	0.55	10.28	1.99	0.19	19.30	0.99	No
Spring	22/11/2006	0.45	8.46	0.83	0.10	15.17	0.77	No
Spring	23/11/2006	0.39	8.30	0.65	0.08	12.22	0.77	No
Summer	18/02/2007	0.38	5.39	1.76	0.33	4.62	0.91	No
Summer	19/02/2007	0.37	9.87	3.11	0.32	7.23	0.92	No
Summer	20/02/2007	0.36	12.12	3.39	0.28	8.18	0.96	No
Summer	21/02/2007	0.36	11.84	3.44	0.29	7.67	0.97	No
Summer	22/02/2007	0.35	11.80	3.14	0.27	7.04	0.98	No
Autumn	7/05/2007	0.49	8.81	2.60	0.30	8.07	0.95	Yes
Autumn	8/05/2007	0.46	8.69	3.00	0.35	9.77	0.93	Yes
Autumn	9/05/2007	0.44	6.60	2.17	0.33	8.59	0.94	Yes
Autumn	10/05/2007	0.43	5.21	1.33	0.26	7.32	0.96	Yes
Autumn	11/05/2007	0.42	7.39	2.41	0.33	8.83	0.95	Yes
Winter	21/08/2007	1.16	10.79	1.15	0.11	17.94	0.87	Yes
Winter	22/08/2007	1.08	7.78	2.44	0.31	11.25	0.55	Yes
Winter	23/08/2007	1.01	9.83	2.29	0.23	15.22	0.65	Yes
Winter	24/08/2007	0.66	4.94	1.38	0.28	10.10	0.69	Yes
Winter	25/08/2007	0.91	8.18	0.66	0.08	12.38	0.81	Yes
Spring	19/11/2007	0.47	7.17	2.89	0.40	8.63	0.90	No
Spring	20/11/2007	0.43	9.84	3.07	0.31	10.17	0.93	No
Spring	21/11/2007	0.41	14.06	4.15	0.30	14.84	0.92	No
Spring	22/11/2007	0.39	9.05	2.42	0.27	8.58	0.91	No
Spring	23/11/2007	0.37	10.12	2.36	0.23	9.84	0.93	No
Summer	19/02/2008	0.83	24.66	7.98	0.32	9.52	0.90	No
Summer	20/02/2008	0.82	23.03	8.23	0.36	8.65	0.93	No
Summer	21/02/2008	0.80	25.01	8.53	0.34	9.67	0.93	No
Summer	22/02/2008	0.80	14.79	6.88	0.46	5.50	0.53	No
Summer	23/02/2008	0.79	20.69	8.80	0.43	7.64	0.71	No
Autumn	19/05/2008	1.11	3.99	3.35	0.84	9.03	0.83	Yes
Autumn	20/05/2008	1.09	4.89	3.38	0.69	8.20	0.92	Yes
Autumn	21/05/2008	1.08	5.47	2.80	0.51	7.79	0.91	Yes
Autumn	22/05/2008	1.07	8.40	2.80	0.33	7.73	0.95	Yes
Autumn	23/05/2008	1.06	12.96	3.87	0.30	9.34	0.94	Yes

Appendix 2. Rates of gross primary production (GPP) for five study sites on rivers in the Manawatu-Wanganui Region. Box plots show the median, upper and lower quartiles and range of values. Green boxes indicate GPP calculated using corrected data. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al*. (2008): below the orange line is 'healthy', above the orange line is 'satisfactory' and above the red line is 'poor'. Note *Y* axis is on a $\log_{10}$-scale.

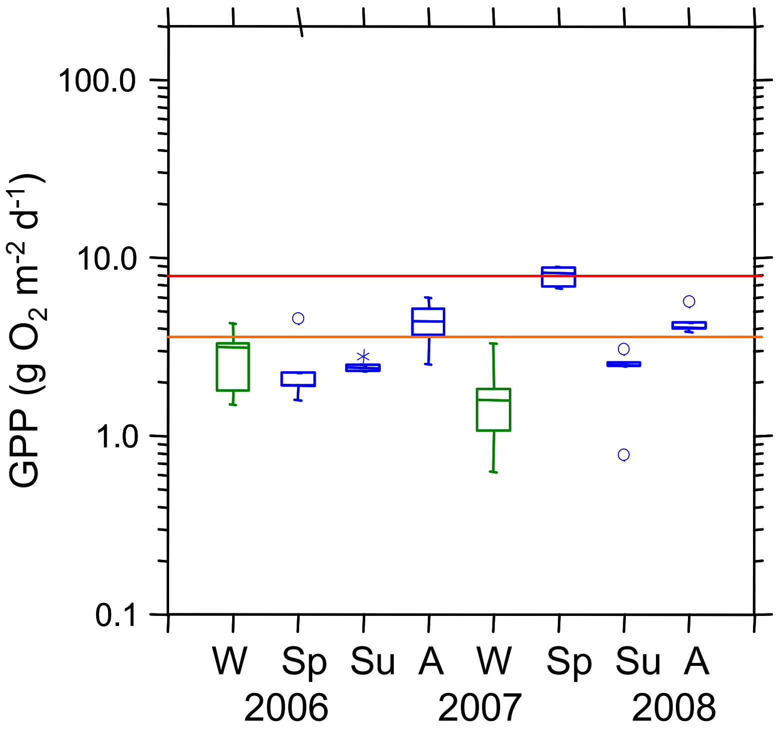


Manawatu River
at Hopelands

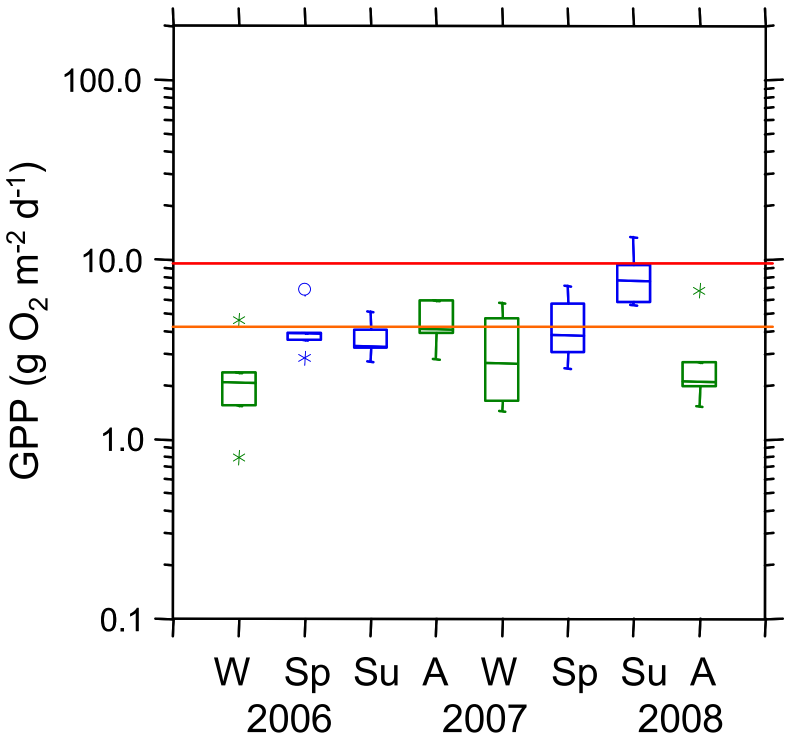


Manawatu River
at Teachers College

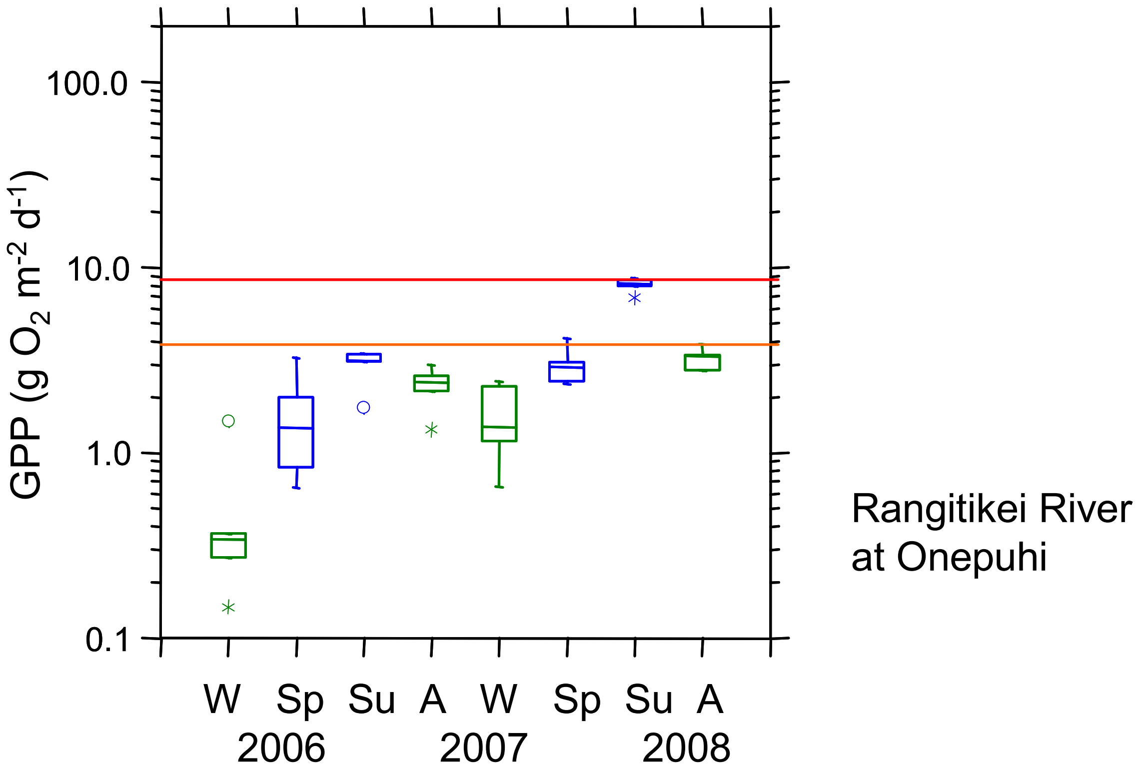
CAWTHRON



Mangatainoka River
at Pahiatua

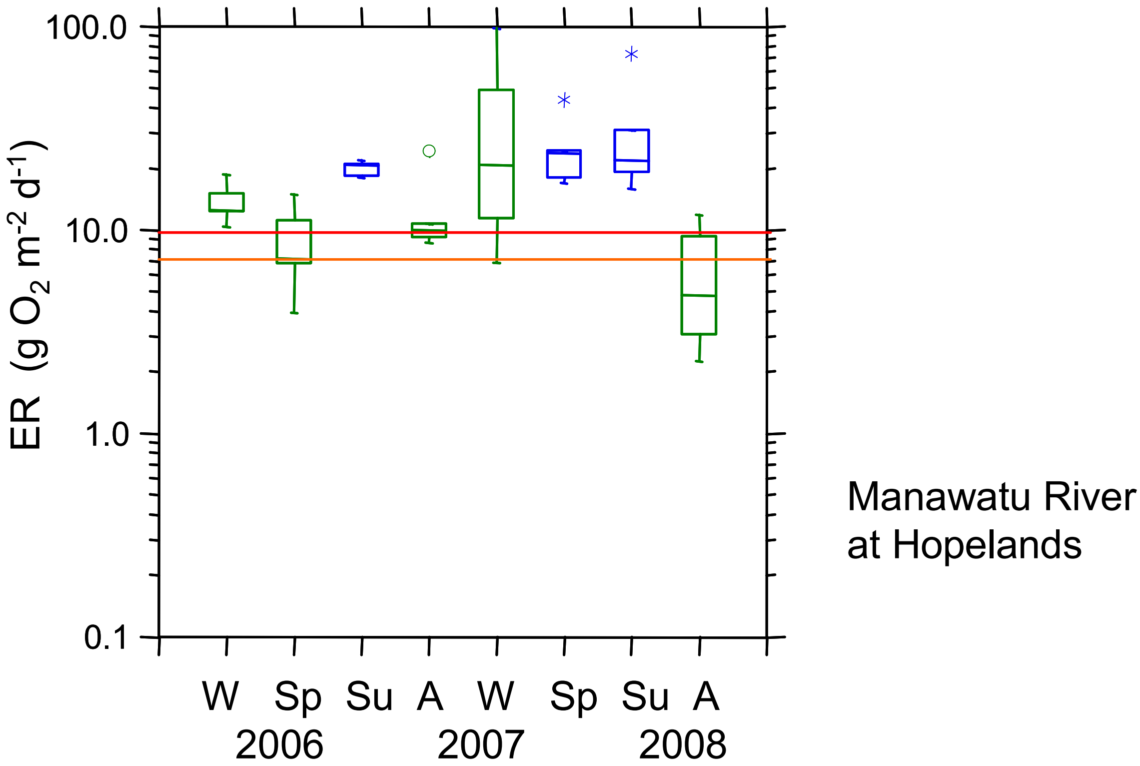


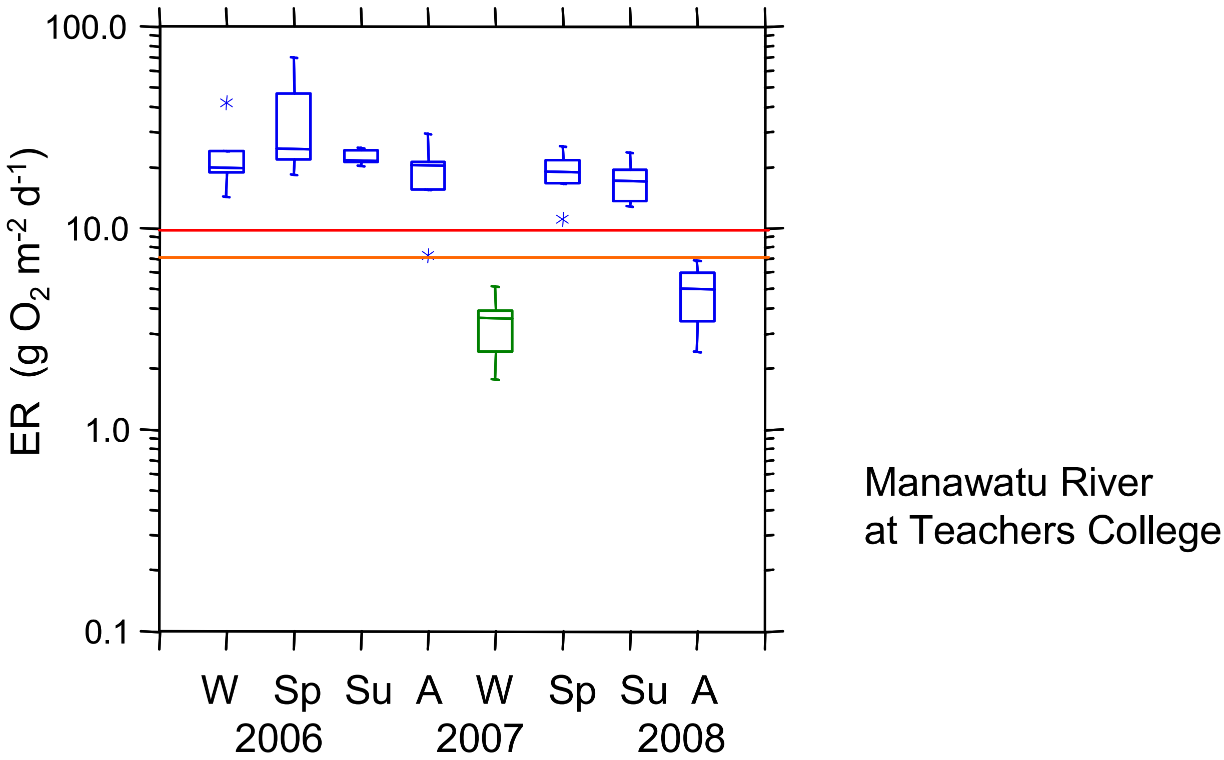
Rangitikei River
at Mangaweka

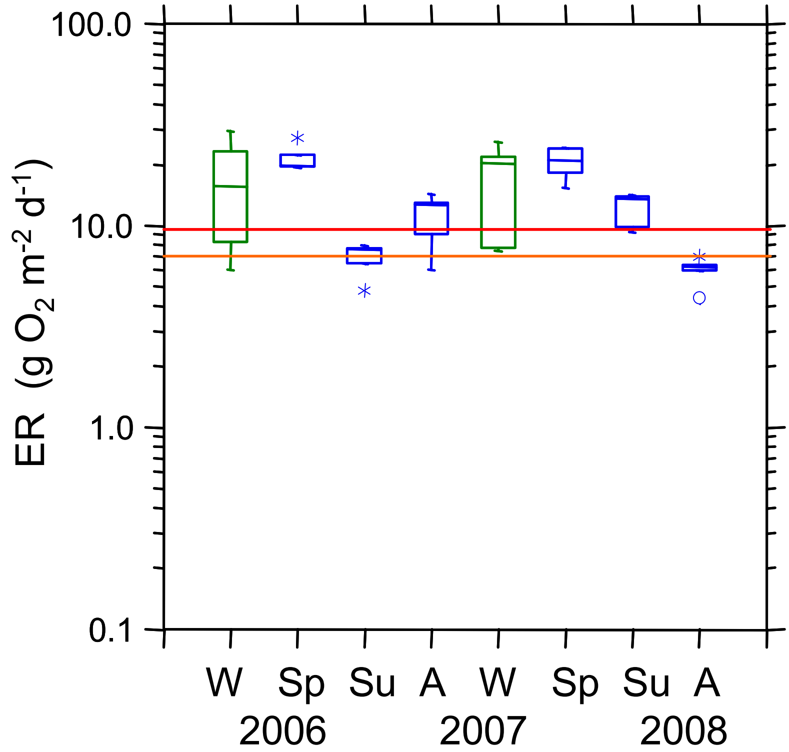


100.0
10.0
1.0
0.1
GPP (g O2 m-2 d-1)
W Sp Su A W Sp Su A
2006 2007 2008
Rangitikei River
at Onepuhi

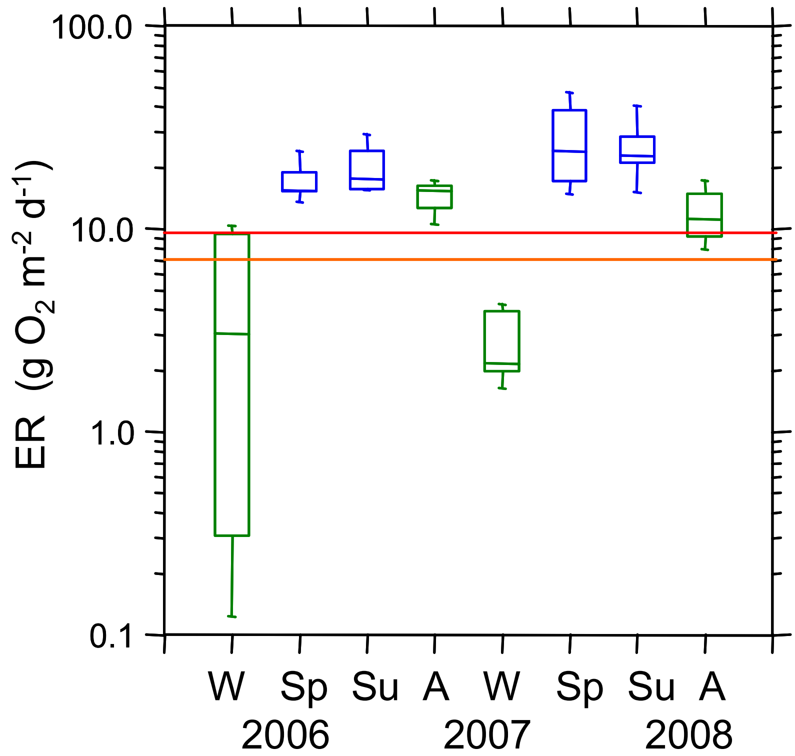
Appendix 3. Rates of ecosystem respiration (ER) for five study sites on rivers in the Manawatu-Wanganui Region. Box plots show the median, upper and lower quartiles and range of values. Green boxes indicate ER calculated using corrected data. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al*. (2008): below the orange line is 'healthy', above the orange line is 'satisfactory' and above red line is 'poor'. Note *Y* axis is on a $\log_{10}$-scale.



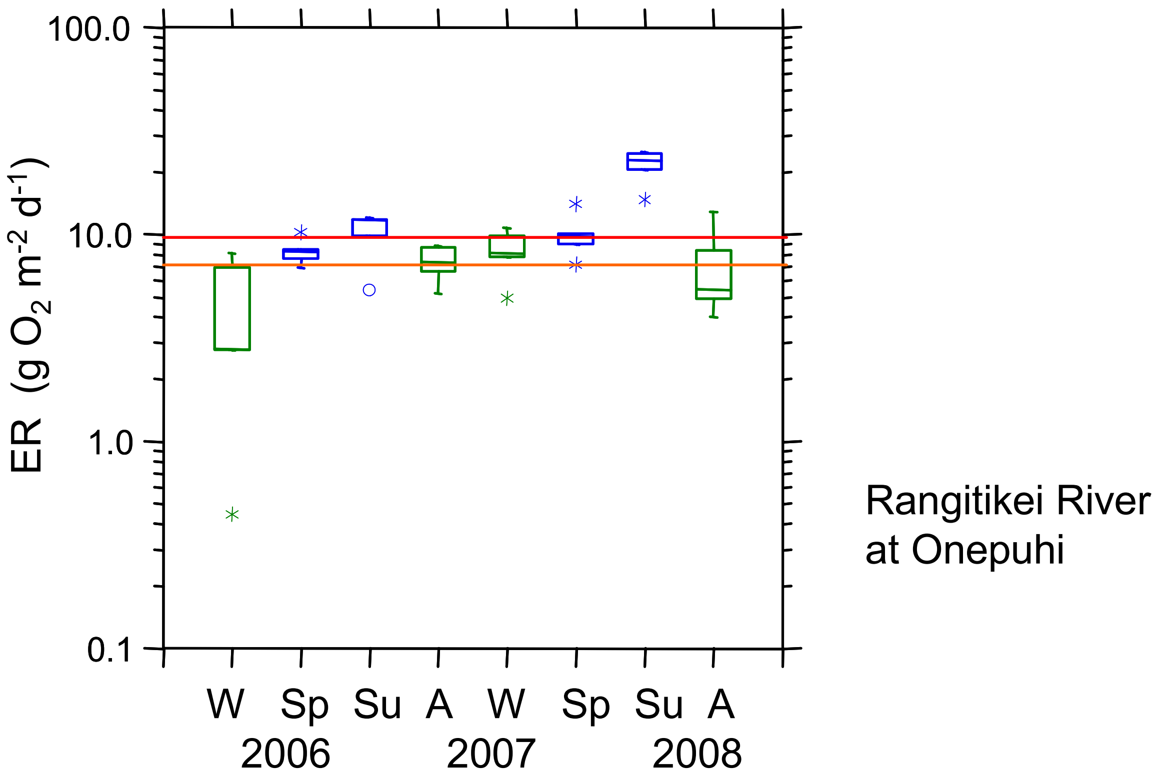




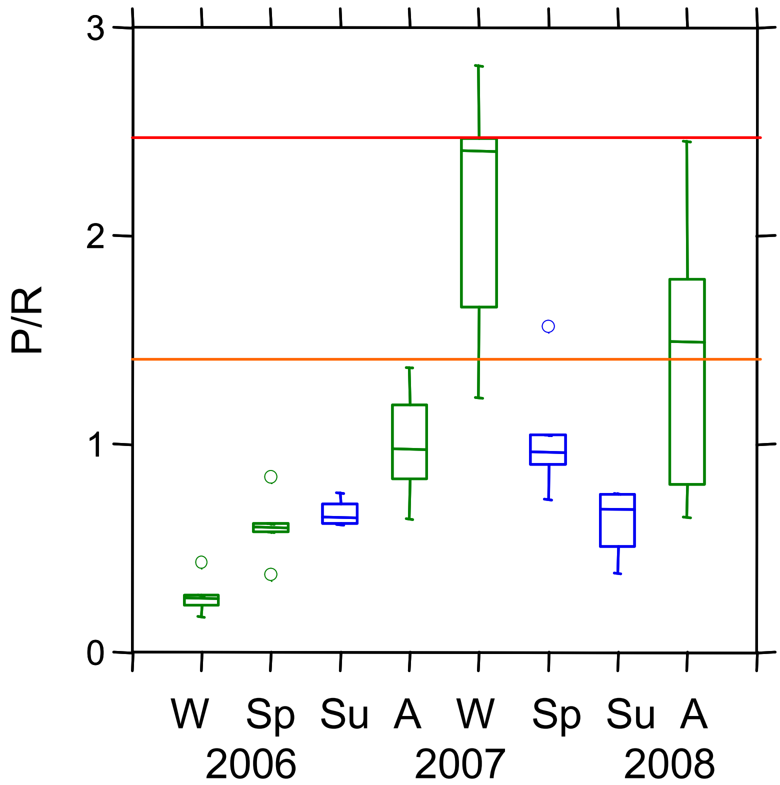
Mangatainoka River
at Pahiatua



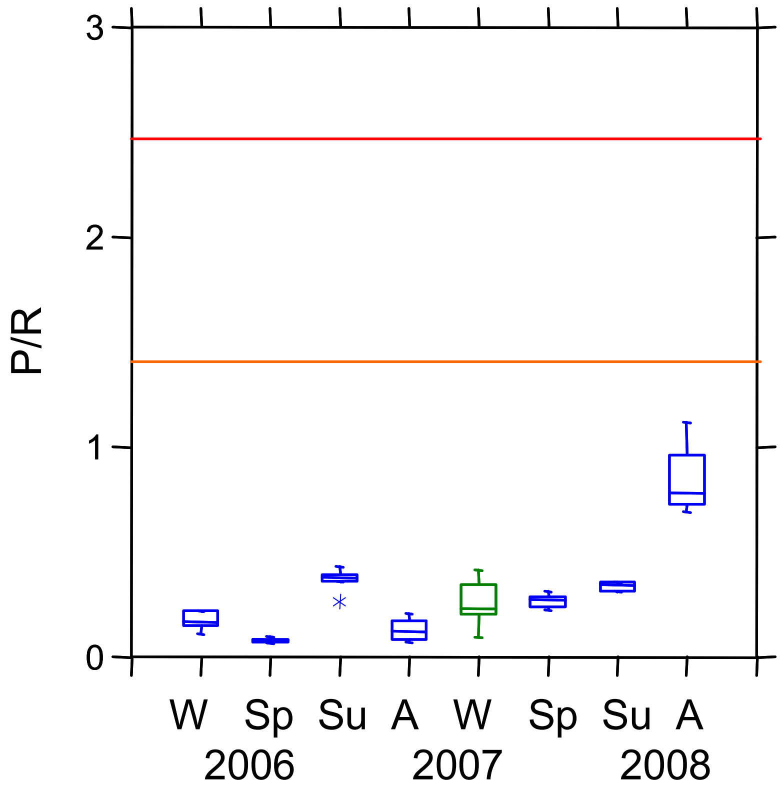
Rangitikei River
at Mangaweka


100.0
10.0
1.0
0.1
ER (g O_2 m^{-2} d^{-1})
W Sp Su A W Sp Su A
2006 2007 2008
Rangitikei River
at Onepuhi

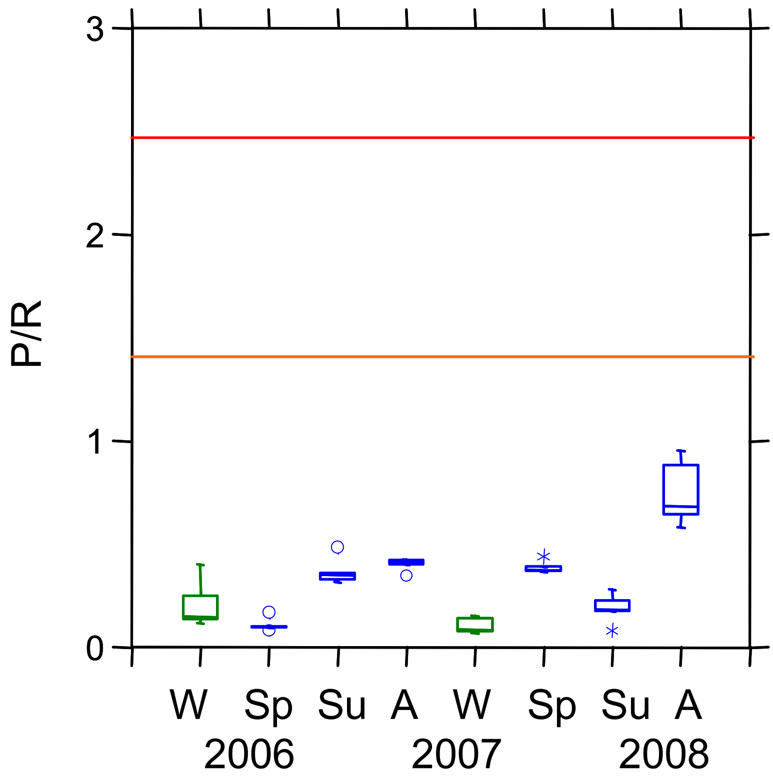
Appendix 4. The ratio of GPP to ER for five study sites on rivers in the Manawatu-Wanganui Region. Box plots show the median, upper and lower quartiles and range of values. Green boxes indicate P/R calculated using corrected data. Horizontal lines mark absolute values used to assess ecosystem health from Young *et al*. (2008): below the orange line is 'healthy', above the orange line is 'satisfactory' and above red line is 'poor'.



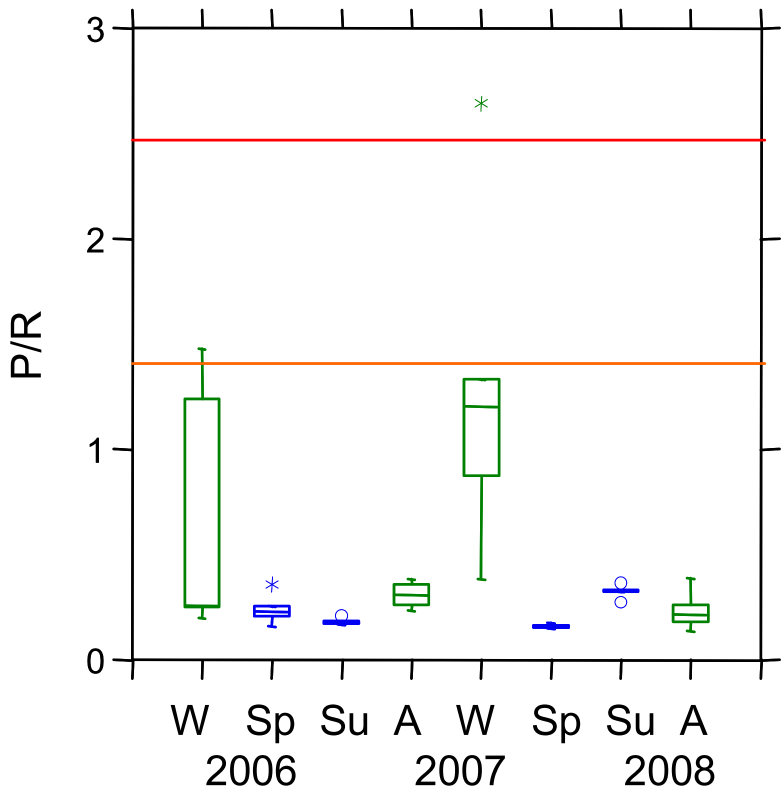
Manawatu River
at Hopelands



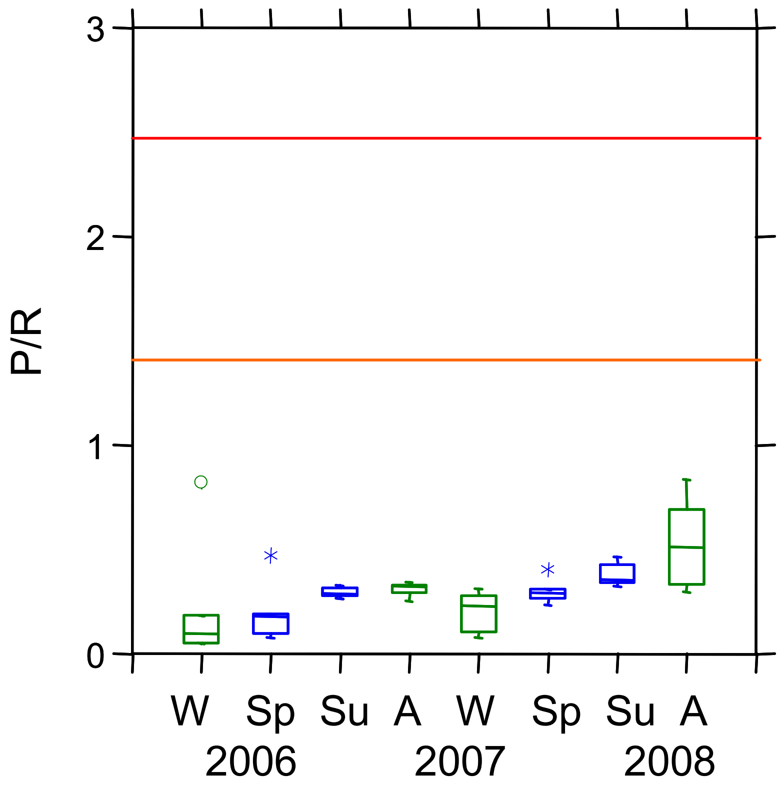
Manawatu River
at Teachers College



Mangatainoka River
at Pahiatua



Rangitikei River
at Mangaweka



Rangitikei River
at Onepuhi