

Temperature and light

*Peter M. Davies, Stuart Bunn, Thorsten Mosisch¹,
Barbara Cook and Terry Walshe*

Summary

- ~ Riparian vegetation shades streams, decreasing the amount of direct and diffuse sunlight reaching the water surface and reducing daily and seasonal extremes of water temperature.
- ~ Shading controls primary productivity within the stream to a greater extent than nutrient levels, as the growth of most aquatic plants is regulated by light availability. At sites with elevated nutrient levels, shading can therefore control the effect of nutrient enrichment.
- ~ In cleared streams, water temperature can exceed the lethal limits for aquatic fauna, directly influencing local biodiversity and, at lower temperature levels, the growth and development of aquatic plants and animals.
- ~ The temperature tolerance of Australian aquatic macroinvertebrate fauna is similar to that measured elsewhere in the world. In temperate systems, a target of 21°C is recommended, and in northern systems, 29°C for stream water temperatures.
- ~ The degree of shade created by riparian vegetation is influenced by several factors, including canopy height, foliage density, channel width and orientation, valley topography, latitude and season. The effect of shading on the structure and function of stream ecosystems is greatest in small streams.
- ~ Typically, riparian replanting is best conducted in the upland streams of a catchment, particularly those orientated east-west, as this will have a flow-on effect for temperature in the lower reaches. However, for cooler-water refugia in large rivers, replanting tributaries close to the confluence can have considerable benefits for native fish.
- ~ Stream shade has three components — macrotopographic shade (provided by nearby hills), bank shade and vegetation shade. Any restoration activities need to recognise the differential effects of these components.

¹ Thorsten Mosisch co-wrote this chapter for the previous edition.

3.1 Water temperature

Riparian vegetation is a major regulator of the ecological health of streams and rivers and consequently a primary focus of river restoration. Despite this important role, it has remained difficult to be prescriptive about the actual amount of vegetation required to achieve ecological goals. A reduction in water temperature is an ecologically-meaningful and easily measured outcome of riparian replanting. In the absence of shade, water temperatures often exceed thermal tolerances of aquatic fauna (Davies et al. 2004a, b). Replanting riparian zones can reduce water temperatures to benefit downstream receiving ecosystems.

Riparian vegetation is very effective in moderating stream temperatures. For example, research in sub-tropical and temperate Western Australia showed that cleared stream sites could heat water at a rate of $10^{\circ}\text{C}\cdot\text{km}^{-1}$ (Rutherford et al. 2004). These high rates only applied over a short stream reach as water temperatures quickly reached a dynamic equilibrium. Due to the typical patchy nature of the shade found along the streams studied, it was difficult to determine how long water takes to reach equilibrium, however, it has been estimated that this occurs after ~ 1200 metres (about 4 hours travel time) (Rutherford et al. 2004).

Temperature has both direct and indirect effects on the ecological health of streams. Colder waters contain higher dissolved oxygen concentrations compared to warmer waters (Horne & Goldman 1994). For example, a 10°C increase in temperature (a change commonly-recorded in streams following riparian clearing) can reduce oxygen concentration by over 2.5 mg/L^{-1} , which may represent a quarter of the total oxygen present.



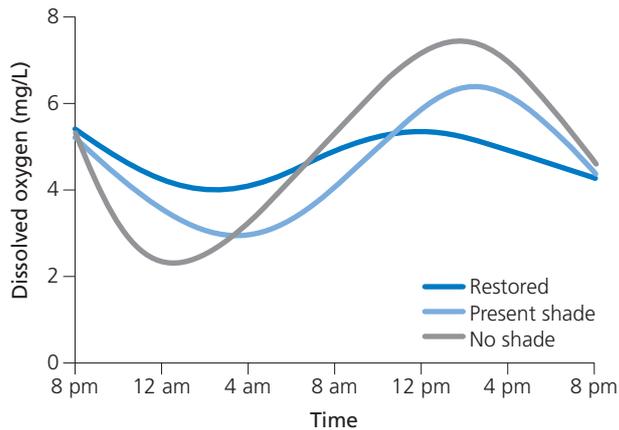
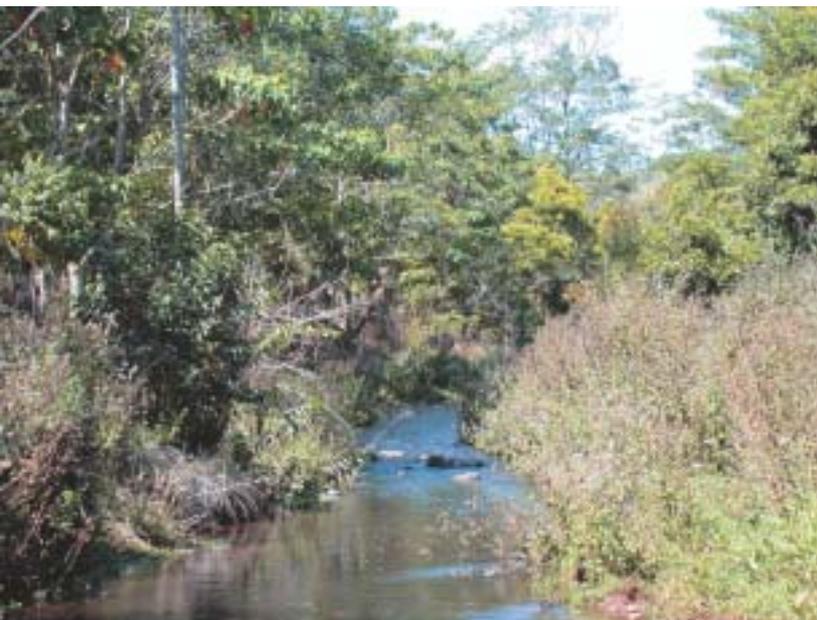


Figure 3.1. The effect of riparian clearing on the amplitude of 24 hour dissolved oxygen concentrations.

Elevated water temperatures generally raise ecosystem respiration and consequently oxygen consumption. Following riparian clearing, the combined effects of a lowering in oxygen saturation and increased respiration can drive systems anoxic, particularly at night (Bunn & Davies 1992, Davies et al. 2004a).

Figure 3.1 shows a series of 24 hour dissolved oxygen (DO) curves for three systems differing in the level of riparian shade. The curve for “no shade” shows DO values close to zero prior to sunrise, largely a consequence of elevated respiration. The amplitude of the DO curve for “no shade” is more extreme than the sites with increased riparian protection. The photos below show Tranter Creek (far north Queensland) at three stages of restoration: no shade, present shade and restored).

Three stages of restoration: opposite page, no shade; below left, present shade and below right, restored. Photos Peter Davies.



Sub-lethal impacts of elevated water temperatures

Water temperature, including elevated temperatures, can have the following direct effects on aquatic fauna.

- ~ Effects on growth and development of most aquatic organisms (such as algae, invertebrates, fish, reptiles and amphibians) (see the photos on following page).
- ~ Control of larval development (Vannote & Sweeney 1980).
- ~ Influencing egg development, timing of hatching, and emergence of adults (Hynes 1970).
- ~ Premature emergence of adults, possibly at times when climatic conditions in the terrestrial environment are unsuitable for adult survival or when few mates from adjacent forested sites are present.
- ~ Overall reduction in fecundity because larvae mature at smaller sizes in warmer water and smaller insects produce fewer eggs (Vannote & Sweeney 1980).
- ~ Modifying the trigger for migration, spawning, egg development and hatching of many fish species (Sloane 1984, Cadwallader & Lawrence 1990, Gehrke 1994).

The effect of temperature on the life-cycles of many aquatic invertebrates is substantial. For example, the onset of egg development and hatching of the common glass shrimp *Paratya australiensis* in subtropical rainforest streams are both strongly influenced by temperature (Hancock & Bunn 1997).



Examples of aquatic fauna and algae.



Glass shrimp



Ephemeroptera (mayfly) larvae



Odonata (dragonfly) larvae



Mary River cod



Algal bloom



Filamentous green algae

Photos this page Peter Davies.

The rate at which many fish grow also increases with temperature, although it probably declines in most species as they reach their upper thermal limit. Fish have higher rates of feeding and digestion at warmer temperatures, however, the amount of energy used up in finding and digesting more food at these temperatures means that growth is not commensurate with the higher rates of feeding and digesting (Allan 1995).

Temperature influences the broad taxonomic composition of aquatic algal assemblages, although each species may have its own optimum and range. Diatoms (for example, the benthic forms in Australian arid streams) tend to dominate at approximately 5–20°C, green and yellow–green algae at 15–30°C, and blue–green algae at greater than 30°C (DeNicola 1996). Many species of stream animals, particularly invertebrates but also some fish, are adapted to cool stream water with high oxygen concentrations and are susceptible to elevated temperatures. Some data on temperature preferences and tolerances for aquatic invertebrates and fish in New Zealand are available (Collier et al. 1995). However, little similar information is available for Australia. One Australian example is that larval lampreys (ammocoetes) will die at or above 28.3°C; this accounts for their distribution being restricted to Australia's southernmost streams.

Determining upper lethal temperatures in aquatic insects

Exceedance of thermal limits of aquatic biota has a major influence on local biodiversity. Early studies of the temperature tolerances of aquatic invertebrates have mainly been in the USA, and showed that some groups, such as mayflies (Ephemeroptera) and stoneflies (Plecoptera) were sensitive to elevated temperature. In New Zealand, the upper thermal tolerances of 12 stream aquatic invertebrates collected from the Waihou River has been assessed (Quinn et al. 1994), and a wide range of upper thermal tolerances were observed. Again, mayflies and stoneflies were shown to be temperature sensitive.

Setting target temperatures for Australian systems

To ensure the survival of mayflies in Australian systems, the most sensitive group to elevated temperatures, 'target' temperatures of 21°C ('cold' water species) and 29°C (northern water species) have been recommended (Davies et al. 2004a) (Table 3.1). These are similar to values derived by Rutherford et al. (1997) who adopted a 'conservative' upper limit target stream temperature of 20°C for New Zealand streams.

Table 3.1. Upper lethal temperatures for a variety of aquatic invertebrates occurring in streams worldwide. Highlighted in blue are values for Australian species.

Group	Species	Lethal temperature (°C)	Acclimation (hours)	Author(s)
Planaria	<i>Dugesia tigrina</i>	31.9	5.0	Claussen & Walters (1982)
	<i>Dugesia dorocephala</i>	32.4	5.0	Claussen & Walters (1982)
	AVERAGE	32.2		
Amphipoda	<i>Paramelita nigroculus</i>	34.1	13.5	Buchanan et al. (1988)
	<i>Paracalliope fluviatilis</i>	24.1	15.0	Quinn et al. (1994)
	<i>Gammarus limnaeus</i>	14.6	6.4	Gaufin & Hern (1971)
	AVERAGE	24.3		
Decapoda	<i>Paratyta curvirostris</i>	25.7	15.0	Quinn et al. (1994)
	<i>Cambaroides japonicus</i>	27.0	16.0	Nakata Kazuyoshi et al. (2002)
	<i>Pacificastacus leniusculus</i>	31.1	16.0	Nakata Kazuyoshi et al. (2002)
	<i>Orconectes rusticus</i>	34.4	5.0	Claussen (1980)
	<i>Orconectes rusticus</i>	35.6	15.0	Claussen (1980)
AVERAGE	30.8			
Diptera	<i>Atherix variegata</i>	32.0	10.0	Nebeker & Lemke (1968)
	<i>Atherix variegata</i>	32.4	6.4	Gaufin & Hern (1971)
	<i>Simulium</i> sp.	25.1	6.4	Gaufin & Hern (1971)
	AVERAGE	29.8		
Coleoptera	<i>Hydora</i> sp.	32.6	15.0	Quinn et al. (1994)
Ephemeroptera	<i>Nyungara</i> sp.	21.9	15.0	Davies et al. (2004a)
	<i>Centroptilum</i> sp.	20.5	15.0	Davies et al. (2004a)
	<i>Ephemerella subvaria</i>	21.5	10.0	Nebeker & Lemke (1968)
	<i>Deleatidium</i> sp.	22.6	15.0	Quinn et al. (1994)
	<i>Zephlebia dentata</i>	23.6	15.0	Quinn et al. (1994)
	<i>Stenonema ithaca</i>	31.8	10.0	DeKozlowski & Bunting (1981)
	<i>Stenonema tripunctatum</i>	25.5	10.0	Nebeker & Lemke (1968)
	<i>Ephemerella invaria</i>	22.9	10.0	DeKozlowski & Bunting (1981)
	<i>Cinygmula</i> sp.	11.7	6.4	Gaufin & Hern (1971)
	<i>Ephemerella doddsi</i>	15.5	6.4	Gaufin & Hern (1971)
	<i>Ephemerella grandis</i>	21.5	6.4	Gaufin & Hern (1971)
	<i>Hexagenia limbata</i>	26.6	6.4	Gaufin & Hern (1971)
	AVERAGE	22.1		
Plecoptera	<i>Zelandobius furcillatus</i>	25.5	15.0	Quinn et al. (1994)
	<i>Taeniopteryx maura</i>	21.0	10.0	Nebeker & Lemke (1968)
	<i>Isogenus frontalis</i>	22.5	10.0	Nebeker & Lemke (1968)
	<i>Allocaupnia granulata</i>	23.0	10.0	Nebeker & Lemke (1968)
	<i>Pteronarcys dorsata</i>	29.5	10.0	Nebeker & Lemke (1968)
	<i>Acroneuria lycorias</i>	30.0	10.0	Nebeker & Lemke (1968)
	<i>Paragnetina media</i>	30.5	10.0	Nebeker & Lemke (1968)
	<i>Paragnetina media</i>	33.0	10.0	Heiman & Knight (1972)
	<i>Isogenus aestivalis</i>	16.5	6.4	Gaufin & Hern (1971)
	<i>Pteronarcella badia</i>	24.4	6.4	Gaufin & Hern (1971)
	<i>Pteronarcys californica</i>	27.0	6.4	Gaufin & Hern (1971)
	AVERAGE	25.7		

Table 3.1. continued

Group	Species	Lethal temperature (°C)	Acclimation (hrs)	Author(s)
Odonata	<i>Austroaeschna anacantha</i>	33.8	15.0	Davies et al. (2004)
	<i>Boyeria vinosa</i>	32.5	10.0	Nebeker & Lemke (1968)
	<i>Ophiogomphus rupinsulensis</i>	33.0	10.0	Nebeker & Lemke (1968)
	<i>Libellula</i> sp.	42.8	15.0	Martin & Gentry (1974)
	<i>Macromia illinoiensis</i>	43.1	12.0 to 32.0	Garten & Gentry (1974)
	<i>Neurocordulia alabamensis</i>	42.6	12.0 to 32.0	Garten & Gentry (1976)
	AVERAGE	38.0		
Trichoptera	<i>Cheumatopsyche</i> sp. AV2	30.7	14.0	Davies et al. (2004)
	<i>Parapsyche elsis</i>	21.7	6.5	Gaufin & Hern (1971)
	<i>Limnephilus ornatus</i>	24.8	6.4	Gaufin & Hern (1971)
	<i>Neothrema alicia</i>	25.9	6.4	Gaufin & Hern (1971)
	<i>Drusus</i> sp.	27.3	6.4	Gaufin & Hern (1971)
	<i>Brachycentrus occidentalis</i>	29.7	6.4	Gaufin & Hern (1971)
	<i>Brachycentrus americanus</i>	29.0	10.0	Nebeker & Lemke (1968)
	<i>Aoteapsyche colonica</i>	25.9	15.0	Quinn et al. (1994)
	<i>Pycnocentroides aureola</i>	32.4	15.0	Quinn et al. (1994)
	<i>Pyconocentria evecta</i>	25.0	15.0	Quinn et al. (1994)
	<i>Symphitopsyche morosa</i>	30.4	10.0	DeKozlowski & Bunting (1981)
	<i>Brachycentrus lateralis</i>	32.8	10.0	DeKozlowski & Bunting (1981)
	<i>Hydropsyche</i> spp.	30.3	6.4	Gaufin & Hern (1971)
	<i>Chimarra obscura</i>	36.5	19.0	Moulton et al. (1993)
	<i>Chimarra obscura</i>	31.4	12.0	Moulton et al. (1993)
	<i>Chimarra aterrima</i>	33.6	19.0	Moulton et al. (1993)
	<i>Hydropsyche simulans</i>	35.6	19.0	Moulton et al. (1993)
	<i>Hydropsyche simulans</i>	34.4	12.0	Moulton et al. (1993)
	<i>Ceratopsyche morosa</i>	34.2	19.0	Moulton et al. (1993)
AVERAGE	30.1			
Mollusca	<i>Potamopyrgus antipodarum</i>	32.0	10.0, 16.0 and 24.0	Winterbourn (1969)
	<i>Potamopyrgus antipodarum</i>	32.4	15.0	Quinn et al. (1994)
	<i>Sphaerium novaezelandiae</i>	30.5	15.0	Quinn et al. (1994)
	AVERAGE	31.6		
Oligochaeta	<i>Lumbriculus variegatus</i>	26.7	15.0	Quinn et al. (1994)



Modelled temperatures for Australian systems

Modelled water temperatures for Australian streams without riparian vegetation are shown in Figure 3.2. For most bioregions, the absence of riparian cover results in water temperatures which exceed the tolerance levels for aquatic biota.

Targets and priorities for riparian restoration

The temperature and light inputs of an individual stream reach will depend on a number of factors, including:

- ~ meteorological conditions at the reach,
- ~ channel morphology of the reach,

- ~ flow within the reach,
- ~ the amount of vegetative and topographic shade at the reach, and
- ~ upstream meteorological, channel morphology, flow and shade conditions.

Contrasts between Australian bioregions and catchments depend largely on seasonal effects of air temperature and rainfall. Summer stress will be relatively more exaggerated where high air temperatures co-occur with times of low flow, as is the case in regions with a Mediterranean climate. In the tropics, where high flows occur in summer, in-stream temperatures will exhibit less diurnal variation. An illustration of this biogeographic contrast is provided in Figure 3.3, where

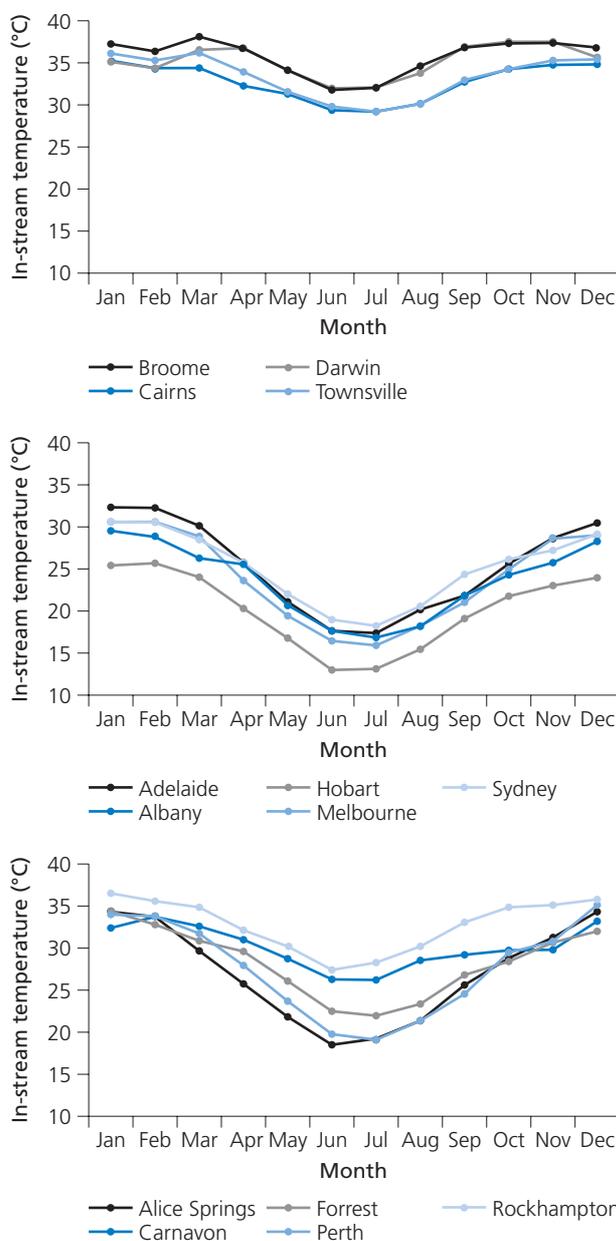


Figure 3.2. Average maximum daily in-stream temperatures at 14 locations for a hypothetical first-order stream having zero shade.



Different types of first-order streams in varying riparian environments. Photos: (top) Canegrowers, (middle and bottom) Peter Davies.

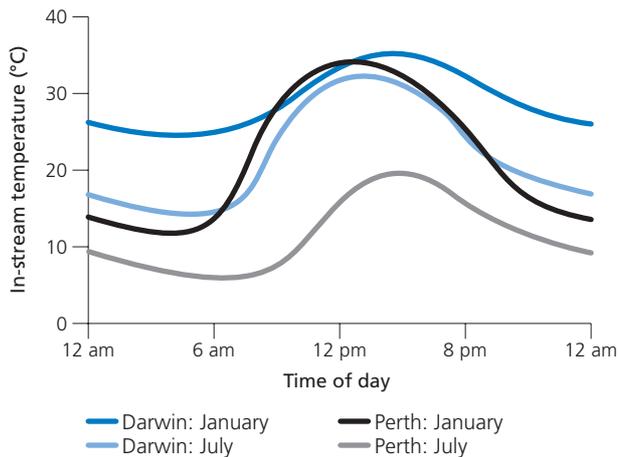


Figure 3.3. Biogeographic and seasonal contrasts in diurnal in-stream temperature. The curves are model simulations representing first order streams having zero shade under flow and weather conditions typical of summer and winter in Darwin and Perth. Note that Darwin's summer curve is considerably flatter than Perth's summer curve because of the higher summer flow in the tropics relative to Mediterranean climates.

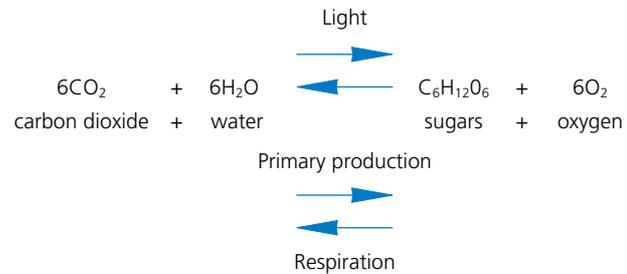
average weather and flow conditions for summer and winter are used to simulate the daily change in in-stream temperature for a first order stream located in south-west Western Australia and in the tropics.

Because *average* monthly weather and flow conditions are used, the curves in Figure 3.3 under-represent the magnitude of day to day variation in in-stream temperature. Individual rainfall events and extreme weather conditions within any one month can have a strong influence on in-stream temperature, even within higher-order streams.

Prior to European settlement and broad scale land clearing, it is reasonable to assume that during the warmest times of the year and during times of low flow, most bioregions and catchments in Australia still experienced periods of temperature stress that equated to lethal or sub-lethal effects for resident biota. At large spatial scales, in times of elevated thermal stress higher order streams would effectively act as seasonal refugia for sensitive components of the biota. At a more local scale, deeper pools in lower order streams may also provide refugia. Under natural conditions, the interplay of climate and flow would sometimes result in the transient loss of habitat and the imposition of thermal barriers to effective dispersal. With the widespread removal or degradation of riparian vegetation, the problem today is that what was once a localised and transient loss of habitat, has become a common feature in space and time throughout many catchments. Shade provided by intact native vegetation is dependent on structural form and plant height (Table 3.2).

3.2 Light

All aquatic plants need sunlight (diffuse or direct) in order to photosynthesise. During photosynthesis, inorganic carbon (CO_2) is transformed into carbohydrates in a reaction described by the 'photosynthetic equation', which (in highly simplified form) can be summarised by $\text{CO}_2 + \text{H}_2\text{O} = \text{CH}_2\text{O} + \text{O}_2$.



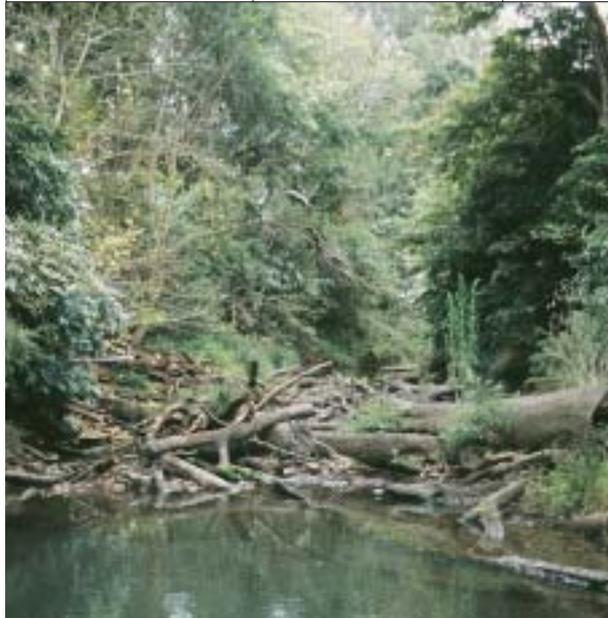
Primary production is determined by the rate of photosynthesis (or the rate at which light energy is converted to organic carbon). Respiration is the opposite process. In respiration, carbon dioxide is a by-product of the consumption of organic carbon by animals and microbes and also of the processes of cellular maintenance in aquatic plants. Consequently, light plays an essential role in the process and rate of photosynthesis, the products of which in turn support the respiration and growth of other aquatic organisms.

The distribution and production of aquatic plants in stream systems can be affected by a number of factors, but light availability is clearly the most important (Hill 1996). An increase in solar irradiation can result in increased production and enhanced biomass values in communities consisting of benthic algae (Lowe et al. 1986, Hill & Knight 1988, Hill et al. 1995) and macrophytes (Canfield Jr & Hoyer 1988).

Optimum light requirements differ for various plant groups and there is evidence that light intensity is a major factor determining the composition of stream algal assemblages (Hill 1996, Mosisch et al. 1999, 2001). For example, chlorophytes (green alga) require higher light intensities than diatoms (Langdon 1988). In a review of published minimum and maximum growth irradiances of phytoplankton groups, cyanobacteria and diatoms were found to be able to tolerate lower light intensities than were chlorophytes (Richardson et al. 1983). The filamentous chlorophyte *Spirogyra* required high irradiance levels to grow and is unable to survive under low light conditions (Graham et al. 1995). Filamentous chlorophytes (particularly members of the Zygnematales, including *Spirogyra*, *Zygnema* and *Mougeotia*) are common in clear-cut, forest streams (Lyford & Gregory 1975, Shortreed & Stockner 1983).

Table 3.2. Structural formations of Australian vegetation (adapted from Specht et al. 1995).

Life form and height of tallest stratum	Foliage cover of tallest stratum (%)			
	100–70	70–30	30–10	<10
Trees >30 m	Tall closed-forest	Tall open-forest	Tall woodland	
Trees 10–30 m	Closed-forest	Open-forest	Woodland	Open-woodland
Trees 5–10 m	Low closed-forest	Low open-forest	Low woodland	Low open-woodland
Trees <5 m	Very low closed-forest	Very low open-forest	Very low woodland	Very low open-woodland
Shrubs >2 m	Closed-scrub	Open-scrub	Tall shrubland	Tall open-shrubland
Shrubs 0.25–2 m	Low closed-scrub	Low open-scrub	Low shrubland	Low open-shrubland
Shrubs <0.25 m			Dwarf open-shrubland	Dwarf sparse-shrubland
Hummock grasses			Hummock grassland	Open hummock grassland
Herbaceous layer	Closed-grassland	Grassland	Open-grassland	Sparse-grassland
Sedges	Closed-sedgeland	Sedgeland	Open-sedgeland	Sparse-sedgeland
Herbs	Closed-herbland	Herbland	Open-herbland	Sparse-herbland
Ferns	Closed-fernland	Fernland		
Reeds/rushes	Closed-reedland	Reedland		



Examples of diverse riparian vegetation. Above: Closed forest. Photo Ian Rutherford. Below: Low open forest. Photo Ian Dixon.

Top: Open heathland. Above: Low open woodland. Below: Open grassfield. Photos this column Peter Davies.





Shaded streams have lower water temperatures that favour in-stream health and productivity. Photos: (left) Roger Charlton, (right) Natalie Blood.

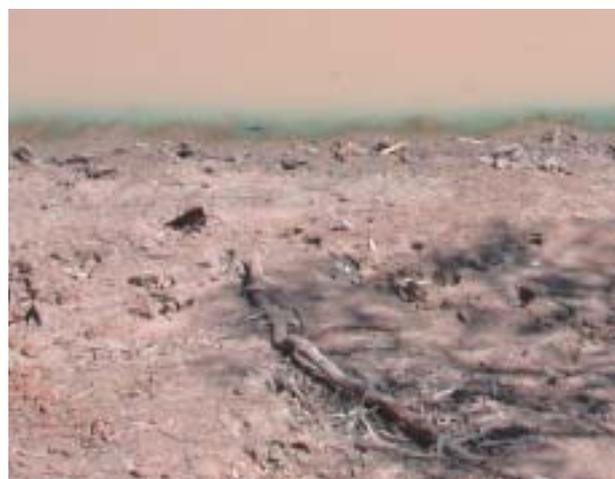
Assessment of aquatic food webs has shown that micro-algae such as diatoms are more readily consumed by organisms higher up the food chain than are larger plants such as filamentous algae and macrophytes (Bunn et al. 1998). Lower light inputs to streams (caused by shade and/or turbidity) and lower water temperatures enhance the production of palatable food material (Bunn et al. 1998, Bunn & Davies 2000). Furthermore, excessive growths of macrophytes and filamentous green algae in stream channels, when stimulated by high light intensity and high nutrient levels, cause major changes in aquatic habitat and can reduce oxygen levels through plant respiration and the decomposition of accumulated organic matter. At high light levels, there is a shift in plant growth to macrophytes (Bunn et al. 1998) which do not readily enter aquatic food webs (Bunn et al. 1997). In this case, macrophytes encroach the channels, increasing the incidence of localised flooding. Shading alone, independent of nutrient status, was found to control invasive macrophytes that had choked the channels of open streams in the tropical canelands of far north Queensland (Bunn et al. 1998) and streams in the sub-tropics (Mosisch et al. 2001).

It is worth noting here that riparian shading may not be the only factor limiting light availability within the water column in some streams and rivers. In many of the inland-draining river systems in central Queensland (such as the Paroo, Warrego, Cooper and Diamantina) sustained high turbidities, which limit light availability, are a natural characteristic. A study of ecosystem processes in the permanent pools of Cooper Creek, near Windorah in Queensland, has revealed a highly productive littoral band of benthic filamentous cyanobacteria (*Schizothrix*)

as a “bath-tub ring” (see photo below) (Bunn & Davies 1998, Bunn et al. 2003). The vertical distribution of this productive band is clearly light-limited in these highly turbid systems.

The previous discussion demonstrates that variations in productivity and composition of aquatic plant groups, which often reflect changed light availability (e.g. following clearing of riparian vegetation), can lead to dramatic changes in the structure and function of stream ecosystems. At one extreme, productive diatom communities in cool, shaded streams can represent a high-quality source of food for primary consumers. At the other extreme, prolific growth of filamentous green algae and invasive macrophytes in open stream channels can lead to loss of aquatic habitat and severe water quality problems.

With turbid water, in-stream production is possible only near the surface and along the shallow margins. Photo Peter Davies.



3.3 Factors influencing the degree of shading by riparian vegetation

The effectiveness of riparian vegetation in shading a stream channel depends on factors such as canopy height, foliage density, channel width and orientation, valley topography, bank height, latitude and season (see Figure 3.4). Up to 95% of the incident solar radiation can be blocked by a full riparian tree canopy covering a narrow stream channel (Hill et al. 1995, Hill 1996). Nuisance stream algae and macrophytes can be significantly restricted by a dense canopy of overhanging riparian vegetation (Mosisch et al. 1999, 2001).

Probably the most visual factor determining the effectiveness of riparian shading is stream channel width. Moving down the stream network, the shading effect of riparian vegetation decreases as the stream channel widens. The total quantity of light available for algae and other aquatic plants in streams is also dependent on

latitude and on seasonal differences in day length and sun angle. An important factor determining the impact of this is the orientation of the stream channel in relation to the trajectory of the sun. In addition to seasonal (or long-term) variations in incident sunlight, benthic stream communities can also be subjected to short-term variations in irradiance; for example, through the sun-fleck effect in a stream channel shaded by dense riparian vegetation (Hill 1996).

Factors such as orientation can have a local effect; canopy cover alone in south-east Queensland explains most of the variation in below-canopy light regime (Bunn et al. 1999, Mosisch et al. 1999). In this study, 75% canopy cover was required to reduce light intensities below the thresholds required for growth of filamentous algae. However, although 75% shading may be needed to reduce the light threshold for aquatic plants, more moderate levels of shading (for example, 50%) may be sufficient to reduce water temperatures — vegetation has

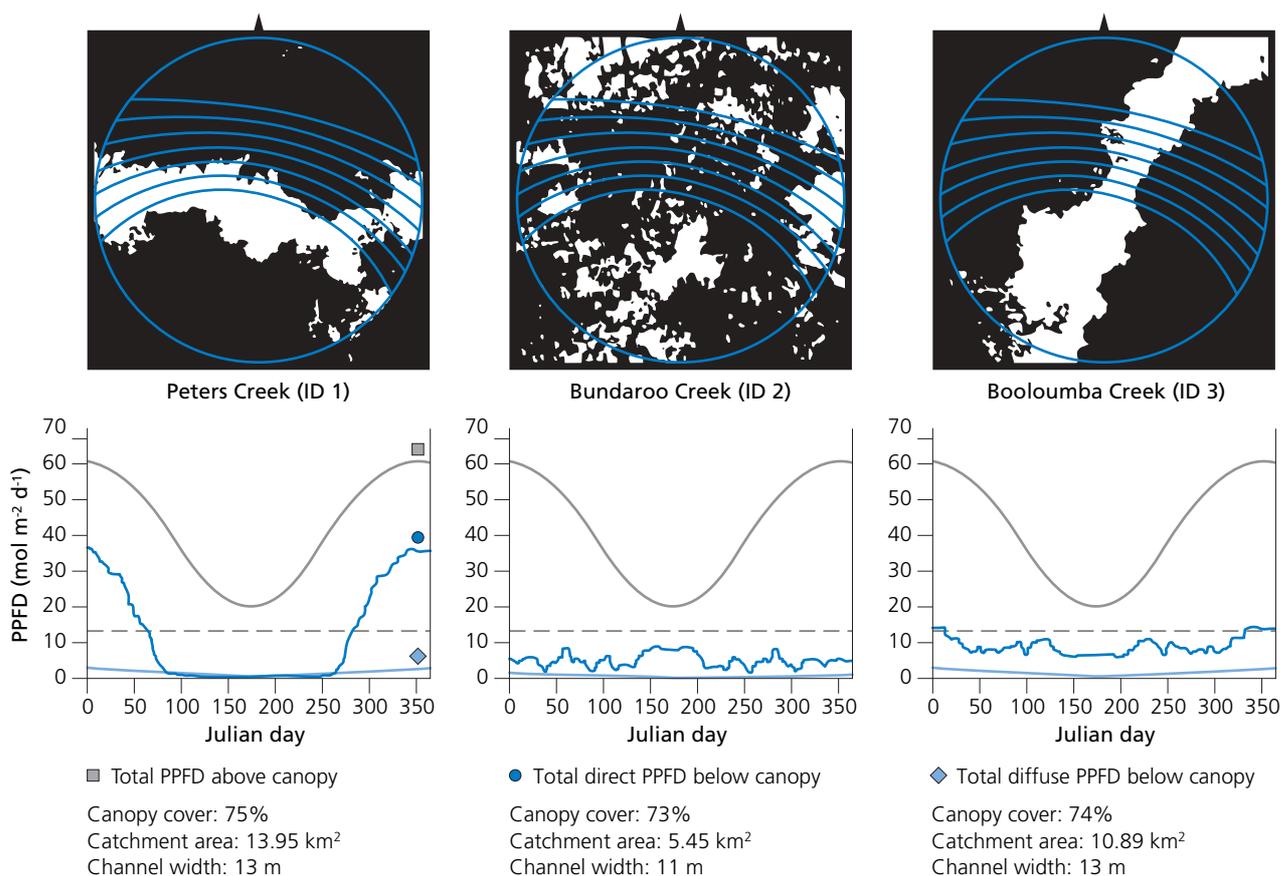


Figure 3.4. Canopy photos and light intensities of forest streams showing effect of orientation in south-east Queensland (Mary River). The dashed line indicates the threshold level of radiation required for growth of filamentous algae (PPFD of 12.8 mol m⁻² d⁻¹). The east–west aligned channel (Peters Creek) is subjected to greatly reduced irradiance levels during the middle of the year as a result of shading by riparian vegetation along the northern stream bank. During summer, stream communities are subjected to highly elevated light intensities as a result of the solar tracks passing along the long axis of the canopy gap. This results in light conditions favourable for the growth of filamentous chlorophytes. In contrast, the north–south oriented channel of the Booloumba Creek site is subjected to much less extreme variation in irradiance because all solar trajectories pass over only a short distance of the canopy gap. Irradiance levels in this case stay at, or below the threshold level required for increased growth of filamentous chlorophytes. Source: Bunn (1997).

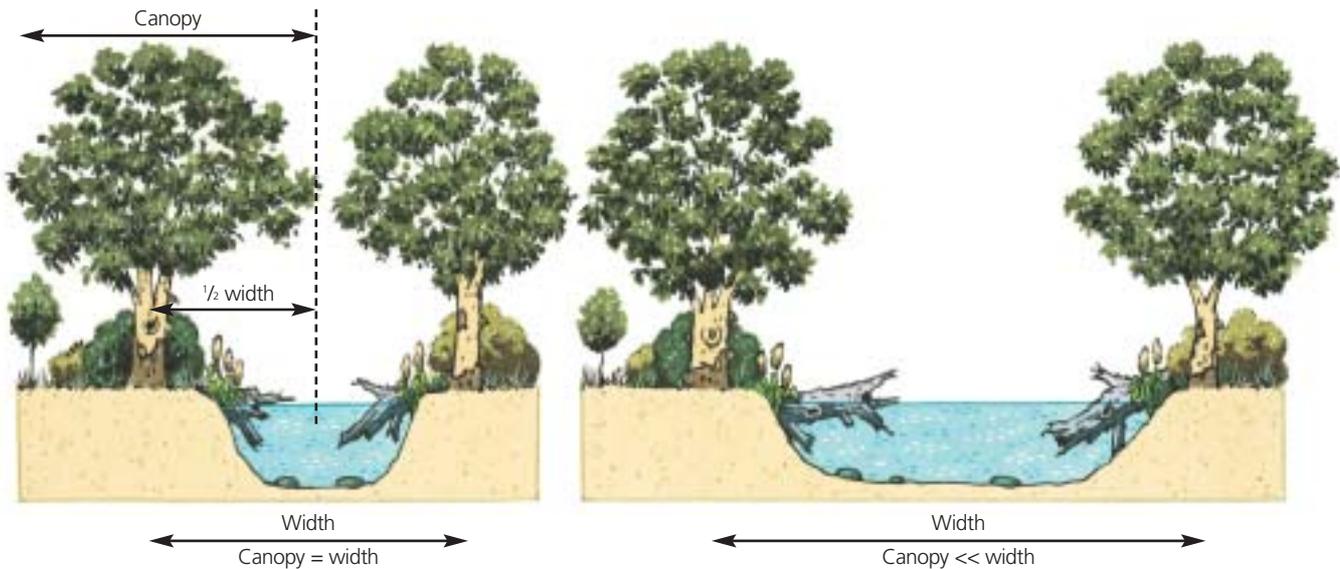


Figure 3.5. Influence of channel width on cover. A small stream could be completely shaded if the active channel width (w) was equal to or less than the width of the tree canopy (c). As channel dimensions increase, and vegetation height and width remain relatively uniform, riparian shading of the channel becomes less effective. Note that the shallow littoral zone may still be effectively shaded even in these larger streams. Source: Unpublished data, T. Mosisch (1997). Illustration Paul Lennon.

a greater filtering effect in the infra-red/red region of the solar spectrum, that is responsible for most of the heating of surface water. Stream orientation may be more important in influencing water temperature in temperate systems.

Even in situations where the main part of a wide stream channel does not receive any shade, algae and aquatic macrophytes located along the edges of the channel can still be subjected to the shading influences of trees and large shrubs for some period of the day (Hill 1996). Consequently, riparian vegetation may exert a major control on the distribution and productivity of semi-aquatic and aquatic plants in the shallow littoral zone of larger rivers.

In rainforest streams, 75% cover can be achieved by mature vegetation on channels about 8–10 metres wide or less; which translates to sub-catchments of ~8–10 km² or less. Note that these relationships will vary with latitude. At higher latitudes (for example, southern Victoria and Tasmania) the canopy cover required to prevent excessive growths of filamentous algae is less than this due to the lower intensity of incoming solar radiation. In more-open forest types, effective shading (75% cover) may be achieved along only smaller streams. Nevertheless, this shade is important as most of the total catchment area is made up of such streams.

This chapter demonstrates that riparian vegetation, which influences the amount of light reaching streams and also water temperatures, has the ability to affect the growth of aquatic plants and animals, water quality, aquatic habitat and ecosystem function. Controlling the

light and temperature environment by maintaining or replanting riparian vegetation is, therefore, an important consideration in the management of riparian areas.

The following guiding principles are important for setting priorities for riparian restoration to meet temperature and light targets (see Davies et al. 2004b):

- ~ Restore upland (lower order) streams before higher order streams (however, for thermal refugia for fish in major rivers, revegetation of tributaries is recommended near the confluence).
- ~ Restore reaches with negligible riparian vegetation before trying to improve low density vegetation.
- ~ Restore streams on north-west aspects before those on south-east aspects.
- ~ Preferentially restore reaches where soil properties favour the establishment of replanted vegetation.

To assist stream managers in setting priorities based on in-stream temperature Land & Water Australia's *River and Riparian Management Technical Guideline*, number 5 'Managing high in-stream temperatures using riparian vegetation' provides a step-by-step process that can be used to determine where restoration efforts need to be focussed. The guideline is available from www.rivers.gov.au or in hard copy from CanPrint Communications on 1800 776 616.

References

- Allan, J.D. 1995, *Stream Ecology: structure and function of running waters*, Chapman & Hall, London.
- Buchanan, J.A., Stewart, B.A. & Davies, B.R. 1988, 'Thermal acclimation and tolerance to lethal high temperature in the mountain stream amphipod *Paramelita nigroculus* (Barnard)', *Comparative Biochemistry and Physiology*, vol. 89A, pp. 425–31.
- Bunn, S.E. & Davies, P.M. 1992, 'Community structure of the macro-invertebrate fauna and water quality of a saline river system in south-western Australia', *Hydrobiologia*, vol. 248, pp. 143–60.
- Bunn, S.E. & Davies, P.M. 1998, *Aquatic food webs in turbid arid zone streams: Preliminary data from Cooper Creek, western Queensland*, NSW National Parks Service, ISBN 0 0349 0991 1.
- Bunn, S.E. & Davies, P.M. 2000, 'Biological processes in running waters and their implications for the assessment of ecological integrity', *Hydrobiologia*, vols 422/423, pp. 61–70.
- Bunn, S.E., Davies, P.M. & Mosisch, T. 1999, 'Ecosystem measures of river health and their response to riparian and catchment degradation', *Freshwater Biology*, vol. 41, pp. 333–45.
- Bunn, S.E., Davies, P.M. & Mosisch, T.D. 1998, 'Contribution of algal carbon to stream food webs', *Journal of Phycology*, vol. 34, pp. 10–11.
- Bunn, S.E., Davies, P.M. & Winning, M. 2003, 'Sources of organic carbon supporting the food web of an arid zone floodplain river', *Freshwater Biology*, vol. 48, pp. 619–35.
- Bunn, S.E., Davies, P.M., Kellaway, D.M. & Prosser, I. 1998, 'Influence of invasive macrophytes on channel morphology and hydrology in an open tropical lowland stream, and potential control by riparian vegetation', *Freshwater Biology*, vol. 39, pp. 171–78.
- Cadwallader, P. & Lawrence, B. 1990, 'Fish', in N. Mackay & D. Eastburn (eds), *The Murray*, Murray–Darling Basin Commission, Canberra.
- Canfield Jr, D.E. & Hoyer, M.V. 1988, 'Influence of nutrient enrichment and light availability on the abundance of aquatic macrophytes in Florida streams', *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 45, pp. 1467–72.
- Claussen, D.L. 1980, Thermal acclimation in the crayfish, *Oronectes rusticus* and *O. virilis*, *Comp. Biochem. Physiol.*, vol. 66A, pp. 377–84.
- Claussen, D.L. & Walters, L.M. 1982, 'Thermal acclimation in the freshwater planarians *Dugesia tigrina* and *D. dorotocephala*', *Hydrobiologia*, vol. 94, pp. 231–36.
- 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 managing New Zealand's rivers and streams. Volume 1: concepts*, Department of Conservation, New Zealand.
- Cox, T.J. & Rutherford, J.C. 2000, 'Thermal tolerances of two stream invertebrates exposed to diurnally varying temperature', *New Zealand Journal of Marine and Freshwater Research*, vol. 34, no. 2, pp. 209–15.
- Davies, P.M., Cook, B., Rutherford, J.C. & Walshe, T. 2004a, 'Riparian restoration reduces in-stream thermal stress', *RipRap*, edition 26, pp. 16–19. ISSN 1324-6941.
- Davies, P.M., Walshe, T. & Cook, B. 2004b, 'Managing high in-stream temperatures using riparian vegetation', *River and Riparian Land Management Technical Guideline*, no. 5, Land & Water Australia, ISSN 1445-3924.
- De Kowzowski, S.J. & Bunting, D.L. 1981, 'A laboratory study of the thermal tolerance of four south-eastern stream insect species (Trichoptera, Ephemeroptera)', *Hydrobiologia*, vol. 79, pp. 141–45.
- DeNicola, D.M. 1996, 'Periphyton responses to temperature at different ecological levels', in R.J. Stevenson, M.L. Bothwell & R.L. Lowe (eds), *Algal ecology — freshwater benthic ecosystems*, Academic Press, San Diego, California.
- Garten, C.T. & Gentry, J.B. 1976, 'Thermal tolerance of dragonfly nymphs. II. Comparison of nymphs from control and thermally altered environments', *Physiological Zoology*, vol. 49, pp. 206–13.
- Gaufin, A.R. & Hern, S. 1971, 'Laboratory studies on tolerance of aquatic insects to heated waters', *Journal of Kansas Entomological Society*, vol. 44, pp. 240–45.
- Gehrke, P. 1994, 'Effects of flooding on native fish and water quality in the Murrumbidgee River', in J. Roberts & R. Oliver (eds), *The Murrumbidgee, Past and Present*, Proceedings of the forum on past and present research on the lower Murrumbidgee River, Griffith, NSW, April 1992.
- Graham, J.M., Lembi, C.A. Adrian, H.L. & Spencer, D.F. 1995, 'Physiological responses to temperature and irradiance in *Spirogyra* (Zygnematales, Charophyceae)', *Journal of Phycology*, vol. 31, pp. 531–40.
- Hancock, M.A. & Bunn, S.E. 1997, 'Population dynamics and life history of *Paratya australiensis* Kemp, 1917 (Decapoda: Atyidae) in upland rainforest streams, south-east Queensland', *Marine and Freshwater Research*, vol. 48, pp. 361–69.
- Heiman, D.R. & Knight, A.W. 1972, 'Upper-lethal temperature relations of nymphs of the stonefly, *Paragnetina media*', *Hydrobiologia*, vol. 39, pp. 479–93.
- Hill, W.R. & Knight, A.W. 1988, 'Nutrient and light limitation of algae in two northern California streams', *Journal of Phycology*, vol. 24, pp. 125–32.
- Hill, W.R. 1996, 'Factors affecting benthic algae — effects of light', in R.J. Stevenson, M.L. Bothwell & R.L. Lowe (eds), *Algal Ecology — freshwater benthic ecosystems*, Academic Press, San Diego, California.
- Hill, W.R., Ryon, M.G. & Schilling, E.M. 1995, 'Light limitation in a stream ecosystem: responses by primary producers and consumers', *Ecology*, vol. 76, pp. 1297–1309.
- Horne, A.J. & Goldman, C.R. 1994, *Limnology*, 2nd edition, McGraw-Hill Inc.
- Hynes, H.B.N. 1970, *The Ecology of Running Waters*, Liverpool University Press, Liverpool, UK.
- Langdon, C. 1988, 'On the causes of interspecific differences in the growth-irradiance relationship for phytoplankton. II: a general review', *Journal of Plankton Research*, vol. 10, pp. 1291–1312.
- Lowe, R.L., Golladay, S.W. & Webster, J.R. 1986, 'Periphyton response to nutrient manipulation in streams draining clearcut and forested watersheds', *Journal of the North American Benthological Society*, vol. 5, pp. 221–29.

- Lyford, J.H. & Gregory, S.V. 1975, 'The dynamics and structure of periphyton communities in three Cascade Mountain streams', *Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie*, vol. 19, pp. 1610–16.
- Martin, W.J. & Gentry, J.B. 1974, 'Effect of thermal stress on dragonfly nymphs', in J.W. Gibbons & R.R. Sharitz (eds), *Thermal Ecology*, Atomic Energy Commission, pp. 133–45.
- Mosisch, T., Bunn, S.E. & Davies, P.M. 2001, 'The relative importance of shading and nutrients on algal production in subtropical streams', *Freshwater Biology*, vol. 46, pp. 1269–78.
- Mosisch, T.D., Bunn, S.E., Davies, P.M. & Marshall, C.J. 1999, 'Effects of shade and nutrient manipulation on periphyton growth in a subtropical stream', *Aquatic Botany*, vol. 64, pp. 167–77.
- Moulton, S.R., Beiting, T.L., Stewart, K.W. & Currie, R.J. 1993, 'Upper temperature tolerance of four species of caddisflies (Insecta: Trichoptera)', *Journal of Freshwater Ecology*, vol. 8, no. 3, pp. 193–97.
- Nakata Kazuyoshi, Hamano Tatsuo, Hayashi Ken-ichi & Kawai Tadashi 2002, 'Lethal limits of high temperature for two crayfishes, the native species *Cambaroides japonicus* and the alien species *Pacifastacus leniusculus* in Japan', *Fisheries Science*, vol. 68, pp. 763–67.
- Nebeker, A.V. & Lemke, A.E. 1968, Preliminary studies on the tolerance of aquatic insects to heated waters, *Journal of the Kansas Entomological Society*, vol. 41, pp. 413–18.
- Quinn, J.M., Steele, G.L., Hickey, C.W. & Vickers, M.L. 1994, 'Upper thermal tolerances of twelve New Zealand stream invertebrate species', *New Zealand Journal of Marine and Freshwater Research*, vol. 28, pp. 391–97.
- Quinn, J.M., Williamson, R.B., Smith, R.K. & Vickers, M.V. 1992, 'Effects of riparian grazing and channelisation on streams in Southland, New Zealand. 2: benthic invertebrates', *New Zealand Journal of Marine and Freshwater Research*, vol. 26, pp. 259–69.
- Richardson, K., Beradall, J. & Raven, J.A. 1983, 'Adaptation of unicellular algae to irradiance: an analysis of strategies', *New Phytologist*, vol. 93, pp. 157–91.
- Rutherford, J.C., Blackett, S., Blackett, C., Saito, L. & Davies-Colley, R.J. 1997, 'Predicting the effects of shade on water temperature in small streams', *New Zealand Journal of Marine and Freshwater Research*, vol. 31, pp. 707–21.
- Rutherford, J.C., Marsh, N.A., Davies, P.M. & Bunn, S.E. 2004, 'Effects of patchy shade on stream water temperatures; how quickly do small streams heat and cool?', *Marine Freshwater Research*, vol. 55, pp. 737–48.
- Shortreed, K.S. & Stockner, J.G. 1983, 'Periphyton biomass and species composition in a coastal rainforest stream in British Columbia: effects of environmental changes caused by logging', *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 40, pp. 1887–95.
- Sloane, R.D. 1984, 'Upstream migration by young pigmented freshwater eels (*Anguila australis australis* Richardson) in Tasmania', *Australian Journal of Marine and Freshwater Research*, vol. 35, pp. 61–73.
- Specht, R.L., Specht, A., Whelan, M.B. & Hegarty, E.E. 1995, *Conservation Atlas of Plant Communities in Australia*, Southern Cross University Press, Lismore, Australia.
- Vannote, R.L. & Sweeney, B.W. 1980, 'Geographic analysis of thermal equilibria: a conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities', *American Naturalist*, vol. 115, pp. 667–95.
- Winterbourn, M.J. 1969, 'Water temperature as a factor limiting the distribution of *Potamopyrgus antipodarum* (Gastropoda-Prosobranchia) in the New Zealand thermal region', *New Zealand Journal of Marine and Freshwater Research*, vol. 3, pp. 453–58.