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Functional indicators of river ecosystem health – results from regional case studies of leaf decomposition

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Functional indicators of river ecosystem health – results from regional case studies of leaf decomposition

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Cover Photo: Mahoe leaves after 30 days in a stream: Cawthron 2005

EXECUTIVE SUMMARY

River health monitoring, which has traditionally concentrated on the use of *structural measurements* (such as water quality or taxonomic composition of aquatic organisms), should be complemented in future by *functional indicators*, such as rates of ecosystem metabolism and organic matter decomposition, to provide a more complete and accurate assessment of the state of these environments. This report describes the results of case-studies conducted throughout New Zealand trialling the use of organic matter decomposition as an indicator of river health. The aims of the case studies were to; provide regional council staff with experience using the techniques, plug gaps in information about stream types that have received limited attention in the past, demonstrate how functional indicators can be used in habitats where existing techniques are inappropriate, and provide information that could be used to help develop criteria for distinguishing between healthy and unhealthy sites. Organic matter decomposition was measured in four ways – mass loss of leaves, toughness loss of leaves, tensile strength loss of cotton strips, and mass loss of wooden sticks.

Some interesting patterns in ecosystem functioning were observed with decomposition rates reflecting differences in land use and the percentage of native forest upstream. Differences in decomposition rates as a result of water abstraction, and along the length of river systems, were also observed. Cotton strip strength loss was positively correlated with concentrations of dissolved inorganic nitrogen and *E. coli*, and negatively correlated with macroinvertebrate community index (MCI) scores. Leaf toughness loss was also negatively correlated with MCI scores. Stick mass loss was measured in only a small subset of the sites, but was correlated with the percentage of native forest upstream. In contrast to toughness and stick mass loss, leaf mass loss was not correlated with other measures of river ecosystem health.

Leaves were deployed for 1 month, which was slightly too long since the amount of material remaining ranged from 0 – 45 %. A deployment period corresponding with approximately 50 % mass loss would allow better resolution among sites with different leaf decomposition rates.

Leaf mass loss rates were the broadest measure used in the trials since they potentially respond to macroinvertebrate consumption, microbial decomposition and physical breakdown of leaf material caused by the friction, turbulence and abrasion associated with moving water. A broad response could be considered as an advantage and leaf mass loss rates did highlight differences in ecosystem functioning at some sites that were not evident using other measures. However, a broad response is also a potential disadvantage if contrasting stressors counteract each other’s effects on decomposition rates.

Leaf toughness loss responds primarily to microbial decomposition and thus is a more focussed measure than mass loss. However, toughness measurements vary widely on individual leaves depending on the position of the penetrometer pin relative to leaf veins. More toughness measurements per leaf pack (up to 25) may help to reduce the relatively high within-site variability that was observed in the case-studies. Despite this variability, toughness loss did vary among sites and was correlated with other measures of river health.

Artificial substrates such as cotton strips and wooden sticks have the advantage that they have a consistent composition and are relatively cheap and easy to source. Wooden stick mass loss is primarily governed by microbial decomposition mechanisms, while cotton strength loss is even more specific and focussed on bacterial decomposition. The decay rates of these artificial substrates should be considered as an assay, rather than a realistic measure of natural decomposition processes. Nevertheless, they were correlated with several other indicators of river ecosystem health, which supports the concept that these are useful measures.

The framework proposed by Gessner & Chauvet (2002) for distinguishing between healthy and unhealthy systems using decomposition rates appears to be suitable when considering mass loss. However, the greater within-site variability associated with losses of leaf toughness and cotton strip strength means that wider bands around ‘reference’ condition are required for these measures. There was little within-site variability in stick weight loss at the subset of sites where sticks were deployed, which is very encouraging. Further work is underway to see if this finding is consistent across a broader range of sites.

TABLE OF CONTENTS

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1. INTRODUCTION

This report is part of a three year project funded by the NZ Minister for the Environment's Sustainable Management Fund and other stakeholders that aims to provide a framework for the use of functional indicators for assessing river ecosystem health in New Zealand. Accurate approaches to measuring the health or integrity of river ecosystems are required so the causes of poor health, or the success of rehabilitation efforts, can be measured. Traditional approaches to river ecosystem health assessment have focussed solely on structural indicators such as the composition of stream invertebrate communities (Boulton 1999). However, functional indicators, such as the rates of organic matter decomposition or ecosystem metabolism, are direct measurements of functions that river ecosystems perform and provide an alternative, but complementary, view of ecosystem health (Bunn 1995; Gessner & Chauvet 2002; Brooks et al. 2002).

During the first year of the project, we produced an interim guide (Young et al. 2004) that provided an overview of functional indicators and how they are measured, summarised the likely response of these functional indicators to a variety of impact types, listed the advantages and disadvantages of each method, and provided guidance on when and where functional indicators might improve biomonitoring in New Zealand. Two functional indicators, leaf litter decomposition and ecosystem metabolism, appeared to have the most promise as effective indicators of river ecosystem health. This report builds on the information presented in the interim guide and summarises the results of case-studies involving the use of these functional indicators that have been conducted throughout New Zealand over the last 12 months. The initial plan was to include both ecosystem metabolism and leaf litter decomposition in the case-studies. However, limitations in the availability of oxygen loggers in many regions meant that metabolism was only measured at a subset of the sites. Therefore the focus of this report is on leaf litter decomposition and associated measurements.

The main aims of the case-studies were to:

1) provide regional council staff with practical experience of the techniques so that effective protocols could be developed.
2) plug gaps in information on the response to stressors in stream types that have received limited attention in the past (*e.g.* spring-fed streams, soft-bottomed streams).
3) demonstrate how functional indicators can be used to solve specific problems or allow effective monitoring in habitats that can not be monitored using existing techniques (*e.g.* large non-wadeable rivers).
4) Provide information that could be used to help develop criteria for distinguishing between healthy and unhealthy sites across a range of river types.

2. SITES

Sixty-five sites within 10 regions of New Zealand were used in the study (Appendix 1). These sites were arranged into 5 groups as follows:

- 20 spring-fed sites located in Hawkes Bay (6), Taranaki (1), Marlborough (6), Tasman (1), West Coast (3) and Southland (3).
- 9 sites in Auckland covering soft-bottomed (7 sites) and hard-bottomed (2 sites) streams in 3 land use types (native, rural and urban)

- 25 sites covering gradients down the length of river systems (8 sites Motueka River, Tasman District; 8 sites Rangitikei Catchment, Horizons Region; 4 sites Ruamahanga River, Wellington Region; 5 sites Patea/Waingongoro/Kapuni rivers Taranaki Region)

- 5 sites in large unwadeable rivers in the Waikato Region.

- 6 sites associated with a Massey University study on the impacts of water abstraction on river ecosystems – 3 upstream sites and 3 downstream sites.

Leaf decomposition rates were measured at all sites, while cellulose decomposition potential was measured only at the sites in the Marlborough, Tasman and Waikato regions (20 sites). In conjunction with this project, Environment Waikato studied wood decay rates at the five unwadeable river sites in their region.

3. METHODS

3.1 Leaf litter decomposition

Mahoe (*Melyctus ramiflorus*) leaves were used for the leaf litter decay experiments because they decay relatively fast (so the exposure time can be relatively short) and are commonly available throughout New Zealand. Mahoe has regularly been used in studies of leaf litter decomposition in New Zealand (Linklater 1995; Parkyn & Winterbourn 1997; Hicks & Laboyrie 1999; Quinn et al. 2000) and breakdown rates appear to be similar to those of fast-decaying leaf species commonly used in the northern hemisphere (*e.g.* alder *Alnus glutinosa*), thus allowing comparisons to be made with similar northern hemisphere studies.

Existing information on breakdown rates indicated that mahoe leaves lost between 30% (Parkyn & Winterbourn 1997) and 75% (Hicks & Laboyrie 1999) of their initial mass over a period of one month. Therefore, one month seemed to be a suitable period of exposure for the leaf packs.

The leaves used in the case-studies were picked from a single mahoe tree growing in Nelson, so variability among leaves was minimised. After being picked, the leaves were air-dried for 2 weeks and transferred to 5 mm mesh bags. Each mesh bag contained 3-5 g of dry leaves and the weight of the contents of each bag was recorded to the nearest 0.001 g. A waterproof label that was too large to pass through the mesh was placed in each bag. The ends of the bags were sealed using cable ties.

3.1.1 Field protocol

A brief set of instructions for deploying the leaf bags was provided to each council staff member along with the leaf bags. The following protocol was listed within the instructions. Five replicate leaf bags were deployed at each site and secured using 50 cm lengths of 8 mm diameter reinforcing bar or short warratahs. Each leaf pack was attached to its own metal bar using 2 mm nylon cord (Figure 1). Wherever possible, the leaf packs were secured in riffles. If riffle habitats were not present at the site, then the bags were placed in areas resembling riffles (i.e. relatively shallow with flowing water and stable substrate). If possible, the five replicate leaf packs were spread out across the channel at each site so that the leaf packs experienced the range of depths and velocities that occurred at each site. The metal bars were driven down into the substrate leaving only the top exposed so that flow conditions were not altered and the bars would not catch passing debris. In many cases, rocks were placed over the cord connecting the leaf bag to the metal bar in order to keep the leaf bag submerged near the riverbed and not spinning in the current. Orange flagging tape was tied to each metal bar to help relocate the leaf bags, although flagging tape was not used in locations where the flagging might attract unwanted attention from passers-by. Site photos and/or drawings were encouraged at each site to further assist with relocating the leaf bags.

Figure 1 A leaf pack and cotton strip deployed in a stream

The leaf bags were recovered after 4 weeks. Recovery started at the downstream end of each site. Each leaf bag was placed in a separate labelled plastic bag and immediately placed in a chilli-bin containing ice. The leaf bags were frozen after collection before being couriered back to Cawthron.

Information on the depth and velocity at each leaf pack location was requested, along with any background information on flow, water quality (conductivity, nutrient concentrations, faecal indicator bacteria concentrations), macroinvertebrate community composition, and the temperature regime at each site. This information was patchy and only available at two thirds of the sites.

3.1.2 *Laboratory protocol*

After thawing, the contents of each leaf bag were placed in a sieve (0.5 mm mesh) and gently washed using a spray bottle and/or gentle rubbing. Any organic material found in the plastic bag containing the leaf bag was also rinsed into the sieve.

The label number of each bag was scratched into the bottom of an aluminium pie dish and then the contents of each bag were transferred to the pie dish. Any gravel, sediment, algae or stream invertebrates associated with the remaining leaf material were discarded.

The toughness of the leaves in each leaf bag was measured using a penetrometer (Figure 2). The penetrometer works by measuring the weight (in this case volume of water) required to force a blunt pin through a leaf. Five toughness measurements on different leaves were recorded for each leaf bag. Care was taken to ensure that the toughness measurements were not taken from parts of the leaf dominated by thick veins.

Figure 2 The penetrometer used to measure leaf toughness

After the toughness measurements, the leaf material was dried in a 105°C forced draft oven for at least 3 days. The dried leaf material was then weighed (to the nearest 0.001 g), ashed in a 550°C furnace for 1 hour and then reweighed to determine the inorganic (ash) and organic (ash free) components of the leaf material.

In order to estimate the initial ash-free dry weight and toughness of each leaf pack we soaked five preweighed air-dried leaf packs for 24 hours (to account for the at least some of the initial leaching process that occurs when leaves are placed in water but can not be counted as 'decomposition') and then processed them in the same way as the other samples (i.e. frozen, thawed, washed, toughness measurements, oven-dried, weighed, ashed, reweighed). The post leaching ash-free dry weight of these leaf bags averaged 77% (range 76-80%) of their initial air-dry weight. This correction factor was applied to all the other leaf packs and accounted for the difference between air-dried weights and ash-free dry weights, plus the effects of initial leaching.

3.1.3 *Data analysis*

The simplest method of reporting breakdown rates is to use the percentage of the initial weight of leaf material remaining after a certain time period (%R).

$$\%R = 100 \times \left(\frac{W(t_f)}{W(t_i)} \right) \tag{1}$$

where $W(t_i)$ is the initial ash free weight of leaf material and $W(t_f)$ is the ash-free weight of material remaining after time (t). The percentage of the initial material lost per day can be calculated for comparison among sites. This method assumes that decomposition is linear and that a constant amount of material is lost throughout the decomposition process.

However, research studies on leaf litter breakdown often observe exponential decay of the leaf material where a constant proportion of the material remaining at any time is lost throughout the decomposition process. Therefore it is more accurate to report breakdown rates in terms of an exponential decay coefficient (k, day^{-1}) (Petersen & Cummins 1974).

$$k = -\log_e\left(\frac{W(t_f)}{W(t_i)}\right)/(t_f - t_i) \tag{2}$$

The decomposition rates mentioned in this report are exponential decay coefficients and thus refer to the proportion of leaf material lost per day.

Measurements of leaf breakdown in terms of changes in leaf toughness were calculated in the same way by substituting average toughness measurements from each leaf pack for weight measurements. Leaf bags with no remaining leaf material were considered to have zero leaf toughness.

Statistical comparisons among sites were conducted using either one-way ANOVA or nested ANOVA (see further details below). Data were transformed before analysis where appropriate. Posthoc comparisons among individual sites were conducted using Tukey tests.

3.2 Cellulose decomposition potential/Cotton strip tensile strength

A promising alternative technique to measuring leaf decomposition is the "cellulose decomposition potential" method (Hildrew et al. 1984; Boulton & Quinn 2000) first used in streams by Egglishaw (1972). Strips of standard cotton cloth are deployed at a site for a certain period, and the extent of cellulose decomposition is measured as loss in tensile strength of the cotton strips. This assay has been commonly used by soil scientists as an indicator of microbial activity in soils.

We used standard Shirley Soil Burial Test Fabric, which was initially obtained from Shirley Dyeing and Finishing Ltd., Hyde, Cheshire, UK, although this company appears to have gone out of business recently. This material is 100% combed cotton and has a series of coloured threads incorporated into the weave of the material which allow the strips to be cut/frayed to a standard width (3 cm = 100 threads).

We had a limited amount of the cloth and only deployed cotton strips at sites in the Marlborough, Tasman and Waikato regions. The cloth was initially cut into strips of 4 cm wide and 30 cm long. Four replicate cotton strips were deployed at each site in Marlborough (6 sites) and Tasman (9 sites), while 5 strips were deployed at four sites in Waikato. The cotton strips were secured at the sites using nylon cord attached to metal bars (Figure 1).

Following Boulton & Quinn (2000), the cotton strips were retrieved after 7 days and then frozen awaiting analysis. After being thawed, the cotton strips were gently washed and dried at 20°C for 24 hours in a forced draft oven. Threads were frayed from the side of each strip until only the brown marker threads were left along the sides of the strip, leaving a width of exactly 3 cm. Each strip was then cut into two 9 cm lengths avoiding the area of cotton where the cord was attached. Each length of cotton strip was labelled using a marker pen and sent to Landcare Research (Hamilton) where the tensile strength (in kg) of each strip was determined using a commercial tensometer.

The initial tensile strength of the strips was determined using a set of control strips that were soaked for 1 day and then frozen and processed in the same way as the other strips.

The tensile strength data was analysed in the same way as the leaf breakdown data and reported in terms of an exponential decay coefficient. Statistical comparisons among sites were conducted using one-way ANOVA and post hoc Tukey tests.

3.3 Wood decay

In conjunction with the functional indicators study, Environment Waikato measured wood decay at each of the 5 sites in the Waikato region using birch wood coffee stirrers (114 x 10 x 2 mm, Figure 3). Holes were drilled at one end of the sticks and fresh-weights were measured before tying 5 sticks onto nylon ties for deployment into the streams. Five sticks were kept aside to determine the difference between fresh weight and oven-dry weight, which averaged 90.0% (range 89.7 – 90.4%). Three sets of sticks were put out at each site by securing them to rope and metal stakes (all within 5 m of each other) driven into the riverbanks and where necessary attaching metal weights. Sticks were deployed concurrently with other substrates (leaves & cotton strips) and retrieved after 7, 27 and 84 days immersion.

Figure 3 A set of wooden sticks ready for deployment

Following retrieval, sticks were kept on ice and then frozen until processing. Following thawing, sticks were washed of loosely adhering material and then dried to a constant dry weight at c. 60°C. Initial oven-dry weights were estimated by multiplying the fresh stick weights by the correction factor mentioned above.

The change in wood mass data was analysed in the same way as the leaf breakdown data and reported in terms of an exponential decay coefficient. Statistical comparisons among sites were conducted using one-way ANOVA and post hoc Tukey tests.

3.4 Compensating for the effects of temperature

Temperature is a primary factor controlling decomposition rates, particularly if microbial activity is the main mechanism of decomposition (Young et al. 2004). Differences in decomposition rates would therefore be expected among sites with differing temperature regimes. In some situations it is appropriate to include the effects of any differences in temperature in the analysis. For example, the removal of riparian vegetation along a stream will have a major impact on the temperature regime and any changes in the decomposition rate of organic matter at that site are an indication of a change in ecosystem health. However, decomposition rates will also respond to natural thermal differences caused by climatic, latitudinal or altitudinal changes that are not indicative of changes in health. This is particularly a concern if data are being compared across a broad geographical area. In such cases, it would be an advantage to factor out the effects of temperature on decomposition rates so any differences in ecosystem health are not masked/exacerbated by thermal differences.

If temperature is measured continuously at each site throughout a study, the effects of temperature can be compensated for by calculating breakdown rates using degree days rather than days as the measure of time (Minshall et al. 1983). Degree days can be calculated by summing all the daily average water temperature measurements during the period when the leaves/cotton/wood were decomposing. For example, if the average water temperature at a site was 15 °C for a day then that site would have accumulated 15 degree days on that day. Degree days accumulate quickly at warm sites and slowly at cool sites.

Temperature records were available at 34 of the sites used in this case-study. The number of degree days accumulated at these sites during the month-long leaf deployment ranged from 311 degree days (average temperature 11.1 °C) in a stream near the headwaters of the Motueka River to 629 degree days (average temperature 22.5 °C) in the Otara Stream, an urban system in Auckland (Appendix 1).

4. RESULTS AND DISCUSSION

There were a large number of sites used in the case-studies, therefore this section of the report is fairly lengthy. The relationships among the different decay measures are examined initially and then the results from the different case-studies are presented. Temperature compensated decay rates are presented for the spring-fed streams and for the sites along the Motueka River. The final part of the results section looks at the relationships between the decay measures and other measures of river ecosystem health.

4.1 Relationships among decay measures

Using data from all the sites, there was a strong relationship between the percentage of leaf mass remaining and the percentage of initial leaf toughness (r = 0.75). Toughness loss was generally faster than mass loss and leaves at 7 sites were decomposed to such an extent that leaf toughness was close to or less than the minimum level that could be measured using the penetrometer. However, there were only 2 sites (Lucas Creek, Auckland; Porangahau River, Hawkes Bay) where no leaf material (i.e. zero mass) remained in any of the leaf bags. Although they are obviously related to some extent, mass loss and the decline in leaf toughness each provide a slightly different measure of the decomposition process. Mass loss incorporates biological processing of the leaf material (i.e. bacterial and fungal decomposition and consumption by macroinvertebrates) plus physical processing (i.e. leaf breakdown caused by the friction and turbulence associated with moving water and the abrasion caused by suspended sediment in the water column). In contrast, leaf toughness is expected to be primarily affected by microbial processing of the leaves and not as sensitive to physical breakdown processes. For example, leaves exposed to fast turbulent flow might lose a considerable proportion of their original mass after a month due to physical damage to the leaves, but the remaining leaf material may still be quite tough if microbial processing rates are low.

Cotton strip strength loss was measured at a subset of the sites (19), and was not significantly correlated with either mass loss ($r = 0.06$) or toughness loss rates ($r = 0.17$). This suggests that strength loss is measuring a different combination of ecological processes than leaf mass or toughness loss. Cotton strip strength loss is expected to be primarily affected by bacterial breakdown of leaves, since fungi and invertebrates are not known to colonise or consume cotton.

Mass loss rates of wooden sticks were only measured at 5 sites in the Waikato. Stick mass loss rates were not significantly correlated with any of the other decay measures at the $\alpha = 5\%$ level, although this lack of significance was almost certainly due to the small number of sites involved. The relatively high correlation coefficients between stick mass loss and leaf mass loss ($r = 0.85$) and stick mass loss and cotton strip strength loss ($r = 0.70$) were indicative of linkages between these measures.

4.2 Spring-fed Streams

The Tennis site in Marlborough is close to the source of Spring Creek, one of many spring-fed streams that emerge in the lower part of the Wairau Plain. Water quality is reasonably good at this site compared to many other spring-fed streams and it supports a diverse range of fish and macroinvertebrate species (Young et al. 2000; Young et al. 2002). Therefore, it was considered to represent ‘reference’ condition for spring-fed streams and thus the decay rates measured at this site were used as a benchmark for comparison with the other spring-fed streams.

Following Gessner & Chauvet (2002), decay rates within the range 0.75 to 1.33 of reference were tentatively considered to be equivalent to reference condition. Similarly, decay rates falling within the range from 0.5-0.75 or 1.33-2.0 of reference were considered slightly impaired, while decay rates outside these ranges (<0.5 or >2.0 of reference) were considered to indicate impaired condition or poor ecosystem health (Gessner & Chauvet 2002). The healthy and slightly impaired bands are shown in Figure 4 using green and orange, respectively. These tentative criteria for indicating good, moderate and poor ecosystem health are based on a limited amount of information about the natural variability in mass loss rates and may need to be refined as more information becomes available. It is likely that separate criteria are required for mass loss and toughness loss rates. However, in the interim they indicate how decay rates could be used to make interpretations of ecosystem health.

4.2.1 *Mass loss rates*

The rates of mass loss for the spring-fed streams ranged from 0.035 – 0.28 day^{-1} (Figure 4 upper graph). These exponential loss rates correspond to a % mass remaining after one month of 38% and 0%, respectively. Mass loss was significantly higher than reference condition in the Porangahau River in Hawkes Bay and the Tawhiti Stream in Taranaki (Figure 4). Mass loss rates at all of the sites, except the Porangahau River, fell within the good or slightly impaired range. The rates of ecological processes within the Porangahau River were clearly different from those in most other spring-fed streams around the country. [Note: Further discussion with Brett Stansfield (HBRC) has in fact indicated that the Porangahau River is not a good example of a spring-fed stream.]

With one exception (Pipitea, Marlborough) all the sites that approached or were beyond the normal range of mass loss rates were higher than reference. Warm water temperatures and high nutrient concentrations will stimulate microbial activity and are likely to be the cause of faster decay rates. Pipitea appeared to be different in that decomposition rates in this site tended to be abnormally low, although not significantly lower than reference. Pipitea is a highly degraded system and is almost anoxic. The lack of oxygen available in this stream may be the cause of the relatively low organic matter decomposition rates.

The Riverlands site in Marlborough is also a highly degraded system (very high nutrient and faecal indicator bacteria concentrations), but the mass loss rates at this site were equivalent to reference condition (Figure 4).

The Pupu site in Tasman is at the well known Waikoropupu Springs and would be considered to be representative of a healthy system. Mass loss rates at this site were equivalent to the reference site (Figure 4).

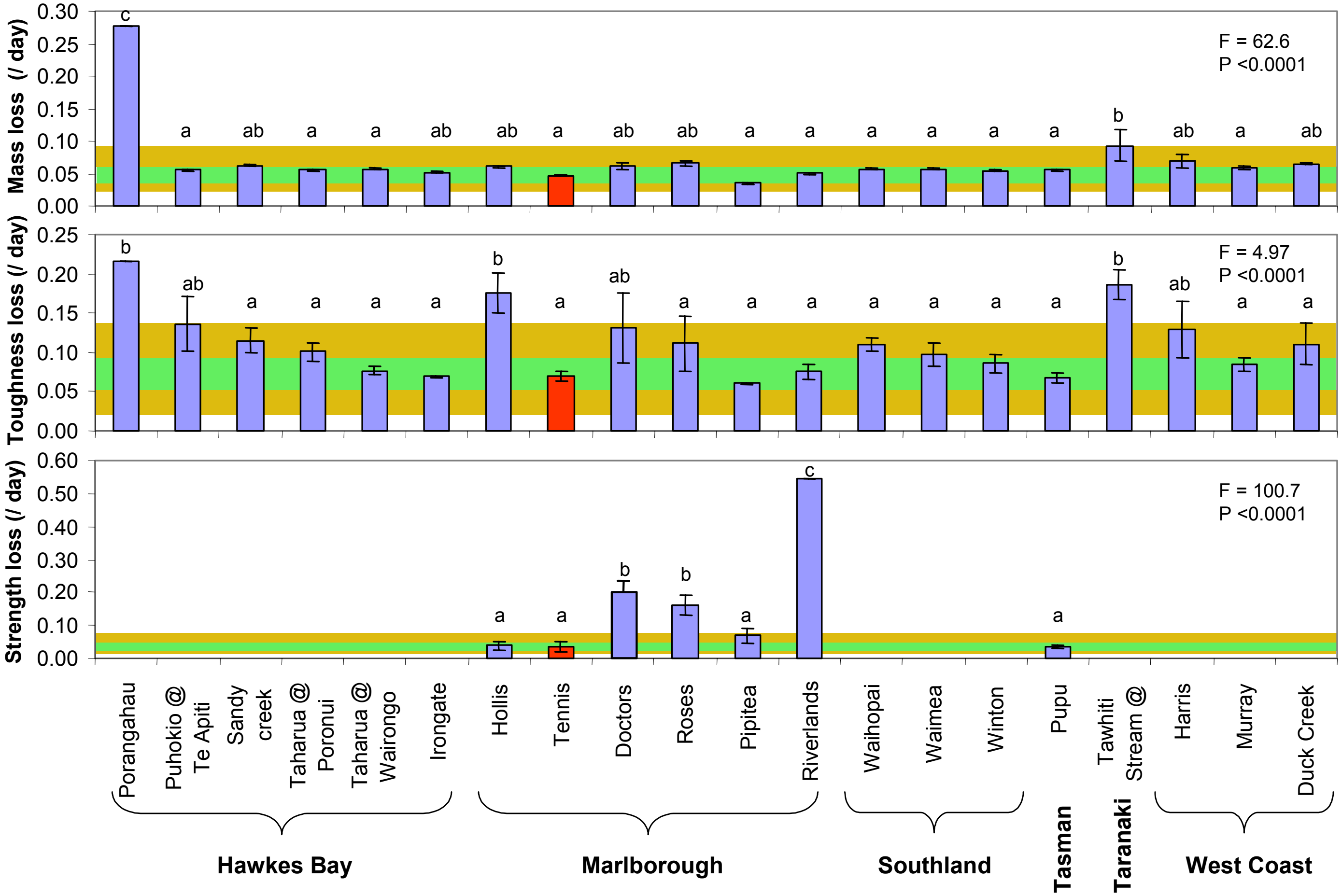

Figure 4 Rates of mass and toughness loss (±SE) for leaf packs in the spring-fed streams. Tensile strength loss (±SE) of cotton strips is also shown for 7 spring-fed streams where cotton strips were deployed. The upper reaches of Spring Creek (Marlborough's Tennis site – marked red) was chosen to represent reference condition for spring fed streams. A band representing healthy condition (0.75 to 1.33 times reference) is shown in green, while a band representing slightly impaired health (0.5-0.75 and 1.33-2.0 times reference) is shown in orange. Values beyond the orange band would be considered impaired. Within each graph, bars with the same letter above them are not significantly different from each other.

4.2.2 *Toughness loss rates*

The variability in toughness loss rates within and among sites was considerably higher than the variability in mass loss rates (Figure 4). Toughness loss rates ranged from 0.060 – 0.22 day^{-1}, which corresponds to a % toughness remaining after one month of 18% and 0%, respectively.

Toughness loss rates were significantly higher than reference, and indicative of unhealthy conditions, in the Porangahau River, Tawhiti Stream and Hollis Creek. These results show some consistency with mass loss rates which were also high in the Porangahau River and Tawhiti Stream, but were relatively normal in Hollis Creek.

As was the case for the mass loss rates, the slowest toughness loss rate was in Pipitea (although not significantly lower than the reference), perhaps again explained by the low dissolved oxygen concentrations at that site.

Toughness loss rates in the heavily degraded Riverlands site were again equivalent to reference condition (Figure 4).

The toughness loss rates at the high quality Pupu site were equivalent to the reference site (Figure 4).

4.2.3 *Cellulose decomposition potential/Cotton strip tensile strength*

Cotton strips were only deployed at 7 spring-fed streams. However, some interesting patterns were apparent. Tensile strength loss coefficients covered a much wider range than mass loss rates or toughness loss rates and ranged from 0.035-0.55 day^{-1}. This range corresponds to a % strength remaining after 7 days of 80% to 0%, respectively.

Interestingly, the heavily degraded Riverlands site had a significantly faster tensile strength loss rate than the other sites (including reference), despite having relatively normal mass loss and toughness loss rates. Tensile strength loss rates at the Doctors and Roses sites were also significantly higher than the reference site and indicative of poor ecosystem health. Tensile strength loss rates at the Hollis site and high quality Pupu site were equivalent to those at the reference site.

The contrast between leaf mass and toughness rates and cotton tensile strength loss rates at the highly degraded Riverlands site was unexpected and difficult to explain. The tensile strength loss data clearly show that the rate of microbial decomposition in Riverlands was substantially greater than at the other sites studied, which makes sense given the extremely degraded water quality at this site (Appendix 1). However, the rates of mass loss and toughness loss measured at this site were equivalent to those measured at the reference site. It is possible that decomposition of the leaves was accelerated by the warm temperatures and high nutrient concentrations at this site, but concurrently slowed down by the effects of low dissolved oxygen concentrations. Niyogi et al. (2003) found a similar response to this in a study of leaf decomposition in some Otago streams where the positive effects of high nutrient concentrations on decomposition rates were counteracted by the negative effects of sediment deposition, resulting in decomposition rates that were similar to more pristine sites.

The question then is why decomposition of the cotton strips at the Riverlands site was either stimulated to a greater extent, or inhibited to a lesser extent, than the leaves. It is likely that cotton strips are more susceptible to bacterial decomposition than leaves, given their large surface area and the relatively labile nature of the cotton itself. Concentrations of the faecal indicator bacteria *E. coli* at the Riverlands site reach extremely high levels (20 000 cfu/100 mL - roughly an order of magnitude higher than recorded at any of the other sites where faecal bacteria concentrations have been measured – Appendix 1) suggesting that bacterial abundance and activity is particularly high at this site.

4.2.4 *Temperature compensated decay rates*

The comparison of decomposition rates in spring-fed streams was from sites throughout New Zealand. Therefore it is appropriate to compensate for any natural differences in temperature that may occur. After taking differences in temperatures among sites into account, mass loss rates at the reference site (Tennis) were statistically similar to all the other sites except Parangahau (Figure 5). Mass loss rates per degree day in Pipitea and Riverlands were significantly lower than in Parangahau, Taharua, Pupu and Tawhiti (Figure 5). Mass loss rates in Parangahau and Tawhiti were also relatively high without temperature compensation, whereas mass loss rates in Taharua and Pupu were similar to the reference site (Figure 4).

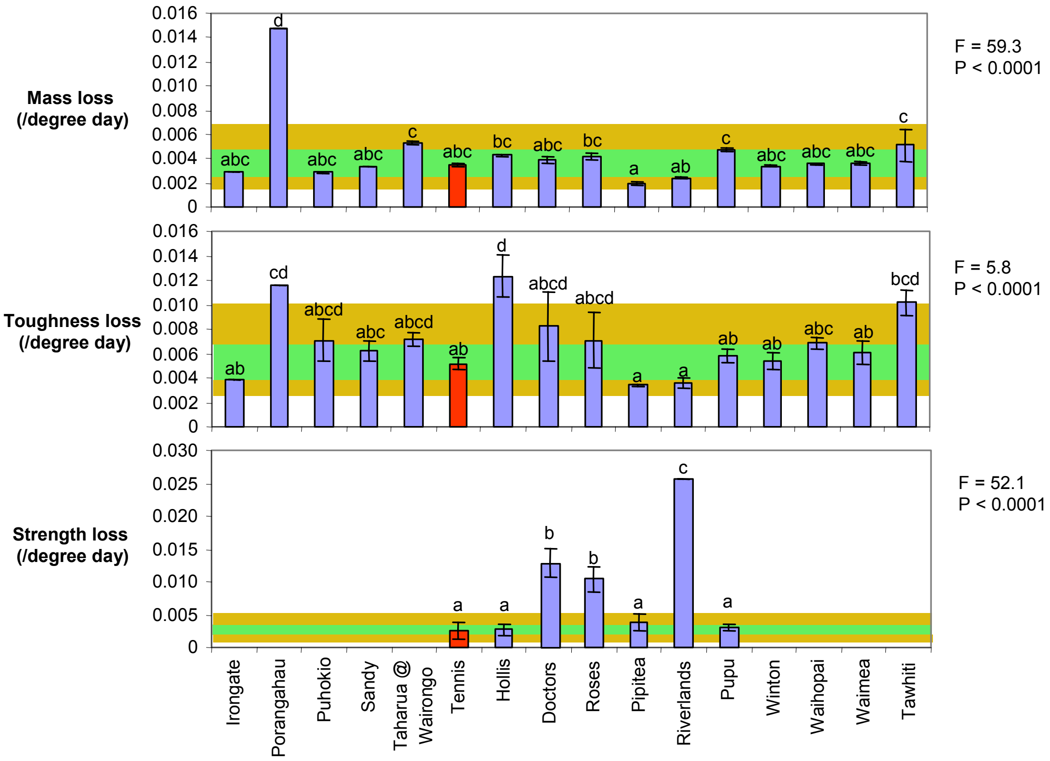

Figure 5 Temperature compensated decay rates (±SE) for leaf packs and cotton strips in the spring-fed streams. The Tennis sites (marked in red) is considered to represent reference condition. A band representing healthy condition (0.75 to 1.33 times reference) is shown in green, while a band representing slightly impaired health (0.5-0.75 and 1.33-2.0 times reference) is shown in orange. Values beyond the orange band would be considered impaired. Within each graph, bars with the same letter above them are not significantly different from each other.

After temperature compensation, toughness loss rates were high in Parangahau, Hollis and Tawhiti (Figure 5), a similar pattern to that seen without temperature compensation (Figure 4). Strength loss rates also showed little difference as a result of temperature compensation, with the Riverlands site again having a much higher decay rate than the other sites (Figure 5).

4.3 Auckland Streams

West Hoe Stream is considered to represent reference condition for the soft-bottomed streams in the Auckland region (Stark & Maxted 2004). Cascade Stream represents reference condition for hard bottomed streams. Using the tentative criteria mentioned above, the decay rates for West Hoe were used as a benchmark to compare with results from the other sites.

Mass loss rates ranged from 0.053 – 0.27 day^{-1}, which corresponds to a % mass remaining after one month of 22% and 0%, respectively. Mass loss rates for all the native and rural streams were equivalent to reference condition (Figure 6). However, mass loss rates for the urban streams were significantly higher than reference and indicative of mild (Oakley, Otara) or severely (Lucas) compromised stream functioning (Figure 6).

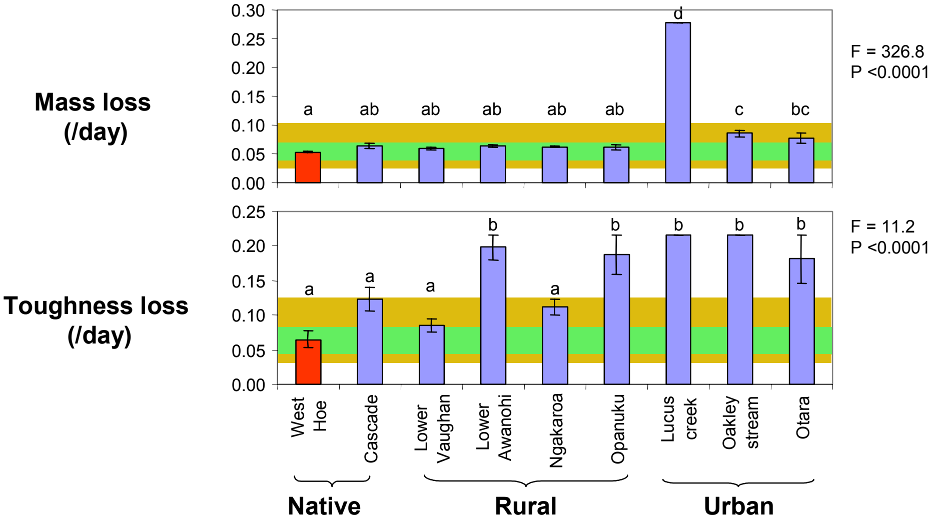

Figure 6 Rates of mass and toughness loss (±SE) for leaf packs from the Auckland streams. West Hoe (marked red) was chosen to represent reference condition. A band representing healthy condition (0.75 to 1.33 times reference) is shown in green, while a band representing slightly impaired health (0.5-0.75 and 1.33-2.0 times reference) is shown in orange. Values beyond the orange band would be considered impaired. Within each graph, bars with the same letter above them are not significantly different from each other. Cascade and Opanuku are hard-bottomed streams, while the remainder are soft-bottomed.

As was seen for the spring-fed streams, toughness loss rates were more variable within and among sites than mass loss rates and ranged from 0.065 – 0.22 day^{-1}, which corresponds to a % toughness remaining after one month of 21% and 0%, respectively. The urban streams had significantly faster toughness loss rates than the other land uses, although toughness loss was also fast at the Opanuku and Lower Awanohi sites (Figure

6). The toughness loss rate at the hard-bottomed reference site (Cascade) was slightly faster than at the soft bottomed reference site and in the range suggesting mild impairment.

4.4 Large unwadeable rivers

The Kaniwhaniwha (39%) and Waipa (31%) sites have a higher proportion of native forest in their catchments than the other three Waikato sites (Punui, 15%; Mangapiko, 7%; Mangapu, 7%) and would be expected to have better ecosystem health than the other sites as a result. Nutrient concentrations and turbidity are lower in the Kaniwhaniwha and Waipa rivers than in the other sites (Smith 2005).

Mass loss rates ranged from 0.062 – 0.083 day^{-1} and were statistically equivalent among all the large unwadeable rivers at the $\alpha = 5\%$ level (Figure 7). However, the pattern of mass loss rates among sites was similar to that seen for tensile strength loss rates and stick weight loss rates with slowest decay in the Kaniwhaniwha River and fastest decay in the Mangapu River.

Toughness loss rates ranged from 0.083 – 0.22 day^{-1} (Figure 7). Toughness loss rates in the Punui River were significantly faster than in any of the other large unwadeable rivers (Figure 7).

Tensile strength loss rates ranged from 0.037 – 0.108 day^{-1} and were significantly slower in the Kaniwhaniwha River than at Punui or Mangapu (Figure 7).

The rate of stick weight loss after 84 days emersion are shown for comparison in Figure 7. Stick weight loss rates were slowest in the Kaniwhaniwha River, slightly higher in the Waipa and Punui river, higher again in the Mangapiko River and highest in the Mangapu River (Figure 7). The variability in stick weight loss within each site was relatively low compared to the other decay measures meaning that the differences mentioned above were statistically significant.

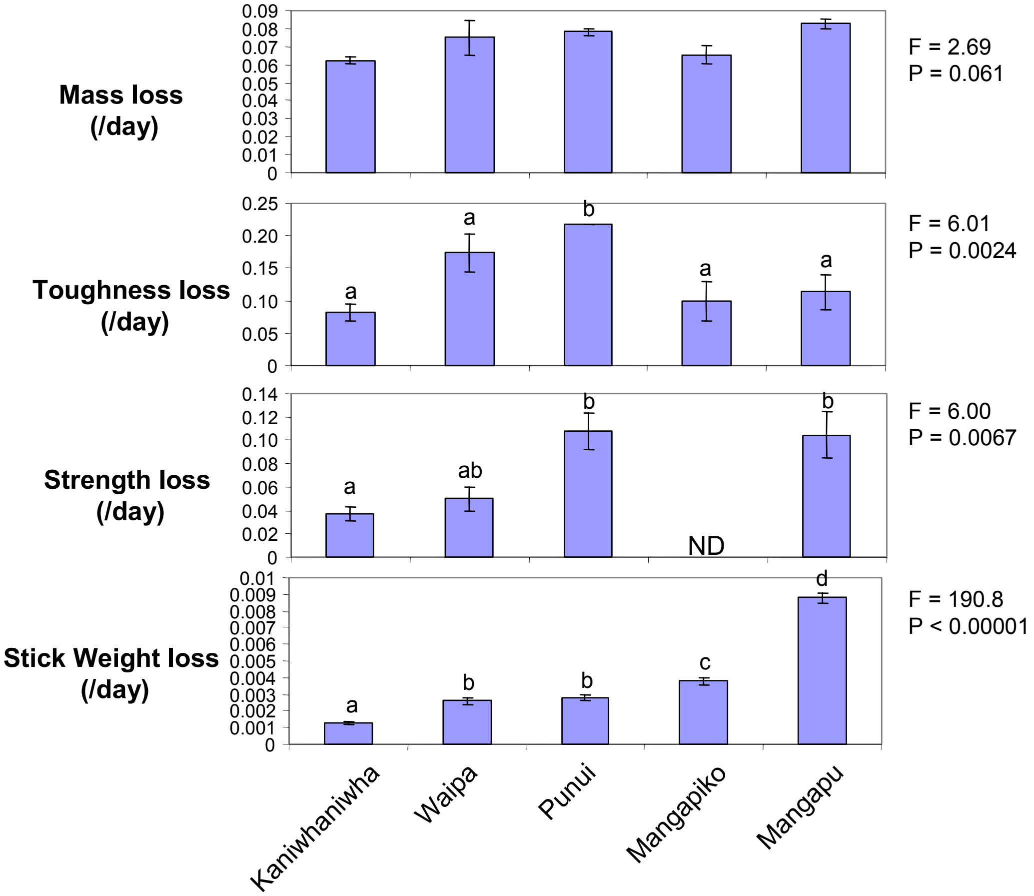

Figure 7 Rates of mass loss and toughness loss (±SE) for leaf packs, tensile strength loss (±SE) of cotton strips, and stick weight loss (±SE) after 84 days from the large unwadeable Waikato rivers. Of these rivers, the Kaniwhaniwha River has the largest percentage of native forest in its catchment. Within each graph, bars with the same letter above them are not significantly different from each other. Cotton strips were not deployed in the Mangapiko River.

Sticks were also retrieved after 7 days and 27 days allowing stick weight loss rates to be calculated separately for each of these retrieval periods (Figure 8). The Kaniwhaniwha River consistently had the lowest stick weight loss rates on all sampling occasions. In contrast, the Mangapiko River had the fastest stick weight loss after 7 days of emersion, while the Mangapu River had the highest stick weight loss rates after 27 and 84 days of emersion (Figure 8). The Waipa River had variable stick weight loss rates over time with the second highest stick weight loss after 27 days, but the second lowest stick weight loss after 7 and 84 days. The differences among sites increased with the length of the deployment period, while the within site variability was lowest for sticks collected after 84 days. This indicates that a 3 month deployment period gives a better resolution among sites than shorter deployment periods.

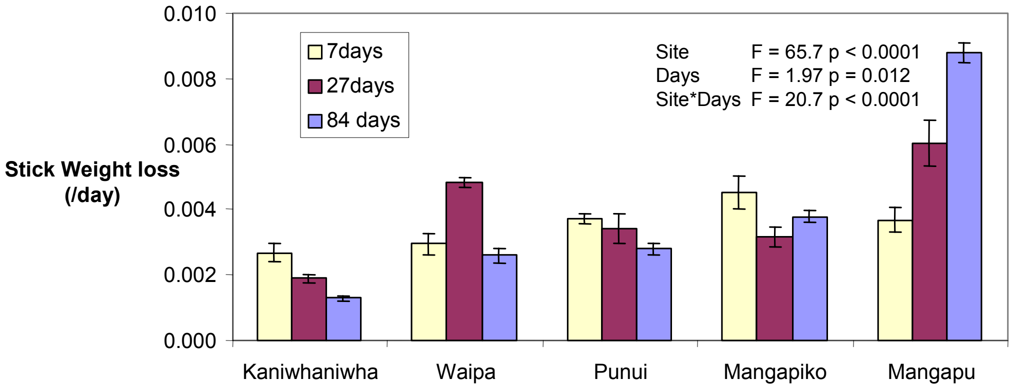

Figure 8 Rates of stick weight loss (±SE) calculated separately after 7, 27 and 84 days from the large unwadeable Waikato rivers.

The comparison of 4 independent measures of decay rates in the Waikato rivers is very useful. In these rivers, stick weight loss and tensile strength loss appeared to be more sensitive to differences in ecosystem health than leaf mass or toughness loss measured over 1 month. Stick weight loss also tended to be less variable within individual sites than any of the other measures.

4.5 Effects of water abstraction

As part of their PhD studies at Massey University, Alex James and Zoe Dewson have set up an experimental water abstraction from three streams in the Wairarapa. Water abstraction resulted in a reduction in flow of 96%, 92% and 74% at the Booth's Creek, Campbell Farm, and Forest park sites, respectively. Leaf packs were deployed upstream and downstream of the abstraction in each stream.

Significant differences in mass loss rates were observed among streams and also between positions upstream and downstream of the abstractions (Figure 9). Mass loss rates at Booth's Creek and Forest Park tended to be higher upstream of the abstraction than they were downstream (Figure 9).

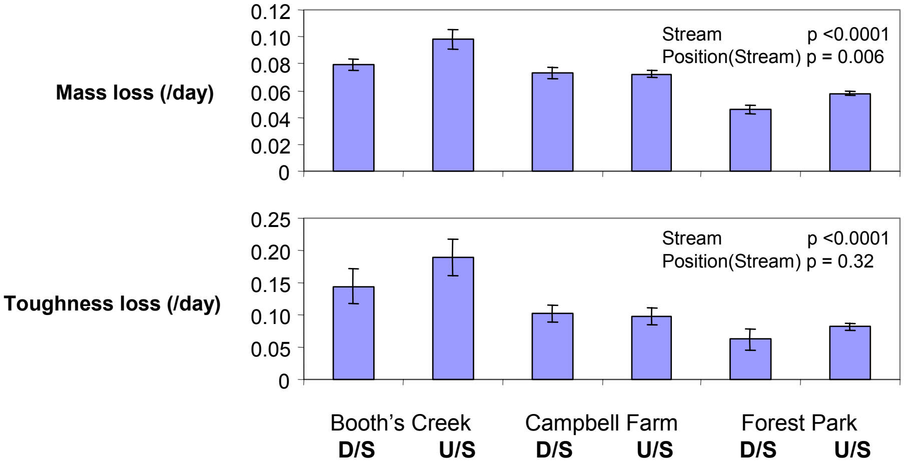

Figure 9 Rates of mass and toughness loss (±SE) at sites upstream and downstream of water abstraction in three Wairarapa streams.

Significant differences in toughness loss rates were also observed among streams (Figure 9). However, there was no indication of a difference in toughness loss rates above and below abstraction points.

The difference in mass loss rates upstream and downstream of the abstraction in Booth's Creek was interesting. I had imagined that water temperatures might be warmer downstream of abstraction thus stimulating faster microbial decay in the section with reduced flows However the opposite pattern was observed with faster mass loss rates upstream of the abstraction. One explanation for the observed pattern was that the greater flow upstream of the abstraction resulted in faster physical breakdown of the leaves. The lack of a difference in leaf toughness loss rates between the sites on Booth's Creek also supports the explanation that differences in physical, rather than microbial, processes were responsible for the difference in mass loss rates. An alternative explanation relates to the observations by Alex & Zoe that the water temperatures downstream of the abstraction in Booth's Creek were actually lower than upstream, probably due to cool groundwater inputs making up a more substantial proportion of the flow in the downstream section. Therefore, decomposition rates may have reflected temperatures variations among sites after all. It is also possible that the reduction in flows altered the macroinvertebrate community, limiting the number of leaf eating invertebrates in the section with reduced flows and thus decreasing the mass loss rates.

4.6 Longitudinal patterns down river systems

4.6.1 Motueka River

There is a relatively subtle decline in water quality down the length of the Motueka River, primarily associated with changes in the proportion of agricultural land in the catchment upstream (Young et al. 2005). Turbidity, and the concentrations of suspended solids, nitrate-nitrogen, total nitrogen and dissolved reactive phosphorus increase downstream, whereas water clarity decreases downstream. The thermal regime also varies down the length of the Motueka River with warmer daily mean temperatures and higher daily minimum temperatures downstream (Young et al. 2005).

Rates of mass loss in the Motueka Catchment ranged from 0.032 – 0.077 day^{-1} and mass loss rates tended to decrease downstream along the length of the river (Figure 10, R^2 = 0.18, p = 0.007).

Toughness loss rates ranged from 0.043 – 0.138 day^{-1} and showed no significant pattern along the length of the river (Figure 10). Variability in toughness loss rates within sites was higher than that for mass loss rates.

Rates of tensile strength loss ranged from 0.013 – 0.112 day^{-1} and increased significantly downstream (Figure 10, R^2 = 0.20, p = 0.01). Variability in tensile strength loss rates within sites was also relatively high compared to the variability in mass loss rates.

It is difficult to understand why mass loss rates decreased downstream while tensile strength loss rates increased downstream. The increasing concentrations of nutrients and warmer water downstream would be expected to stimulate microbial activity resulting in an increase in decay rates, as observed for the tensile strength loss rates. Presumably, factors other than microbial decay were responsible for the declining mass loss rates down the river. It is possible that physical processing capacity varied along the river due to changes in water velocity and/or abrasion. Physical processing would be expected to affect mass loss to a greater extent than tensile strength loss. However, an analysis of velocity measurements taken at the locations where the leaf bags were deployed showed no significant pattern downstream.

The most likely explanation for the decline in mass loss rates downstream is that macroinvertebrate consumption was a major factor controlling rates of leaf mass loss and decreased downstream with changes in the composition of the macroinvertebrate community. Macroinvertebrate samples collected in April 2002 at all of these sites indeed showed a significant downstream decline in the density of leaf eating invertebrates (shredders) (Shearer & Young unpublished data; F = 4.37, p = 0.048).

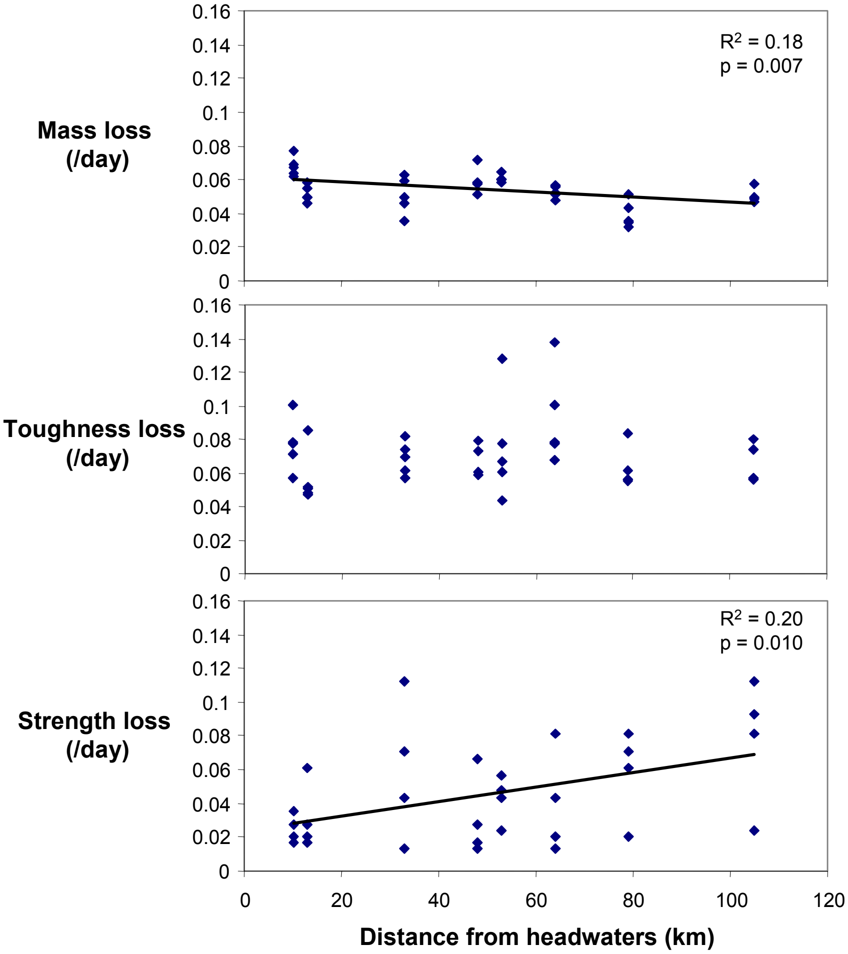

Figure 10 Rates of mass loss, toughness loss and tensile strength loss at sites located along the length of the Motueka River catchment.

4.6.2 *Temperature compensated decay rates – Motueka River*

Natural changes in the temperature regime would be expected down the length of a river system with declining altitude. Indeed, in the Motueka River mean daily water temperatures and minimum daily temperatures increase downstream (Young et al. 2005) and could be responsible for the patterns in decay rates observed without temperature compensation (Figure 10). After temperature compensation, the decline in mass loss rates down the river was even stronger than without compensation, while the downstream increase in strength loss rates per day that was observed was no longer apparent after temperature compensation (Figure 11 versus Figure 10). This suggests that the warmer waters downstream in the Motueka River were responsible for the faster strength loss rates, whereas some other factor, such as the relative abundance of leaf eating invertebrates, was responsible for the higher mass loss rates near the headwaters of the river. After temperature compensation, there was also weak evidence for a downstream decline in toughness loss rates (Figure 11).

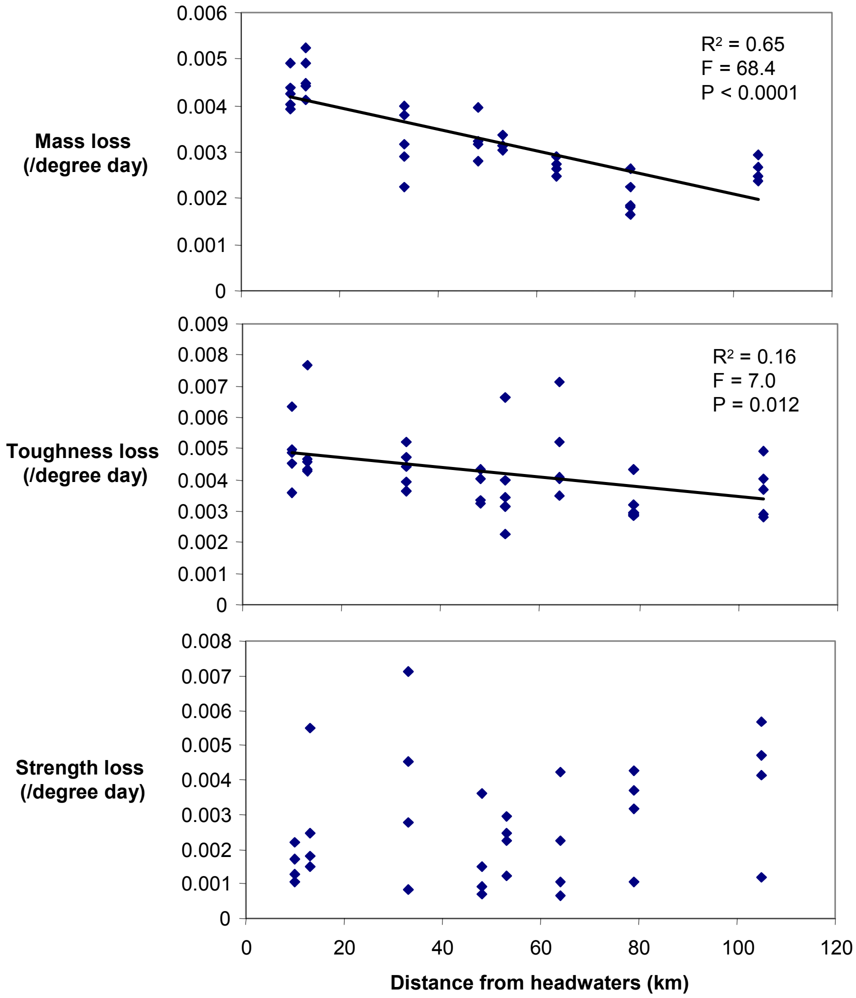

Figure 11 Temperature compensated rates of mass loss, toughness loss and tensile strength loss at sites located along the length of the Motueka River catchment.

4.6.3 Ruamahanga River

The Ruamahanga River emerges from the Tararua Range and then flows south through the Wairarapa Plains. Leaf packs were deployed at four sites along the river; an upper site dominated by native forest (RS31), a site at Masterton upstream of the Masterton sewage inputs (RS32), a site downstream of the Masterton sewage inputs (RS33), and finally a site further downstream (RS34) after the river receives sewage from Greytown, Carterton and Martinborough.

Unfortunately the river changed course during the leaf bag deployment and only one leaf bag was retrieved from site RS33.

Rates of mass loss at the other three sites ranged from 0.061 – 0.166 day^{-1} and tended to increase downstream although the differences among sites were not quite significant at the $\alpha = 5\%$ level (Figure 12).

Toughness loss rates ranged from 0.09 – 0.21 day^{-1} and were significantly slower at Site RS31 than at the other sites (Figure 12).

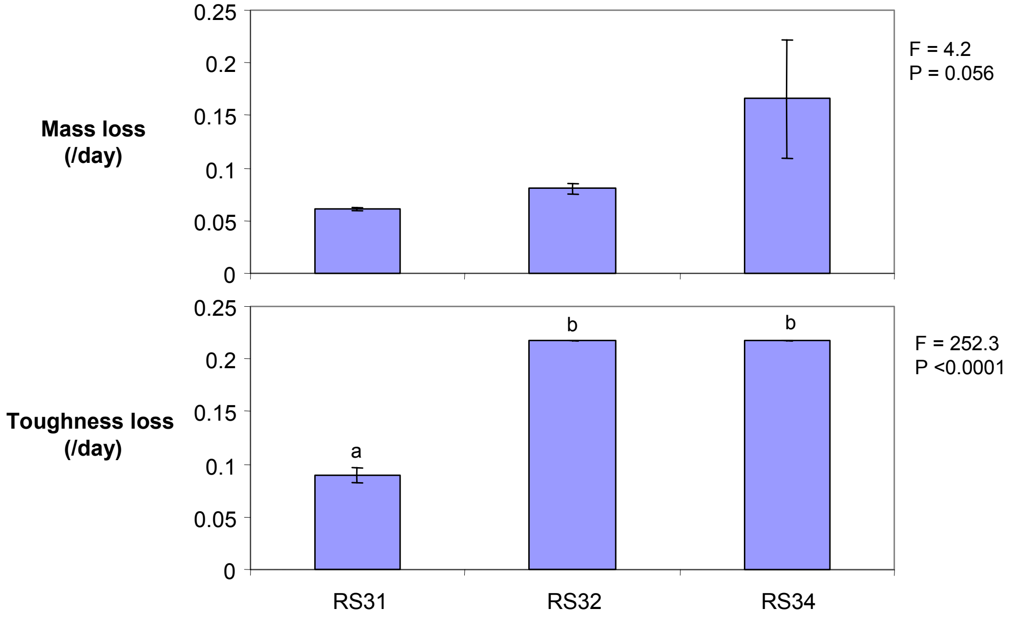

Figure 12 Rates of mass and toughness loss (±SE) at sites located along the Ruamahanga River. Within each graph, bars with the same letter above them are not significantly different from each other.

The combined effects of sewage and non-point source inputs of nutrients from adjacent agricultural and urban land, and possibly warmer water temperatures downstream, appears to have stimulated decomposition rates substantially in the lower reaches of the Ruamahanga River. This downstream change potentially indicates an impairment of the health of the lower reaches of the river, although natural downstream changes in the temperature regime of the river may also be having an effect.

4.6.4 Patea/Waingongoro/Kapuni rivers

Although not part of the same river catchment, leaf packs were deployed at 5 sites representing the upper, middle and lower reaches of Taranaki ringplain rivers. The Patea River @ Barclay Road is at the edge of the National Park boundary and represents reference condition. The Eltham Road site on the Waingongoro River and the two sites on the Kapuni River and are in the middle reaches of the plain, while the SH45 site on the Waingongoro River is in the lower reaches of the plain near the coast.

Rates of mass loss ranged from 0.062 day^{-1} at the Patea @ Barclay Road site to 0.084 day^{-1} at the Waingongoro @ SH45 site, although the differences among sites were not significant at the $\alpha = 5\%$ level (Figure 13).

Toughness loss rates followed a similar pattern and ranged from 0.084 day^{-1} at the Patea @ Barclay Road site to 0.22 day^{-1} at the Waingongoro @ SH45 site (Figure 13). The mean toughness loss rate at the Patea @ Barclay site was significantly slower than the rates at the Waingongoro @ SH45 and Kapuni @ Kokiri sites.

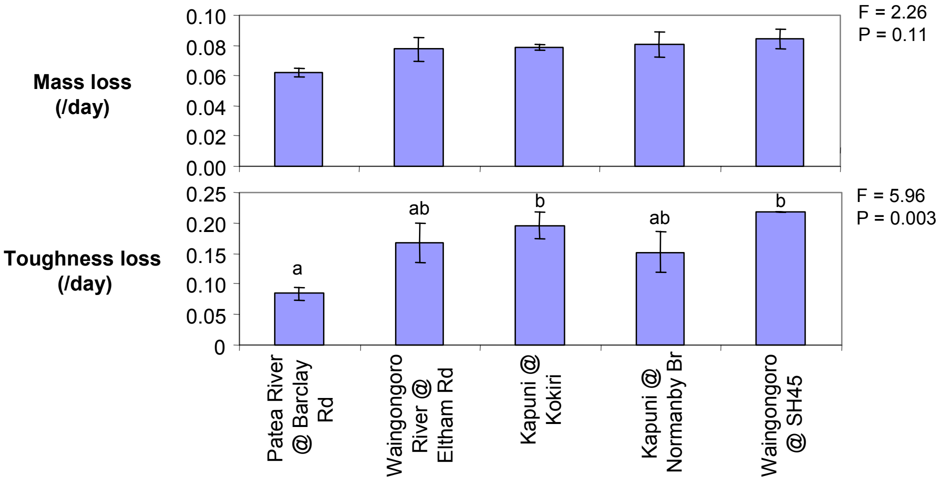

Figure 13 Rates of mass and toughness loss (±SE) at some Taranaki sites. Within each graph, bars with the same letter above them are not significantly different from each other.

The pattern seen in the Taranaki sites is broadly consistent with that seen in the Motueka and Ruamahanga rivers with the slowest microbial decomposition near the headwaters and faster decay downstream. The relatively fast decay rates observed in the Kapuni @ Kokiri and Waingongoro @ SH5 indicates an impairment to the functioning and health of these reaches, although again natural changes in the temperature regime may also be having an effect.

4.6.5 Rangitikei Catchment

Leaf packs were deployed at 6 sites in the Rangitikei River catchment. Two sites were in the Rangitikei River itself (upper catchment and downstream of Mangaweka), while the remaining sites were on smaller tributaries above and below townships and their associated sewage discharges. Unfortunately, 11 leaf packs were retrieved without recording which sites they were from, thus severely reducing the power of the statistical comparison of decay rates among sites.

Rates of mass loss ranged from 0.039 day^{-1} in the upper reaches of the Rangitikei River to 0.059 day^{-1} in the Porewa Stream upstream of Hunterville, although these differences among sites were not significant at the $\alpha = 5\%$ level (Figure 14).

Toughness loss rates ranged from 0.06 day^{-1} in the upper Rangitikei to 0.15 day^{-1} in the Rangitikei at Mangaweka, although again these differences were not statistically significant at the $\alpha = 5\%$ level (Figure 14).

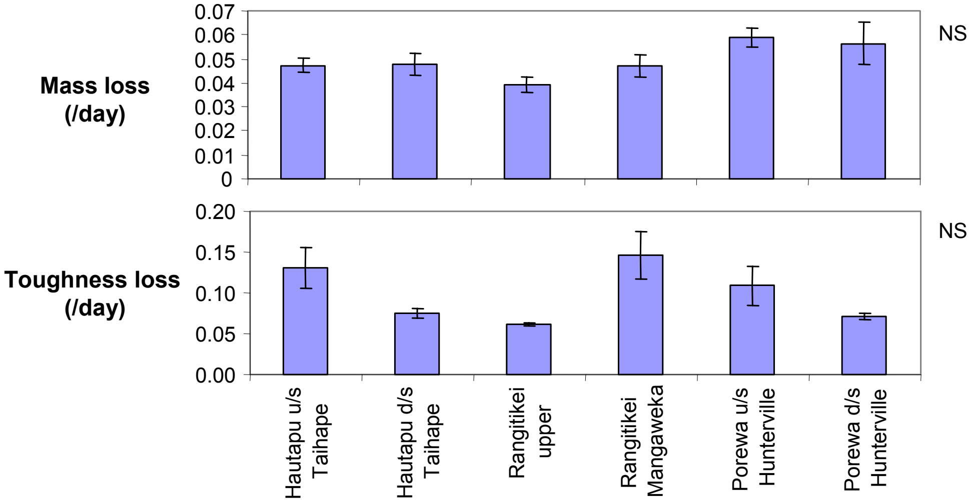

Figure 14 Rates of mass and toughness loss (±SE) at sites in the Horizons region.

4.7 Relationships between decomposition rates and other measures of river health

In order for decomposition rates to be considered as a potentially useful indicator of river health there needs to be a predictable relationship between decay rates and the intensity of likely stresses or disturbances. One possibility is that decay rates would vary in a linear fashion with stress intensity (Figure 15a). For example, an increase in nutrient concentrations might stimulate decomposition rates in a linear fashion and a site with high nutrient concentrations (and potentially poor health) would have higher decay rates than sites with lower nutrient concentrations. This is the most simple situation, but probably not the most realistic. A more complicated non-linear response is more likely (Figure 15b). For example, low intensity development of a catchment may initially stimulate decay rates via an increase in nutrient concentrations. However, as the intensity of the disturbance increases, the effects of sediment and low oxygen concentrations counteract any stimulation of decay rates. In this situation a heavily modified system would have the same decay rate as a healthy system, while a system with an intermediate level of development would have a much higher decay rate. This non-linear response may initially be seen as a problem, however, it is normally easy to distinguish sites at the extreme ends of the impact spectrum. There is often more difficulty distinguishing the early stages of an impact and it is in this area of the response curve where the resolution is greatest (Figure 15b). The only difficulty with this is that there is no way of knowing whether the measurement is from the rising part of the response curve, or the falling part of the response curve (Figure 15b).

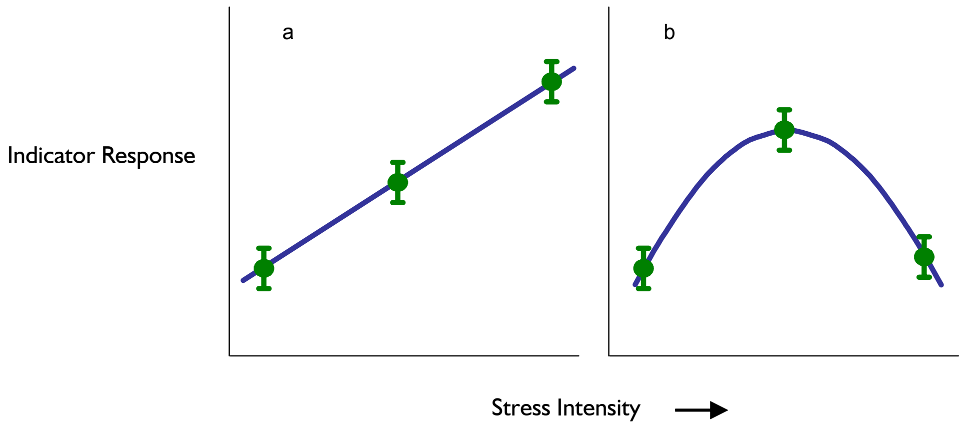

Figure 15 Two hypothetical responses (linear and non-linear) from an indicator detecting changes in the intensity of a stress. Indicator measures and associated error are shown for three sites along the impact spectrum for each response.

In the large unwadeable rivers in the Waikato region there was an indication of a linear relationship between the percentage of the catchment upstream in native forest and the stick weight loss rate (r = -0.72; Figure 16a). Similarly, after looking at all the sites from the case studies where water quality data was available, there appeared to be a linear relationship between cotton strength loss and *E. coli* concentration during the deployment period (r = 0.91; Figure 16b), although this relationship was driven by the extremely high values at Riverlands and more trials with sites that have intermediate faecal indicator bacteria concentrations would be required to confirm this relationship. There was also a linear relationship between dissolved inorganic nitrogen (DIN) concentrations and cotton tensile strength loss rates (r = 0.68; Figure 16c).

Surprisingly, there were no hump-shaped relationships observed using the full data-set. It is possible that the range of stress intensity was not wide enough to cause a non-linear response similar to that shown in Figure 15b. There were some indications that mass loss and toughness loss were depressed in two of the most degraded spring-fed streams in Marlborough (Pipitea and Riverlands; Figure 4) relative to the other Marlborough spring-fed streams, however these sites were atypical and had extremely low dissolved oxygen concentrations.

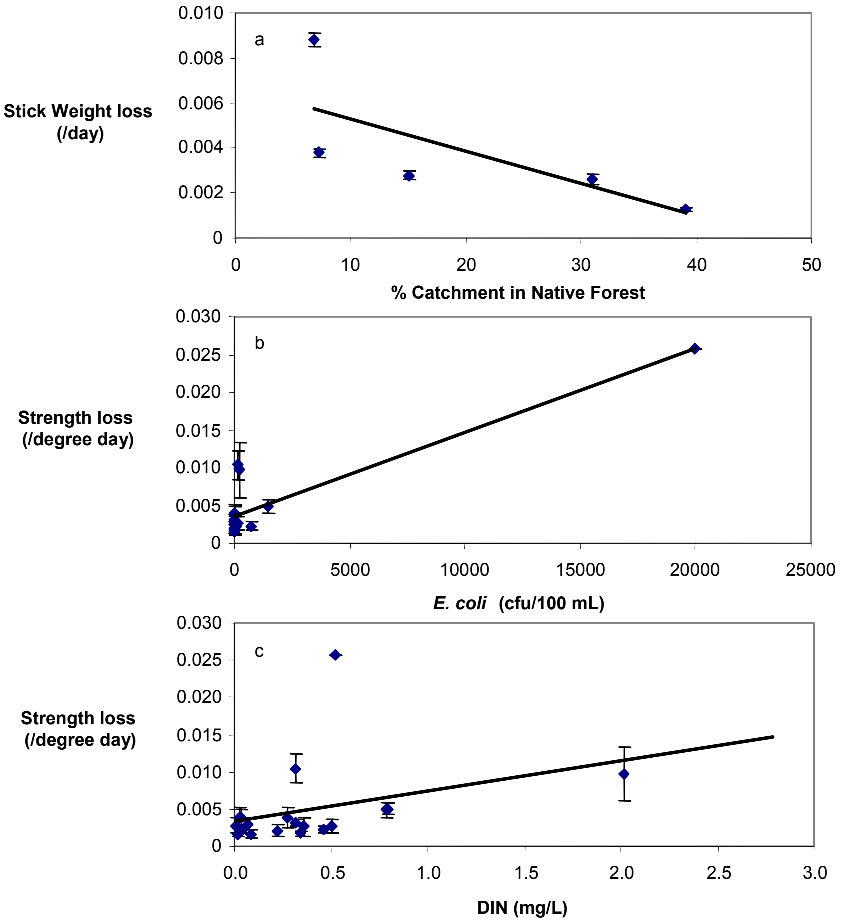

Figure 16 Some linear correlations between different measures of stress intensity and functional indicator response. DIN = dissolved inorganic nitrogen.

Macroinvertebrate community index (MCI) scores are a typical way of assessing the structural health of river ecosystems in New Zealand (Boothroyd & Stark 2000) and were available from 22 of the case-study sites. MCI scores were correlated with rates of toughness and strength loss (r = -0.54 and -0.68, respectively; Figure 17), but there was no significant correlation between MCI scores and mass loss rates (r = -0.03).

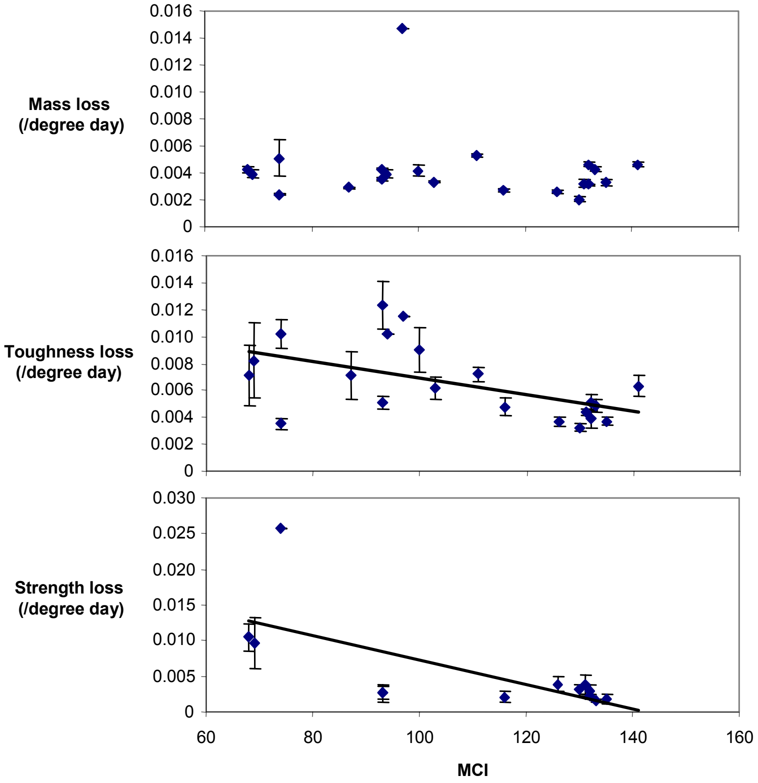

Figure 17 Relationships between MCI scores and decay rates.

5. SUMMARY

The case-studies have been a useful exercise to trial the different approaches to using decomposition rates as an indicator of river ecosystem health. Each approach has various advantages and disadvantages that are discussed further below.

5.1 Mass loss rates

Mass loss rates are simple and cheap to measure and respond to a broad range of decomposition mechanisms including macroinvertebrate consumption, microbial decomposition and physical loss of leaf material through abrasion and leaf breakage. Being a broad measure is both an advantage and a disadvantage since mass loss rates respond to a variety of effects that could be linked with river ecosystem health. However, the effects of one decomposition mechanism may be counteracted or swamped by the effects of others. For example, increased nutrient concentrations may stimulate microbial decomposition rates, but reduce the numbers of leaf-eating invertebrates and thus leaf consumption rates. In this situation the two effects of reduced ecosystem health are working against each other and potentially resulting in an intermediate level of mass loss that is not indicative of poor ecosystem health. To some extent this was observed among the sites distributed down the Motueka River catchment (see Figure 10).

Another concern with mass loss rates is related to the collection of leaf material. Ideally the leaves should be as similar as possible so that comparisons among sites are not compromised by differences in the leaf material. Even within a single species there will be differences in the chemical composition of leaves depending on their age, position on the tree, and the location and soil type where the tree is growing (Boulton & Boon 1991). The availability of suitable leaves is also an issue. We chose to use mahoe leaves in the case-studies because they are common throughout New Zealand. However, it is not always easy to find a suitable source of leaves and it takes some time to collect and dry a sufficient amount of leaves. After they are dry, leaves are also relatively fragile and need to be treated with care before being deployed.

Existing information on decay rates of mahoe leaves indicated that a deployment period of 1 month would result in a 30-75% loss of their initial weight (Linklater 1995; Parkyn & Winterbourn 1997; Hicks & Laboyrie 1999). However, in the case-studies the amount of material remaining ranged from 0 – 45% of their initial weight, which was less than expected. In hindsight it would have been preferable to have a shorter deployment period, which may have allowed more resolution in decay rates among sites (Figure 18). Leaf decay begins with the fast leaching of soluble compounds, followed by relatively fast decomposition of the fleshy parts of the leaf. The tougher veins decompose more slowly and at most sites were all that remained after 1 month of deployment. So in essence there are at least three distinct decay rates occurring as a leaf decomposes, and not necessarily the smooth exponential loss that might be expected from a more homogenous material such as cotton or wood. This presents some problems when trying to interpret the decomposition rates, especially if there is a fixed deployment period and only a single retrieval time. In the RIVFUNCTION project, a large European project focussing on the use of leaf decay as a functional indicator, a considerable amount of effort has been spent on determining the expected time required for 50% loss of leaf material (t_{50}). This involved pilot studies at many sites and sequential recovery of leaf packs (i.e. leaf packs recovered after 7 days, 14 days, 28 days, etc.) so that decay rates and the t_{50} could be predicted at different latitudes throughout Europe. If leaf decomposition is accepted as a useful tool for river health assessment, there would be merit in providing guidance on suitable deployment periods in different parts of New Zealand, and/or in streams with contrasting temperature regimes.

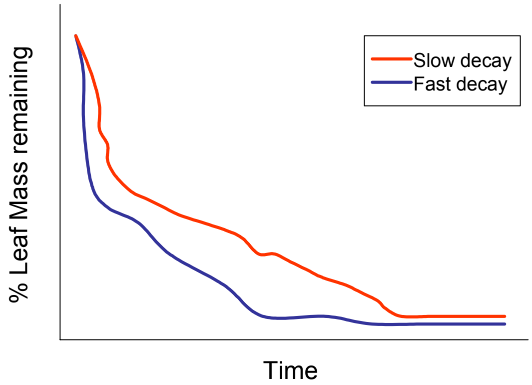

Figure 18 Hypothetical decay curves for leaves in two streams, one with fast decay and one with slow decay. Note that the decay rates calculated from a single leaf pack retrieval, and the amount of difference between streams, would vary substantially depending on when the retrieval took place.

In the case studies, we saw no clear evidence of a relationship between leaf mass loss rates and other measures of ecosystem health such as nutrient concentrations or MCI scores. This suggests that mass loss rates may be too broad to act as a general measure of ecosystem health. However, mass loss rates did show some interesting patterns among sites and, in particular, identified a gradient in mass loss rates along the Motueka river that was probably due to changes in the macroinvertebrate community along the river. This was not picked up with any of the other indicators. Mass loss rates also identified some sites with abnormal ecosystem functioning, such as Lucas Creek in the Auckland area that had much higher mass loss rates than any other stream sampled. The catchment is urbanizing and undergoing intensive residential development; 22% of the catchment is covered in impervious surfaces. The macroinvertebrate community there is in relatively good condition with MCI-sb scores ranging from 92-118 from 2002 to 2005 (John Maxted, pers. comm.). However, there are features of this catchment that are causing markedly different mass loss rates. It is possible that the disturbance of land caused by subdivision construction may have an even greater effect on ecosystem functions than completed urban development. It may be related to a combination of high sediment loading and construction related contaminants. Further investigation of the water quality data collected over the last 14 years at this site may provide additional insights. Similarly, the Parangahau River in Hawkes Bay had markedly different mass loss rates than any of the other spring-fed systems. This was surprising considering that the water quality and macroinvertebrate data from this system showed nothing out of the ordinary and demonstrates the value of incorporating functional indicators in a monitoring programme.

5.2 Toughness loss rates

Toughness loss rates are also reasonably easy to measure using a simple penetrometer. They are more focussed measurements than mass loss rates and presumably most closely related to microbial decomposition rates, although other decomposition mechanisms will also have some impact. Toughness loss rates can be measured on a small amount of leaf material, so the period of deployment is not so crucial as is the case for mass loss rates.

Measurements of toughness loss rates are affected by the same issues regarding leaf variability mentioned above. In addition, toughness loss rates have to consider the variability among positions on leaves. Considerable differences in toughness are expected depending on whether the penetrometer pin is placed above thick veins, fine veins, or soft leaf tissue. Variability within sites for leaf toughness measurements tended to be higher than for mass loss rates (e.g. see Figure 4, 6 & 7). It is possible that this variability was caused by variability in toughness among leaves within leaf packs, rather than among leaf packs themselves. Five penetrometer measurements were taken per leaf pack and care was taken to ensure that the pin was not placed directly over large leaf veins. Nevertheless, I would advise that more measurements per leaf pack should be conducted to reduce this source of variability. Matthaei et al. (2004) used 25 penetrometer measurements per leaf pack and found that variability in toughness rates within sites was less than or similar to that for mass loss.

Toughness loss rates generally showed a similar pattern to mass loss rates and there was a significant correlation between the two. However, there were situations where toughness loss rates showed a different pattern among sites. For example in Hollis Creek, a spring-fed stream in Marlborough, mass loss rates were similar to the reference site, whereas toughness loss rates were significantly higher than at the reference site.

This difference suggests that microbial decomposition was relatively high at the Hollis site, but mechanisms affecting mass loss were not elevated.

Toughness loss rates were correlated with the MCI score (Figure 17), which provides support that this measure is providing an indication of ecosystem health that corresponds with existing tools. The fact that toughness loss, rather than mass loss correlated with MCI scores is rather surprising considering that toughness loss is primarily related to microbial processing of leaves. A correlation between mass loss rates and the MCI score would have been expected to be more likely considering that mass loss rates are affected by macroinvertebrate consumption of leaves.

5.3 Cotton strips/Cellulose Decomposition/Tensile strength loss rates

Artificial substrates like cotton strips and wooden sticks have an advantage over leaves in that they have a consistent composition, which is reassuring when making comparisons among sites. Cotton strips are cheap and relatively easy to source, although the original company that was making the Soil Burial Test Fabric that were used in these case-studies is no longer operating. An alternative source of 100% cotton tape has been found and trials are underway with this material. An additional advantage of using tape instead of cloth is that each section does not need to be frayed to a standard width before the strength assessments. Cotton strips are not fragile like leaves and can be deployed without bags which saves on time and costs. Unfortunately, tensile strength measurement requires a specialised tensometer which involves a cost (approx. $15 per measurement = $75 per site for 5 replicates).

Cotton strip decomposition is probably the most specialised of the functional indicators considered in the case studies and is primarily related to rates of bacterial decomposition. Aquatic fungi make a substantial contribution to leaf litter breakdown, but do not colonise cotton cloth (Felix Barlocher, pers. comm.). Cotton is also unlikely to be a preferred food for macroinvertebrates, so the effects of macroinvertebrate consumption are not assessed using cotton. Indeed cotton decomposition rates should be considered as an assay, rather than a realistic measure, of natural decomposition processes. Cotton cloth is not a natural substrate that would be expected to occur regularly in streams. Therefore, you would expect that only a subset of the organisms living in the stream would be attracted to it. However, cotton is composed almost entirely of cellulose, which is a common constituent in most types of plant material and thus not too different from much of the organic matter present in rivers.

The short deployment period for the cotton strips (7 days) means there is less likelihood of losing the cotton strips due to flooding etc. However, the short deployment period also means that the measure of health is only integrated over the 7 day period.

Within site variability of the tensile strength measurements was higher than for the mass loss measurements, but tended to be less than that for the toughness loss measurements (see Figures 5, 7 & 10). The cotton strips also appeared to be more sensitive to differences among sites than mass loss or toughness loss. The most striking example of this was the extremely high strength loss rate at the Riverlands site (Figure 5).

Strength loss rates were not significantly correlated with either mass loss or toughness loss rates. However, strength loss rates were correlated with the concentrations of *E. coli* and dissolved inorganic nitrogen (Figure 16). Strength loss rates were also closely correlated with MCI scores (Figure 17), which again provides support for the concept that this is a reliable measure of ecosystem health.

5.4 Stick weight loss

Like cotton strips, wooden sticks are easy to source, robust, and provide a standardised substrate for comparison of decomposition rates among sites. Another advantage is that stick mass loss is easy to measure and can be done relatively cheaply using an accurate balance. Stick mass loss is also a focussed measurement and primarily related to microbial decomposition (both fungi and bacteria), since few freshwater organisms consume wood directly (Tank et al. 1998). However, some mass loss may be also be associated with physical abrasion, particularly in sites with high sediment transport rates.

Wood is relatively common in many rivers and streams and therefore wood decay is probably a better reflection of a natural process than cotton decay. Nevertheless, the size shape and chemical composition of birchwood coffee stirrer sticks is probably somewhat different from most twigs and sticks that get into streams, so wood decay rates could also be considered as an assay, rather than a measure, of realistic decay rates.

The long deployment period required for wooden sticks (recommend 3 months) is a disadvantage since there is an increased likelihood of losing the sticks due to flooding. However, the long deployment period means that the decay rates that are measured integrate conditions at the sites over an extended period.

One of the most appealing features of using wooden sticks is the low within-site variability that was observed in the large Waikato rivers (Figure 7). It is possible that this low variability was due to the fact that all five replicate sticks were deployed together on a single warratah, whereas the leaf packs and cotton strips were spread out throughout the river channel. However, if this low variability is a consistent feature of wooden stick decay then the ability to detect significant differences in decay rates among sites will be more powerful than using the other decay measures. Further trials are underway in the Mangaokewa River near Te Kuiti to assess the variability in decay rates of wooden sticks deployed in different microhabitats.

5.5 Future work

As is always the case with studies like this, more work could be done to confirm or refine the conclusions made in this report. Some specific issues that could be addressed in future work include:

- Provide guidance on suitable deployment periods in different parts of New Zealand, and/or in streams with contrasting temperature regimes

- Conduct a trial of leaf toughness and mass loss with substantially more toughness measurements per leaf pack to see if this source of within-site variability can be reduced.

- Conduct further trials using cotton strips and wooden sticks in combination with leaf packs to determine if the artificial substrates really are a more powerful tool to detect differences among sites, and also produce results that make ‘ecological sense’.

- Conduct trials over a wider range of stress intensity to determine if non-linear responses to stress need to be considered when interpreting the results from these indicators.

- Investigate if the effects of other naturally varying parameters, such as nutrient availability, could be compensated for when interpreting decay rates. Statistical techniques such as ANCOVA would be an obvious approach to use.

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Appendix 1

Details of case-study sites

Appendix 1 Details of the case study sites. DIN = dissolved inorganic nitrogen, DRP = dissolved reactive phosphorus. Nutrient and bacterial data presented here are medians of the entire data record that was available. Average temperatures were determined from temperature loggers deployed either at the sites during the case-studies, or during the same period in earlier years.

Region	Council SiteID	Site Description	Easting	Northing	Type	DIN (mg/L)	DRP (mg/L)	*E. coli* (cfu/100 ml)	Av. Temp. (°C)
Hawkes Bay	14	Porangahau River @ Kates quarry	2814329	6094957	Springfed - ag runoff	0.044	0.005	3	18.8
Hawkes Bay	316	Sandy creek u/s Mahiaruhe Stream	2846565	6215599	Springfed - ag runoff	0.302	0.054	1400	18.7
Hawkes Bay	394	Puhokio stream at Te Apiti road	2850622	6145648	Springfed - ag runoff	0.84	0.009	390	19.2
Hawkes Bay	487	Irongate	2836546	6166379	Springfed - urban	1.2	0.019	290	17.9
Hawkes Bay	2446	Taharua River @ Wairogo	2794022	6249129	Springfed - dairying	2.277	0.021	16	10.7
Hawkes Bay	2442	Taharua River @ Poronui	2794173	6237757	Springfed - dairying	1.027	0.014	2	
Marlborough		Tennis Courts	2585965	5970320	Springfed - Good	0.475	0.006	16	13.4
Marlborough		Hollis	2587900	5970615	Springfed - Good	0.435	0.0105	115	14.3
Marlborough		Doctors	2588615	5965380	Springfed - Medium	1.54	0.024	210	15.9
Marlborough		Roses	2589900	5971810	Springfed - Medium	0.425	0.019	145	15.7
Marlborough		Pipitea Sth	2596102	5968623	Springfed - V Poor	0.274	0.18	10	17.9
Marlborough		Riverlands Industrial	2595210	5963119	Springfed - V Poor	0.52	1.3	20000	21.3
Tasman		Waikoropupu above Salmon Farm	2490615	6039940	Springfed - High Quality	0.32	0.001	5	11.7
Tasman		Rainy	2494600	5944045	Longitudinal	0.03	0.016	5	15.8
Tasman		Quinneys	2494660	5971920	Longitudinal	0.212	0.012	87	19.3
Tasman		Rolling	2473890	5972405	Longitudinal		0.006	5	11.1
Tasman		Wangapeka u/s Dart	2480355	5976445	Longitudinal	0.043	0.005	20	15.7
Tasman		Wangapeka @ Walters	2489535	5984870	Longitudinal	0.1	0.0045	5	18.2
Tasman		Motueka @ Hinetai	2492370	5986115	Longitudinal	0.18	0.007	5	19.3
Tasman		Motueka @ Woodstock	2494985	5993945	Longitudinal	0.11	0.003	5	19.2
Tasman		Motueka @ Woodmans Bend	2506630	6009470	Longitudinal	0.12	0.006	35	19.8
Horizons		Porewa Stream u/s Hunterville	2729672	6136890	Above oxidation Pond	0.04	0.03		
Horizons		Porewa Stream d/s Hunterville	2719200	6122500	Below oxidation pond	0.38	0.028		
Horizons		Rangitikei River @ Pukeokahu	2771300	6170800	Upper reaches	0.03	0.005		
Horizons		Rangitikei River @ Mangaweka	2750300	6151300	Mid reaches		0.007		
Horizons		Hautapu River d/s Taihape	2751400	6165100	Below oxidation pond		0.054		
Horizons		Hautapu River u/s Taihape	2750500	6166900	Above oxidation pond	0.12	0.008		
Wellington	RS31	Ruamahanga River 1	2727428	6047462	Longitudinal				

Wellington	RS32	Ruamahanga River 2	2735588	6024740	Longitudinal				
Wellington	RS33	Ruamahanga River 3	2731125	6011816	Longitudinal				
Wellington	RS34	Ruamahanga River 4	2707855	5992730	Longitudinal				
Southland		Winton Stream at Lochiel	2147443	5435023	d/s discharges	1.46	0.049	4300	16.0
Southland		Waihopai River u/s Waihopai Dam	2155864	5414999	Lowland Macrophyte - ag runoff	1.94	0.014	800	16.0
Southland		Waimea Stream at Mandeville	2184664	5460676	Lowland macrophyte - ag runoff	2.07	0.016	87	16.0
Waikato		Waipa at SH3	2703575	6332190	31% Native	0.46	0.012	750	21.4
Waikato		Mangapu @ Otorohanga	2703255	6331830	7% native	0.789	0.03	1450	
Waikato		Puniu at Barton	2711475	6349955	15% native	0.798	0.022		
Waikato		Mangapiko @ Bowman	2709285	6355940	7% native	1.87	0.083		22.3
Waikato		Kaniwhaniwha @ Wrights	2698480	6368035	39% native	0.345	0.008		
Taranaki	PAT000200	Patea River @ Barclay Rd	2612695	6208310	Edge of National Park boundary	0.04	0.016	90	13.4
Taranaki	WGG000500	Waingongoro River @ Eltham Rd	2620360	6199100	Mid ringplain catchment above industry/municipal discharges	1.44	0.016	275	18.7
Taranaki	WGG000900	Waingongoro River @ SH45	2613950	6180275	Lower ringplain catchment	2.45	0.048	215	21.4
Taranaki	KPN000360	Kapuni River @ Kokiri Rd	2609606	6187641	Mid ringplain				20.0
Taranaki	KPN000400	Kapuni River @ Normanby Rd	2609200	6185462	Mid ringplain	1.02	0.011		20.1
Taranaki	TWH000240	Tawhiti Stream @ Ohangai Rd	2620960	6182100	Spring fed	1.65	0.017	610	18.3
Auckland		West Hoe	2658703	6512350	Native	0.099			16.7
Auckland		Cascade	2646043	6478123	Native				16.5
Auckland		Lucas	2662232	6496226	Urban	0.332			18.9
Auckland		Oakley	2662346	6479208	Urban	1.722			19.5
Auckland		Otara	2678726	6470029	Urban	0.346			22.5
Auckland		Opanuku	2652585	6477288	Rural				18.8
Auckland		Ngakaroa	2685544	6443214	Rural	2.144			19.1
Auckland		Lower Vaughan - 2 years of data	2665939	6500463	Lifestyle				21.4
Auckland		Awanohi	2661879	6500421	Lifestyle				
Massey Student Sites		Booths Creek upstream	2722765	6011160	Upstream flow diversion				
Massey Student Sites		Booths Creek downstream	2722765	6011160	Downstream flow diversion				
Massey Student Sites		Campbell Farm upstream	2742720	6040565	Upstream flow diversion				
Massey Student Sites		Campbell Farm downstream	2742720	6040565	Downstream flow diversion				

Massey Student Sites	Forest Park upstream	2724290	6040985	Upstream flow diversion
Massey Student Sites	Forest Park downstream	2724290	6040985	Downstream flow diversion
West Coast	Murray Creek	2348950	5814600	Springfed ag runoff
West Coast	Harris Ck	2347580	5815410	Springfed ag runoff
West Coast	Duck Creek	2349140	5817460	Springfed