

Restoring Fundamental Ecological Processes in Small, Forested Upland Streams: The Importance of Riparian Vegetation.

Peter M. Davies¹ and Stuart E. Bunn²

SUMMARY: Knowledge of the sources and fate of energy within ecosystems is considered fundamental for successful management. In three forested regions of Australia, two basic ecological processes involving the sources and fate of energy (measurement of stream community metabolism and carbon isotope food-web tracing) were measured. These measurements showed low rates of metabolism in all streams and the increasing importance of algal material in macroinvertebrate food webs with decreasing latitude. In a focal catchment in southern Queensland where stream conditions ranged from degraded to un-impacted, these ecological processes were measured in association with physical parameters including riparian shade, land-use, nutrient levels and channel morphology. Rates of stream-reach metabolism were highly correlated with the degree of riparian shading with other parameters including in-stream nutrient levels explaining little additional variation. In these upland streams, riparian vegetation is considered to have a dual role in terms of ecosystem processes; shading regulates algal growth and detritus from the riparian zone forms an important component of macroinvertebrate food-webs. Based on these results, we believe restoration of riparian zones, particularly in small catchments (*e.g.* <10km²), will enable the re-establishment of fundamental ecological processes. The restoration of these basic processes is an important pre-requisite for the recovery of structural components of the system (*e.g.* biodiversity).

MAIN POINTS

- Measurement of ecological processes (*i.e.* sources and fate of energy) is an insightful way of assessing the health of rivers and streams.
- Important ecological processes in upland streams are largely dependent on riparian vegetation.
- Proposed shading (by riparian vegetation) of 50%, particularly in small catchments, will have a significant improvement on ecological functions of upland streams.
- Improvements in the upland streams (*e.g.* lower water temperatures) may also protect downstream reaches.

1. INTRODUCTION:

The ecological "health" of rivers and streams is a fundamental water management issue in Australia (Schofield & Davies, 1996). Although assessment of health of rivers typically involves measurement of the patterns of species' distribution and abundance, these ecological "patterns" may not lead to an understanding of basic processes; that is how the system actually "works" (Harris, 1994; Bunn 1995; Bunn *et al.* 1998). In addition, many management priorities of river management and subsequent protection typically refer to ecosystem-level processes (*i.e.* ANZECC 1992).

Direct measurements of ecosystem-level processes, which include the sources and fate of energy

typically integrate the effects of a range of influences possibly over large spatial scales (*e.g.* the catchment). These influences can include increased nutrient concentrations from diffuse or point sources, alterations to the light regime (*e.g.* riparian clearing) and sedimentation. This paper describes stream ecosystem processes in undisturbed catchments, and the consequence of the loss of riparian vegetation in a focal catchment. These ecological processes were studied through the direct measurement of benthic metabolism (*i.e.* amounts of organic carbon produced and consumed within the system), and analysis of the fate of terrestrial and in-stream sources of organic matter in the aquatic food web (stable carbon isotope analyses).

¹ Department of Zoology, The University of Western Australia, Nedlands, Western Australia, 6907 Australia. (tel: 61-8-9380 2275; fax: 61-8-9380 1029; email: pdavies@cyllene.uwa.edu.au).

² Centre for Catchment and In-Stream Research, Faculty of Environmental Sciences, Griffith University, Nathan, Queensland, 4111, Australia. (tel: 61-7-3875 7407; fax: 61-7-3875 7615; email: s.bunn@ens.gu.edu.au).

2. METHODS: Data on undisturbed forested streams were compiled from studies on the Mary River catchment (sub-tropical rainforest) in south-east Queensland, the Johnstone River catchment on 20 sites ranging from relatively pristine to degraded within the Mary River catchment. Measurements of catchment features, riparian attributes and water quality (*e.g.* nutrients) were collected from these sites. Additional data on catchment land-use (GIS) above each of the sites in the Mary River were supplied by the Queensland Department of Natural Resources. Channel slope over the study reaches was surveyed using a dumpy level. Field measurements also included active channel width and stream aspect (upstream-downstream alignment in degrees). Other site-specific data (altitude, stream order, catchment area, and total km of stream channel above sites) were obtained from topographic maps (scale 1:25000). Photographs of the riparian canopy were taken mid-stream at about 50-100 cm above the water surface at each of the study sites, using a 35-mm camera and attached fish-eye lens. Images were then analysed for percentage canopy cover, and used to estimate direct and diffuse photosynthetically active photon flux densities (PPFD), above and below the canopy (ter Steege, 1993). Daily estimates for the period of measurement as well as annual estimates were made, taking into consideration height of the vegetation (measured by clinometer), latitude and longitude, relevant time zone, altitude, and Julian day (see Bunn *et al.* 1998 for further details).

2.1 WATER QUALITY: Water samples were collected from each of the 20 stream sites in the Mary River catchment during August 1996 and analysed for nutrients: oxidised nitrogen, Kjeldahl nitrogen, ortho-phosphate phosphorus and total phosphorus.

2.2 METABOLISM: Community metabolism was measured by monitoring dissolved oxygen within benthic Perspex chambers over 24 hours (see Davies 1994). Small perspex chambers were used to measure metabolism from individual cobbles and larger open-bottom chambers were used in gravel, sand and mud habitats, and were sealed by pushing at least 5 cm into the substrate.

All chambers had a central port for the polarographic oxygen sensor (POS; TPS model 501) and side ports for a 12V recirculating pump. Flow within the chambers was maintained at a similar velocity to that of the particular habitat within the stream. Calibration of the POS was conducted in the field immediately prior to their deployment. Data were recorded at 10-minute intervals by a datalogger. After the end of the measurement period,

(tropical rainforest) in far north Queensland and from the northern jarrah forest (Mediterranean, dry sclerophyll) in south-western Western Australia. In addition, we have included data on the volume of water enclosed by each chamber was measured *in situ* by determining the depth the chamber was pushed into the substrate or, in the case of enclosed cobbles, using the volume of water displaced by the cobble. Cobbles were wrapped in aluminium foil which was later dried and weighed, and cobble surface area estimated using a weight/area regression. The active (photosynthetic) surface area of the cobbles was determined to be half the total surface area (Davies 1994). The amount of carbon produced (benthic gross primary production; GPP) and consumed (respiration; R_{24}) at the stream reach scale was estimated by scaling up habitat-level metabolism values (see Bunn *et al.* 1998).

2.3 STABLE ISOTOPE ANALYSES: Major primary sources were collected by hand, including leaves from riparian trees, aquatic macrophytes, filamentous algae, and epilithic algae (mostly diatoms). Samples of fine (250 μm - 1mm) and coarse (>1mm) particulate organic matter were also collected from the benthos. Aquatic macroinvertebrates were collected with kick-net (250 μm) from major habitats. All samples were kept on ice in the field and subsequently frozen until prepared for stable isotope analysis. Exoskeletons of shrimps and crayfish were removed, as were gastropod shells to avoid possible contamination from non-dietary carbonates (see Bunn *et al.* 1995). Aquatic insects were prepared whole and smaller individuals pooled to obtain sufficient sample sizes. All samples were cleaned, rinsed in distilled water and oven-dried at 60°C for 36 - 48 hours.

Algal carbon isotope ratios from most sites in all three regions were distinct from those of terrestrial (riparian) sources, and the possible contributions of the epilithic algae and terrestrial vegetation to the assimilated carbon in consumers were calculated using a simple two end-point mixing model (Bunn *et al.* 1998) and an isotopic fractionation (f) of 0.2 was used (France 1996).

2.5 DATA ANALYSES: Stepwise multiple regression, with hierarchical inclusion, was used to determine which of the independent variables accounted for most of the variation in stream metabolism (GPP and R_{24}). Appropriate transformations were used to normalise the distribution of the data.

Table 1. Mean rates of reach-scale metabolism from forested sites in the three regions sampled. Standard errors are indicated in parentheses.

Region	GPP mg C m ⁻² day ⁻¹		R ₂₄ mg C m ⁻² day ⁻¹		P/R	
	Summer	Winter	Summer	Winter	Summer	Winter
Johnstone River	198 (31)	164 (23)	380 (36)	264 (63)	0.52 (0.04)	0.62 (0.06)
Mary River	-	152 (58)	-	174 (43)	-	0.87 (0.22)
Northern jarrah forest	125 (12)	86 (21)	255 (16)	168 (22)	0.49 (0.02)	0.51 (0.19)

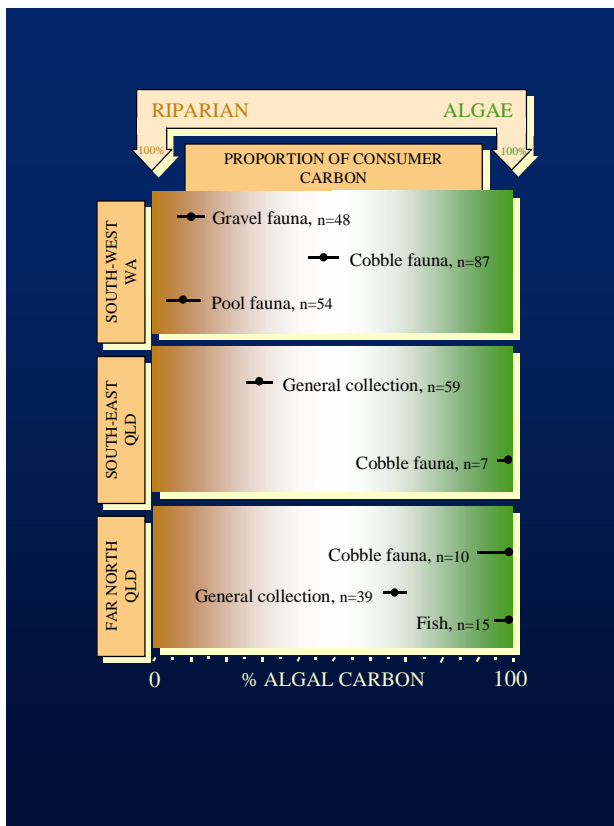


Figure 1. The relative proportion of algal and riparian carbon in the aquatic food-web from three undisturbed sites in the three regions.

3. RESULTS: Rates of benthic metabolism were extremely low in the forested sites from all three regions. Mean rates of GPP ranged from 86 mgC m⁻² day⁻¹ in south-western Australia during winter to 198 mgC m⁻² day⁻¹ in far north Queensland during summer. Mean rates of benthic respiration (R₂₄) were elevated over GPP with values ranging from 168 mgC m⁻² day⁻¹ in south-western Australia during winter to 380 mgC m⁻² day⁻¹ in far north Queensland during summer. All ratios of GPP:R₂₄ were less than one; indicative of a system which is a consumer of carbon.

3.2 STABLE ISOTOPE ANALYSIS: In south-western Australia and south-east Queensland forest streams, algal carbon isotope ratios were more ¹³C-depleted than terrestrial sources. In contrast, algal carbon isotope ratios from streams in the wet tropics in northern Queensland were more enriched (mean δ¹³C ± 1S.E. = -21.8 ± 0.1‰) than terrestrial sources (mean δ¹³C ± 1S.E. = -30.4 ± 0.2‰). These values were used to estimate the contributions of algal carbon to consumer biomass (Bunn *et al.* 1998).

Stream invertebrates in south-western Australia were highly dependent on terrestrial carbon sources in gravel and pool habitats (Figure 1). Although the contribution of algal carbon to macroinvertebrates sampled from cobbles was higher (56%), these represented only a minor proportion of the total stream habitat. Similarly, most invertebrates sampled from south-east Queensland had carbon isotope signatures more similar to terrestrial than algal sources (Fig. 1). However, animals collected from cobbles had carbon isotope signatures very similar to epilithic algae. Most consumers (both invertebrates and fish) sampled from the three forest streams in far north Queensland had values very similar to epilithic algae and quite distinct from terrestrial sources (Fig. 1).

3.3 RIPARIAN INFLUENCES ON ECOSYSTEM PROCESSES: Analyses of sites from relatively pristine to degraded in the Mary River showed that riparian cover accounted for most of the variation in rates of benthic metabolism (Table 1). Riparian canopy cover explained 44% of the variation in GPP at the stream reach scale and 32% of the variation in R₂₄ (Table 2). At the habitat level of cobbles (the major habitat in these streams), riparian canopy cover explained 68% of the variation in GPP and 66% of the variation in R₂₄. Importantly, no other catchment parameters and no water quality parameters were significantly correlated with stream metabolism.

Table 2. Results of stepwise multiple regression with hierarchical inclusion, of benthic metabolism against catchment, riparian and in-stream parameters, for 20 stream sites in the Mary River, winter 1996. The distribution of percentage crops was normalised by an arc-sine transformation. Variation explained by each variable (r^2), and significance levels (p) are shown. Positive or negative values of the slope of the relationships are presented in brackets.

Dependent Variable	Independent Variables	r^2	p
<i>Stream reach</i>			
GPP	Riparian canopy	0.44 (-)	<0.01
	(arcsine) % crops and pasture	0.14 (+)	<0.01
R_{24}	Riparian canopy	0.32 (-)	<0.01
	Water velocity	0.19 (-)	<0.01
	(arcsine) % crops and pasture	0.11 (+)	<0.01
<i>Cobbles</i>			
GPP	Riparian canopy	0.68 (-)	<0.01
	(arcsine) open forest	0.14 (+)	<0.01
R_{24}	Riparian canopy	0.66 (-)	<0.01
	(arcsine) % crops and pasture	0.08 (-)	<0.01

DISCUSSION: Measurements of benthic metabolism in undisturbed forest streams provide a baseline of ecosystem processes in “natural” streams. Consistent with the results of research into forest streams elsewhere in the world (*e.g.* Vannote *et al.*, 1980; Minshall *et al.*, 1985), benthic metabolism of undisturbed streams in the three regions showed they were consumers of carbon ($GPP/R_{24} < 1$). However, although GPP/R_{24} ratios were similar to those reported elsewhere, levels of primary productivity recorded were amongst the lowest measured in the world (Woodwell *et al.* 1978, Webster & Meyer 1997).

Even though undisturbed streams in the three regions were net consumers of carbon (and therefore reliant on the input of carbon from the surrounding terrestrial environment) not all stream food-webs were driven by terrestrial inputs of organic matter. Stable isotope analysis emphasised that stream invertebrates in the northern jarrah forest were almost entirely dependent on terrestrial carbon (also see Gregory *et al.* 1991). The extremely low rates of primary production in these streams (Davies, 1994) and the low diversity of algal grazers (Bunn & Davies, 1990) suggested that algal sources of carbon are not an important food source. However, in contrast, epilithic algae played an important role in the food web of streams in the tropics (far north Queensland). This is despite the low levels of primary productivity and substantial inputs of riparian carbon.

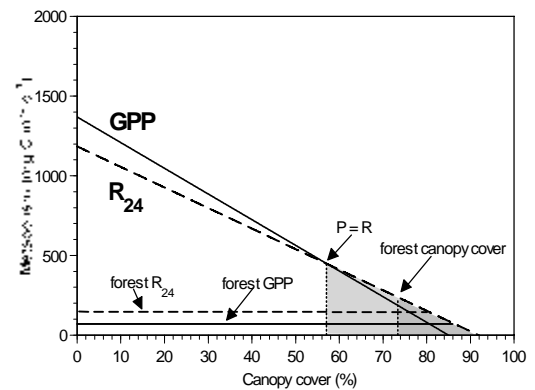


Figure 2: A predictive model of changes in stream metabolism associated with land use (based on data from the Mary River catchment). Light levels in undisturbed riparian zones (*i.e.* >70-75%) should restrict the growth of filamentous algae and invasive macrophytes. However, if canopy cover is reduced below 60%, not only does the stream shift from being a net consumer ($P < R$) to a net producer ($P > R$) of organic carbon, but the composition of aquatic plants shifts from palatable (to macroinvertebrates and fish) microalgae to filamentous algae and macrophytes. After Bunn *et al.*, 1998.

The Mary River catchment indicated that powerful predictive models can be developed that link ecosystem processes with riparian shading (Table 2). Baseline values for GPP and R_{24} obtained for undisturbed forest sites show “natural” rates (see Fig. 2) which were associated with riparian cover of >73% and, using regression equations developed for the Mary River, reductions in canopy cover below this level would result in an increase in primary production. However, a major decline in stream health occurs with increased primary productivity, particularly when GPP exceeds R_{24} and the stream therefore shifts to an autotrophic economy. Based on Figure 2 this would occur when canopy cover is <40-50%.

An important consideration in the assessment of river health is the ability to predict when increased GPP switches from palatable (to macroinvertebrates) microalgae to filamentous algae and/or macrophytes (also see Bunn *et al.* 1997). Filamentous algae have higher light requirements compared to diatoms or benthic cyanobacteria (Langdon 1988, Hill 1996). Much of the variation in below-canopy light in the Mary River sites can be explained by canopy cover alone where: mean daily light ($\text{mol m}^{-2} \text{d}^{-1}$) = $48.1 - 0.48 \times \text{canopy} (\%)$ ($r = 0.90$, $p < 0.001$). Using this relationship, the optimal light threshold for diatoms (*i.e.* $< 9 \text{ mol m}^{-2} \text{d}^{-1}$; Steinman *et al.* 1989) would occur when canopy cover exceeds 80%. In contrast, filamentous green algae such as *Cladophora* ($\sim 26 \text{ mol m}^{-2} \text{d}^{-1}$; Graham *et al.*, 1995), require a canopy cover of less than 50%. Similar relationships have been established between riparian cover and plant biomass (*e.g.* Canfield & Hoyer, 1988).

Riparian vegetation has an important and dual role in ecological processes in streams: the supply of detritus which “drives” aquatic food-webs and the regulation of unpalatable algal growth. A canopy cover of >50% should therefore be the initial target for restoration programs. In addition, riparian shade can substantially reduce water temperatures (Davies-Colley & Payne 1998), the benefits of which (*e.g.* increased dissolved oxygen levels) can be “exported” downstream resulting in improvements in receiving aquatic systems. Riparian regions are also the ultimate supplier of woody debris which is important habitat in streams and rivers (Hawkins *et al.* 1983, Davies & Storey 1998).

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