# Stream Shade:
# Towards a Restoration Strategy

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*prepared for*

# Department of Conservation

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# Foreword

This report is based on studies undertaken by the National Institute of Water & Atmospheric Research over a three-year period from 1992 to 1995, supplemented by key results from subsequent studies. The work was primarily funded by the Department of Conservation, although use is made of findings from research funded by other agencies, notably the Foundation for Research, Science and Technology (Contract CO1516).

These studies were undertaken because manipulation of vegetation in riparian (streamside) areas is seen as the most effective means for restoring stream ecosystems in agricultural catchments[1]. Before riparian restoration can be responsibly advocated, however, there needs to be both: confidence in predicting the beneficial effects; and procedures for implementing schemes in a cost-effective manner. NIWA has conducted a number of interrelated studies at Whatawhata, near Hamilton, on land-riparian-stream interactions. Findings from these studies, when combined with findings from other studies, lead to recommendations for riparian management. This report focuses on the control of light and thermal regimes by riparian shading alongside small streams in hillcountry pasture catchments, and the consequent ecological response of the streams.

The specific objectives of this study were:

- to develop methods for characterising stream shade (Section 1).
- to conduct surveys of temperature, light and water quality in adjacent native forest, exotic forest and pasture streams (Section 2).
- to determine the effects of differing shade conditions on primary productivity, periphyton and invertebrate community structure using streamside channels (Section 3);
- to determine the effects of stream and riparian variables on stream thermal response (Section 4);
- to develop recommendations on shading required to conserve and restore stream ecosystems (Section 5).

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[1] Smith, C. M.; Wilcock, R. J.; Vant, W. N.; Smith, D. G.; Cooper, A. B. 1993: Towards sustainable agriculture: Freshwater quality in New Zealand and the influence of agriculture. *Ministry of Agriculture (Policy) and the Ministry for the Environment Report.* Wellington.

Some readers may prefer to concentrate on Section 5 which provides a synthesis before consulting Sections 1–4 for details of the constituent studies. At the end of each section there is a summary of the main points. Some results have already been reported, notably in our 'Riparian Guidelines'[2], but we have tried to give enough detail for this document to stand alone.

During the course of our investigations it became clear that riparian shade directly affects streambank stability, channel width and sediment input. The scope of the study was, therefore, widened beyond the original brief to include the ramifications of shade restoration for stream width and related aspects of stream ecology.

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[2] Collier, K.J.; Cooper, A.B.; Davies-Colley, R.J.; Rutherford, J.C.; Smith, C.M.; Williamson, R.B. 1995: Managing riparian zones: a contribution to protecting New Zealand's rivers and streams. Department of Conservation, Wellington, July 1995, 2 volumes.

# Summary

1.  Our study reinforces the view that the conversion from native forest to pasture has caused significant changes to the physical, chemical and biological character of New Zealand streams.

2.  Studies of streams in different landuses, and experiments in artificial channels, with different levels of shade have been carried out. These have provided valuable insights into the functioning of stream ecosystems which, together with methods developed for measuring shade and predicting water temperature, will assist managers to restore streams by restoring riparian vegetation.

3.  In this report, restoration is deemed to have a positive effect if it makes streams more like native forest streams. There are good prospects for restoring the ecology of pasture streams by restoring vegetation in riparian buffer strips (c.f., restoring vegetation throughout the entire catchment), but it is also possible to damage stream ecosystems by inappropriate restoration and unsound management practices in the buffer strips.

4.  The restoration of riparian shade can reduce water temperature and primary productivity while the restoration of riparian vegetation (notably groundcover) can reduce sediment and nutrient inputs.

5.  This in turn can help restore stream communities towards those characteristic of shaded native forest streams, which are typified by:

    - low and uniform periphyton biomass,
    - periphyton dominated by diatoms,
    - few filamentous green algae,
    - few algal blooms,
    - woody debris,
    - high retention of coarse particulate organic matter,
    - high habitat diversity,
    - high utilisation by invertebrates of heterotrophic biofilms and detritus,
    - high numbers of mayflies, stoneflies and shredders,
    - low numbers of snails, chironomids and oligochaetes.

6.  An important finding is that, for a given flow, forest streams are wider than pasture streams. If dense riparian vegetation shades out groundcover and destabilises the banks, then we forecast a transition period (lasting perhaps 20 years) during which the channel

widens and bank erosion contributes to sediment input. Eventually a wide, shallow channel is expected to stabilise with lower rates of bank erosion.

7.  If it is important to maintain bank stability, a compromise must be made between providing enough stream shade to reduce water temperature and primary production without over-shading the banks. Our tentative recommendation is a maximum bankside shade level of about 70%. Consideration can be given to re-planting with deciduous trees which provide dense shade during critical summer periods but which allow bankside vegetation to develop during autumn-winter.

8.  Trees in the riparian zone have the potential to help stabilise the streambanks but, if channel widening is likely, care must be taken to ensure that trees planted in the riparian zone are not undermined.

9.  The restoration of shade will change the way streams transform and export nutrients. An unshaded stream acts primarily as a nutrient 'processor', converting inorganic nutrient to plant biomass in the channel under stable flow and flushing it out during storm events. Given the same nutrient inputs, a shaded stream can be expected to retain less nutrient as plant biomass, and to act primarily as a down stream 'transporter' of inorganic nutrient. This may aggravate eutrophication further down stream, unless riparian restoration results in a compensatory decrease of nutrient inputs.

10. Riparian management can help reduce nutrient inputs by:

    - restricting stock access,
    - encouraging groundcover and
    - protecting riparian wetlands.

11. In our studies, differences in plant and invertebrate communities between pine and native streams were much smaller than differences between pasture and forest streams. Based on our observations, there do not appear to be any obvious advantages for the stream ecosystem in replanting with native or exotic trees, apart from growth rate. More detailed comparisons between pine and native forest streams are desirable.

12. Our studies suggest the following tentative shade targets:

    - > 70% to meet water temperature targets,
    - > 60–90% to control algal blooms,
    - > 60–90% to produce significant changes in invertebrate communities,
    - > 90% to reduce periphyton biomass to the low levels seen in forest streams,
    - < 70% to maintain streambank stability.

13. There are few data on the shade characteristics of trees in riparian zones but data from plantation forests indicate:

    - 70% shade under 15–20-year-old eucalypts spaced 6 m apart

    - 70% shade under 15–20-year-old pines spaced 7–14 m apart

    - a maximum shade under eucalypts of 80%

    - 90% shade under pine trees spaced 3.5–10 m apart.

14. The fact that the thermal inertia of small streams is low suggests that if low stream temperatures need to be maintained throughout a stream network (e.g., to maintain suitable fish or invertebrate habitat), then it is more important to maintain dense shade along the small (first- and second-order) than along the larger (third-, fourth- and fifth-order) streams. Similarly, when attempting to reduce stream temperatures in a catchment comprising a network of streams of different orders, it is more efficient to restore riparian shading on the shallow first- and second-order streams than on the deeper third-, fourth- and fifth-order streams.

# 1.    CHARACTERISING STREAM SHADE

## 1.1    Introduction

The radiation climate is of fundamental importance in streams because sunlight powers primary production (both in the stream and in its riparian zone) and also because radiation input strongly influences streamwater temperature. The amount of sunlight reaching the streamwater and riparian zone is reduced by shade elements, notably the streambanks and hills ('topography shade') and riparian vegetation ('canopy shade'). Shade is defined mathematically as the complement of the ratio of lighting at the site of interest to lighting in the open. This definition is deceptively simple, and does not address many complexities to do with the temporal variation of lighting, the spatial distribution of shading objects in relation to the light from the sun (direct solar radiation) and the sky (diffuse solar radiation), and also the spectral properties of shadelight.

While acknowledging its importance, stream ecologists often assess shade subjectively (e.g., Canfield & Hoyer 1988) or semi-quantitatively (e.g., Feminella *et al*. 1989). Some use is made of electronic light sensors or photochemical sensors (such as ozalid paper) (e.g., Boston & Hill 1991) to estimate stream lighting, but often with little thought to spatial and temporal variability or spectral sensitivity. The lighting ratio at shaded and open sites can vary markedly, depending on atmospheric conditions, position of the sun, and distribution of shade elements. A meaningful characterisation can be achieved by averaging point sensor data logged over a very long time period (e.g., months, Anderson 1964a,b). Time averaging removes the marked diurnal variation and, because the sun's position varies throughout the day, time averaging also removes some of the fine-scale spatial variation.

Recognising the difficulty of properly characterising shade under foliage with point sensors, forest ecologists (e.g., Anderson 1966) have developed techniques for analysing shade using fish-eye lens photographs. A fish-eye lens 'looking' vertically upwards focuses the whole upper hemisphere as a circular image on the film (Hill 1924). Analysis of such photographs yields indices of shade, such as the proportion of the total hemisphere blocked by foliage and the proportion of light transmitted under perfect overcast conditions (Anderson 1964a). Quantitative image processing can be done by computer (e.g., Chan *et al*. 1986; Chazdon & Field 1987), although the procedures are complex and slow, and generally have to be done offsite. Even without quantitative analysis, fish-eye lens photographs can be very useful for indicating the *source* of shading, be it foliage, stream banks or hills. One fish-eye photograph only serves to characterise the light environment of just one point in space, when what is often required is an average of the shade over extended areas, for example over a stream reach.

Recently an instrument has become commercially available which is based on a fish-eye lens and can be used to obtain indices of shade rapidly and onsite (Welles 1990, Welles & Norman 1991). This instrument, the LiCor LAI-2000 canopy analyser, views the upper hemisphere through a fish-eye lens that focuses light on five annular ring-shaped detectors, each viewing a certain range of zenith angles. The light measured by each of these detectors is divided by the light measured at an open site under identical sky conditions either with the same sensor or, better, with a second identical sensor operating simultaneously. These measurements yield transmission values known as *gap fractions* which measure the directional structure of shade at a point. A number of readings made at different points along a stream channel can characterise the light environment of that stream reach.

This section describes the protocol that has been developed for measuring stream shade using the canopy analyser. Some illustrative shade data are presented from streams with different land uses and from stands of potential shade trees. This section also investigates aspects of the spectral composition of shadelight because light sensor response varies with wavelength, and light quality may be important ecologically. Of particular importance is the fact that near infra-red (NIR) radiation is absorbed by plant foliage much less efficiently than visible radiation, but is equally significant as regards heating of streamwater. Because of its cost, the canopy analyser is likely to remain a research instrument and we have also investigated the effectiveness of simple methods for quantifying shade. Instantaneous measurements with a matched pair of Photosynthetically Active Radiation (PAR) sensors on a perfectly overcast day (e.g., under widespread frontal rain) quantify stream shade quite well; fish-eye lens photography provides useful qualitative information about stream shade; but visual assessments (e.g., ratio of canopy height to stream channel width) yield inaccurate estimates and cannot be recommended for quantifying stream shade.

## 1.2     Field sites

Most of the stream shade measurements described in this report were made in the Hakarimata Range near Whatawhata, some 25 km west from Hamilton. NIWA has several field study sites in this area: at AgResearch's Whatawhata Hill Country Research Station and in nearby Karikariki Reserve (administered by the Department of Conservation), private farmland, and pine plantation forest (Smith *et al*. 1993). Shade measurements under trees which might conceivably be planted to provide shade have also been used in this report (Ian Power, AgResearch, pers. comm.). We have also taken canopy analyser readings to determine the light climate under pine plantations at Purukohukohu, north of Taupo, and under crack willow stands in swampy areas of the Waipa River catchment near Whatawhata.

## 1.3    Methods

### The canopy analyser

The LAI-2000 canopy analyser was the primary tool used for the assessment of stream shade in this study. This instrument views light coming from the hemisphere above a level plane through a fish-eye lens that focuses light on five annular ring-shaped detectors, each viewing an approximately equal range of zenith angles. Measurements of light received by each of the detectors are expressed as fractions (*gap fractions*) of the light received during reference readings at an open site, ideally under identical lighting. The average gap fraction in each of the five zenith angle ranges provides a measure of the angular distribution of shade.

The index of stream shade derived from measurements using the LAI-2000 was termed diffuse non-interceptance (DIFN), which gives the light received at a stream water surface as a proportion of that from an overcast sky (see Appendix 1).

### Fish-eye lens photography

A visual record of stream-shade was made photographically with a full hemisphere (180º field of view) fish-eye lens (Minolta 7.5 mm f4 MD lens) fitted to a Minolta X300 SLR camera. The camera was placed on its back at stream water level, protected inside a shallow invertebrate sorting tray, at a representative point in the channel. The camera was oriented top to the north and levelled with a bubble spirit level (by shifting stream gravel) so that the lens axis was vertical. The position of the channel thalweg (locus of deepest points) was indicated with a survey pole, marked with alternating black and white bars of 100 mm length, and driven vertically into the sediment. Plates 3–6 show examples of fish-eye lens views from water level in small streams.

### Spectral distribution of lighting

Point sensors for measuring light and/or near infra-red (NIR) radiation were deployed in and near the Karikariki Reserve (map reference S14 934790) in order to study the spectral character of shadelight. In particular, the light recorded at sites along a forested stream reach was compared with that recorded at an open site on a nearby hill, and both records were compared with canopy analyser readings. Li-Cor LI-192SB quantum sensors of photosynthetically available radiation (PAR) were used as point sensors of visible light in the 400–700 nm waveband. Li-Cor LI-200SB pyranometers, based on photodiodes, were used as point sensors of ambient solar radiation in the open. These latter sensors, unlike the PAR sensors, have an *arbitrary* spectral response and so are not suitable for measurements under plant canopies because the spectral quality of the shadelight is greatly shifted from that of sunlight. An Eppley Model PSP precision spectral pyranometer, based on a thermopile sensor (with a uniform spectral

response), was used to characterise the radiation climate under foliage. This sensor was fitted with a standard glass dome (passing all radiation in the 285 to 2800 nm range) for measurement of total short-wave radiation. This sensor was also used as a calibration reference for the Li-Cor pyranometer sensors. The Eppley sensor was fitted with an RG695 long-pass filter for the measurement under foliage of NIR radiation in the range 700 to 2800 nm. Paired measurements with the NIR dome and the clear glass dome were made under fully overcast sky, together with canopy analyser measurements, in order to estimate the ratio of NIR to total short-wave radiation.

Spectral measurements were made of shadelight filtered by native foliage on an overcast day with a Li-Cor LI-1800UW spectro-radiometer. This instrument measures the spectral irradiance as a function of wavelength over the 300 to 850 nm range. A major difficulty for this work was to select a day with perfect overcast but dry foliage, since water strongly absorbs at some wavelengths in the NIR. Overcast conditions are typically associated with rain in humid climates such as that of the western North Island.

**PAR sensors**

To illustrate phenomena associated with stream shade, light at stream level was measured with point PAR sensors and compared with light received by an unobstructed hilltop. A PAR sensor was fixed in position in the channel at a moderately open site in the Whakakai Stream in Karikariki Reserve, west of Whatawhata, while another PAR sensor was positioned on a nearby hilltop, both sensors being connected to LI-1000 loggers set to log at 1-minute intervals. Logging was continued for several weeks in order to 'catch' both extremes of an overcast and a fully clear day. The ratio of stream to hilltop PAR was subsequently calculated. A canopy analyser sensor (fitted with a 270º field of view cap) was also positioned in the stream to measure the DIFN value relevant to lighting under uniform dense overcast. To characterise the distribution of shade relevant to the sunpath on a clear day, the distribution of canopy gaps was measured (with a 12.5º field of view cap) at 15º intervals of azimuthal angle at thirteen different orientations from east to west.

Theoretically it should be possible to use point sensors of light to provide a quick index of stream shade by taking instantaneous measurements under conditions of near-uniform sky lighting (e.g., perfect overcast or near dawn or dusk when the direct solar beam is hidden by the local horizon). To further test this idea, a Li-Cor PAR sensor was positioned on the canopy analyser 'wand' and connected to the LAI-2000 console so as to log PAR at the instant that the LAI-2000 sensor logged the distribution of ambient lighting. A reference PAR sensor was similarly set up on the reference canopy analyser unit. Measurements were made under heavy overcast conditions following the usual field protocol for the LAI-2000 over a 100 m reach of the Whakakai Stream, encompassing the light sensor monitoring point used in the

illustration of stream shade. Measurements were made at 20 points at 5 m intervals along the stream reach at a time of (apparently) perfect overcast on 2 December 1994 between 15:22 and 15:36 NZST. The stream lighting estimated from the point sensor measurements was compared with the predictions from the canopy analyser measurements.

**Visual assessment of shade**

We investigated a simple field protocol for assessing stream shade that would require no special instrumentation. The ratio of canopy height of riparian trees to stream channel width (hereafter termed 'shade ratio') was measured over several 100 m reaches of stream channel in a range of plantation forest streams. Canopy analyser measurements of DIFN were made over the same reaches and the results compared.

## 1.4      Results and discussion

**Characteristics of stream shade**

Plate 3 shows the fish-eye photograph of the Whakaki Stream. An elliptical-shaped gap at the centre of the image, with its long axis roughly aligned with the channel, is accessible to direct sunlight only at high sun angles. The canopy analyser was deployed at this precise point (with a 270º FOV cap) and gave a DIFN value of 11.4% (i.e., the light at the water surface was only 11.4% of that measured at an open site: the other 88.6% was intercepted (shaded) by the canopy and topography).

Figure 1A shows the record of sunlight (PAR) recorded at this precise point in the stream channel on a sunny day using a Li-Cor 192SB PAR sensor. Figure 1B and C show the record for a mostly overcast day, in relation to the records of sunlight at an open site on a nearby hilltop. In all three panels the top line is the PAR record from the reference (hilltop) sensor, and the lower line is the PAR record from the sensor near water level in the stream channel. On the sunny day, the hilltop (reference) sensor recorded a smooth sinusoidal-shaped pattern of irradiance through the day (Fig. 1A). However, the stream sensor recorded a very different and extremely variable pattern of irradiance owing to the movement of the sun. The lighting reaching the stream was very low through most of the day (less than 20 $\mu$einsteins m$^{-2}$ s$^{-1}$ except for some brief spikes of up to 50 $\mu$einsteins m$^{-2}$ s$^{-1}$) when direct sunlight patches (sunflecks) impinged on the sensor. Around mid-day the sun was in the canopy gap (refer Plate 3) and the direct solar beam reached the sensor. Partial blocking of the sun's disc occurred at some times during this period (recognisable as negative spikes on the irradiance record). An intense sunfleck impinged on the sensor at about 11:33 while between 12:08 and 12:44 the sun was completely clear of foliage.

Over the whole of this clear day, 7.2 einsteins m$^{-2}$ of PAR was received by the sensor

in the stream channel, which is 11.3% of the hilltop PAR total of 63.8 einsteins $m^{-2}$. This is remarkably close to the DIFN value (11.4%) estimated from canopy analyser measurements made at the point of monitoring. Notice that, even when the sun was clear of all foliage in the canopy gap, the stream irradiance (= 1805 μeinsteins $m^{-2}$ $s^{-1}$) did not rise as high as the reference irradiance(= 2050 μeinsteins $m^{-2}$ $s^{-1}$). The discrepancy is due to the blockage of much (about 90%) of the diffuse skylight by the foliage and topography (which on this occasion amounted to about 13.5 % of the total irradiance: a fairly typical value, Iqbal 1983).

In pasture streams, spatial variation in shade can sometimes be very high as is illustrated by Fig. 2, which shows gaps measured at ten points on the water surface of a stream (denoted PT2) under discontinuous riparian shade trees (mostly kanuka). Note that the *pattern* of shading with angle varies markedly as well as the size of the gaps. The pattern of gaps also varies markedly between different locations. The only clear overall pattern is that, as expected, the gap fraction is generally lower at high zenith angles where stream banks or hills block the view, than at low zenith angles (overhead) where the sensor is mostly 'seeing' sky *except* where there is a high or overhanging bank or overhanging vegetation. The high point-to-point variability of shade means that a fairly large number of point readings need to be taken with the canopy analyser to give an estimate of reach-averaged shade of reasonable precision.

On the cloudy day (Fig. 1B) the ambient light was somewhat variable, particularly around mid-day when the cloud cover was changeable with some wind. Around 12:45 the cloud cover thinned enough to allow some of the direct solar beam to penetrate for a short time (PAR up to 1500 μeinsteins $m^{-2}$ $s^{-1}$). The stream lighting followed a very similar pattern to the ambient lighting–in complete contrast to the sunny day, on which the stream lighting pattern was very different from ambient. On the cloudy day the ratio of PAR received at the stream (2.45 einsteins $m^{-2}$) to that on the hilltop (25.2 einsteins $m^{-2}$) was 9.7%. The ratio of instantaneous PAR at the stream to that on the hilltop was almost constant (9.6 ± 1.1%) during a time from 13:10 to 16:20 when the overcast was visually stable and the sun invisible.

**Figure 1**    Stream lighting compared to ambient lighting under different atmospheric conditions in the channel of the Whakaki stream, in the Karikariki Reserve. Plate 3 shows a fish-eye view of the upper hemisphere from this point. A. PAR records for a perfectly clear day (7 December 1994). B. PAR records for a fully overcast day (2 December 1994). C. Data as in panel A, but with a log scale of irradiance to emphasise the constancy of the ratio of stream to reference lighting.

**Figure 2**        Patterns of gaps at ten different points on the water surface of the study reach on pasture stream PT 2 (also see Plate 4).
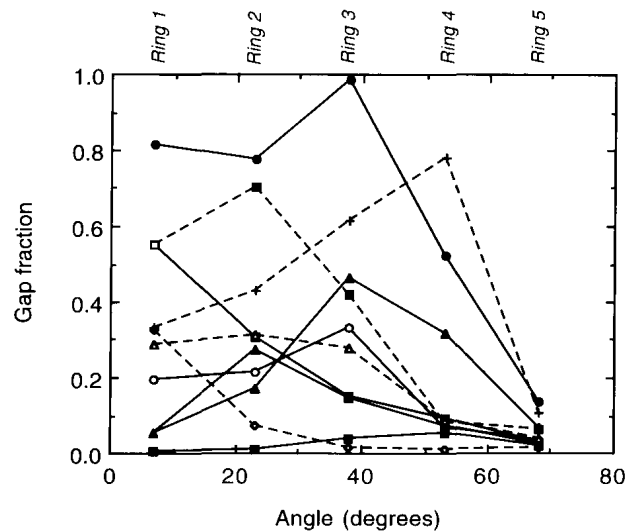


This near-constancy of the ratio of stream to ambient lighting is emphasised by the plots in Fig. 1C on a log scale of PAR. The reference and stream sensor records parallel each other, displaced by a constant log-distance which corresponds to a constant ratio. The ratio of stream to ambient lighting again agrees closely with DIFN value for the site (11.4 %) as measured by canopy analyser, demonstrating that DIFN does indeed give a reasonable estimate of the lighting level under overcast sky. The slight discrepancy can probably be attributed to non-uniformity of the sky lighting, or, possibly, to deviation in angular sensitivity of the two PAR sensors from the ideal cosine-function response. Deviation in sensor calibration is a more remote possibility because the sensors had been matched by running them side-by-side for several days just prior to the field deployment.

**Shade in small streams of contrasting land use**

The lighting of study reaches on ten different second-order streams in the Mangaotama Basin, Whatawhata, four in pasture and three each in native forest and pine plantation, was measured using the canopy analyser. The study sites are described in Smith *et al*. (1993) and Quinn *et al*. (1994a) while the shade experiments are detailed in Spier & van Veen (1994). Figure 3 shows the averaged distribution of shade with direction (angle to vertical) for the ten stream reaches (data from Spier & van Veen 1994). Average gap fractions (geometric means) are plotted on a log scale versus the angles to the zenith of the five different ring-shaped detectors in the canopy

analyser (0º indicating directly overhead). The pattern of gaps as a function of zenith angle at water level was similar in four pasture streams in spite of large differences in magnitude of the gaps and in average lighting (Fig. 3A). Highest gap fractions (lowest shade) occurred at the smallest angle to the vertical (ring 1) with a monotonic decrease in gap fraction (increase in shade) as angle from zenith increased. The change in gap fraction with angle tended to accelerate as angle increased. The gap fraction in ring 5 (zenith angle = 68º) was lowest because the stream banks often blocked the light in this direction (close to the horizon). The variation in magnitude of lighting between different pasture sites can be attributed to differences in stream width, bank height and vegetation. Site PA1, with the lowest gap fractions (for all rings) and the lowest DIFN value, was almost completely overgrown with pasture species and herbs which achieved 'canopy closure' over the channel at several points at the time of the measurements. On the other hand PW2 is a comparatively open stream, with relatively low stream banks, and the average gaps and lighting level were much higher. A fish-eye lens photograph taken at stream site PT2 (which, like PW3, had gaps of intermediate magnitude) illustrates the typical sources of shade in pasture catchments (Plate 4). The sky appears as an elliptical-shape at the centre of the image with its long axis roughly aligned with the channel (upstream is indicated by the black-and-white survey pole on the upper right). High streambanks covered with herbs caused most of the shading on both sides of the stream. In the upstream and downstream directions shade by hills replaced that by banks. Riparian trees (mostly kanuka in this case) contributed further shade.

At bank level the variation amongst the pasture sites was less than at stream level (Fig. 3D) because all bank sites were very open. As would be expected, the gap fractions were all high except at comparatively high angles (low to the horizon) where some blocking was caused by nearby hills. Site PT2 had a lower gap fraction than the other pasture sites at high angles because of the abundant trees and shrubs along the stream channel (see Plate 4).

The native streams, as expected, were much more heavily shaded than the pasture sites (Figs. 3A and B). The gap fractions for native sites decreased rapidly with angle for rings one to four (i.e., the streams are lit most strongly from directly overhead). There was little difference between the fourth and the fifth rings because at these large angles from the vertical, light levels were similar and very low. The differences between gap fractions at stream and bank level (Figs. 3B and E) in native sites were small, showing that the banks contributed negligible extra shade. Plate 5 shows the diversity of riparian vegetation at a fairly representative native site. Prominent shading plants in the photograph include tree fern, nikau palm, tree fuchsia, and an overstorey of tawa trees. The streambanks were not prominent shade features, and this appears to be typical of most native streams, with the exception of reaches through steep, bedrock gorges.

The pattern of gaps for the sites in catchments planted in pines was broadly comparable to that at native sites, at both water and bank level (Figs. 3E and F). Again the difference in shading at bank level and stream water level was small. One stream (EZ) was heavily shaded at stream level by a dense understorey of tree ferns below the pines. More typically, we have found that lighting at bank level in plantation forest streams was only slightly higher than at stream level. Plate 6 shows a fish-eye lens photograph of a typical pine plantation stream (EM2). Most of the shading at pine sites was by ferns and tree ferns, as well as by high streambanks (higher than in typical native sites). Little of the pine overstorey can be seen in Plate 6, because of the erect habit of these trees, compared with the more spreading natives. The pine-forest streams had a more definite canopy gap directly overhead than did native streams, apparently reflecting the difference in growth habit.

Average levels of lighting (DIFN values) calculated from the gaps plotted in Fig. 3 are annotated on the curves for each of the streams. In pasture streams DIFN values were extremely variable from point to point (see Fig. 2) giving rise to high standard deviations for the averages. The high spatial variability arises from two sources: firstly, shade varies with transverse location (being higher near the stream banks than near the stream centreline), and secondly, the cross-sectionally averaged shade varies with bank height, channel orientation and riparian vegetation. The very 'shady' pasture site (PA1) had appreciable riparian vegetation (overhanging sedges, etc.) and 'box canyon'-shaped channel sections. The other sites were somewhat wider streams with comparatively low banks and less riparian vegetation. One important finding from this study is that, although they seem to be much more open than forested streams, pasture streams still have high levels of shade (average DIFN ranged from 4.2 to 47%). At Whatawhata, 'topographic' shading of the streamwater surface by the banks and steep hillslopes, as well as shading by low riparian vegetation, was often significant in otherwise open pasture streams. The forested streams (average DIFN from 0.7 to 4%), as expected, were more heavily shaded than the pasture streams. Our measurements of lighting levels along small streams in native rainforest are comparable with the 1% average level reported for native forests in New Zealand by McDonald & Norton (1992). It is interesting to note that the most heavily shaded pasture stream (PA1, 4.2%) was comparably shaded to the most open forested stream surveyed (NW2, 4%), a finding which is qualitatively consistent with the canopy photographs from these two sites (Spier & van Veen 1994).

**Figure 3**    Patterns of shade in ten stream reaches in three different land uses (site locations are given by Smith *et al.* 1993, and further characterising information in Quinn *et al.* 1994a).
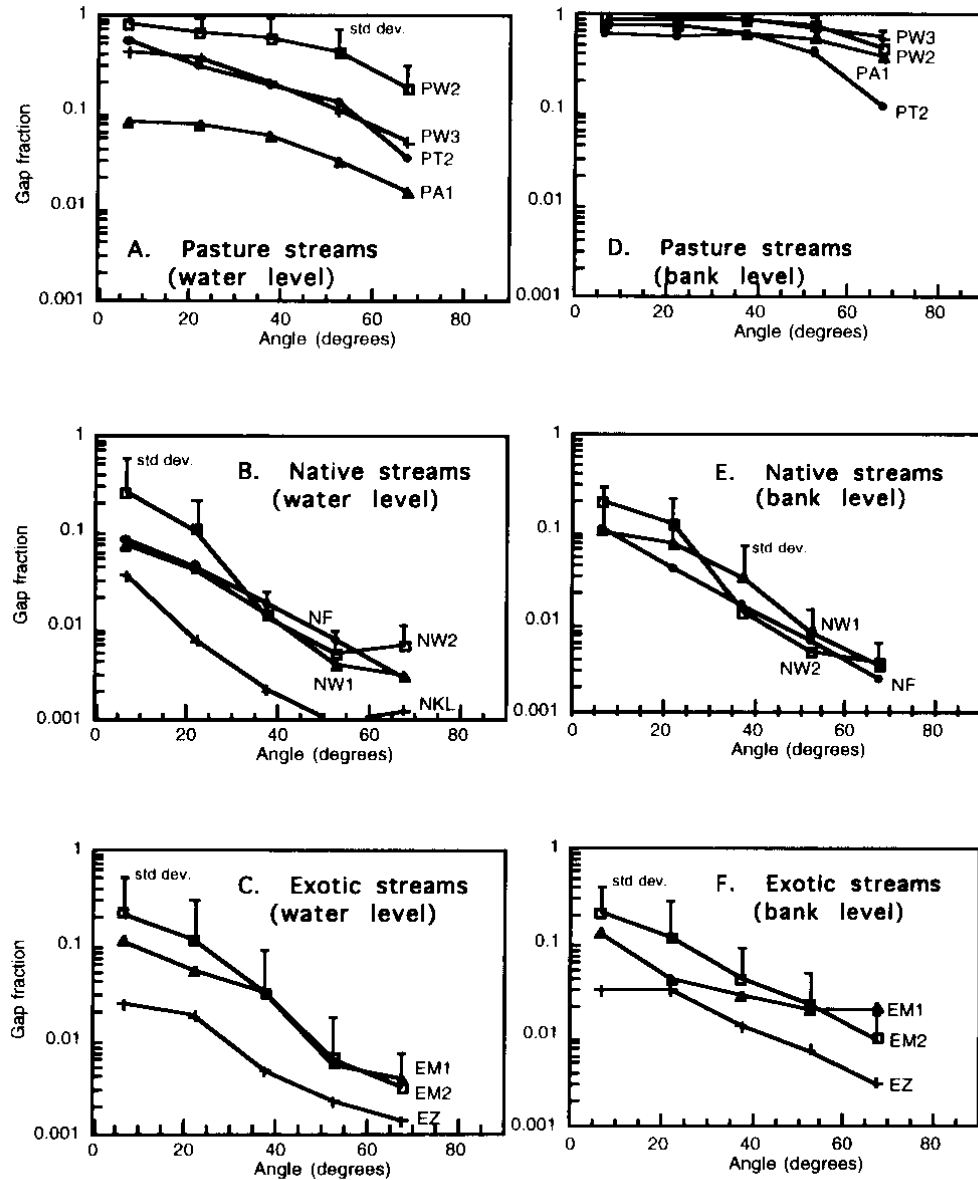
**Shade in tree stands**

Measurements have been made under stands of a variety of trees which might conceivably be present, or be planted, in stream riparian areas to provide shade (Table 1). The measured average DIFN values are plotted versus either tree stem density or crown length density in Fig. 4. Trees in plantation forest had all been pruned to 6 m above ground level.

In A, the eucalypts are 17-year-old *Eucalyptus regnans* near Murupara at six different stem densities (50 to 1111 stems ha$^{-1}$). The 15-year-old *Pinus radiata* are at Goudie's Block, near Murupara (100, 200 and 400 stems ha$^{-1}$). The 23-year-old *Pinus radiata* are at Tikitere, near Rotorua (50, 100, 200 and 400 stems ha$^{-1}$). Stands of 23-year-old pine at Purukohukohu (Puriki catchment), north of Taupo were also surveyed (separate subcatchments at 180, 275 and 550 stems ha$^{-1}$). In B, *Acacia melanoxylon* (Tasmanian blackwood) stands at Lake Okareka near Rotorua are at three different densities (1700, 800 and 500 stems ha$^{-1}$) and the trees (8 years old) are pruned to 6, 3 or 1.5 m crown length. Crown length times stem density gives crown length density in m ha$^{-1}$, which relates to light interception (seven combinations are plotted).

In the pine plantations, shade varied strongly as an inverse (power law) function of stem density (with exponents of around $-1$), such that a doubling of stem density approximately doubled the shade (i.e., halved the lighting as measured by DIFN). As could be expected, the younger pine trees (15 years) caused much less shading than the older trees (23 years). A possible reason why the pines at Tikitere produced more dense shading (by a factor of two) compared with those of similar age at Purukohukohu is that the former site has better soil and a milder climate (Ian Power, AgResearch, Whatawhata, pers. comm.).

**Figure 4**    Lighting in different forest stands suitable for planting for stream shade. A. DIFN versus stem density for pines and eucalypts. B. DIFN values versus crown length density for *Acacia melanoxylon.* Data are courtesy of Ian Power, AgResearch, except for the Pine data, but all data are taken with the same canopy analysers.
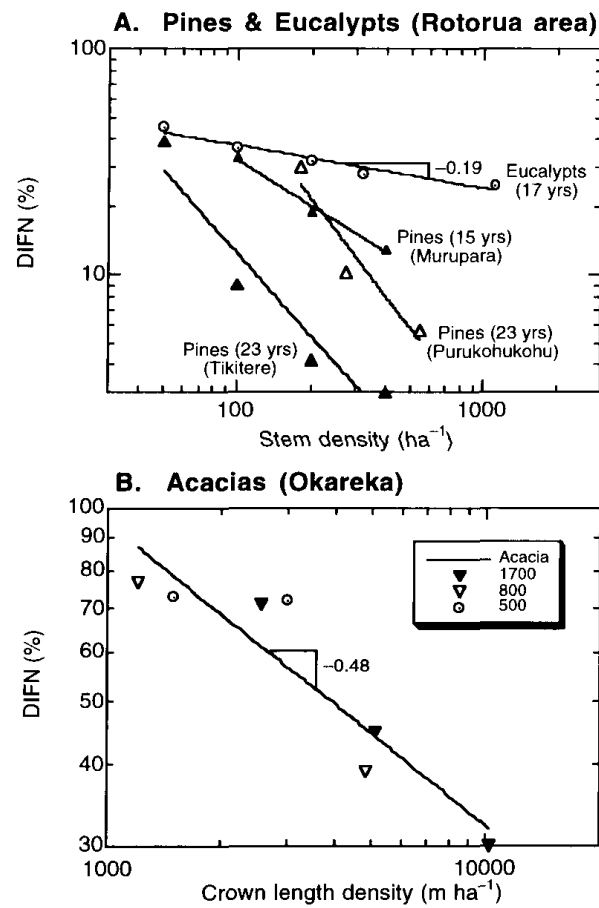
**Table 1**      Tree stands characterised as to lighting at different tree planting (stem) densities.

| Species | Location | Stem densities | Age (years) | Notes |
|---|---|---|---|---|
| **Agresearch data** | | | | |
| *Eucalyptus regnans* | near Murupara | 50, 100, 200, 325, 400, 1117 | 17 | |
| *Pinus radiata* | Tikitere, near Rotorua | 50, 100, 200, 400 | 23 | |
| *Pinus radiata* | Goudies Block, near Murupara | 100, 200, 400 | 15 | |
| *Acacia melanoxylon* | Hignetts Block, Okareka | 500, 800, 1700 | 8 | Pruned to 3 different crown lengths (1.5, 3, 6 m) |
| **NIWA data** | | | | |
| *Pinus radiata* | Purukohukohu, near Taupo | 180, 275, 550 | 23 | Puruki subcatchment (3 sub-subcatchments) |
| *Salix* sp. | Swampy area near Whatawhata | (not surveyed) | ? | 8 to 12 m high trees |

Eucalypts were generally less heavily shading than the pines. Furthermore, for eucalypts shade only increased slightly with increasing stem density (power law exponent = –0.19) such that a doubling in stem density only increased shade by about 13%. This suggests that the foliage density of eucalypts reduces strongly with increase in stem density. Eucalypts may be a useful species for riparian planting if comparatively high levels of lighting are required. For pruned blackwoods, shade correlated closely with the crown length density (crown length times tree density = crown length per hectare, a measure of foliage density). Again, the data show an inverse relationship between tree foliage density and lighting, with the value of the exponent (= –0.47) being intermediate between that for pines (approximately unity) and that for eucalypts (low). This suggests that the actual amount of foliage per metre of the acacia tree crown declines somewhat as crown length density increases. Acacias may well be another species suitable for situations where comparatively low levels of shade are required.

Willows are common riparian species along New Zealand streams. For comparison canopy analyser measurements were made in dense 'crack willow' stands in swampy backwaters of the Waipa River, near Whatawhata, where tree height varied from 8 to 12 m. DIFN values were variable but averaged around 2% (Table 1).

**Near infra-red enrichment in light transmitted through vegetation**

Figure 5 shows how the near infra-red (NIR) content of light under riparian native forest changed with change in visible lighting. The proportion of NIR in total short-wave radiation as measured with an Eppley precision spectral pyranometer is plotted as a function of the visible light as indexed by the DIFN value measured with a canopy analyser. Measurements were taken at sites of differing shadiness along a 200 m reach of the Whakaki Stream, and on a very heavily shaded first-order tributary, in the Karikariki Reserve at map reference S14 934790. A line corresponding to a power law is fitted to the data (solid), and the inferred trend of the relationship (dashed) is indicated: towards 47% NIR in the open and towards 100% NIR at very high shade. Unshaded skylight under overcast sky has around 49% NIR radiation and 51% visible radiation. It can be seen that as the average lighting was reduced by increased canopy shade, the proportion of NIR in the total radiation increased. Under low-moderate shade the ratio of NIR/total solar radiation approximated the 49% expected for unshaded skylight. Thus NIR enrichment only became significant under heavy shade: DIFN values less than about 10%. Note, however, that the NIR/total ratio increased sharply with increasing shade below DIFN values of 10%. At highly shaded points in the native forest studied, NIR constituted more than 90% of the total radiation reaching the forest floor. Although some of the scatter of points in Fig. 5 can be attributed to experimental error in the measurement of NIR, total radiation and DIFN,

much of the scatter is related to the diversity of foliage character in the native forest at this site. The foliage of podocarps and other conifers (including *Pinus radiata*) absorb visible and NIR radiation nearly equally, whereas the leaves of broadleaf trees such as tawa and willow absorb visible radiation more strongly than NIR. We expect the optical properties of different types of foliage to vary from fairly neutral (e.g., podocarps) to strongly spectrally selective (e.g., tawa and willows). Thus, measurements in foliage composed of thick, opaque leaves (e.g., pine needles) would be expected to plot below the curve through the data in Fig. 5, indicating less enrichment of NIR in the total radiation (Gates *et al.* 1965). In contrast, the curve for foliage composed of thin, transparent leaves (e.g., tawa or willows) would probably plot somewhat higher. Attempts to define a curve of NIR/total radiation versus DIFN for a stand of crack willow were frustrated by rain, which wetted the foliage and appreciably shifted the shade light quality.

The observed enrichment of shade radiation with NIR in native rainforest was expected, given the optical properties of plant foliage (e.g., Gates *et al.* 1965), because leaves transmit and reflect far more NIR than visible light (Fig. 5). NIR enrichment has also been reported by Torquebiau (1988), who found that 6% of the incident total radiation, but only 0.8% of the incident PAR, reached the ground in a Sumatran rainforest. A trend towards increasing NIR enrichment with increasing visible shade has also been demonstrated by Szeicz (1974) (for row crops) and by Baldocchi *et al.* (1984) (for temperate broadleaf forest).

The NIR enrichment of radiation under riparian shade is important for attempts to explain the thermal behaviour of streams (see Section 4). Although shading of visible radiation can be fairly readily measured (e.g., using the canopy analyser) such measurements *underestimate* the total amount of solar radiation reaching the stream (i.e., shade for visible light *overestimates* shade for total shortwave radiation). Figure 5 indicates that for low-moderate shade, NIR enrichment is negligible, which implies that shade measurements made using visible light sensors (e.g., PAR sensors or the canopy analyser) furnish unbiased estimates of total shade. Under dense shade, however, such sensors will seriously *overestimate* total shade. Figure 5 can be used to make an approximate estimate of *total* shade (i.e., shade for visible light plus NIR) in a stream reach where *visible* shade (i.e., shade for visible light) has been measured (e.g., using the canopy analyser).

$$SHADE_{tot} = \frac{DIFN}{2(1 - R(DIFN))} \qquad\qquad 1$$

where $SHADE_{tot}$ = total shade; $DIFN$ = measured visible shade; and $R(DIFN)$ = ratio NIR/total solar radiation (from Fig. 5). For example, when $DIFN = 0.01$ (1%), Fig. 5 gives $R = 0.75$ (75%) and Eq. 1 gives $SHADE_{tot} = 0.02$ (2%).

**Figure 5** Enrichment of near-infrared (NIR) radiation under native forest.
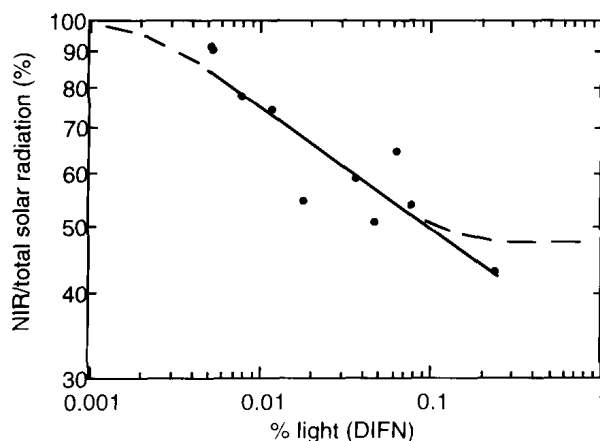


There are two caveats on the use of Fig. 5 for 'correcting' shade measurements. Firstly, Fig. 5 applies to situations where the shade is entirely by the forest canopy. In a stream channel both topographic and canopy shade will contribute to the measured DIFN value. Topographic shade is spectrally neutral (i.e., it blocks 100% of visible and NIR radiation) and so in situations where the stream is shaded entirely by the banks, there is no need to 'correct' for spectral shift. In situations where there is *dense* shade (DIFN < 10%) and the banks and the canopy *both* contribute to stream shade, Eq. 1 will tend to underestimate total shade. There is no simple way to separate the contributions to visible shade made by the banks and the canopy, 'correct' the latter for spectral shift, and re-combine them to estimate total shade. Fortunately, the situation described above is fairly rare: dense shade is usually found only in forest streams (native and pine) and forest streams tend to have low banks (for details see Section 3). Thus in most situations either stream shade is not high enough to warrant correcting for spectral shift, or shade is predominantly from the canopy, enabling Fig. 5 to be used. Secondly, the data and curve in Fig. 5 relate to a specific type of vegetation (mixed tawa, tree fern, broadleaf forest); other curves would need to be added for other types of vegetation (notably pines, eucalypts and willows). We suspect that some curves (e.g., pines) will plot below the line in Fig. 5 while other curves (e.g., willows) will plot above.

**Green shift in visible light transmitted through vegetation**

The spectral quality of light at the water level along Firewood Creek in the Hakarimata Reserve was investigated with a spectro-radiometer on an overcast day (Fig. 6). Measurements were made under near-perfect overcast with a Li-Cor LI-1800UW spectroradiometer in the Karikariki Reserve at map reference S14 934790. The canopy transmission spectrum was obtained by simply dividing the shadelight spectrum by the ambient daylight spectrum. Figure 6A shows the spectrum of shade light reaching the water surface of the stream compared with that measured at an open site a few minutes earlier. Figure 6B shows the canopy transmittance, calculated as the ratio of the spectral irradiance curves in Fig. 6A. Our spectroradiometer can only scan to 850 nm but this is sufficient to demonstrate the strong NIR enrichment of light under native rainforest which was discussed in the previous section. Of particular interest is the fact that green light (centred on 550 nm, in the middle of the visible spectrum) was enriched (Fig. 6B), but that this enrichment was comparatively weak. The native forest canopy at Firewood Creek was more *scattering* of light than (differentially) absorbing and there was little net shift in the spectral composition of visible light. This is in contrast with the significant NIR enrichment discussed above.

DeNicola *et al*. (1992) have also reported comparatively minor green light enrichment under riparian trees (black willows and cottonwood poplars) along streams in Nebraska. Federer & Tanner (1966) have reported somewhat more green enrichment of shadelight under clear sky (away from sunflecks) in a variety of tree stands. We would expect somewhat more green enrichment of the shadelight on a sunny day, since proportionally more of the measured light in the shade would have all been transmitted by foliage, compared with an overcast day when much of the light is diffuse (white) skylight which has penetrated canopy gaps.

The available information indicates that changes in the spectral quality of visible light as it passes through riparian vegetation are relatively small. There is some speculation in the literature about the likely ecological effects (e.g., plant growth and animal vision) of spectral shifts under plant canopies but there appears to be little or no experimental evidence. This is a topic which merits further investigation. Given that the spectral shifts are comparatively small it seems unlikely that they would have a strong effect on stream ecology. The fact that the spectral changes in visible light under a riparian canopy are small also has an important practical implication: pairs of sensors can safely be used to measure visible shade. Provided that the sensors only respond to visible light, they should furnish reliable estimates of visible shade (i.e., the ratio of visible light at the shaded and open sites) regardless of whether or not they respond uniformly to light of different wavelengths.

**Figure 6** Spectral quality of shadelight under native forest.
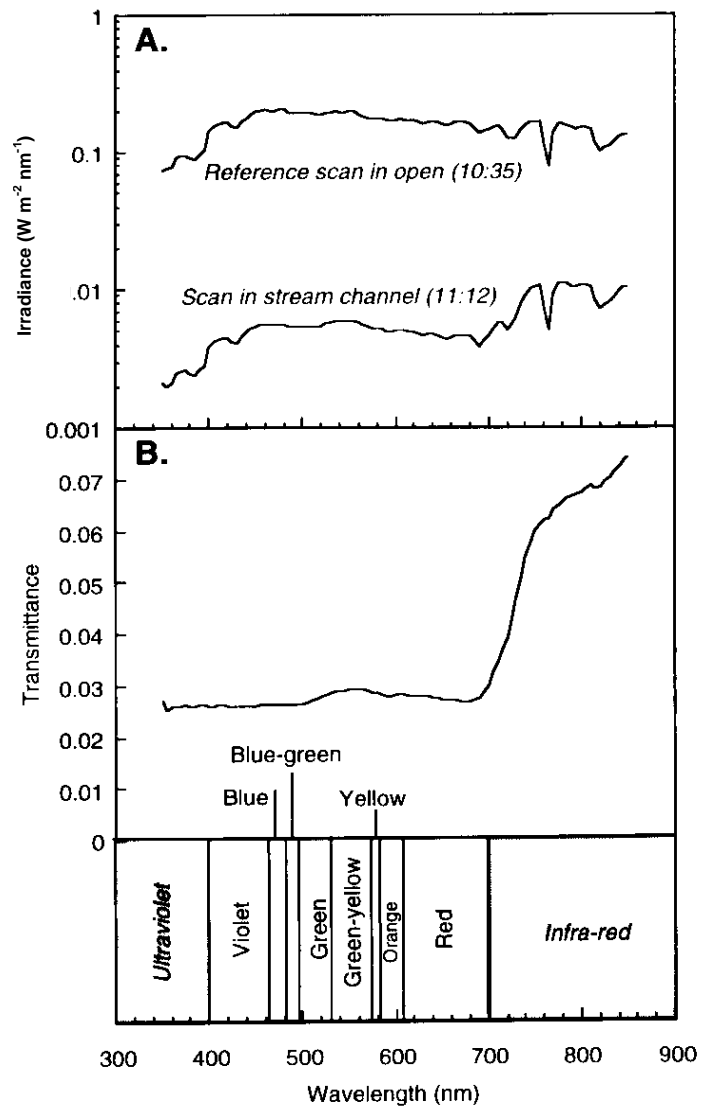


### Shade measurements with PAR sensors

Because of its cost, the canopy analyser is likely to remain a research instrument. Many ecologists, however, have access to other types of radiation sensor, and we assessed the use of a matched pair of quantum PAR sensors (Li-Cor LI-192SB) to quantify stream shade by comparing PAR sensor and canopy analyser shade measurements. The PAR sensor measures photosynthetically available radiation (PAR) in the 400–700 nm waveband (i.e., visible light) from the entire hemisphere (cosine-corrected). The canopy analyser (with blue filter) measures light in the 420–490 nm waveband which means that it slightly underestimates the total amount of PAR. As discussed above, the spectral changes in these wavebands as light passes through the canopy are small (i.e., there is only a slight green shift), which means that

shade measurements made by the two instruments are directly comparable. Measurements were made at twenty points along a 100 m reach of the Whakakai Stream, a native forest stream near Whatawhata, under conditions of uniform, dense overcast. To obtain the data, a PAR sensor was attached to the LAI-2000 canopy analyser sensor, and the control unit was configured to log PAR simultaneously with readings from the LAI-2000 sensor.

Figure 7 shows DIFN values (calculated from the canopy analyser readings) plotted versus ratios of PAR irradiance in the stream channel to that in the open (measured using Li-Cor sensors). DIFN values for uniform sky lighting are plotted as solid points (solid line) and DIFN values calculated assuming the Moon & Spencer (1942) distribution of lighting under overcast conditions as open circles (thick dashed line). Linear regression lines may be compared with the 1:1 line indicating perfect agreement (thin dashed line). In spite of some scatter, the DIFN values are numerically very close to the corresponding PAR ratios as shown by fact that the regression line almost overlays the 1:1 line. On average, the DIFN values were 5% higher than PAR ratios, which is not significantly different from equality. The data scatter probably reflects errors arising from the effect of non-uniformity of lighting over the hemisphere. Overcast sky is not uniformly lit but tends to be somewhat brighter at zenith than at the horizon.

The practical implication of this work is that stream shade can be characterised by making a series of instantaneous measurements on a perfectly overcast day with point sensors. To measure *total* shade in a stream reach (e.g., for temperature prediction) measurements should be made with sensors having a spectrally neutral response encompassing both visible and NIR solar radiation (e.g., thermopile-based Eppley pyranometer). To measure *visible* shade (e.g., for plant growth prediction) PAR (or other 'light') sensors can be used. Using empirical relationships between total and visible shade (e.g., Fig. 5), it is possible to 'correct' *visible* shade measurements and hence estimate *total* shade. Sensors with an arbitrary spectral response (which are sensitive to NIR as well as visible radiation (e.g., photodiode pyranometer sensors like the Li-Cor LI 200SA) should not be used because NIR enrichment will cause bias. Sensors responding to NIR should not be used under damp foliage because the strong NIR absorption by water will bias the results, giving an over-estimate of shade.

Two sensors are required: one at an open, reference site and the other for stream channel measurements. The channel sensor can be moved around in order to sample a range of canopy and bank configurations. The sensors should be matched (i.e., cross-calibrated to give identical readings under a range of light levels). A logger (or chart recorder) is required to store measurements made by the reference sensor while a fairly large number of measurements (e.g., 20) are made along the stream channel in

order to account for spatial variability. Measurements should be made on a day of stable overcast light, such as that under widespread rain. Any change of light will degrade the measurements, as will any major variation of lighting over the hemisphere, such as may occur when clouds break or thin, thus permitting the direct solar beam to reach the sensors.

**Figure 7**     Comparison of directly measured lighting, with lighting (DIFN values) as inferred from canopy analyser measurements.
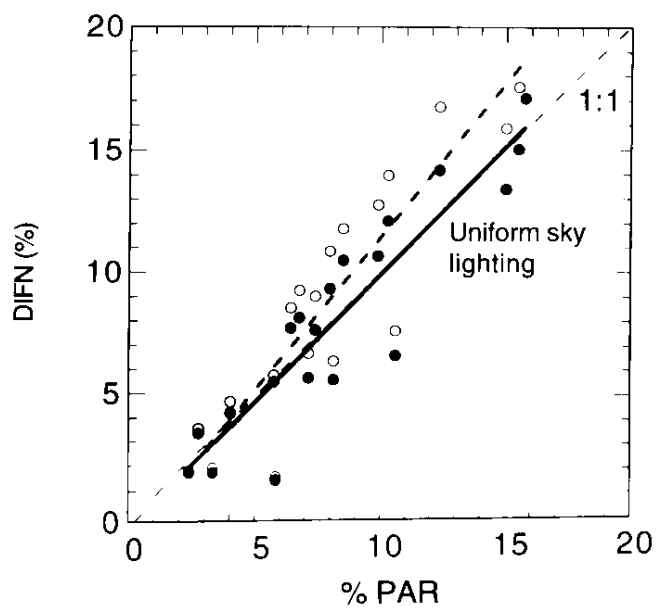
**Figure 8**     Stream lighting compared to ambient lighting on a perfectly clear day (7 December, 1994). The top (dashed) line is the PAR record from the reference (hilltop) sensor, and the lower (solid) line is the PAR record from the sensor near water level in the stream channel.
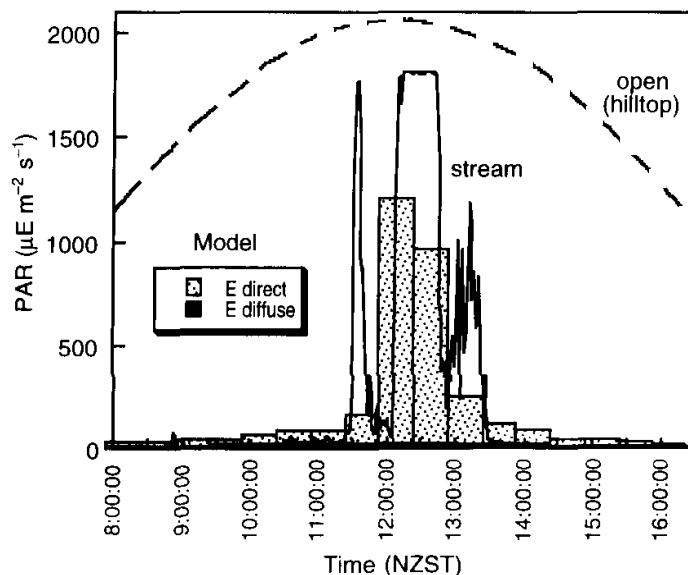


### Shade measurements on clear days

As discussed above, shade measurements are best made on days of uniform and dense overcast (e.g., under widespread rain). In principle, however, canopy analyser gap fractions measured on sunny days can be used to estimate the lighting received over a stream reach, but modelling is required to account for temporal variations of direct solar radiation. To test this idea, the canopy analyser was used to measure the gap fraction every 15° of azimuthal angle from due east, through north, to west. Half-hourly average lighting was calculated from the average gap fractions measured in the direction of the sun. It was assumed that 85% of the total irradiance (in the open) came from the direct solar beam and 15% from the sky irradiance (Iqbal 1983). That is, the simple model assumed was:

$$PAR_{stm} = [0.85T(\theta_s, \phi_s) + 0.15 \, DIFN_{stm}] \, PAR_{ref} \qquad 2$$

where $PAR_{stm}$ & $PAR_{ref}$ = hourly averaged PAR at the stream (shaded) and reference (open) site (Note: $PAR_{ref}$ is the total hemispherical radiation measured at the open reference site using a cosine corrected PAR sensor); $DIFN_{stm}$ = DIFN value at the shaded site measured using the canopy analyser; $\theta_s$ = zenith angle of the sun (from vertical); $\phi_s$ = azimuth angle of the sun (from north); and $T(\theta_s, \phi_s)$ = gap fraction

measured in the direction of the sun. Figure 8 shows the PAR computed using this simple model from the PAR measured at the reference sensor shown in Fig. 1A. The histogram gives direct sunlight irradiance and indirect skylight predicted (using the simple model outlined in the text) at hourly intervals from the canopy gaps in the direction of the sun measured by canopy analyser. The PAR records at stream level were obtained with a sensor positioned at a point in the channel of the Whakaki Stream in the Karikariki Reserve. Plate 3 shows a fish-eye lens view of the upper hemisphere from this point. It can be seen that the general form of the irradiance at stream level is reproduced, although not the detail because of the coarseness of the half-hour time step. The modelled irradiance integrated over the full day was 6.7 einsteins $m^{-2}$ which is very similar to the time-integral of the measured irradiance (7.2 einsteins $m^{-2}$). Chazdon & Field (1987) have adopted a similar approach to model the PAR on sunny days in tropical rainforest using computer analysis of fish-eye lens photographs. They obtained satisfactory agreement between modelled lighting at 2-minute intervals and measured average lighting levels at a number of sites where point light sensor records were logged.

**Visual assessment of shade**

The visual assessment of 'shade ratio' (i.e., the ratio of the canopy height of riparian trees to stream channel width) was rather weakly correlated with DIFN as measured by canopy analyser (r = -0.48). Besides the inevitable human error, variation in foliage density and overhang of the channel affect stream lighting and are not accounted for by the shade ratio.

In principle, a better approach than the shade ratio would be an estimate of the blocking of octets of sky over the hemisphere: similar to the approach for estimating cloud cover. There are two difficulties with this approach: firstly it is difficult to observe the full 360º arc of the sky from the stream surface, and secondly, percentage of sky blocked is *not* the same as the DIFN value because the latter is cosine-weighted (i.e., takes into account the angle from which the radiation approaches the surface of interest, in this case the horizontal streamwater surface). At present we cannot recommend visual assessment of shade as a substitute for objective measurement, although further work on developing a visual assessment protocol may be justified.

### 1.5     Summary

1.  Instantaneous lighting in stream channels under a riparian canopy is extremely variable both in space and time. Lighting varies with time when the sun is shining steadily (because the relative location of the sun and the shade elements changes throughout the day) and lighting is even more highly variable under patchy cloud. Lighting under stable overcast skies is less time variable and hence more easily measured and/or predicted.

2.  Shade varied spatially (both across the channel and longitudinally) in the pasture streams studied. It tended to be higher near the stream banks than near the centreline of the channel because the banks obscured a large proportion of the sky. As discussed in Section 4, shade at the centreline of the stream channel underestimates the cross-section average shade, typically by 10–20%. Longitudinal variations in shade arose from variations of bank height, channel width, channel orientation and riparian vegetation.

3.  For ecological studies we are normally interested in time-averaged (e.g., hourly or daily averaged) and space-averaged (e.g., cross-section and/or reach averaged) lighting. Time-averaged lighting requires either continuous measurement of lighting or measurement of shade characteristics and calculation of lighting levels (as discussed in Section 4). Shade varies both along and across stream channels, which means that measurements of either lighting or shade characteristics are required at a large number of points (e.g., 20) to obtain an accurate estimate of reach-averaged shade.

4.  Qualitative assessments of stream shade can be made by photography with a fish-eye lens. Lenses are moderately expensive (NZ$2500 for our Minolta 7.5 mm lens) but are available for most good-quality single lense reflex cameras. Quantitative analysis of photographs is feasible, but time consuming, and it would have been very onerous to obtain precise reach-averaged shade estimates by photography in the pasture streams studied.

5.  We have developed and tested an experimental protocol (see Appendix 1) for using a canopy analyser to characterise shading of stream channels by riparian vegetation and the streambanks, and also to measure lighting under various types of tree stands.

6.  Canopy analyser measurements of visible shade (i.e., shade to visible solar radiation) tend to overestimate total shade (i.e., shade to visible plus NIR solar

radiation). This occurs because a greater proportion of the incident radiation penetrates the canopy for NIR than for visible light (i.e., leaves absorb visible light more efficiently than NIR). Both NIR and visible radiation are important in heat budget studies (see Section 4).

7.   Our measurements show, however, that NIR enrichment only becomes significant (> 10%) under heavy shade (DIFN < 10%). Thus in many situations of partial shade, visible shade (e.g., measured using PAR sensors or the canopy analyser) closely approximates total shade. We have derived an empirical relationship using NIR and visible radiation measurements made under a forest canopy which can be used, in situations of heavy canopy shade, to 'correct' the bias in visible shade measurements and estimate total shade.

8.   It is more difficult, but also less important, to 'correct' visible shade measurements made in streams where both topography and canopy shade are significant.

9.   The canopy analyser, because of its expense, is likely to remain a research instrument. We have shown, however, that it is possible to obtain reliable measurements of visible shade using more commonly available PAR sensors. There is some slight spectral change in visible light as it passes through the canopy (i.e., 'green shift') but this is not enough to bias these visible shade estimates significantly. The method requires: near-perfect overcast conditions (as occurs during steady rain); a matched pair of light sensors; sensors with a proper cosine-corrected spatial response; and sensors that are spectrally neutral (e.g., LI-192SB quantum sensors) but not sensors which have an arbitrary spectral response to both visible light and NIR (e.g., LI-200SA or SB photodiode pyranometers). Note that, as for canopy analyser measurements, estimates of visible shade may need to be 'corrected' for NIR enrichment under heavy canopy shade in order to estimate total shade.

10.   Alternatively, a pair of thermopile-based pyranometers which measure total solar (visible plus NIR) radiation can be used to measure total shade directly. Such measurements should also be made under dense, steady overcast, with the additional proviso that the riparian foliage must be perfectly dry so as not to introduce artefacts related to NIR absorption by water.

11.   We do not recommend visual assessment of shade as a substitute for objective measurement of shade.

12.   The major ecological effect of shade is to reduce the radiation fluxes reaching

the water surface, including photosynthetically active radiation (PAR) and total solar radiation (which affects the stream thermal response; see Section 4).

13. One unresolved question is the ecological significance of the green enrichment of visible light when it passes through leaves. In our studies the changes in spectral quality of shadelight were small (i.e., there was at most a slight green shift in visible shadelight measured under trees) and we are of the opinion that changes in the spectral quality of shadelight are less important ecologically than changes in light quantity.

14. Small streams in native forest are usually dimly lit, with typical PAR values around 1% of that at open sites. The streambanks of native streams in our study contributed little to stream shading because the banks were low and the channels wide.

15. Streams in pine plantation forests were also well-shaded, with the light climate having features broadly similar to native streams.

16. Pasture stream *banks* were usually very open and well lit. Light levels at the *water surface* of the small pasture streams studied (which were characterised by narrow channels and steep banks overhung with herb vegetation) were surprisingly low, typically < 50 % of the incident radiation.

17. Lighting under unmanaged forest is usually very low (typically around 1% PAR) but *managed* tree stands can achieve a wide range of lighting with pruning and/or different stem densities. Therefore, it should be possible to 'design' stream shade for particular purposes (e.g., to avoid extinguishing desirable understorey species such as pasture grasses).

## 2. STREAM ECOSYSTEM RESPONSE TO LANDUSE CHANGES

### 2.1 Introduction

In order to study the effects of shade on small streams, the chemical, physical and biological characteristics of sixteen second-order streams under pasture, pine and native forest were surveyed during summer in 1992–1993. The stream catchments had similar geology and soils and were located in the Hakarimata Ranges, west of Hamilton. The pasture catchments had been converted from native podocarp-broadleaf forest approximately 60 years ago. The pine forest catchments, which had earlier been in pasture for at least 40 years, were planted in *Pinus radiata* 15 years ago, with canopy closure 5–7 years ago. They provide a natural experiment on the effects of afforestation on streams. The surveys have improved our understanding of the way riparian shade affects the characteristics of small streams, enabling better prediction of the changes likely to occur following removal or restoration of riparian vegetation.

### 2.2 Methods

In eleven streams, 80–140 m long reaches were selected. Places where bedrock determined stream morphology were avoided. In these eleven reaches, physical and biological characteristics were surveyed once in November 1992 under baseflow conditions, while visual clarity and water quality were measured on three occasions at fortnightly intervals. Five other stream reaches were sampled for water quality and/or benthic invertebrates: logistical constraints precluded sampling for all determinands at these sites. Background information on the study streams is given in Table 2 while methods used to characterise the study streams are summarised in Table 3.

The mean values for each reach were compared between landuses using one-way, non-parametric analysis of variance (ANOVA on ranks) (Conover & Iman 1981). Similarities in the overall composition of the invertebrate communities amongst the sites were examined using detrended correspondence analysis (Hill 1979) to ordinate the sites. Invertebrate communities were also compared between sites using seven indices incorporated in the Index of Biotic Integrity (IBI) of the USEPA Rapid Bioassessment Protocol III (Plafkin *et al*. 1989) with the following modifications: (1) the Quantitative Macroinvertebrate Community Index (QMCI) (Stark 1985) was substituted for Hilsenhoff's Biotic Index; and (2) the percentage of the total density due to individuals belonging to the relatively pollution-sensitive Ephemeroptera, Plecoptera and Trichoptera (EPT) families was substituted for the ratios of scraper/collectors and EPT/chironomid densities, because the latter indices have been

found to be unsatisfactory (Barbour *et al*. 1992). NW1 was selected as the native forest reference site for this analysis because its slope, baseflow, catchment area and particle size were average for the study streams.

**Table 2**    Reach and catchment characteristics grouped by landuse and notes on measurements.

| Reach code | Map ref. (260 S14) | Site elev. (m) | Catchment area (km$^2$) | Channel slope | November base flow (L s$^{-1}$) | Comments |
|---|---|---|---|---|---|---|
| **Exotic pine forest sites** | | | | | | |
| EM1 | 961859 | 50 | 0.884 | 0.012 | 11 | |
| EM2 | 968861 | 35 | 1.310 | 0.018 | 17 | |
| ES | 947845 | 50 | 1.120 | ND | ND | WQ, T only |
| ET | 955854 | 55 | 0.427 | ND | ND | WQ, T only |
| EZ | 928844 | 90 | 0.960 | 0.020 | 12 | No WQ, T |
| **Pine (79%) with native riparian site** | | | | | | |
| E/N | 945846 | 55 | 0.691 | 0.020 | 8 | No WQ, T |
| **Native forest sites** | | | | | | |
| NF | 976888 | 40 | 2.01 | 0.008 | 32 | |
| NKL | 919775 | 120 | 0.525 | 0.039 | 10 | |
| NMT | 989911 | 35 | 0.985 | ND | ND | WQ only |
| NW1 | 917785 | 90 | 0.982 | 0.019 | 11 | |
| NW2 | 917786 | 90 | 0.602 | ND | 9 | WQ, T, Inv. only |
| **Pasture sites** | | | | | | |
| PA1 | 954906 | 55 | 0.443 | 0.057 | 11 | |
| PT1 | 928747 | 70 | 0.756 | ND | ND | WQ, T only |
| PT2 | 928747 | 70 | 0.756 | 0.021 | 8 | |
| PW2 | 923764 | 90 | 0.948 | 0.032 | 16 | No T |
| PW3 | 924763 | 100 | 0.488 | 0.035 | 7 | |

ND = no data; WQ = water quality; T = temperature, Inv. = invertebrates. Site E/N was grouped with the native forest streams because it has undisturbed native riparian vegetation.

**Table 3**     Methods used to characterise stream reaches.

| Characteristics | Measurement methods |
|---|---|
| channel slope | surveyor's level |
| current velocity & depth | at 10%, 30% and 50% width at 20 cross-sections; velocity measured at 0.4 x depth (Montedoro-Whitney Model PVM-2A electromagnetic meter) |
| water & channel width | tape measurements at 20 cross-sections |
| streambank stability | erosion surveys, measuring length of streambank which is stable, slumping, scouring etc. |
| volume of coarse woody debris | calculated from lengths and mid-length diameters of wood (diameter >1 cm) in 20, 1m wide, cross-sections |
| CPOM (>1mm) & MPOM (0.25 - 1 mm) | dry mass (DM, 105°C for 24 h) and ash-free dry matter (AFDM, 400°C for 6 h) of material collected in ten Surber samples (0.04 $m^2$, 250 µm nets) at random points at 10 cross-sections |
| suspendable inorganic sediment (SIS) | material suspended by stirring bed sediments (to a depth of c. 5 cm) enclosed by a cylinder (23 cm diameter) at 7 randomly selected sites was subsampled (300 ml), GF/C filtered and analysed for DM and AFDM. SIS/$m^2$ then calculated from cylinder area and volume enclosed allowing for background DM and AFDM in the water |
| epilithon and algal biomass under stable baseflow | DM, AFDM and chlorophyll *a* (APHA 1989) of material scrubbed with a nylon-bristled brush from 15 stones selected randomly through reach. Exposed stone surface areas were assumed to be 50% of total surface areas calculated from axis lengths (Dall 1979). |
| benthic respiration and photosynthetic oxygen production | *in situ* rates were calculated from rate of change of dissolved oxygen at 1 minute intervals (YSI Model 56 meter attached to a LiCor datalogger) over 30 minute periods in dark and light in a recirculating respirometer (Hickey 1988) that enclosed a 0.06 $m^2$ area of either natural streambed or (in cobbly bedded sites) enclosed stones placed in a sealed base. (Plate 7). |
| dissolved reactive phosphorus (DRP) | automated molybdate method with ascorbic acid reduction |
| dissolved inorganic nitrogen (DIN) | $NH_4$ = automated indophenol blue method; $NO_2+NO_3$ = Cd reduction and colorimetric determination |
| dissolved organic carbon (DOC) | alkaline persulphate with UV photo-oxidation and $CO_2$ detection by infrared gas analyser |
| shading at the stream surface | diffuse non-interceptance (DIFN) using LiCor LAI-2000 canopy analyser from point measurements at stream surface at 20 cross-sections relative to a reference unshaded hilltop (see Section 1) |
| stream temperature | at 15 min. intervals for 1 to 5 weeks between 3/11/92 and 8/12/92 |
| visual clarity | Horizontal black disk visibility (Davies-Colley 1988) |
| turbidity | HACH 2100A meter |
| suspended solids | GF/C filtration and 24 h. at 105°C |
| macroinvertebrates | animals collected in ten Surber samples (0.04 $m^2$ , 250 µm nets) at random points at 10 CS sorted live from detritus and sediment, counted and identified in the field, and preserved in 70% isopropyl alcohol for laboratory checks/identifications as necessary. Biomass in 6 of the 10 Surber samples per reach was measured as air-dried mass - snail shell weight was excluded. (Plate 8) |

## 2.3 Results

### Shade

DIFN values (the ratio of lighting at the stream surface to lighting at an open site) showed that pasture streams ($29 \pm 8\%$, mean $\pm$ SE) were much less shaded than the forest streams (pine $96 \pm 1\%$, native $98 \pm 1\%$) (see Fig. 9). There was a surprisingly large amount of shade in the pasture streams provided by topographical features, riparian grasses and shrubs: together these reduced the incoming solar radiation by an average of 71%. Pine and native streams were similarly heavily shaded.

### Channel morphology

Channel morphology differed between landuses in several ways (Fig. 10). The pasture reaches had 50% higher mean velocity and were 32% narrower than the native forest reaches despite their very similar mean slopes (0.026 & 0.029) and mean catchment areas (0.731 & 0.733 km$^2$). The pine catchment channels were intermediate in velocity and width. Plate 9 shows examples of pasture, pine and native streams with similar catchment area.

**Figure 9**     Comparison of diffuse non-interception (DIFN) (mean + SE) between streams with differing landuse. Non-parametric ANOVA shows a significant difference between landuse classes.
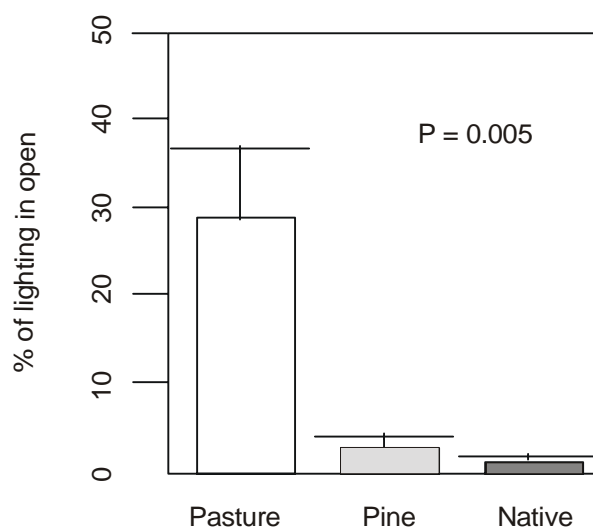
**Figure 10**     Comparison of channel characteristics (mean + SE) between streams with differing landuse. Non-parametric ANOVA is used to test whether there is a significant difference (P < 0.05) or no significant difference (NS) between landuse class. Sites PA1 and NF were excluded from the width comparisons because of their atypical catchment areas (see Table 2).
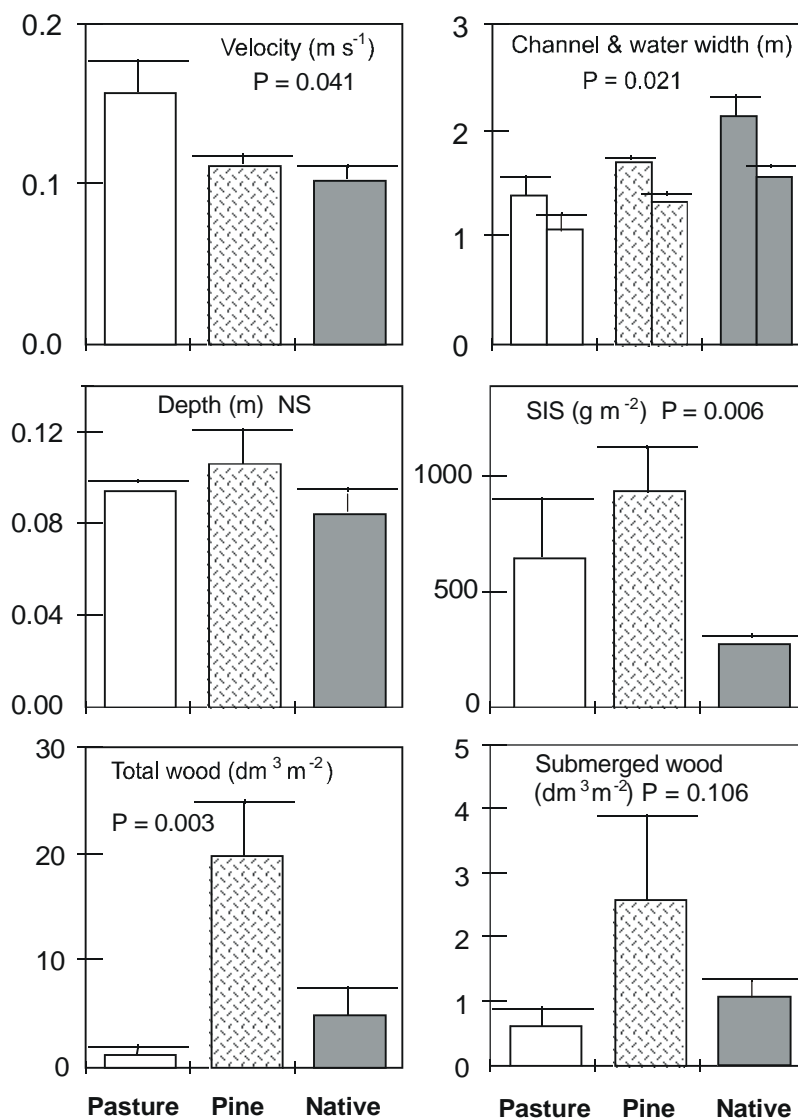
The suspendable inorganic solids (SIS) content of the streambed was low in native streams, fairly high in pasture streams and slightly higher again in pine streams (Fig. 10). This is a surprising finding because one might expect a higher input of fine sediment from pasture than from pine forest. It can be explained by our observations of bank stability and channel morphology. In pine streams, over 40% of the length of banks was unstable (i.e., either bare soil or actively slumping and eroding). In addition, the pine streams contained occasional large, isolated blocks of soil which had slumped into the channel from the streambank. In pine streams, the banks lacked either tree roots (which helped stabilise the native streams) or pasture grasses (which helped stabilise the pasture streams). In pasture streams, active bank slumping and erosion affected 20–40% of the channel length. Of these the PA1 reach was worst affected with clear evidence of recent pugging and streambank collapse caused by cattle. Pasture grasses encroached into the stream channel in the open pasture reaches. Consequently many of the parafluvial areas, which in the native streams would have been bare gravel bars, were covered with grasses in the pasture streams (Plate 9). Woody debris was more abundant in pine streams than in native streams (Fig. 10) and there was very little wood in the pasture streams. Submerged wood showed a similar pattern although there was higher variability. The small amount of wood present in the pasture streams comprised remnant native tree fragments which can be expected to decay over time without being replaced.

**Benthic metabolism and biomass**

Pasture streams had significantly higher gross photosynthesis rates (Fig. 11) and higher periphyton biomass (Fig. 12) than the more heavily shaded pine and native forest streams. This would be expected given the higher light inputs. Benthic respiration rates, however, were not significantly different between pasture and pine streams, although there is a suggestion that they were lower in native streams. Both autotrophic periphyton communities and heterotrophic bacterial and fungal biofilm communities contribute to respiration and epilithon ash-free dry mass (AFDM). The measured P/R ratios (mean photosynthesis/mean respiration) were 0.6 (native), 1.2 (pine) and 2.8 (pasture). This indicates that community metabolism was dominated by periphyton in pasture streams, was dominated by heterotrophs in native streams, and was intermediate in pine streams. Epilithon AFDM was high in pasture streams (reflecting high periphyton biomass), low and similar in pine and native streams. Our results are consistent with many previous studies which have shown that in forest streams heterotrophic productivity (by bacterial and fungal biofilms sustained by particulate and dissolved carbon) is high. In forest streams, benthic invertebrates are likely to derive their energy needs from heterotrophic biofilm communities and/or allochthonous detritus while in pasture streams they are likely to utilise periphyton.

**Figure 11**    Comparison of benthic metabolism (mean + SE) between streams with different landuse. Non-parametric ANOVA is used to test whether there is a significant difference (P < 0.05) or no significant difference (NS) between landuse class.
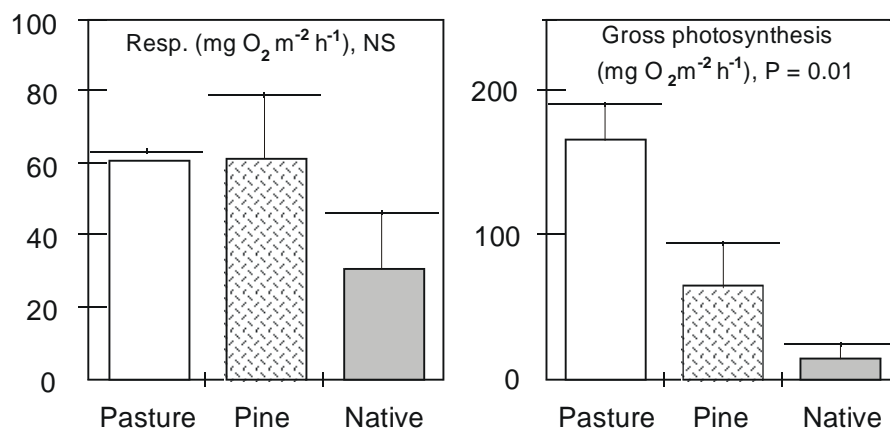


### Particulate material

Total coarse and medium particulate organic matter (CPOM & MPOM) varied widely amongst streams and disguised any differences that might exist between landuses (Fig. 12). Leaf and bark litter were less abundant in pasture streams than forest streams. As expected, pine needles made up the bulk of the total leaf litter in the pine forest streams: when pine needles were excluded, the pine and native catchments had similar quantities of leaf litter.

### Water temperature

The lower shade in pasture streams resulted in daily maximum temperatures being 6–7°C higher than in pine and native streams (Fig. 13). Daily maxima frequently exceeded 20ºC in pasture streams but only rarely exceeded 15ºC in forest streams. Daily minima, however, were similar in all streams. The daily means averaged about 15ºC in pasture streams and were about 2ºC lower in forest streams.

### Visual clarity

Turbidity and visual water clarity were most degraded in the pine streams (Fig. 13), with intermediate levels in the pasture streams. These differences were consistent with the observed pattern of fine suspendable inorganic sediment in the surface of the streambeds (SIS in Fig. 10). Although turbidity was higher and clarity lower in the pine than in the pasture streams, there was no difference in suspended solids concentration (SS in Fig. 13). This suggests that suspended solids are finer, and thus more effectively light attenuating, in the pine streams.

**Figure 12**    Comparison of benthic particulate carbon densities (mean + SE) between streams with different landuse. Non-parametric ANOVA is used to test whether there is a significant difference ($P < 0.05$) or no significant difference (NS) between landuse class.
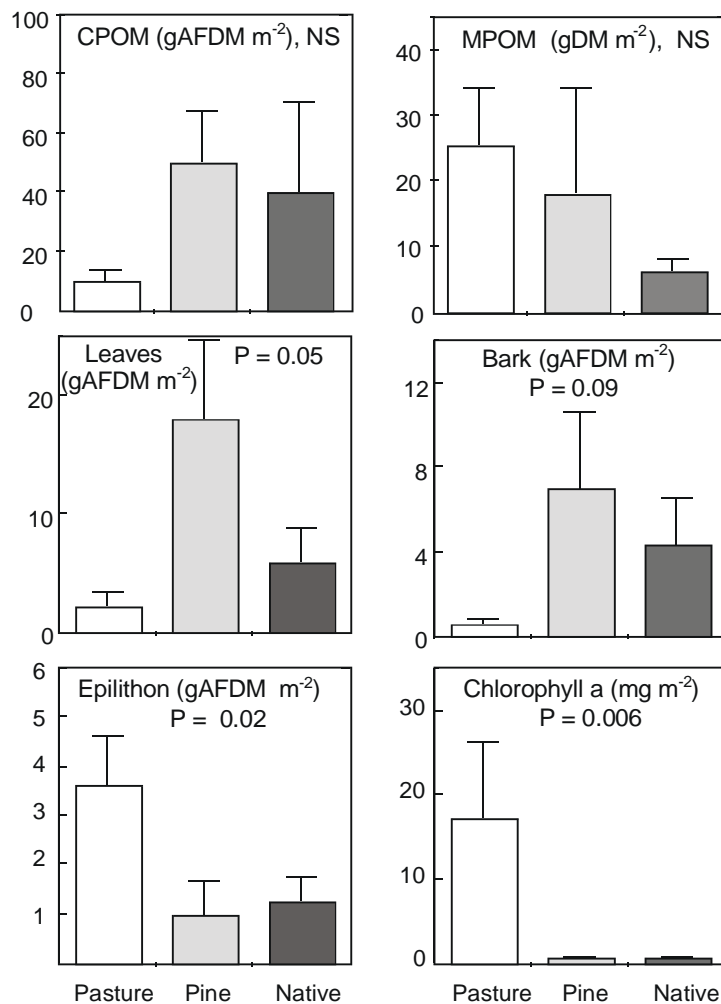


**Dissolved organic carbon**

Dissolved organic carbon (DOC) concentrations were lower in native streams than in pine and pasture streams (Fig. 13). DOC concentrations reflect the balance between inputs from the catchment, in-stream utilisation (e.g., uptake by heterotrophic biofilms) and in-stream production (e.g., leaching from periphyton and invertebrate communities). We are unable to quantify these processes separately.

**Figure 13**    Comparison of water quality characteristics (mean + SE) between streams of differing landuse. Non-parametric ANOVA is used to test whether there is a significant difference (P < 0.05) or no significant difference (NS) between landuse class.
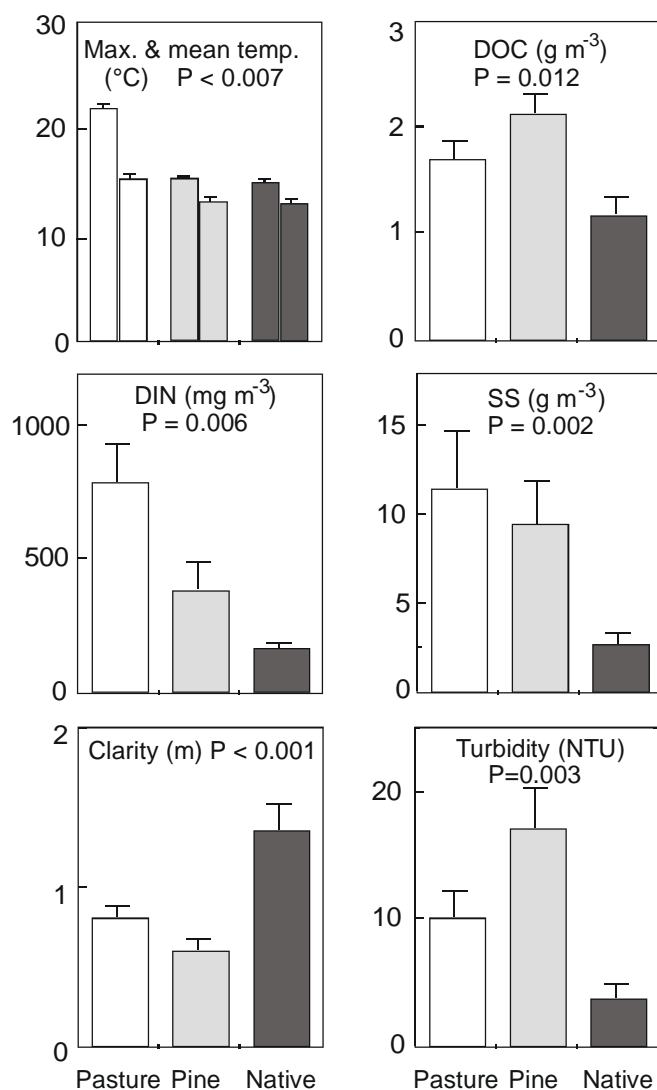


### Nutrient concentration

In November 1992 dissolved inorganic nitrogen (DIN) was higher in the pasture than native streams (Fig. 13). This suggests a strong landuse effect, with high DIN inputs to pasture streams. A different picture emerges from results of monitoring concentrations of nitrate (the dominant DIN species) at intervals of 1–2 weeks over the entire summer (Fig. 14). As the flows declined, nitrate concentrations declined more quickly in a pasture (PW2) than a native stream (NKL) so that, towards the end of summer, nitrate concentrations were higher in the native stream. Periphyton cover (assessed visually) in the pasture stream increased from thin diatom films in early summer to an abundant cover of a community dominated by filamentous diatoms

(*Melosira*) and green algae (*Spirogyra*) in January. In the native stream, periphyton was barely visible throughout the summer.

Measured nitrate concentrations reflect the balance between upstream inputs, lateral inputs and in-stream processing (i.e., uptake by periphyton and recycling from detritus). It is not possible to quantify each of these from concentrations measured at a single point, but a likely explanation for the observed low streamwater nitrate concentrations in the pasture stream during summer low flows is high nitrate uptake by periphyton and/or low lateral inputs. During summer, high solar radiation, warm temperatures and low scour favour high periphyton biomass, productivity and nitrate uptake rate. In addition, during summer, soils dry out and lateral inflows enter the stream through bankside wetland zones in which denitrification rates are high (Cooper 1990).

In contrast to nitrogen, dissolved reactive phosphorus (DRP) varied widely between streams and there was no significant landuse effect. Phosphorus appeared to be available to excess throughout the year. This is thought to result from volcanic soils with high natural P content and/or superphosphate applications. This indicates that factors such as catchment geochemistry override any landuse influences on DRP in these catchments. DRP concentrations were never significantly depleted whereas, during summer low flows, DIN concentrations were reduced to the levels likely to limit periphyton growth. Apparently, low nutrient concentrations occasionally limit periphyton growth in these pasture streams (e.g., during summer low flows) and, when this occurs, nitrogen is more likely to be limiting than phosphorus.

**Figure 14**     Changes with time of nitrate concentration in a pasture and a native forest stream and of flow in the pasture stream during spring and summer.
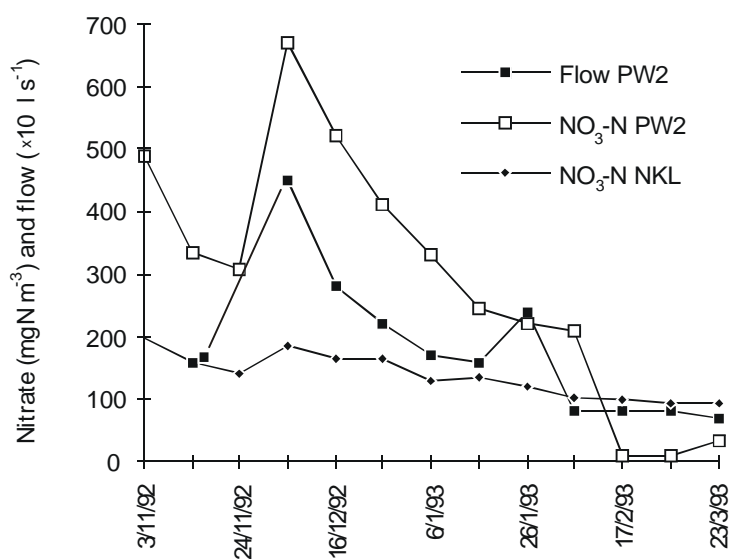


**Benthic invertebrate communities**

The pine and native forest streams had fairly similar benthic invertebrate communities but several features of the benthic invertebrate community differed between the pasture and forest streams. This is shown most clearly in Fig. 15. The pasture reaches were separated strongly from the forest sites on the first axis of the ordination based on the invertebrate species densities. The ordination indicates that the pine forest sites either overlap in overall fauna composition with the native forest reaches or are intermediate between the native forest and pasture reaches. The E/N site (pine with native riparian vegetation, denoted pine/native in Fig. 15) overlapped with the native forest sites.

Three groups of grazers (the snail *Potamopyrgus,* chironomids, and the algae-piercing caddis *Oxyethira*) were more abundant in the pasture than forest streams (Fig. 16). This is consistent with the high periphyton biomass and primary productivity measured in the well-lit pasture streams (see Figs 11 & 12). Oligochaetes were significantly more abundant in pasture streams, which is an indication of organic enrichment associated with high periphyton biomass.

The collector-browser mayfly *Deleatidium* was significantly more abundant in native and pine than pasture streams (Fig. 16). *Deleatidium* is widely recognised as a 'pollution-sensitive' insect, and is most abundant in cold, well-aerated, headwater

streams. Its low numbers in pasture streams may be the result of lack of suitable food resources (e.g., fine particulate organic matter FPOM), adverse environmental conditions (e.g., high water temperatures, low dissolved oxygen concentrations) and/or lack of suitable habitat (e.g., because of fine sediment in the bed). In marked contrast with *Deleatidium*, neither the collector-browser mayfly *Zephlebia* nor the collector-gatherer beetle larvae *Elmidae* showed any landuse effect. Neither appeared to be adversely affected by differences in food resources between the study streams (i.e., between heterotrophic biofilms which predominate in shaded forest streams and periphyton which predominate in open pasture streams). On the other hand, neither appeared able to increase its biomass by exploiting the increased primary production in pasture streams, possibly because of sub-optimal environmental conditions (e.g., high temperature), increased predation, or unsuitable habitat.

The filter-feeding sandfly *Austrosimulium* was significantly more abundant in pasture than forest streams. This is surprising since one might expect that the high periphyton biomass (covering potential attachment sites) and high sediment loads (potentially abrasive and/or clogging) which we observed in the pasture streams would be prejudicial to such filter-feeders.

The total number of invertebrates was markedly higher (3-fold) in the pasture streams largely as a result of increases in the numbers of snails and chironomids. Invertebrate biomass was highly variable and there was no statistically significant landuse effect (Fig. 17). Landuse did not affect overall taxonomic richness, but the sensitive Ephemeropteran, Plecopteran and Trichopteran (EPT) insect orders were slightly more abundant and taxanomically richer in the native streams. The Quantitative Macroinvertebrate Community Index (QMCI) values were significantly higher in forest streams, indicating that the pasture stream communities were more tolerant of organic enrichment. Periphyton chlorophyll *a* was positively correlated with the mean densities of chironomids and oligochaetes across the sites (Spearman rank coefficients r = 0.71 & 0.78) and negatively correlated with EPT density (r = -0.85) and QMCI value (r = -0.88).

Comparison of the relative abundance of the common taxa (> 5% of total at least one site) reinforces this pattern (Fig. 18). A core group of five EPT taxa dominated the pine and native forest sites, but none of these were common in the pasture streams, where the faunas were dominated by chironomid, snail and dipteran species.

The Index of Biotic Integrity analysis classified the pasture sites as moderately impaired, whereas two of the three exotic forest sites were slightly impaired relative to the native stream reference site (Table 4).

**Figure 15** Ordination of streams with contrasting landuse using invertebrate species densities.
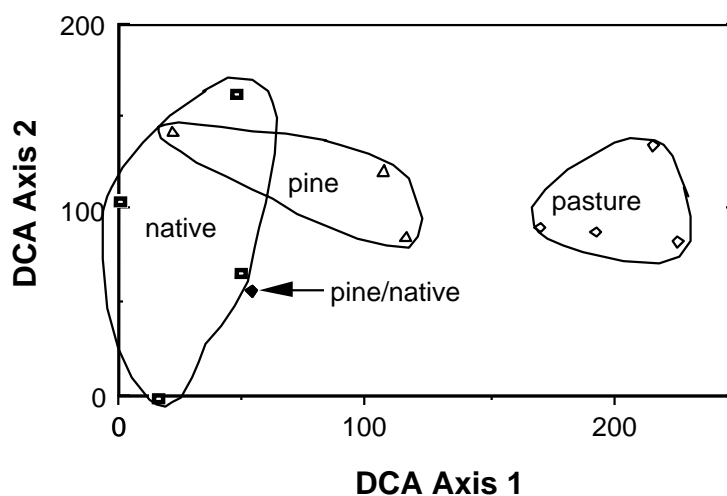


**Table 4** Relative scores of study sites for seven invertebrate bioassessment 'metrics' and overall Index of Biotic Integrity (IBI) classifications.

| Site | Taxa richness | QMCI | EPT | % EPT density | % domin. | comm. loss index | % shredder | IBI | IBI impairment class |
|------|---------------|------|-----|---------------|----------|------------------|------------|-----|----------------------|
| EM1 | 21 | 8.47 | 11 | 94.8 | 44.9 | 0.86 | 0.3 | 20 | slight |
| EM2 | 31 | 8.59 | 16 | 93.0 | 29.1 | 0.45 | 3.7 | 38 | nonimpaired |
| EZ | 22 | 7.34 | 11 | 82.0 | 32.3 | 0.50 | 1.8 | 32 | nonimpaired |
| EN | 21 | 8.14 | 15 | 93.4 | 36.0 | 0.71 | 0.0 | 24 | slight |
| NF | 28 | 7.96 | 18 | 89.6 | 41.5 | 0.32 | 2.6 | 34 | nonimpaired |
| NKL | 26 | 7.95 | 14 | 84.3 | 40.2 | 0.38 | 5.3 | 32 | nonimpaired |
| NW1 | 30 | 7.79 | 19 | 84.8 | 56.7 | 0.00 | 2.3 | 34 | nonimpaired |
| PA1 | 30 | 4.75 | 13 | 16.5 | 46.8 | 0.60 | 2.0 | 16 | moderate |
| PT2 | 25 | 3.44 | 10 | 22.7 | 24.1 | 0.68 | 0.6 | 16 | moderate |
| PW2 | 31 | 2.83 | 14 | 6.22 | 39.5 | 0.64 | 0.7 | 14 | moderate |
| PW3 | 28 | 2.51 | 12 | 7.35 | 63.8 | 0.71 | 0.1 | 10 | moderate |

**Figure 16**     Landuse effects on common invertebrate taxa of different feeding groups. Bars and whiskers represent numbers of individuals m$^{-2}$ (mean + SE) Land uses joined by an underline did not differ significantly (P > 0.05, Scheefe post-hoc tests on log transformed data). Feeding group codes: CB = collector-browser; CG = collector gatherer; F = filterer; G =grazer; and Pi = algal piercer. Site E/N was excluded.
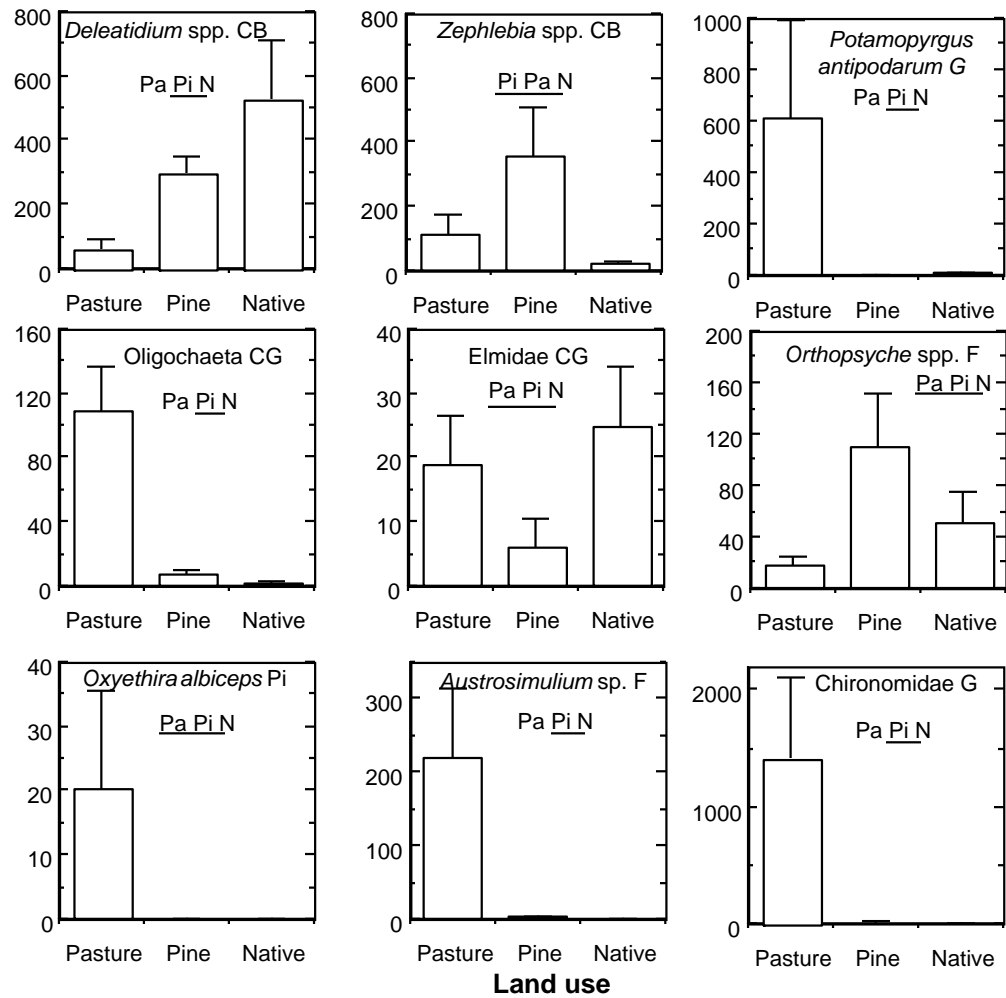
**Figure 17**     Comparison of benthic invertebrate community characteristics (mean + SE) between stream with different landuse. Non-parametric ANOVA is used to test whether there is a significant difference (P > 0) or no significant difference (NS) between landuse class. Site E/N was excluded.
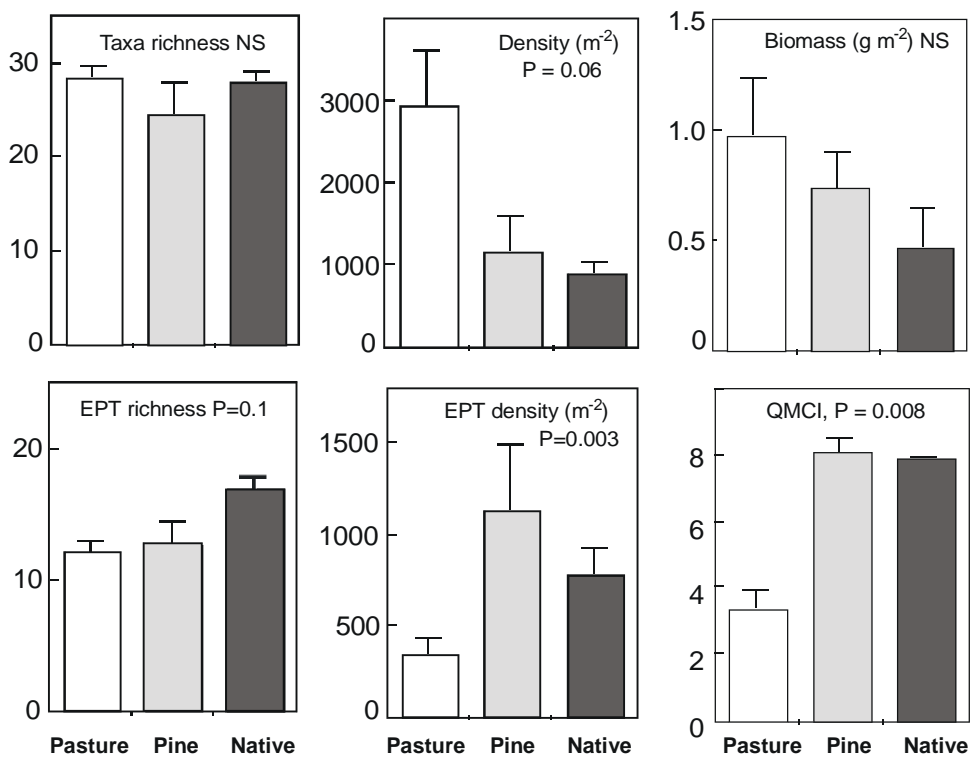
**Figure 18**    Landuse effects on relative abundance of common taxa. Pine-native refers to site E/Z where native riparian vegetation occurs for c. 500 m upstream of the study site in a predominantly pine catchment.
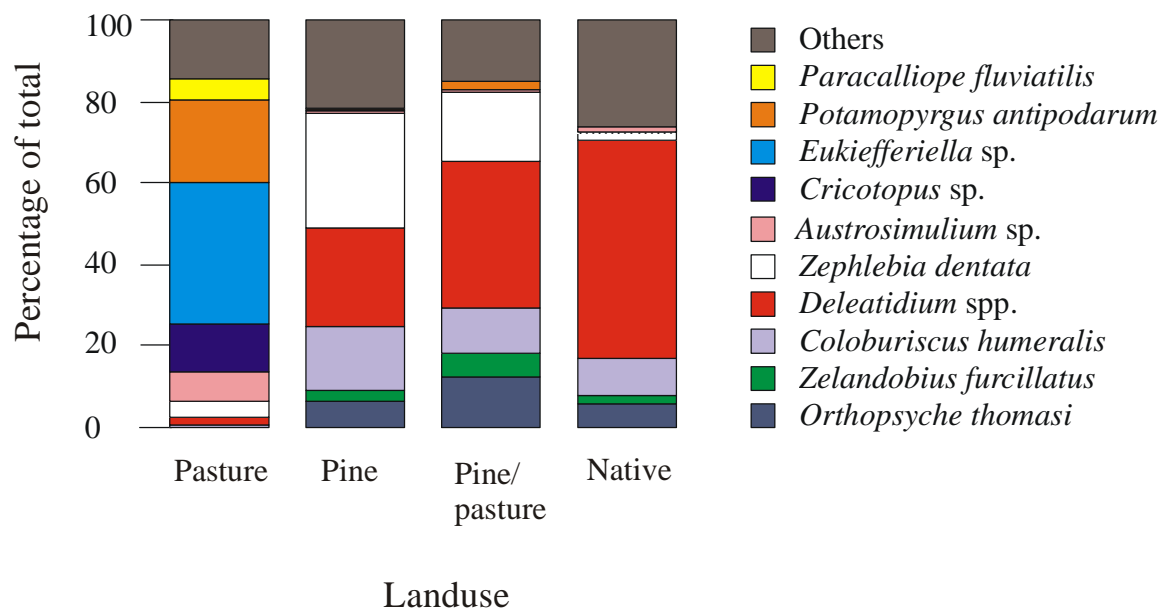


## 2.4    Discussion

### Experimental design

In this study we investigated differences between streams with different landuses in order to better understand the changes that take place in a given stream when the landuse is changed. This approach furnishes results more quickly than long-term studies through time of individual catchments which are undergoing change. There is the disadvantage that we only studied these streams under the conditions prevailing in November 1992 and we must assume that the differences observed are the result of landuse and not other factors. We have tried to minimise these problems in our study design by: matching the sites as closely as possible for key features (such as catchment size, slope, geology and soils), measuring a wide range of habitat features to provide information on the processes involved in the changes observed, and confining the study to adjacent sites and replicating the landuse treatments. We are reasonably confident that the differences observed can be attributed to their different landuses.

**Shade levels**

As expected, forest streams were heavily shaded (95–98% reduction of incoming diffuse radiation). Pasture streams were more open but still had surprisingly high levels of shade (average 71%). More detailed shade surveys in these same pasture streams (see Section 1) gave similar high levels of shade (53–96% shade).

**Sediments**

The pasture streams studied were clearly impacted by fine sediment with high suspendable sediment in the bed (Fig. 10), high water column suspended solids concentration and high turbidity (Fig. 13). One source of sediment was easily identifiable: pasture streams were characterised by steep banks, many of which were actively eroding and slumping into the stream, especially at bends. Peak flood flows are generally higher in pasture than forest streams and this results in erosion damage to banks at bends. A second potential source of sediment is overland flow, which we suspect is important in these pasture streams. Overland flow occurs more frequently in pasture than forest catchments. It has the potential both to erode catchment soils (especially in areas where pasture has been damaged by stock or roading) and to transport the eroded sediment to the stream.

The native forest streams studied were less impacted by fine sediment than either the pine forest or the pasture streams (Figs 10 and 13). Bank erosion was less apparent in forest than pasture streams: the forest streams studied tended to be wide and shallow with low banks stabilised by numerous tree roots and ferns. High rainfall interception and long catchment concentration times in forested catchments generally result in lower peak flood flows and a lower likelihood of bank erosion than in pasture streams. In addition, forest soils tend to be porous because of a high litter content and little compaction. Such soils are likely to absorb rainfall more rapidly, thereby reducing the likelihood of overland flow with its associated potential to erode soils and transport sediment into the stream.

The pine forest streams studied were clearly impacted by sediment: suspendable sediment in the bed (Fig. 10) and turbidity (Fig. 13) were higher in pine than pasture streams. This is, at first sight, a surprising finding because one would expect sediment delivery to pine forest streams from the catchment to be small because of high rainfall interception, porous soils, and low overland flow. The likely explanation lies in the effects of riparian shade on bankside vegetation and bank stability. Fifteen years after reafforestation, shade levels in the pine streams were close to those in the native streams. In the pine streams there was very little groundcover along the streambanks, presumably because the pasture grasses, present prior to re-afforestation, were shaded out when the pine canopy closed over the stream channel. There was evidence that

the pine streams were actively widening: over 40% of the stream banks were eroding, turbidities were high, and channel widths were intermediate between those in native and pasture streams. This suggests that the pine stream channels were in transition from the narrow, deep channels characteristic of pasture streams to the wide, shallow channels typical of native forest streams.

Channel narrowing in response to deforestation has been reported in White Clay Creek, Pennsylvania (Sweeney 1993), and in streams in Victoria, Australia (Campbell 1993). Sweeney (1993) found that low-order forest streams were 2.5 times wider in forested than deforested streams and 4th-order streams were 35% wider in forested than meadow sections. Channel narrowing appears to be caused by the encroachment of pasture grasses into the stream channel. Forest stream channels are typically wide, with numerous gravel bars which are only inundated at high flow. Dense riparian shade prevents plants from becoming established on these gravel bars at low flow. When the forest is replaced by pasture, the high light regime allows pasture grasses to colonise these exposed bars. This vegetation then traps sediment both from within the stream and eroded from the catchment and as a result the stream becomes narrow and the banks steep. The mass movement of soil from the hillslopes (i.e., soil creep, slumping and landslides) may also contribute to channel narrowing.

**Water temperature**

Riparian shade reduces the radiation inputs, which in turn influence water temperature. The landuse comparisons (this Section), and the thermal budget and computer model studies (Section 4) indicate that daily maximum temperatures in summer are typically 5–7°C (occasionally 10°C) higher in pasture than forest streams. A temperature increase of 5°C decreases the dissolved oxygen saturation concentration by about 10% and increases the respiration rates of biofilm, periphyton and invertebrate communities, typically by 25%. One would expect this to cause at most a small reduction in the water column dissolved oxygen concentration (of the order 1 g m$^{-3}$). Where oxygen concentrations may become significantly depleted is in the stream bed. If periphyton and/or silt accumulation reduces the benthic mass transfer rate (i.e., the flow rate of oxygenated water from the water column to the bed sediments) then the sediments will become deoxygenated. High water temperatures accelerate deoxygenation, but low benthic mass transfer rates (caused by increased periphyton biomass and fine sediment input) are probably more important. Thus high temperature and bed siltation may act synergistically to increase oxygen stress. Low sediment oxygen concentrations may adversely affect sensitive benthic invertebrate species.

Field observations and laboratory temperature tolerance studies indicate that New Zealand Plecoptera are particularly sensitive to elevated temperatures. Quinn & Hickey (1990) found that stonefly abundance declined markedly in New Zealand rivers once maximum summer temperatures exceeded 19ºC. In a laboratory study, Quinn *et al.* (1994b) found that the lethal temperature for invertebrates (i.e., the temperature at which 50% of test animals acclimated at 15ºC died during a 96-hour test) varied from 22.6–26.8ºC (*Deleatidum* spp., the most sensitive species tested) to 32.4–32.6ºC (*Potamopyrgus antipodarum, Pycnocentrodes aureola* and *Hydora* spp., the three least sensitive species tested). Typically in fish studies the 'acceptable' temperature (for long-term survival) is set 3ºC lower than the critical thermal maximum (the temperature at which adverse effects are measured) (Simons 1986). Assuming the same 'safety margin' for invertebrates gives a thermal tolerance of about 20ºC for sensitive species, similar to the figure of 19ºC derived from field data correlation studies (Quinn & Hickey 1990). Thus, taking a conservative approach, the thermal tolerance for sensitive invertebrates appears to be about 20ºC. In pasture streams, the daily mean temperature during November 1992 (typically about 15ºC) was consistently below this thermal tolerance range, but the daily maxima (typically about 20ºC) frequently overlapped it. Measured daily maximum temperatures in the partially shaded pasture stream PKL rarely exceeded 20ºC in December 1993 and April 1995 although model predictions suggest daily means and maxima approaching 20ºC and 25ºC respectively under more extreme meteorological conditions (see Fig. 40). Under low flow and extreme meteorological conditions, high water temperatures in pasture streams can thermally stress sensitive invertebrates. Elevated temperatures alone may explain the absence of such organisms from pasture streams, although we cannot rule out other factors such as high silt loads and low sediment oxygen concentrations.

**Primary production**

In our landuse comparisons, both photosynthesis rates and periphyton biomasses were higher in pasture than forest streams. This is clearly the result of increased PAR input. Increased primary production can be viewed as beneficial in that it increases the supply of carbon to the food web. On the other hand, high periphyton biomass can adversely affect stream aesthetics, increase diurnal dissolved oxygen and pH variations, reduce benthic mass transfer rates, and reduce oxygen concentrations in the bed.

Increased primary production need not necessarily result in increased periphyton biomass. McIntire (1973) found that, when logging reduced shade in small Oregon streams, periphyton productivity increased significantly, but snail numbers also increased and heavy grazing pressure prevented periphyton proliferation. In our

landuse comparison there was clear evidence that increased primary productivity stimulated grazer numbers (notably snails and chironomids). We can infer, however, that the increase in grazing pressure associated with this increase in grazer numbers did not keep pace with the increased periphyton productivity because we also saw an increase in periphyton biomass. Apparently, in our study streams, grazer numbers were limited by some other factor (e.g., growth rate, predation, flood disturbance, a shortage of suitable habitat, high sediment loads or unfavourable high temperatures).

The periphyton biomasses measured in November during the landuse comparisons are 'snapshots', and we would expect to see variations throughout the year. The open pasture streams have a high periphyton growth rate and, if there is a low-flow period when grazing pressure is low (e.g., because of high water temperatures) and loss processes are low (e.g., low shear velocity and abrasion), then there is the potential for periphyton proliferation in the pasture streams with its attendant problems. We did not monitor frequently enough during summer low flows to identify differences in 'nuisance' level blooms between landuse. We did observe, however, prolific growths of filamentous green algae in pasture stream PW2 during late summer. We conclude that periphyton can attain biomasses which are visually significant in the pasture streams studied, but that such 'nuisance' proliferations are sporadic. Three factors could contribute to nuisance blooms during summer low flows: the release of periphyton from 'top-down' grazing control by invertebrates (perhaps as a result of high temperatures), a reduction in periphyton loss rate (reduced scouring during long baseflow periods), or a temperature-related increase in periphyton growth rate. It is not clear from our landuse comparison which of these processes predominates.

**Invertebrates**

The strong positive correlation between epilithic chlorophyll *a* and chironomid density, and the negative correlations between chlorophyll *a*, QMCI and EPT densities, indicate that the effect of shade on periphyton has flow-on effects for the benthic invertebrates. The landuse comparison showed a significantly higher density of oligochaetes in pasture than forest streams. It is not clear whether these detritus feeders were stimulated by autochthonous carbon production (originating from the periphyton communities) or by allochthonous carbon (which collects passively in the periphyton mats). Grazers including chironomids and snails were significantly more abundant in pasture than forest streams and this was almost certainly the result of higher autochthonous production in the open pasture streams (McIntire 1973). Oligochaetes, snails and chironomids are known to be tolerant of organic enrichment and probably of low dissolved oxygen concentrations in periphyton mats and the streambed (Stark 1985). The increase in snail, chironomid and oligochaete numbers results in pasture streams having a slightly higher biomass, and significantly higher

total numbers, of invertebrates than forest streams. This can be regarded as beneficial in that there is a greater food supply for predators (e.g., koura, eels and native fish). Several other surveys of New Zealand streams have noted similar correlations between benthic invertebrates and epilithic algae (Quinn & Hickey 1990; Quinn *et al.* 1992).

Some grazers and collector-browsers utilise heterotrophic biofilms, either in addition to, or in preference to, periphyton (Rounick & Winterbourn 1983a). Heterotrophic biofilms are not affected directly by shade, although in pasture streams they must compete for space with periphyton and may be subject to increased grazing pressure if increased periphyton production leads to increased grazer numbers. In the landuse comparison we did not quantify heterotrophic biofilm biomass, productivity or their role as a food source for benthic invertebrates. The fact that respiration rates were comparable, but photosynthesis rates lower, in forest than pasture streams (Fig. 11), however, suggests that heterotrophic metabolism was significant in these streams.

**Nutrients**

During November, DIN concentrations were markedly higher in pasture than native streams, which indicates higher nitrogen input from pasture than native forest. This probably reflects: greater nitrogen fixation by the legumes (clover) in the pasture, increased nitrate leaching from animal urine and dung in the pasture, and greater nitrogen recycling efficiency under forest than pasture (Gandar 1983; Cooper 1986; Keeney 1986). The intermediate nitrate concentrations between pasture and native streams in the pine catchments suggest that nitrate losses may be declining with time since afforestation. It is important to remember, however, that in-stream nutrient concentrations are the net result of inputs and in-stream transformations above the point of measurement. As the groundwater level drops during summer, lateral inputs will be confined to permanent seeps and riparian wetlands where denitrification is likely to be greatest (Cooper 1990). In the pasture streams, uptake by plants (periphyton and macrophytes) will also contribute to lower nitrate concentrations (Triska *et al.* 1983, Cooper & Cooke 1984, Cooper & Thompson 1988, Cooper 1990, Kim *et al.* 1992). Plant uptake has a greater effect on stream nitrate concentrations when depths are low and residence times are large. In-stream uptake by periphyton was almost certainly responsible for the marked reduction of DIN concentration observed during summer low flows in pasture stream PW2 (Fig. 14). During this time, DIN concentrations fell to the levels likely to restrict plant growth rates (Stockner & Shortreed 1978, Griffith & Perry 1993, Grimm 1988, Lohman *et al.* 1991). By comparison, high DIN concentrations in forest streams throughout the year reflect the fact that periphyton growth rate, and hence nutrient demand, is low because of light limitation. DRP concentrations were consistently above the levels

likely to restrict plant growth in both pasture and native streams, and showed no significant depletion during summer low flow in the pasture stream PW2.

**Particulate carbon**

Differences in vegetation (particularly riparian vegetation) between landuses also have the potential to influence ecosystem function by altering the supply and type of coarse particulate organic matter (CPOM) entering the stream ecosystem. CPOM provides food directly for shredders and indirectly (after shredding, mechanical grinding and microbial conditioning) for collectors of fine particulate organic matter (FPOM) (Cummins *et al*. 1989, Cummins 1992). CPOM levels were slightly higher in the pine and native forest streams than the pasture streams although, because of high variability between streams, the difference between landuses was not statistically significant (Fig. 12). This same pattern was found in small streams of Waiau River catchment in North Canterbury (Harding & Winterbourn 1995). A major storm (c. 150 mm rainfall) 3–4 weeks before our November surveys may have reduced the benthic CPOM levels. Flow disturbance patterns have been identified as an important factor influencing both CPOM and invertebrate shredder abundance in New Zealand streams (Rounick & Winterbourn 1983b, Quinn *et al*. 1993). The effects of riparian CPOM inputs on stream ecosystems are expected to be greatest in regions where flow variability is low (e.g., Central volcanic plateau of North Island) (Jowett & Duncan 1990). We found that shredding invertebrates were relatively scarce in our study streams, and this may be because streambed CPOM levels were low during our surveys following washout. Further surveys over a wider range of flows are required to better quantify shredder numbers, and the importance of riparian vegetation of a source of CPOM.

## 2.5 Summary

1. Forested streams were very heavily shaded (95–98%). Pasture streams were more open but were still significantly shaded by streambanks and bankside vegetation (50–70%) shade.

2. Pasture streams had significantly higher daily maximum temperatures (by 6–7ºC) and daily mean temperatures (by 2–3ºC) than forest streams. November temperatures were typically 15ºC (daily mean) and 20ºC (daily maximum) in pasture streams but modelling suggests they could reach 20ºC (mean) and 25ºC (maximum) under extreme flow and meteorological conditions.

3. Pasture streams channels were narrower, more deeply incised and swifter than forest streams channels. Channel narrowing appears to result from pasture encroachment into the stream under a high light regime although the mass movement of soils may also contribute.

4. Channels appeared to be actively widening in pine forest streams (reafforested 15 years ago) resulting in bank erosion, high turbidity and a high percentage of fine sediment in the bed.

5. There was little woody debris in pasture streams.

6. Primary productivity, chlorophyll and epilithon biomass were significantly higher in pasture than forest streams. Respiration rates were comparable between streams, indicating that heterotrophic community metabolism was significant in shaded forest streams.

7. Phosphorus appeared to be available to excess throughout the year. This is thought to result from volcanic soils with high natural P content and/or superphosphate application practices. Nitrogen inputs to pasture streams appeared to be higher than to native forest streams. For much of the year DIN was present in excess in both pasture and forest streams. In-stream processing of nitrogen was more noticeable in pasture streams and nitrogen appeared to limit periphyton growth in pasture streams during summer low flows.

8. Invertebrate communities were significantly different between pasture and forest streams but similar in pine forest and native forest streams. Grazers (notably snails and chironomids) were more abundant in pasture than forest streams, presumably because of increased periphyton productivity. Oligochaetes

were more abundant in pasture streams either because they are tolerant of, or are stimulated by, organic enrichment.

9. Some collector-browsers/gatherers were equally abundant in pasture and forest streams. This suggests that they can switch between food sources and use either heterotrophic biofilms (in shaded streams) or autotrophic periphyton (in open, pasture streams). They appear unable to exploit the higher primary production in open pasture streams, possibly because they are limited by other factors (e.g., predation, high temperature or high sediment loads).

10. Taking a conservative approach, we estimate that the thermal tolerance for sensitive invertebrates is about 20ºC.

11. Some mayflies and stoneflies were less abundant in pasture than forest streams. This probably reflects thermal stress although other factors (e.g., high sediment inputs and/or low sediment dissolved oxygen concentrations) may also be involved.

12. Although we did not set out to study 'nuisance' periphyton growths, we did observe conspicuous growths of filamentous green algae during summer low flow in small, headwater pasture streams. We conclude that periphyton can attain biomasses which are visually significant in the pasture streams studied, but that such 'nuisance' proliferations are sporadic.

## 3.    EFFECTS OF SHADE ON NITROGEN LEVELS, PERIPHYTON, AND INVERTEBRATES

### 3.1    Introduction

The comparison of stream reaches in catchments draining contrasting land uses (Section 2) indicates that riparian shade has important influences on several aspects of hill-country streams, including instream primary production, nutrient dynamics, periphyton biomass, and benthic invertebrate communities. It is not possible from that comparison, however, to isolate the direct effects of shade from other potentially important variables (e.g., temperature, velocity, nutrient inputs) because landuse has multiple influences on stream habitat and water quality. To improve our understanding of the direct effects of shade on stream ecosystems, we manipulated the light exposure of replicated streamside channels and measured the effects of four different shade levels on periphyton biomass and productivity, nutrient concentration (principally nitrogen), and benthic invertebrate abundance and type. The insights gained will help guide riparian management decisions relating to the use of shade control for improving instream habitat conditions in pasture streams in the absence of other broader catchment management actions.

Periphyton is important in streams because: it can cause diurnal fluctuations in stream dissolved oxygen and pH, excessive growth can be unsightly and can block water supply intakes, photosynthetic activity provides fixed carbon to the base of the stream food chain, it traps particulate carbon and inert sediment, it provides habitat for benthic invertebrates, it affects flows into and out of the streambed, and its uptake of nutrients can significantly alter the nitrogen and phosphorus dynamics of streams and delivery of these nutrients to downstream ecosystems. A fundamental conceptual model of riverine systems, the river continuum concept (Vannote *et al.* 1980), has instream primary productivity making only a small contribution to the total energy flow of forested streams because of riparian shading. Upon catchment development to pasture, this riparian shading is greatly reduced (see Section 1), and we might expect an increase in periphyton productivity and biomass. The response to increased light may not be as simple as we expect because periphyton productivity may be limited by some other factor (e.g., nutrient or temperature) and because biomass accumulation may be limited by yet another factor (e.g., grazing by invertebrates or removal by high flows). The effect of removing or restoring riparian shade on periphyton biomass and productivity will depend on how the changed light exposure influences the balance of processes affecting periphyton. Current quantitative understandings in this area are limited. In order to provide better advice on what might happen to streams when removing riparian trees or implementing a riparian planting strategy we sought to determine the effect of shading level on: periphyton biomass and species composition, community metabolism (photosynthesis and respiration), and nitrogen uptake.

Benthic invertebrates are important in streams because: they consume periphyton and heterotrophic biofilms, they consume coarse and fine particulate carbon (detritus), they recycle nutrients, they provide food for higher organisms (e.g., koura, eels), they are general indicators of ecosystem health, and they are integrators of stream water quality. Some invertebrates are intolerant of high organic loadings, eutrophication and high temperatures and are found only in cold, swift, stony and well-oxygenated headwater streams. Others are more tolerant of organic enrichment and predominate in slow, warm, silty, lowland streams. We might expect changes in stream conditions caused by shading to influence invertebrate populations.

We hypothesised that:

1. heavy shade would reduce the growth and biomass of autotrophs (periphyton), which in turn would reduce invertebrate abundance and alter community composition,
2. partial shade would result in greater autotrophic production and invertebrate abundance (particularly of grazers) than dense shade,
3. filter-feeding invertebrates would be favoured by the cleaner stone surfaces present under high shade.

Our experiment was carried out in twelve streamside channels to allow replication of treatments, avoid disruption of the experiment by floods, and provide good control of shade, current velocity, substrate, and initial conditions whilst still retaining the stream water quality, temperature, and drift of colonists from up stream. The streamside channel experiment mimics the effect of shading a short section of a pasture stream (e.g., under isolated riparian trees or small woodlots).

## 3.2 Methods

### Channel design

Twelve parallel channels (0.2 m wide, 0.05 m deep, 2.4 m long) (see Plate 10) were constructed adjacent to the pasture branch of the Mangaotama Stream, just down stream of the NIWA flow and water quality monitoring site PW5 (NZMS1 S14 928777) at AgResearch's Whatawhata Hill-country Research Centre. Stream water is supplied by gravity at 16 l s$^{-1}$ via a 200 mm PVC pipe from an intake immediately below the flow recorder weir at a 4 m high waterfall 80 m up stream of the channels. To release air bubbles that otherwise accumulate in the supply pipe and reduce water flow, a 'snorkel' (3 m long, 20 mm diameter PVC tube) was installed half way along the intake pipe. The stream intake box was set on a ledge in the waterfall and covered with a metal grid (2 cm spaces) to exclude woody debris and large sediments. The pipe fed via a flow control valve to a headerbox (0.4 m x 1.3 m x 1.0 m) fitted with an angled baffle-board, made of plywood drilled with 40 mm diameter holes, to distribute

the flow evenly to the channel intakes. The base of the headerbox sloped down at one end to a 50 mm drain to the stream to reduce the build-up of fine sediment. Water delivery to the channels was controlled by adjusting the channel slope and the height of gate valves at the header box end. Water depths were adjusted using flaps at the downstream end of each channel. Neither the intakes nor outlets of the channels were screened, so the flux of sediment, coarse particulate organic matter (CPOM) and invertebrates was unimpeded.

Just prior to the experiment the channels were lined with natural stream gravel. Benthic invertebrates collected from runs and riffles using Surber samplers (0.1 m$^2$, 250 μm mesh) were introduced to the channels to provide a pool of initial colonists. To reduce drift losses, water flow through the channels was halted when the invertebrates were added. This initial input of invertebrates was supplemented by natural stream drift throughout the experiment.

The experiment began on 12 October 1993 and ran through the spring and summer, ending 142 days later on 4 March 1994. Different grades of black shade-cloth were attached to wooden frames that fitted over individual channels. The shading of the different cloths were measured using a PAR line sensor (LiCor Li-195A). Four treatments were randomly allocated amongst the 12 channels (i.e., 3 replicates per treatment) corresponding roughly to heavily grazed pasture (0% shade), low density riparian plantings (60%), dense riparian plantings (90%), and dense forest (98%) (Section 1).

**Periphyton**

Thirty numbered clay tiles (5 cm x 10 cm x 0.7 cm) were placed at regular intervals along each channel on the surface of the gravels with their long axes across the channels. A single tile was selected at random from each channel at approximately weekly intervals and removed for periphyton sampling. All tile surfaces were scrubbed with a stiff nylon brush and scraped with a scalpel blade. The larger macroinvertebrates were removed with forceps and returned to the channel without being counted. Smaller chironomids were removed from the periphyton mat in the laboratory and counted, but not returned to the channels. The periphyton suspension was thoroughly mixed (by blending if necessary) and subsamples were taken for filtration and analysis of dry weight, chlorophyll *a* (90% acetone extraction with phaeophytin correction, APHA 1989), and particulate carbon and nitrogen (Anon. 1994). The cleaned tiles were returned to the channels to maintain a constant surface area for invertebrate colonisation, but were not resampled as part of the main experiment.

Periphyton were sampled for species identification and pigment analysis on one occasion during summer. Subsamples of scrapings from tiles collected on 10 February

were bulked according to treatment and preserved in Lugol's iodine. Algae were subsequently identified and counted using standard settling and microscope techniques. On 28 February an additional subsample from one tile in each channel was filtered and analysed for pigment composition using high-pressure liquid chromatography (Downes *et al.* 1993). PAR (photosynthetically active radiation) and water temperature were recorded at 15-minute intervals (except during breakdowns). A recording PAR sensor was placed on the roof of a pump house adjacent to the artificial channels. A recording thermistor was secured in the header box of the channels. Stream water was sampled weekly at the channel intake and analysed for $NH_4$-N, $NO_3$-N and DRP by autoanalysis methods.

### Epilithon community metabolism

On three occasions during the experiment, the effect of shade treatment on community metabolism was measured on sampled tiles prior to analysis for chlorophyll. The tiles were individually transported to the laboratory in small water-filled containers and placed in a small recirculating respirometer filled with streamwater (Fig. 19) Care was taken to minimise the disturbance to the periphyton during this process. An oxygen probe was fitted in the flow return tube of the respirometer to measure changes in the concentration of oxygen in the chamber water over time resulting from periphyton respiration and/or photosynthesis. Output from the oxygen probe was passed through a ten-times voltage expander to a chart recorder so that a full-scale deflection on the chart recorder was equal to a $1 \text{ g m}^{-3}$ change in oxygen concentration. The experiment was run outdoors with the respirometers placed in a cooling water bath and maintained at a constant temperature (15ºC) using a refrigeration unit.

Each tile was incubated in darkness (when the rate of decrease of dissolved oxygen represented respiration) and also under the shade treatment from which it was gathered (when increasing oxygen concentrations represented net photosynthesis). The rate of gross photosynthesis was taken as the sum of the absolute values of the rate of net photosynthesis (oxygen production) and respiration (oxygen consumption). Photosynthetic carbon fixation rates were calculated by assuming a 1:1 molar ratio between oxygen produced and carbon fixed. Incubation times were 15–30 minutes which was sufficiently long to obtain a reliable estimate of rate of change of dissolved oxygen concentration.

To examine the relationship between irradiance and photosynthesis, at the end of the mesocosm experiment each of the sampled tiles was incubated under total darkness and under a range of light levels. After measuring epilithon community metabolism, nitrogen uptake rate was measured. A 1 ml aliquot of $^{15}$N-$KNO_3$ solution (containing 1 mg of $^{15}$N) was injected through a septum into the respirometer as a nitrogen tracer. This increased the concentration of $NO_3$-N in the recirculating water by 2–5 times that of the original streamwater and well above that thought to limit algal uptake rate (50–

150 mg m$^{-3}$). After incubation for 20–60 minutes, samples of respirometer water were taken and analysed for $NO_3$-N concentration. Subsamples of periphyton from the tiles were ground and analysed for $^{15}$N using a Carlo Erba NA 1500 elemental analyser coupled to a Europa Scientific tracer mass spectrometer. Although algae can show isotope discrimination during uptake of $NO_3$-N (e.g., Montoya & McCarthy 1995), such discrimination would be an insignificant error in this experiment and was ignored when calculating total $NO_3$-N uptake.

## Benthic invertebrates

### Main experiment

To test for pre-treatment differences between the channels, benthic invertebrates were sampled at 0.4 m, 1.2 m and 2.0 m from the upstream end of each channel using Surber samplers (0.225 m$^2$, 250 μm mesh) on 11 October, just prior to shade treatment. Samples were live-sorted, identified to the lowest level practicable in the field using hand lenses (10 x magnification), and counted before being returned to the channels from which they were collected. Post-treatment effects on the communities within the gravels (as opposed to those on the tiles) were evaluated by repeating this sampling at the end of the experiment on 4 March. Samples were preserved in 10% formalin and processed in the laboratory.

The effects of the shade treatments on benthic invertebrates throughout the main experiment were monitored by sampling seven randomly selected tiles (total 350 cm$^2$ planar surface area) from each channel on six occasions during the experiment (days 9, 23, 37, 64, 100 and 142). The tiles were uplifted into a small hand-net (250 μm mesh), and the larger animals (excluding chironomids) from all seven tiles were composited in a tray, identified and counted in the field, and then returned to their channel. Invertebrates firmly attached to tiles were counted without removal. Chironomids were abundant in some treatments, and difficult to identify and count in the field. Consequently, these were sorted and counted in the laboratory from the single tile per channel from which periphyton was sampled.

### Recolonisation experiment

The effects of the shade treatment on invertebrate recolonisation during mid-summer were investigated by resampling (on 28 February 1995) tiles from which periphyton and invertebrate had been removed 18, 25, 32, 39, 46 and 53 days previously. Invertebrates on individual tiles were sorted, identified and counted in the field and the tiles replaced. Species of uncertain identity were preserved in alcohol and identified in the laboratory.

### Statistical analysis

Differences between shade treatments of invertebrate communities inhabiting the gravels were investigated using one-way analysis of variance (ANOVA) of log-transformed measurements made at the beginning and end of the experiment, with post-hoc Scheffe multiple inference (Day & Quinn 1989). Differences between shade treatments of invertebrate communities on the tiles were analysed using a nested ANOVA of log-transformed measurements made at intervals throughout the experiment (Zar 1984).

**Figure 19**  Diagram of apparatus used to measure periphyton photosynthesis and respiration.
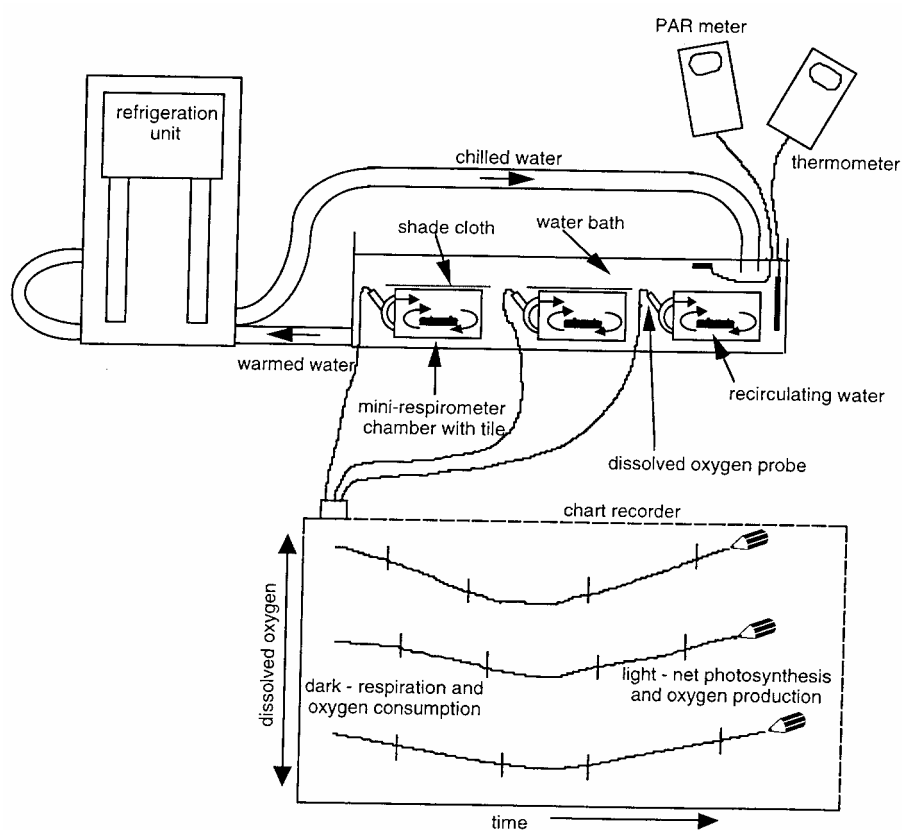
**Figure 20** Light, temperature and nutrient concentrations during the channel experiments (October 1993 and March 1994).
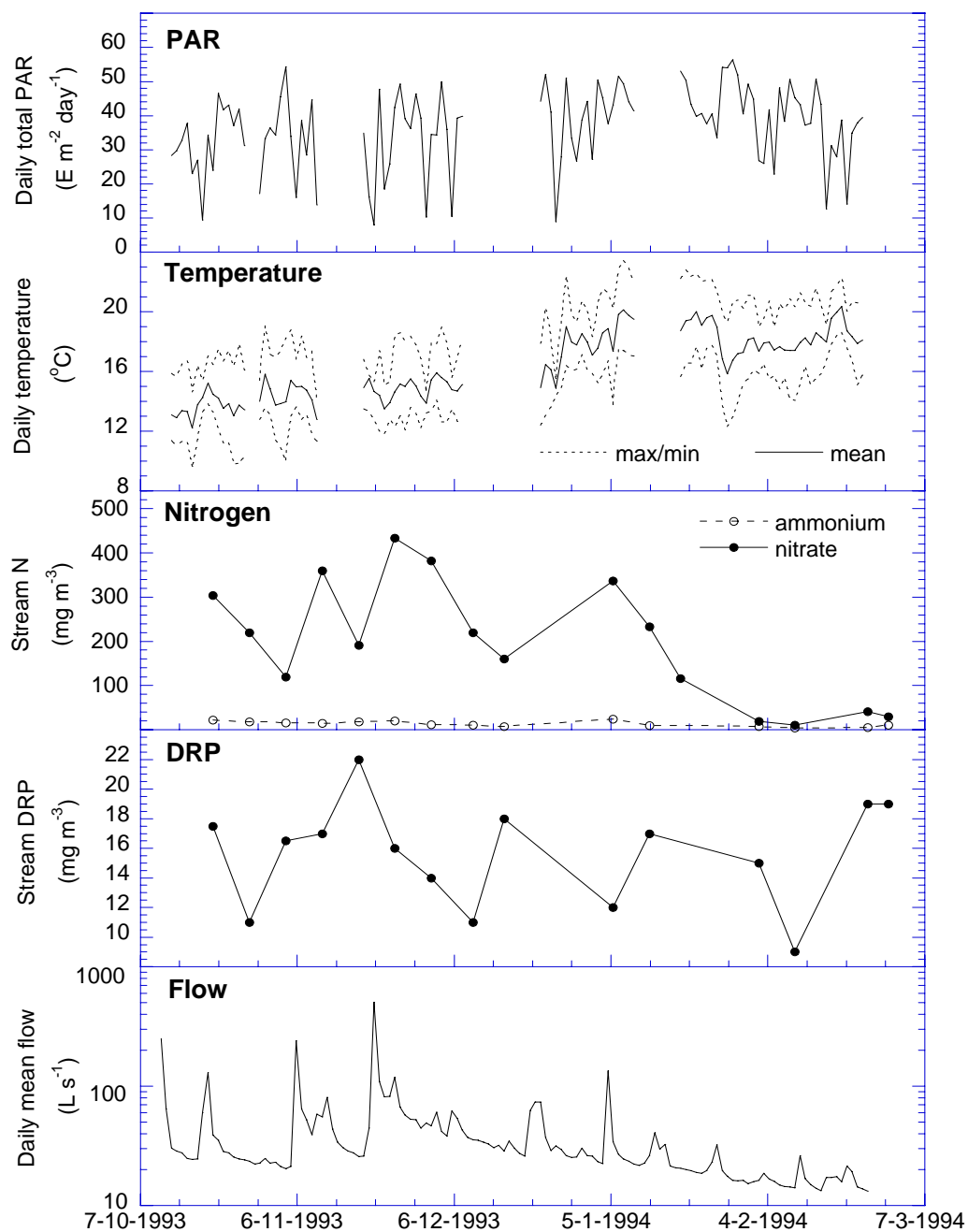
### 3.3 Results

**Light, temperature and nutrients**

Figure 20 shows time series of PAR, water temperature and nutrient concentration between October 1993 and March 1994. Gaps in PAR and temperature correspond to data logger breakdowns. Solar radiation reaching the site ranged from 8 einsteins $m^{-2}$ $d^{-1}$ on days of heavy cloud to over 50 einsteins $m^{-2}$ $d^{-1}$ on clear days. During the course of the experiment, stream temperatures increased from daily means of 12–16ºC in October-November to 16–20ºC in January-February. Minimum temperatures occurred near dawn (around 0600 hours) and maximum temperatures in late afternoon (around 1500 hours).

Stream dissolved nutrient concentrations fluctuated during the experiment, with DRP varying between 9 and 22 mg $m^{-3}$ (mean 16 mg $m^{-3}$) and nitrate ($NO_3$-N) varying between 11 and 443 mg $m^{-3}$ (mean 205 mg $m^{-3}$). Ammonium ($NH_4$-N) was always a minor portion of the total dissolved inorganic nitrogen, which was largely $NO_3$-N. While the DRP fluctuations showed no consistent temporal pattern, $NO_3$-N showed a marked decline during January to reach very low levels through February (Fig. 20). This decline in streamwater $NO_3$-N concentration through the summer of 1993–94 was similar to that observed in the summer of 1992–93 and correlated with high periphyton biomass (see Fig. 14, in Section 2).

**Periphyton biomass and composition**

Under low light conditions (90% and 98% shade), algal biomass remained low throughout the experiment (Chl. $a$ < 17 mg $m^{-2}$), with a low coefficient of variation between replicate channels (Fig. 21). The 0% and 60% shade treatments showed occasional high algal biomass (Chl. $a$ > 40 mg $m^{-2}$) and a high coefficient of variation between replicates (see Plate 11). Observations of the channels confirmed these findings: all tiles under heavy shade showed a thin, dark black-green film, whereas in the less shaded channels there was distinct patchiness, with green filaments on some tiles but not others. These patterns were not so apparent in the particulate carbon data (see Fig. 21B) and this may reflect the settling and trapping of incoming detritus on to the tiles. The role of this incoming carbon, compared with algal carbon fixation, is discussed below.

**Figure 21** Periphyton biomass (A) and particulate carbon (B) during the channel experiments (October 1993 and March 1994).
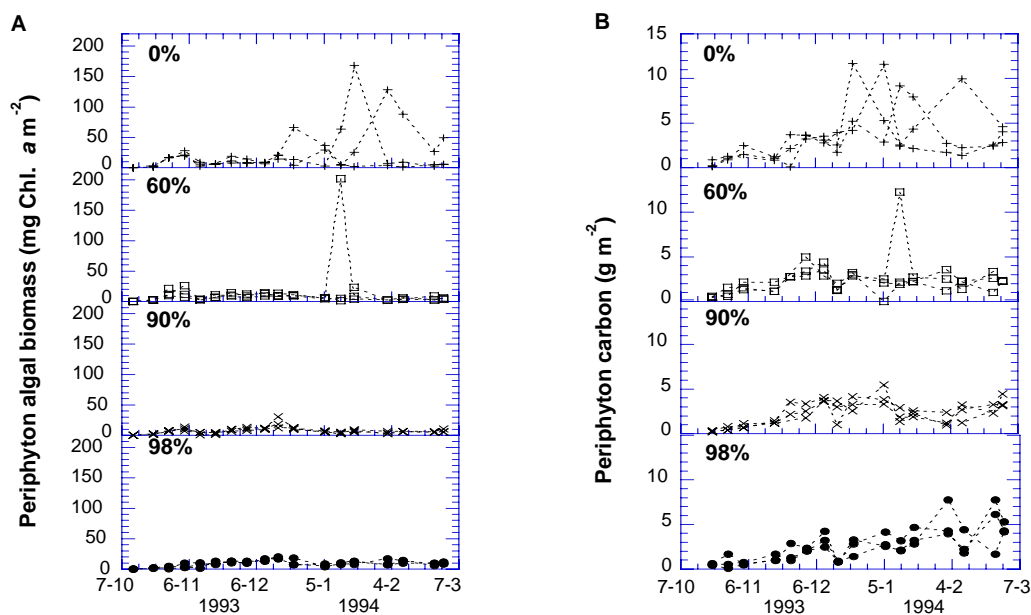


On the one occasion when the algal composition was examined, diatoms dominated the periphyton in all treatments, but taxonomic composition was influenced by shade (Table 5). The open channel flora (0% shade) was dominated by the *Navicula* and *Melosira*; the 60% and 90% shade treatments were dominated by *Rhiocosphenia* and *Cocconeis*; and the 98% shade treatment by *Navicula* and *Cocconeis*. The open channel flora was more diverse, with 17 taxa compared with 10–12 taxa in the shaded channels. The unicellular greens *Nitzschia, Gyrosigma* and *Pinnularia* were only found in the unshaded channels, and the filamentous green *Spirogyra* was only found in the unshaded and 60% shade treatments. The taxa list of the 0% shade treatment was significantly different from those of the other three treatments (Cochran Q test, P < 0.01).

**Algal pigments**

HPLC analyses showed the major photosynthetic pigments in all treatments to be chlorophyll *a* (46–69% of total pigment) and chlorophyll *b* (12–21%) (Table 6). Major accessory pigments were beta-carotene (3–15%) and fucoxanthin (4–14%), with beta-carotene highest in the unshaded channel (0% treatment) and lowest under heavy shade (98% treatment). The relative abundance of pigments was not influenced by shading (Spearman's rank correlations > 0.9 for all paired tests).

**Table 5** Species composition of periphyton sampled on 10 February (Day 120).

| Group | Form | Taxa | 0% | 60% | 90% | 98% |
|---|---|---|---|---|---|---|
| | | | | | Shade Level | |
| Diatom | Unicellular | *Navicula* | 65.7 | 17.4 | 14.4 | 40.0 |
| Diatom | Unicellular | *Rhiocosphenia* | 3.3 | 33.7 | 28.1 | 13.8 |
| Diatom | Filamentous | *Melosira* | 12.5 | 2.0 | 2.0 | 5.6 |
| Diatom | Unicellular | *Cocconeis* | 2.7 | 31.5 | 36.3 | 18.1 |
| Diatom | Unicellular | *Gomphonema* | 1.2 | 0.8 | 5.9 | 0.4 |
| Diatom | Filamentous | *Fragilaria* | 2.8 | 2.0 | 0.8 | 1.9 |
| Green algae | Filamentous | *Spirogyra* | 2.1 | 1.4 | 0.0 | 0.0 |
| Diatom | Unicellular | *Cymbella* | 1.7 | 2.8 | 1.2 | 1.9 |
| Diatom | Unicellular | *Acnanthes* | 2.0 | 0.0 | 0.0 | 0.2 |
| Diatom | Unicellular | *Nitzschia* | 0.0 | 0.0 | 0.0 | 0.0 |
| Diatom | Unicellular | *Gyrosigma* | 0.2 | 0.0 | 0.0 | 0.0 |
| Blue-green algae | Filamentous | *Lyngbya* | 3.6 | 0.0 | .0.0 | 8.4 |
| Diatom | Unicellular | *Pinnularia* | 0.3 | 0.0 | 0.0 | 0.0 |
| Green algae | Filamentous | *Mougeotia* | 1.2 | 0.0 | 3.9 | 5.8 |
| Green algae | Filamentous | *Ulothrix* | 0.0 | 0.4 | 0.0 | 0.9 |
| Green algae | Unicellular | *Closterium* | 0.2 | 4.2 | 1.6 | 0.0 |
| Green algae | Filamentous | *Microspora* | 0.3 | 4.2 | 5.5 | 3.0 |

**Table 6** Algal pigments in periphyton sampled on 10 February (Day 120).

| Pigment | 0% Treatment | 60% Treatment | 90% Treatment | 98% Treatment |
|---|---|---|---|---|
| Beta-carotene | 15.4 | 7.3 | 7.0 | 3.3 |
| Lutein | 4.2 | 3.5 | 3.8 | 1.8 |
| Violaxanthin | 1.1 | 0.3 | 1.6 | 0.8 |
| Taraxanthin | 0.9 | 0.3 | 0.3 | 0.5 |
| Fucoxanthin | 9.7 | 4.1 | 5.6 | 13.7 |
| Chlorophyll *b* | 21.3 | 14.5 | 16.2 | 12.4 |
| Chlorophyll $c_1$ & $c_2$ | 1.6 | 1.3 | 2.0 | 2.7 |
| Chlorophyll *a* | 45.7 | 68.8 | 63.5 | 65.0 |