

**COMPARISON OF CARBON SOURCES
SUPPORTING AQUATIC FOOD WEBS
ABOVE AND BELOW D'ALBERTIS
JUNCTION**



Report prepared for

Ok Tedi Mining Ltd

By

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Frontispiece: River banks at ARM450 (left) and Kuambit (right) illustrating differences in water clarity, presence of algal growth above and within the water, and the ‘tide’ line at Kuambit below which there was no apparent plant growth (Photos Andrew Storey, September/October 2003).

1. EXECUTIVE SUMMARY

Sampling was conducted in the Fly River above and below D'Albertis Junction (ARM450 and Kuambit, respectively) in September/October 2003 to compare the contribution of algal carbon to the aquatic food webs at each location. The study was designed to test the hypothesis that mine impacts had reduced the contribution of algal carbon to the aquatic food web, with the result that riverine food webs downstream of the mine were now more dependent on riparian (rainforest) inputs.

Sampling involved the collection of as many primary sources (algae and terrestrial plants) and primary and higher consumers (prawns, aquatic insects and fish) at each site. Stable isotopes of nitrogen and carbon were then determined in the laboratory to determine sources of carbon (energy) supporting the riverine aquatic food webs at each site.

Analyses indicated that the aquatic food web in the river channel downstream of the mine (Kuambit) had a much reduced contribution of algal carbon compared with the food web above the influence of the mine (ARM450). Comparisons at the species level were constrained by there being few species occurring at both sites. Even so, those species taken from both sites consistently had a more enriched signature (i.e. greater algal carbon contribution) at ARM450 than at Kuambit. Similarly, for species that occurred only at one site, those at ARM450 consistently had a greater percent algal carbon contribution than species taken from Kuambit.

Prior to analysis, carbon isotope data were standardized to allow for between-site differences in the $\delta^{13}\text{C}$ signature of the algal sources; riparian sources had the same signatures across sites. This difference in algal signatures was not readily explicable, but may have been related to between sites difference in the predominant source of CO_2 being assimilated by algae during photosynthesis (i.e. atmospheric versus dissolved organic versus that derived from carbonate rock). There was also a significant temporal difference in algal signatures between the current study and samples collected in 1998. Spatial and temporal variability in algal carbon signatures requires further investigation.

The difference in algal carbon contribution between the two sites corresponded with observed differences in algal cover whilst sampling. At ARM450 algal growth was apparent along the banks and into the water, on exposed unconsolidated mud banks, and on objects floating close to

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the water surface, however, at Kuambit there was no observable algal growth on these habitats except for small patches of algae higher up the banks. An obvious “tide” mark was apparent at Kuambit, with no apparent algal growth below the upper water level.

The influence of turbidity on algal growth was discussed in the context of likely mine-derived stressors affecting algal growth, being:

- ◆ chronic toxicity of algae (i.e. growth retardation) from labile dCu
- ◆ abrasion of algae due to increased TSS
- ◆ limited primary production due to a reduced photic zone, and
- ◆ physical smothering of algal biofilm and microhabitats by silt.

In agreement with world literature on concepts of how tropical rivers function ecologically, it was considered that the organic carbon driving Fly River riverine food webs was likely derived through a range of processes, including downstream transport of organic carbon from forested headwaters, transport of organic matter off the floodplain and into the channel, and local inputs in the forms of in-stream production (algae) and riparian inputs (leaf litter, fruits and woody debris). It was previously calculated that approximately 40% of fish biomass in the river channel had an algal carbon signature, but the proportion of algal carbon derived from riverine versus floodplain production was unknown. However, based on observations in this study, it is likely that in-stream production is a major source of the algal carbon present in the food web of upper forested reaches of the Fly River, and this agrees with a recent review of how Australian tropical rivers function.

Finally, recommendations were made for work to: 1) further our understanding of the spatial variability in algal growth/production; 2) assess temporal variability in the carbon signature of riverine species, and; 3) undertake laboratory studies to differentiate the relative effects of metal toxicity versus suspended sediment on algal growth. These studies will assist in progressing the Bayesian Networks models currently under development as part of the 2005 Environmental and Human Health Risk Assessment.

2. INTRODUCTION

2.1. Background and Rationale to Study

In 1998 OTML undertook a study to identify the carbon (energy) sources supporting the fish faunas of a forested floodplain (OXB06 @ ARM 346; Adjusted River Mile, being the distance upstream in nautical miles from the mouth of the Fly River) and a forested riverine site (upper Fly River at Kawok @ ARM 440) (Bunn *et al.*, 1999). Both locations were believed to be minimally exposed to mining effects (riverine site upstream of mine inputs, and monitoring data at the oxbow lake showed no detectable mine effects), and therefore the study established baseline conditions for the food webs of a riverine and a forested oxbow on the middle/upper Fly River. The stable isotope study identified that for the Fly River upstream of D'Albertis Junction approximately 40% of riverine fish biomass (carbon) was derived from algal sources, with the remaining 60% derived from riparian inputs (fruits, leaves, insects etc), and on the floodplain, approximately 70% of oxbow fish biomass was derived from algal carbon. These percentages were calculated by determining the proportion of the averaged total annual fish catch comprised by each species of fish, and weighting the proportion from each species by the percent contribution of algal carbon to the mean carbon signature of each species. There by deriving an overall mean percent contribution of algal carbon for the fish fauna.

The relatively high contribution by algal carbon to the riverine food web was unexpected, since the Fly River is turbid and it was not thought that significant algal growth was likely. However, algal growth was evident along the channel margins and on floating objects close to the surface. This supports Bunn *et al.* (2003) who reported that a narrow band of algal growth in the photic zone along the margins of highly turbid pools in an arid zone northern Australia river support much of the aquatic food web; the bathtub ring concept. More recently, the contribution of algal carbon to tropical riverine food webs was identified by Douglas *et al.* (2005), who proposed five general principles for how Australian tropical rivers function, one of which being that river and wetland food webs are strongly dependent on algal production.

The importance of algae in providing energy to the Fly River riverine food web has implications with respect to impacts of the mine on the Fly River. From various toxicity tests conducted by OTML on fish, prawns, invertebrates and algae, it is known that algae are the most susceptible to levels of labile copper observed in the river. This has again been shown in routine toxicity tests undertaken by CSIRO in which growth retardation of algae has been observed when

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exposed to levels of bioavailable Cu that occur in the river under the current water quality regime. It therefore seems likely that in-stream algal productivity is reduced due to dCu levels downstream of the mine. In addition to chronic toxicity to dCu, it has also been hypothesised that increased suspended sediment levels, as have occurred due to mine-waste discharge, may reduce algal growth due to a combination of smothering, abrasion and reduced light penetration (i.e. reduced photic zone limiting photosynthesis/area of habitat available for photosynthesis).

Considering the results of toxicity tests, increased TSS, and the observations from the baseline stable isotope study conducted in 1998, it was hypothesised that the component of the riverine food web downstream of the mine dependent upon organic carbon derived from algae could be at risk due to direct effects to algae from one or a combination of factors including:

- ◆ chronic toxicity of algae (i.e. growth retardation) from labile dCu
- ◆ abrasion of algae due to increased TSS
- ◆ limited primary production due to a reduced photic zone, and
- ◆ physical smothering of algal biofilm and microhabitats by silt.

Given the range of potential stressors affecting algae, it was therefore likely that the algal contribution to the food web downstream of the mine could be reduced or even lost. This would mean that the riverine food web downstream of the mine would now be more dependent on riparian inputs, and components previously dependent upon algal carbon, either directly (i.e. grazing invertebrates such as Atyiid shrimps, mayflies and snails) or indirectly (small fish consuming algal grazing insects/Crustacea), may now be lost from riverine sites downstream of the mine.

Monitoring of *Macrobrachium* prawn populations at riverine sites showed that prawns were more abundant downstream of the mine than at upstream control sites (Storey *et al.*, 2001), and fish dietary studies showed that prawns formed a high proportion of the diet of most larger fish species in the river channel compared with floodplain sites (WRM, 1998). Therefore, prawns appear to be a key link in the current riverine food web downstream of the mine. The stable isotope study in 1998 (Bunn *et al.*, 1999) revealed that prawns derive their carbon from riparian sources, and not algae, and would be unlikely to be affected by reduced algal growth *per se*. However, riparian inputs from the forest are likely supporting the prawns, and therefore, indirectly supporting the fish fauna. Given the above stressors likely affecting algal growth, and the predominance of prawns in the diet of riverine fish downstream of the mine, it is

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hypothesised that riverine fish communities below the mine have lost their algal carbon source and are more dependent on riparian inputs.

This raises an added concern in that continued forest dieback throughout the Lower Ok Tedi and upper reaches of the Middle Fly will likely result in further reduced riparian inputs to the river channel. Without these inputs the potential exists for the prawn populations to collapse. This would remove the main food source remaining for riverine fishes downstream of the mine, and would likely lead to a collapse of the riverine fishery.

In response to the issues and concerns listed above, a targeted study of the carbon sources supporting riverine food webs above and below D'Albertis Junction was designed to test the following hypotheses:

- ◆ Is the food web downstream of the mine more dependent upon riparian/detrital organic carbon which would infer the algal carbon signature has been lost?
- ◆ Have sites downstream of the mine lost those species known to depend upon algal carbon?
- ◆ Have species that utilise carbon derived from riparian inputs become more dominant/abundant?
- ◆ Have species predominantly dependent upon algal carbon at upstream sites switched to a riparian signature downstream of the mine, indicating flexibility in diet/resource usage?

2.2. Background to Stable Isotope Analysis

A fundamental consideration to understanding food webs is to first identify the sources of organic carbon that are assimilated by consumers such as aquatic invertebrates and fish. The traditional means for constructing food webs has been to determine what animals are eating by looking at both their feeding mode (grazing, shredding, boring, filtering, predating etc) and their gut contents. However, such direct analysis has inherent deficiencies, including the problems of identifying partly digested items, regurgitation of some foods under capture stress, and underestimation of the importance of those foods which are digested at more rapid rates. In addition, the composition of gut contents only shows what was ingested, it does not tell if ingested items are actually assimilated (i.e. provide energy or structural elements) as opposed to being excreted without further processing. Determination of those components of an animal's diet that are actually assimilated has been simplified with stable isotope tracing techniques (Peterson and Fry 1987, Lajtha and Michener 1994).

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The measurement of stable isotope ratios of carbon and nitrogen in tissue samples has been used to further our understanding of predator-prey relationships and the energy sources supporting aquatic food webs (Peterson and Fry 1987, Lajtha and Michener 1994). The basis of this technique is the accurate measurement of changes in the stable isotope ratios that occur as a result of various biological processes (Peterson and Fry 1987). The carbon isotopes of interest are ^{12}C and ^{13}C and the nitrogen isotopes of interest are ^{14}N and ^{15}N . In order to provide consistency of results, isotopic ratios (R) are usually referenced against a known standard. Results are expressed as shift values (δX) in units of parts per thousand (‰):

$$\delta\text{X} = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 10^3$$

The universally-adopted standard for nitrogen isotope ratio measurements is atmospheric nitrogen, which has a constant isotopic composition, and the standard for carbon isotope ratios is "Pee Dee Belemnite" limestone.

2.3. $\delta^{15}\text{N}$ and its relation to trophic position

Fractionation of nitrogen stable isotopes occurs during trophic transfer and is used to determine the relative trophic position of organisms and the length of food chains (Minagawa and Wada 1984). Enrichment of ^{15}N occurs due to digestion of nitrogen-containing biomolecules (mainly proteins) by organisms and the preferential excretion of ^{15}N -depleted urea and ammonia (Michener and Schell 1999). As a consequence, $\delta^{15}\text{N}$ increases by approximately 3‰ with each trophic level (Minagawa and Wada 1984, Michener and Schell 1999).

Measurement of $\delta^{15}\text{N}$ values also allows some elucidation of intraspecies variations in diet. Fish, which are likely to change their diet as they increase in size, have been found to have increasing $\delta^{15}\text{N}$ with increasing size. For example, a positive relationship has been found between $\delta^{15}\text{N}$ and fork length for king mackerel (Roelke and Cifuentes 1997). Mussels, on the other hand, with a constant feeding strategy throughout the adult life cycle, display no change in $\delta^{15}\text{N}$ over an 8-year period (Minagawa and Wada 1984). In both examples, an enrichment of $\delta^{15}\text{N}$ (3‰) occurred in the consumer, relative to the food.

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The absolute values of $\delta^{15}\text{N}$ of organisms from different systems may not be directly comparable, since differences in $\delta^{15}\text{N}$ values may occur at the base of food-chains. For example, France (1994, 1995) has shown that marine fish may be enriched in ^{15}N compared to freshwater fish, with estuarine and anadromous fish having intermediate values. This may limit the comparison of values across systems or sites. However, differences in baseline variability do not affect the general trend of a 3‰ enrichment of ^{15}N between trophic levels (France 1994, Cabana and Rasmussen 1996).

2.4. $\delta^{13}\text{C}$ and Carbon Sources

The fractionation of carbon stable isotopes occurs at primary producer level. Subsequent trophic transfer of carbon does not appreciably affect ^{13}C ratios. Different photosynthetic routes such as the Calvin cycle (C3), Hatch-Slack cycle (C4) and Crassulacean Acid Metabolism (CAM) result in different $\delta^{13}\text{C}$ values. Terrestrial C3 plants ($\delta^{13}\text{C} \sim -28\text{‰}$) take their carbon from the atmosphere ($^{13}\text{C} \sim -7\text{‰}$) and a net fractionation of about 21‰ occurs during photosynthesis (Peterson and Fry 1987). C4 plants include mainly tropical and salt grasses and their photosynthetic pathway results in a smaller fractionation of about 6‰ (Peterson and Fry 1987). The carbon cycle of aquatic plants is different again, and photosynthesis utilises dissolved CO_2 which may be supplied by carbonate rock weathering, mineral springs, from the atmosphere or from respired organic matter. This causes widely varying $\delta^{13}\text{C}$ values which are subject to site specific and seasonal variations (Peterson and Fry 1987).

Bacterial processes can also affect carbon isotopic signatures (Bunn and Boon 1993). Methanogenic bacteria have been shown to produce methane with significantly depleted $\delta^{13}\text{C}$ (Burke *et al.* 1988, Tyler *et al.* 1988). The depletion depends on the biochemical route of methane formation. Acetate fermentation yields methane with $\delta^{13}\text{C}$ values between -65‰ to -50‰ and this mechanism is thought to dominate in freshwater systems (Hornibrook *et al.* 1997). CO_2 reduction yields methane with $\delta^{13}\text{C}$ values between -110‰ to -60‰ (Whiticar *et al.* 1986). These $\delta^{13}\text{C}$ values are substantially depleted in relation to ratios from photosynthetically-derived carbon compounds.

The variation in carbon isotope ratios for different plants allows consumer organisms to be linked to specific primary producer categories, as the ratio of the food source can be traced through food-chains (Rounick and Winterbourn 1986, Peterson and Fry 1987, Lajtha and

Michener 1994). Due to low water turbulence, periphyton is enriched in ^{13}C compared to pelagic phytoplankton (France 1995). France (1995) has shown that littoral consumers have carbon signatures enriched in ^{13}C compared to pelagic consumers and that this effect is consistent within the extant global data set.

The utility of the $\delta^{13}\text{C}$ method for determining carbon sources, relies upon ^{13}C not being fractionated during food assimilation. In practice, a slight enrichment of $\delta^{13}\text{C}$ occurs with each trophic transfer, however, the fractionation is small (0.5 -1 ‰) in relation to the overall span of $\delta^{13}\text{C}$ values (typically -10‰ to -50‰ for freshwater plants) (DeNiro and Epstein 1978, Rounick and Winterbourn 1986).

Stable isotope analysis of carbon has proved particularly effective in the study of aquatic food webs where there are often marked differences in the isotopic signatures of the major primary sources (e.g. Rounick and Winterbourn 1986; Peterson and Fry 1987; Rosenfeld and Roff 1992; Boon and Bunn 1994). As well as reflecting material assimilated rather than merely ingested, another advantage of stable isotopes over dietary analysis of a consumer is that it provides an integration over time based on body tissue turnover rates (i.e. weeks to months), rather than a snapshot of recently ingested food which may or may not provide energy (Peterson and Fry 1987), and may reflect periodic local abundance of certain food items.

3. METHODS

3.1. Study Design

The current study was based upon replicated sampling of all levels of the aquatic riverine food web from reaches above (Control) and below (Exposed) D'Albertis Junction. The upstream reach, approximately at ARM450, was selected to minimise effects from the mine (i.e. to be generally upstream of effects from overbank flooding, forest dieback and aggradation due to backwater effects; currently mean dCu concentrations at Kiunga, immediately upstream of ARM450 is 0.0056 mg/L, OTML unpub. dat.). The downstream reach, in the vicinity of ARM 410 – ARM420 (referred to as Kuambit), was selected to maximise mine effects (Figure 1).

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Figure 1. The Ok Tedi and Fly River in the vicinity of D'Albertis Junction, indicating the position of ARM450 and Kuambit reaches from which samples for stable isotope analysis were collected in September/October 2003

It was intended to collect replicate samples of all primary sources and primary, secondary and higher consumers at each site, with the aim of collecting as many elements of the food web as possible, with a maximum of 400 samples to be collected from each site. Data collected in the 1998 stable isotope study showed that at least five replicates were required for all major producers (plants, algae etc), and three replicates for major consumers (species of fish, prawns, invertebrates etc) to allow detection of ecologically significant differences in isotopic signatures. Generally, previous studies using this approach demonstrated that variability within sources at a site and time is far less than that between locations or times.

3.2. Field Sampling

Sampling at each site (ARM450 and Kuambit) aimed to collect as many elements of the food web as possible. Sampling included, where present, epi/periphytic algae (collectively referred to from here on as periphyton), seston (including phytoplankton, zooplankton and detritus), submerged and emergent macrophytes, dominant riparian tree/shrub species, detritus, terrestrial grasses, zooplankton, benthic aquatic invertebrates, *Macrobrachium* prawns, and fish species covering different suspected trophic levels and with different dietary sources.

3.3.5. Primary sources

Primary sources were collected by hand from each site. Epibenthic and epiphytic algae were gently scraped with a scalpel blade from leaves and stems of trailing vegetation, roots of trees, the surface of river banks and any other surface where visible algal growth was evident. Banks and exposed bars of fine mud often supported fine growth of filamentous algae. This was isolated by carefully scraping the surface film of silt and algae onto a tray, and then gently washing the material through fine mesh sieves (250 μm , 118 μm and 63 μm) to wash out the silt, leaving the algae behind. Samples of seston (fine particulate organic matter, zooplankton and phytoplankton) were obtained using combinations of fine plankton nets (53 μm , 110 μm and 250 μm mesh) suspended in the flow from the stern of the MV Western Venturer when moored against the shore, and allowing the current to wash seston into the nets.

Aquatic macrophytes and conspicuous, dominant fringing trees, creepers and grasses were collected from each site by removing leaves and (where present) fruits from riparian trees. Generally, the dominant species at each site were selected. Sections of plant with flowers/fruits/seeds were vouchered and sent to the Herbarium at the University of Papua New Guinea in Port Moresby, for confirmation of species names.

Replicate samples of benthic particulate organic matter (POM) were isolated from surficial sediments at each site by elutriation and separation in different mesh sieves. POM was separated into fine (< 250 & >180 μm ; FPOM), medium (< 1.00 & > 250 μm , MPOM) and coarse particulate organic matter (> 1 mm; CPOM).

3.3.6. Invertebrates

At ARM450, vertical clay banks on the outside of meander bends supported burrows of the mayfly *Plethanogesia*. Samples of clay were removed by spade and carefully washed through 4 and 1 mm sieves in an attempt to collect mayfly nymphs.

Four large baited traps were set at each location to catch *Macrobrachium* (Palaemonidae) prawns, with specimens collected from both sites.

Grasshoppers were chosen as representatives of terrestrial primary consumers and were collected from fringing vegetation using a sweep net at both sites. Moths (Lepidoptera) and adult caddis (Trichoptera) were abundant at night around the lights on board the Western

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Venturer, and so specimens were collected opportunistically. An emergence of *Plethanogesia* mayflies occurred during sampling at ARM450, allowing adults to be collected.

Aquatic macroinvertebrates were collected by vigorous sweeping of fringing submerged vegetation, logs and root mats along the banks at each site with a long-handled net (250 µm). Specimens were then picked from a tray. Benthic-dwelling invertebrates (i.e. chironomid midge larvae) were picked from samples of benthic sediment prior to extracting samples of POM.

3.3.7. Fish

Most of the larger fish were caught in standard OTML gill net sets at each location. Hook and line were used opportunistically to collect larger predatory fish. Larval and juvenile fish were sampled from amongst marginal and trailing vegetation and from small backwaters/tributaries using a long handled sweep net. Smaller species and juveniles of larger species were sampled by beach seine net (20 m net, with 2 m drop and 6 mm mesh) deployed off sand bars and exposed banks.

3.3.8. Field processing of samples

All samples were kept on ice in the field and returned to the Western Venturer for processing. Fish were identified to species, individually measured (Standard Length) and a sample of dorso-lateral muscle removed for analysis. Carapace length of prawns was recorded and for large individuals a sample of tail muscle was removed, whilst small individuals were kept intact for subsequent processing. All samples were labelled and frozen prior to being airfreighted to the Stable Isotope Facility at the University of Western Australia, Perth to be prepared under clean room conditions (to avoid contamination) prior to determination of stable isotope signatures (carbon and nitrogen).

3.3. Stable isotope analysis

Primary sources were cleaned and rinsed in distilled water to obtain as pure a sample of each source as possible. Samples of filamentous algae were sorted in a dish to remove any non-algal organic material. Tissue was removed from the exoskeletons of prawns to avoid possible contamination. Small invertebrates were prepared whole and individuals pooled where necessary to provide sufficient biomass for each site. Samples of muscle tissue were used from each of the fish. All samples were then oven-dried at 60°C for 36 - 48 hours, and ground to a powder-like consistency using a miniature ball grinder.

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Dried material was carefully weighed into foil capsules, sealed and then oxidised at high temperature and the resultant CO₂ and N₂ analysed with a continuous flow-isotope ratio mass spectrometer. Ratios of ¹³C/¹²C and ¹⁵N/¹⁴N were expressed as the relative per mil (‰) difference between the sample and conventional standards (PDB carbonate and N₂ in air) where:

$$\delta X = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000 (\text{‰})$$

where X = ¹³C or ¹⁵N and R = ¹³C/¹²C or ¹⁵N/¹⁴N.

3.4. Quality assurance/quality control

Standard QA/QC protocols were applied at all stages of sample analysis:

- (a) Contamination – grinding equipment and other laboratory equipment (including balance) was used only for natural abundance work and was cleaned between each sample to prevent any sample carryover.
- (b) IRMS runs – all runs were checked to ensure beam strengths were within reference sample range and drift corrected. In some instances, (e.g. where considerable variation in isotope signatures was observed among individuals of the same species or if values were different from that expected from previous studies), samples were re-run.
- (c) IRMS precision – all samples were run on dual-isotope mode to obtain both δ¹³C and δ¹⁵N values. In the case of low-N samples (most plant and sediment samples), the %N values were used to re-weigh samples to obtain the same amount of N. These were then re-run in single isotope mode for δ¹⁵N only to enhance precision.
- (d) Reference samples - each sample run included reference samples as well as standards for C and N (reference samples comprise approximately 20% of the total samples analysed in each run). Standards were in turn referenced to Vienna international standards.

3.5. Data Analysis

In the first instance, a process of data reduction was undertaken within each site, using analysis of variance (ANOVA) to test for differences in δ¹³C values amongst closely related sources. For instance, Fine, Medium and Coarse Particulate Organic Matter (FPOM, MPOM and CPOM) from the same location were compared to test for significant differences. Where no differences existed, all replicates were combined as a single source from the site (i.e. the different size fractions of benthic organic matter were combined as POM). Similarly, where different size classes of fish at a site were not significantly different, size classes were combined. This approach reduced the number of individual sources to consider, but increased the sample size for

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each source combined and therefore improved the statistical power of any analyses involving those samples (i.e. ability to detect a difference, should one exist).

As detailed in Section 21., the main aims of the food web study were to determine if the food web downstream of the mine was more dependent upon riparian/detrital organic carbon than at the upstream site relative to algal carbon, whether species known to depend upon algal carbon were absent from the downstream site, whether species that utilise riparian-derived carbon were dominant/abundant downstream, and whether species dependent upon algal carbon at upstream sites had switched to a riparian signature downstream of the mine.

This would be achieved primarily through the pair-wise comparison of primary, secondary and higher consumers collected from ARM450 and Kuambit reaches, to test for significant difference in carbon signatures, which could signify a different carbon source supporting the food web at each site. Prior to undertaking these analyses it was necessary to compare the carbon signatures of the primary sources potentially supporting the food web at each site. Although the carbon signatures of riparian sources (rainforest trees and creepers) are relatively stable spatially and temporally, it is known that the carbon signature of aquatic plants and algae can show considerable spatial and temporal variation, depending on local conditions (France 1994, 1995). This can complicate interpretation of the role of aquatic versus terrestrial carbon sources to aquatic food webs, especially when algal values overlap with terrestrial values, or when carbon signatures of algal sources differ between sites. Without standardising the signatures of comparable sources across sites, it would not be possible to validly interpret between-site differences, since spatial differences in signatures of primary sources could give the appearance of site differences in food web structure, or alternatively, could hide a site difference, such as a systematic shift in carbon signatures.

Analysis indicated that carbon isotope ratios of algal sources were distinct from those of terrestrial (riparian) sources, which will allow the differentiation of algal from riparian carbon at each site. Terrestrial sources had the same carbon signature across both sites, which will allow direct comparison of riparian signatures across sites. However, there was a significant difference in the carbon signature of algal source between ARM450 and Kuambit. This difference was sufficient to prevent direct comparison of unstandardised carbon isotopic signatures between sites, since differences could reflect differences in algal signatures, and not a shift between carbon sources.

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To surmount this issue, the carbon isotopic data were standardised across sites by calculating the contribution of the dominant carbon sources to the assimilated carbon in each higher consumer level using a two end-point mixing model. The model uses the carbon signature of the main, dominant carbon sources (in this case riparian vegetation and algae) to standardise the carbon signature data to percent carbon from a dominant source (algae), thereby facilitating valid between-site comparisons. Carbon isotope data were converted to percentage of assimilated carbon derived from algal sources using the following model:

$$P_A = (\delta^{13}C_{consumer} - f - \delta^{13}C_{sourceB}) / (\delta^{13}C_{sourceA} - \delta^{13}C_{sourceB})$$

where P_A = proportion of carbon in consumer A; and f = isotopic fractionation (‰). In all cases, an isotopic fractionation (f) of 0.2 was used (see Peterson & Fry, 1987, France, 1996, Loneragan *et al.* 1997).

Data from ARM450 were standardised to the percentage of carbon derived from algal sources using the algal signature from ARM450, and similarly, data from Kuambit were standardised to the percentage of carbon in each consumer derived from algal sources collected from Kuambit. Thereby, the data from both sites were standardised to the same scale, as a percentage of assimilated carbon derived from algal sources, allowing inter-site statistical comparisons of carbon signatures.

Stable nitrogen isotope values and data on diet (Storey and Smith 1998) were used to determine which species were secondary (or tertiary) consumers and therefore the approximate trophic position of each consumer.

Mean \pm 95% confidence intervals were calculated for each main group of primary consumers and primary, secondary and higher consumers using the data standardised to the percentage of assimilated carbon derived from algal sources. Dual isotope plots of percent algal $\delta^{13}C$ versus $\delta^{15}N$ were graphed to determine the main carbon sources and the trophic structure of the food webs. Univariate statistics (i.e. ANOVA) were used to test for differences in the carbon signature of each consumer taken from each site and of the whole food web at each site to test for significant between-site differences, which could be interpreted as a mine-effect. Prior to analysis, data were arcsine transformed to meet the assumptions of the ANOVA test on proportional data. Signatures of sources/species collected in 2003 were cross-referenced with

data for the same sources/species collected from Kawok in 1998 to assess temporal change in isotopic signature of carbon sources and consumers at this riverine site.

4. RESULTS

4.1. Field sampling

Field sampling was conducted at ARM450 over 30th September to 1st October 2003, and at the Kuambit reach from 2nd to 4th October. River levels were reasonably stable over the sampling period, fluctuating from a maximum of 7.7 m to a minimum of 6.9 m for the period 30th September to 2nd October (Kawok Rock Bar readings) (Figure 2). Given the relatively small changes in river stage during sampling, it is unlikely that changes in river stage affected the types of habitats or conditions of bank area and habitat that was accessible with respect to wetting and drying and recent past period of inundation.

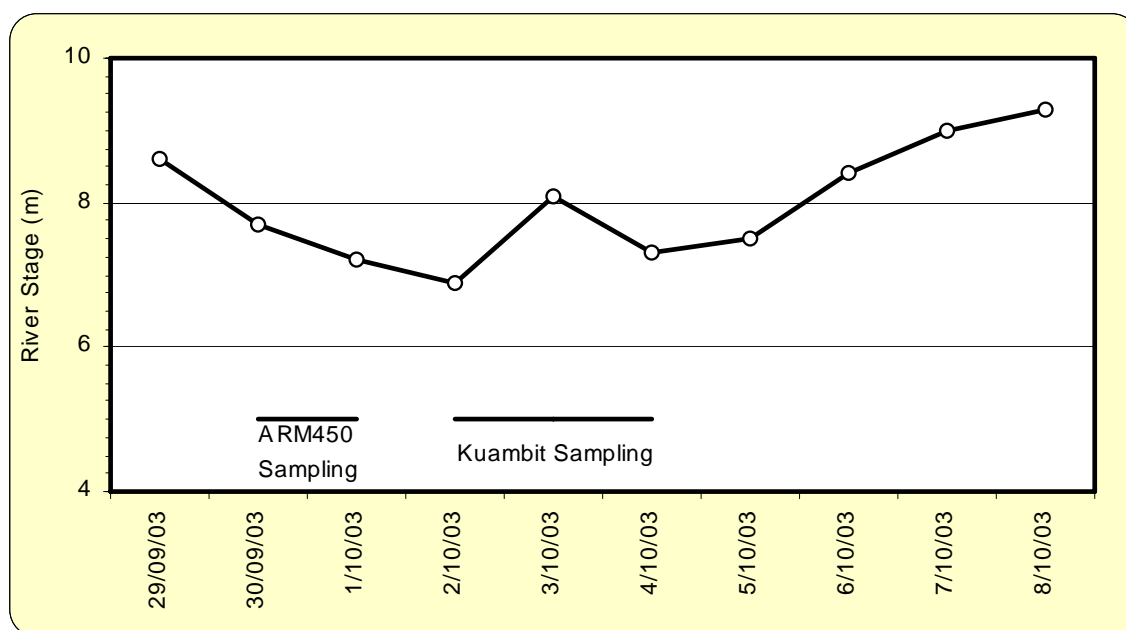


Figure 2. Changes in river stage over the duration of sampling in September/October 2003, indicating periods when ARM450 and Kuambit reaches were sampled. Data taken from Kawok Rock Bar

Attempts were made to collect aquatic macroinvertebrates from each site by extensive, vigorous sweeping of all available habitats, including root mats, woody debris, floating and trailing vegetation and grasses, and accessible river banks and bed. Very few macroinvertebrates were collected from the ARM450 reach, and these consisted of mayfly (Ephemeroptera) and dragonfly (Odonata) nymphs. Insufficient biomass of aquatic invertebrates for isotopic analysis could be found in the Kuambit reach, even after exhaustive searching of all likely/possible habitats.

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Similarly, attempts were made to collect nymphs of the burrowing mayfly *Plethogenesia* from each site. This mayfly constructs deep burrows into clay banks exposed to high velocities, typically found on the outside of meander bends. Burrows were relatively abundant along ARM450, but no nymphs could be recovered from the burrows. However, over the nights of 30th September and 1st October, there was an emergence of adult *Plethogenesia* mayflies, and samples of these adults were collected from the water surface (Plate 1). Adult mayflies live for only 24 hrs, and do not feed, and therefore, their carbon signature should reflect the signature of the nymphs. No burrows were observed on the banks at Kuambit, and no adult mayflies were observed emerging on this reach, therefore, no samples of *Plethogenesia* mayflies could be obtained from Kuambit.

Larval and juvenile fish were collected by vigorous sweep sampling along the shallow edges of the main channel, especially amongst trailing vegetation. Larval and juvenile fish were relatively common and abundant in the ARM450 reach, but were very sparse in the Kuambit reach. Similarly, juvenile fish (i.e. rainbowfish and garfish) were collected by spotlighting and sweep netting at night time at the ARM450 reach, however, the same method failed to capture any fish at Kuambit, and no fish were observed by spotlighting in this reach.

Primary sources at each site consisted of various riparian trees, creepers and grasses on the banks and adjacent floodplain, and algae within the channel. Riparian vegetation at the Kuambit reach has been affected by overbank flooding and associated forest dieback, and therefore was relatively depauperate compared with the ARM450 reach. Algae at ARM450 was observed growing on most substrates, including trailing vegetation, floating woody debris, stems of emergent grasses, mud banks and river banks (Plate 2). Water clarity at ARM450 was such that algae could be seen growing in the water column to a depth of approximately 30 cm (Plate 3). As such, algae at ARM450 were abundant and relatively easy to collect in sufficient quantities to provide adequate biomass for analysis.

The state of algal growth at the Kuambit reach was very different to ARM450. The majority of the banks were devoid of any algal growth (Plate 4), and where there was algal growth, it was very isolated, with sparse cover and was high up the banks. Noticeably, there was a very distinct 'tide' line, with no apparent algal growth below the "high water" mark (Plate 5), and there was no observable algal growth within the water column (Plate 6). Habitats which supported growth of

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algae at ARM450 (i.e. trailing vegetation, floating woody debris, stems of emergent grasses, mud banks) were devoid of algal growth of any form at Kuambit. Samples of algae were obtained from above the 'tide' line on the river banks at Kuambit. Samples were small however, adequate quantities were collected to allow isotopic analysis.



Plate 1. Adult *Plethogenesia* mayflies collected from the Fly River at ARM450.



Plate 2. Extensive algal growth on river banks at ARM450 reach



Plate 3. Algal growth extending into the water column, at ARM450 reach, with a photic zone extending ~ 30 cm below water surface.



Plate 4. Exposed depositional river bank at Kuambit with no observable algal growth.



Plate 5. Exposed river bank at Kuambit supporting algal growth above a distinct 'tide' line.



Plate 6. River bank at Kuambit showing algal growth above a distinct 'tide' line, but with no algae below and no observable algal growth in the water column.

4.2. $\delta^{13}\text{C}$ signatures - ARM450 versus Kuambit

Prior to undertaking the main analyses, ANOVA was used to test for significant between-site differences in the carbon signatures of each main primary source taken from each site. Pairwise analyses of the same sources across sites showed there were no significant between-site differences in the carbon signatures of C3 grasses (Phragmites), C4 grasses (Saccharum, cooch etc), or riparian vegetation (rainforest trees and creepers) (Table 1). There was a small but significant difference in the carbon signature of POM, with Kuambit slightly enriched (-28.90) (i.e. less carbon derived from C3 riparian sources) compared with POM from ARM450 (-29.55), however, this difference wasn't considered ecologically important.

Table 1. Summary of one-way ANOVAs on between-site differences in the carbon signatures of each main primary source taken from each site. Tukeys HSD multiple range test was used to locate between-level differences for significant main effects at $p < 0.05$, and effects are in descending order of $\delta^{13}\text{C}$.

Primary Source	df	F	p-value	Tukeys Multiple Range Test		
Phragmites (C3 grass)	1	0.17	0.7028	Kuambit (-27.3)	=	ARM450 (-27.5)
C4 grasses (Saccharum etc)	1	2.54	0.1452	ARM450 (-11.2)	=	Kuambit (-11.6)
POM	1	20.18	0.0004	Kuambit (-28.9)	>	ARM450 (-29.5)
Riparian trees/creepers	1	0.29	0.5941	Kuambit (-29.8)	=	ARM450 (-29.9)
Algae	1	14.32	0.0014	Kuambit (-20.5)	>	ARM450 (-25.9)

More relevant was a significant between-site difference in the carbon signature of algae (Kuambit = -20.5 and ARM450 = -23.8) and this difference of approximately 3.3 $\delta^{13}\text{C}$ units was considered ecologically significant, especially as algae are known to be a major source of carbon to parts of the food web (Bunn *et al.*, 1999). Because of this difference, further between-site comparisons of primary, secondary or tertiary consumers between ARM450 and Kuambit would be invalid, unless data were first standardised to allow for the between-site difference in algal signatures. Therefore, all data within each site were standardised using the two-point mixing model to convert each $\delta^{13}\text{C}$ value for each consumer to the percentage of assimilated carbon derived from algal sources. For ARM450, the endpoints used in the mixing model were algae (-23.81) and riparian trees/creepers (-29.99), and for Kuambit, the endpoints used in the mixing model were algae (-20.51) and riparian trees/creepers (-29.81). The trophic position of each consumer,

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required to adjust carbon data for fractionation that occurs at each trophic transfer, were assumed from knowledge of life history, diet and from $\delta^{15}\text{N}$ data. Data are presented in Appendix 1, listing each source/consumer by site and faunal/floral group, giving $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ values and percentage of assimilated carbon derived from algal sources for each sample.

Table 2. Summary of two-way ANOVA on between-site and consumer group differences in the standardised carbon signatures of consumers from each site (arcsin transformed). Tukeys HSD multiple range test was used to locate differences for significant main effects at $p < 0.05$, and effects are in descending order of percent algal $\delta^{13}\text{C}$ and effects not significantly different to each other are underlined. Arithmetic mean values for each level are in parenthesis, with values being the percent contribution of algal carbon to total assimilated carbon.

Primary Source	df	F	p-value	Tukeys Multiple Range Test		
Sites	1	34.30	<0.0001	Kuambit (8.0% algal C)	=	ARM450 (18.8% algal C)
Consumer groups	3	24.14	<0.0001	Terrestrial insects (38.2 % algal C)		Prawns (22.2 % algal C)
				Fish (9.3 % algal C)		Aquatic inverts (0.5 % algal C)
Sites x Consumer groups	2	7.88	0.0005			

Once standardized, two-way ANOVA was applied to test for differences in standardised (i.e. the percentage of carbon assimilated from algal sources) $\delta^{13}\text{C}$ signatures of all consumers between-sites ($n = 2$) and broad consumer group ($n = 4$; aquatic invertebrates, terrestrial insects, prawns and fish). Results showed a highly significant between-group difference, as would be expected given the range of species of consumers from different trophic positions sampled. However, a highly significant site effect was also apparent, with a significant interaction term (Table 2). Tukey's HSD range test indicated that consumers at ARM450 contained a significantly greater percent of algal carbon than at Kuambit, and that algal contribution to consumer groups was in the order of terrestrial insects > prawns > fish and aquatic invertebrates. Results are summarised in Figures 3 and 4, showing mean (+/- 1 SE) percent algal carbon for each broad consumer group and individual consumers at each site respectively. Although the interaction term for the two-way ANOVA was significant (Table 2), this likely relates to the absence of aquatic invertebrates at Kuambit and the overlap in SE bars of signatures of prawn compared with fish and terrestrial insects which had no overlap (Figure 3). However, some caution should be exercised when interpreting these results because the mixing models only used signatures of riparian C3 vegetation and aquatic algae as end points. This would therefore imply that terrestrial insects have a high aquatic algal carbon signature. In reality, the inferred high "algal" carbon signature in

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grasshoppers actually reflects consumption of C4 grasses which have an enriched $\delta^{13}\text{C}$ similar to aquatic algae, and the difference in signatures of terrestrial insects between Kuambit and ARM450 (Figure 3) reflects the effects of using riparian v algal end point mixing model on the signatures of this group.

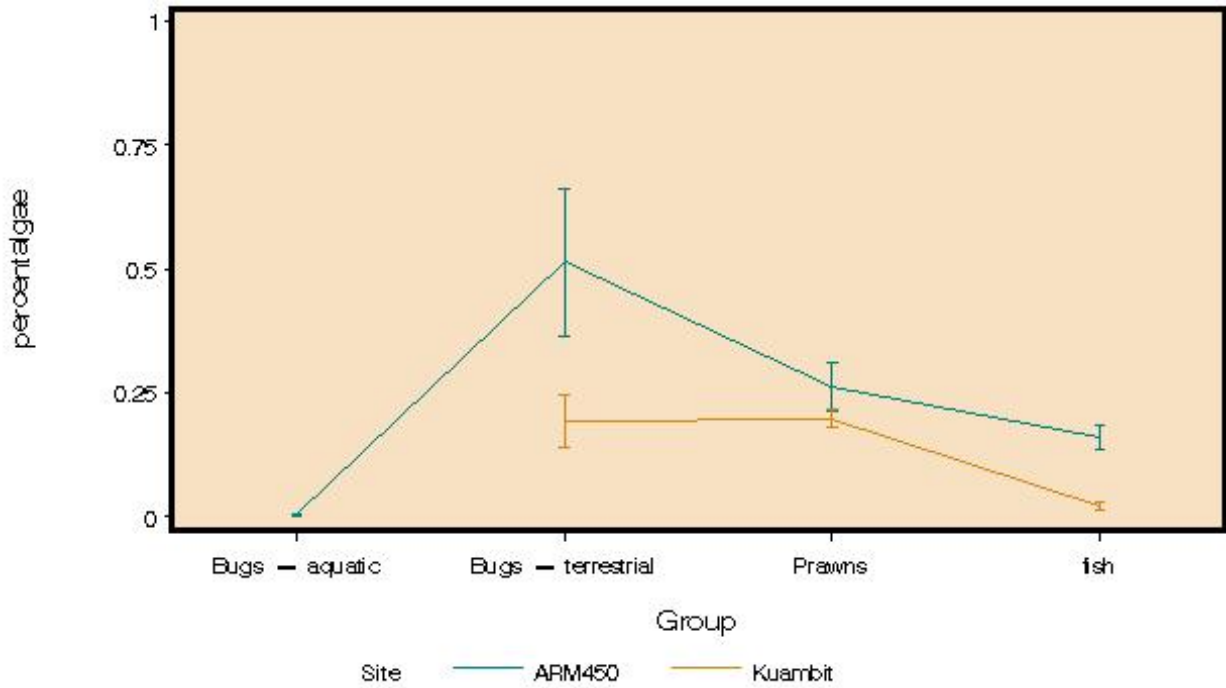


Figure 3. Mean (+/- 1 SE) percent algal carbon in each broad consumer group at Kuambit and ARM450.

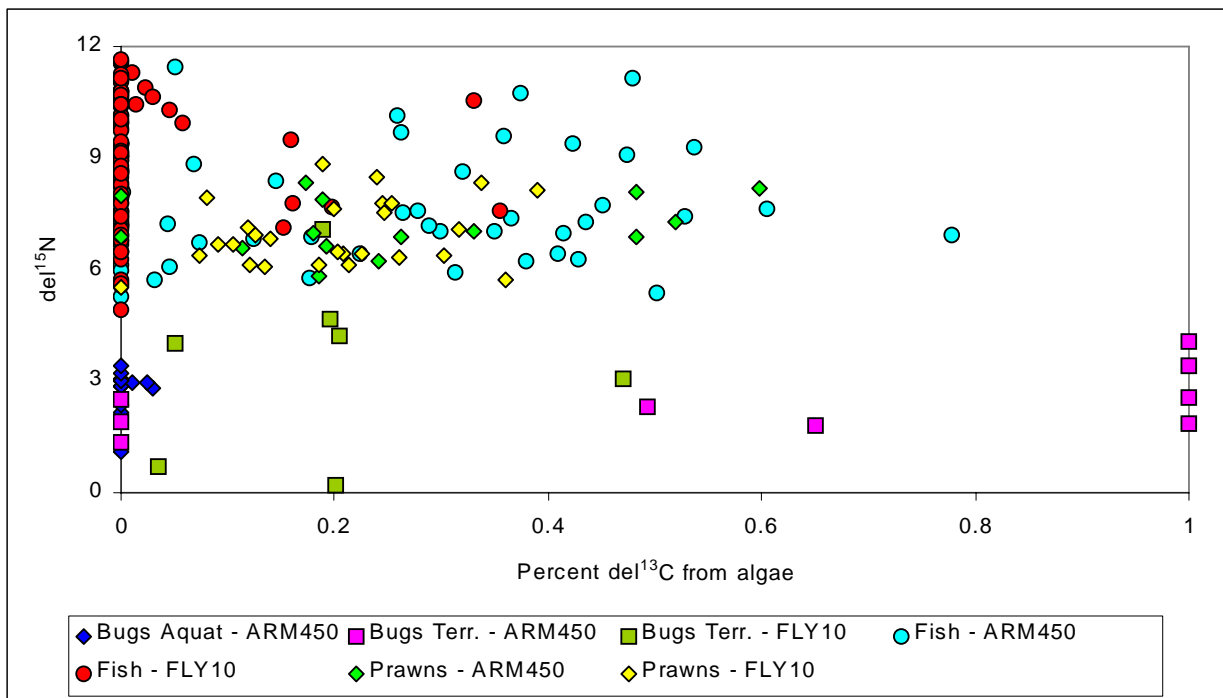


Figure 4. Two-way plot of percent $\delta^{13}\text{C}$ derived from algal carbon versus $\delta^{15}\text{N}$ for consumers classified into broad groupings, indicating individuals collected from ARM450 versus Kuambit (FLY10).

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The two-way plot of $\delta^{13}\text{C}$ by $\delta^{15}\text{N}$ for individual consumers shows a progressive increase in $\delta^{15}\text{N}$ with trophic position (insects/invertebrates < prawns < fish) (Figure 4). The plot also shows that prawns generally have the same $\delta^{13}\text{C}$ signature at both sites, but fish at Kuambit predominantly had a very low algal contribution to their $\delta^{13}\text{C}$ signature (~ 0) compared with fish at ARM450, which had up to 50 to 60% algal carbon (Figure 4).

To further interpret the significance of the between site and consumer group differences in $\delta^{13}\text{C}$ signatures reported by two-way ANOVA, pairwise comparisons of the standardised $\delta^{13}\text{C}$ signature of each individual species and size class within each species collected from both sites was made using one-way ANOVA to test for significant between-site differences. Results of one-way ANOVA by species and size class within species, testing between sites are summarised in Table 3 and Figures 4, 5 & 6. Analyses were constrained by there being relatively few instances of shared species across sites. This likely reflects the differences in species composition above and below D'Albertis Junction due to mine impacts, with species less tolerant of mine impacts, absent from Kuambit. Even so, for tests that were significant, there was a consistent pattern of species/size classes from ARM450 having a greater percent of assimilated algal carbon compared with specimens from Kuambit (Table 3, Figures 4, 5 & 6). For example, $\delta^{13}\text{C}$ signature for *Arius leptaspis* at ARM450 indicated 45% of carbon derived from algae versus 1% at Kuambit, *Neosilurus ater* at ARM450 had 61% algal carbon versus zero at Kuambit, *Macrobrahium rosenbergii* at ARM450 had 48% algal carbon versus 19% at Kuambit, and adult *Melanotaenia splendida* at ARM450 had 37% algal carbon versus 18% at Kuambit (Figure 5). Several other species (i.e. *Oxyeleotris herwerdinii*, *Nibea soldado*) appeared to have a greater contribution of algal carbon at ARM450 compared with Kuambit, but small sample sizes (i.e. $n = 1$ at both sites) provided low statistical power which precluded the tests from detecting any differences.

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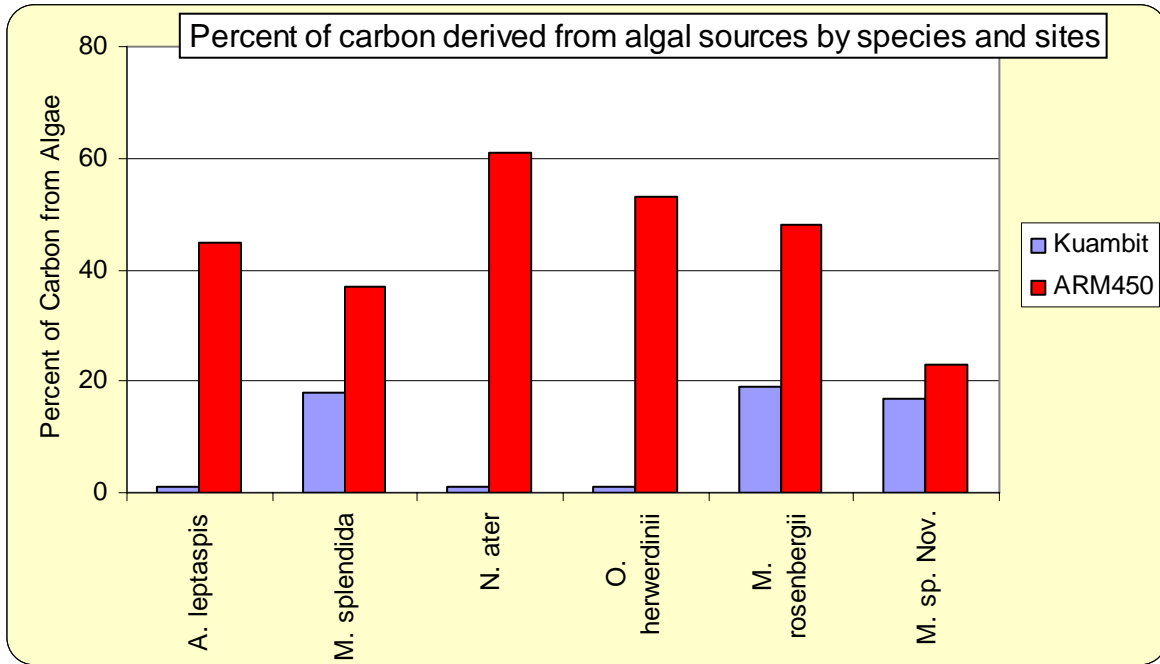


Figure 5. Mean percent $\delta^{13}C$ derived from algal carbon for species of fish and prawns that occurred at ARM450 and Kuambit, illustrating between-site differences.

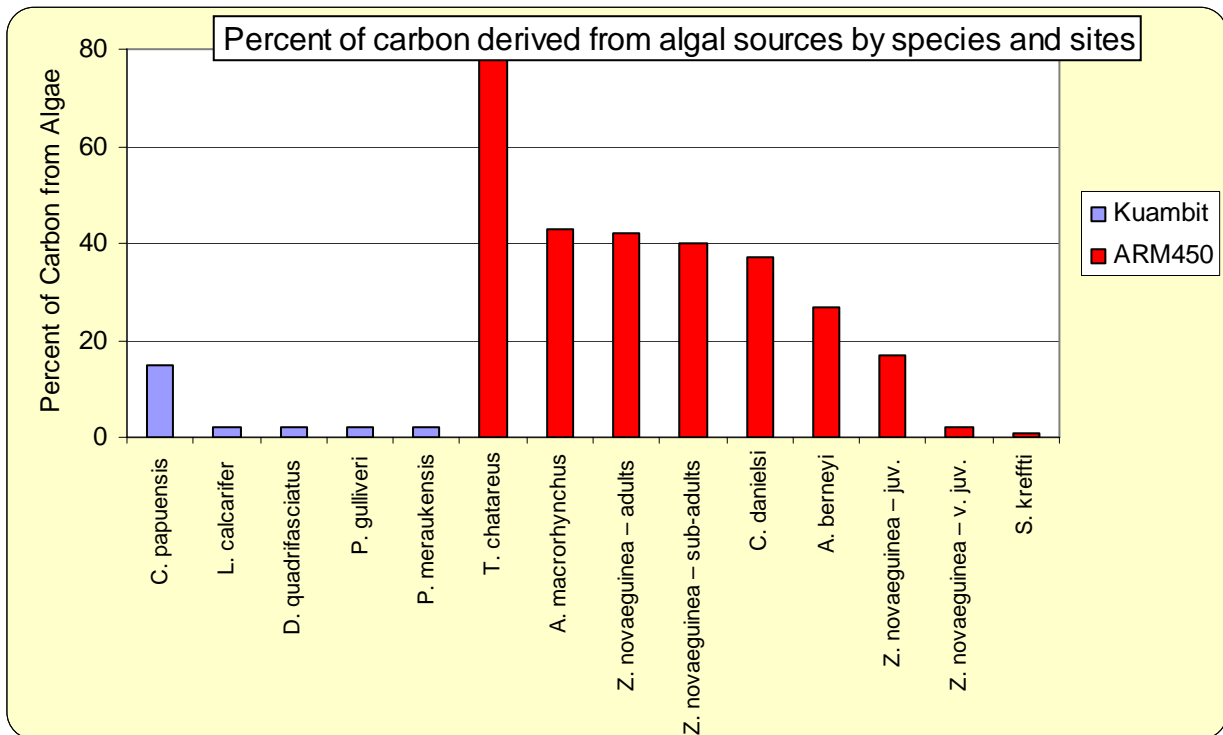


Figure 6. Mean percent $\delta^{13}C$ derived from algal carbon for species of fish taken only from either ARM450 or Kuambit illustrating between-site differences.

As mentioned above, there were large differences in species composition between sites, with approximately half the species recorded only from one site or the other. With a few exceptions,

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those from ARM450 tended to have a relatively high algal carbon contribution, with those from Kuambit generally a low contribution (Table 4, Figure 6).

Table 3. Summary of one-way ANOVAs on between-site differences in the carbon signatures of each species (& size class within species) taken from ARM450 and Kuambit. Tukeys HSD multiple range test was used to locate between-level differences for significant main effects at $p < 0.05$, and effects are in descending order of $\delta^{13}\text{C}$. Arithmetic mean percentage carbon from algal sources are in parentheses.

Species	df	F	p-value	Tukeys Multiple Range Test		
<i>Ambassis agrammus</i>	1	-	-	ARM450 (0%)	=	Kuambit (0%)
<i>Arius leptaspis</i>	1	173.0	<0.0001	ARM450 (45%)	>	Kuambit (1%)
<i>Lutjanus goldeii</i>	1	0.87	ns	Kuambit (0%)	=	ARM450 (0%)
<i>Macrobrachium rosenbergii</i>	1	5.55	0.065	ARM450 (48%)	~>	Kuambit (19%)
<i>Macrobrachium sp.</i>	1	0.08	ns	ARM450 (26%)	=	Kuambit (24%)
<i>Macrobrachium sp. nov.</i>	1	2.36	ns	ARM450 (23%)	=	Kuambit (17%)
<i>Melanotaenia splendida</i> (adults)	1	4.54	0.086	ARM450 (37%)	~>	Kuambit (18%)
<i>Melanotaenia splendida</i> (juveniles)	1	0.27	ns	ARM450 (7%)	=	Kuambit (4%)
<i>Nematalosa sp.</i>	1	0.001	ns	ARM450 (0%)	=	Kuambit (0%)
<i>Neosilurus ater</i>	1	infinity	<0.0001	ARM450 (61%)	>	Kuambit (0%)
<i>Nibeia soldado</i>	1	0.47	ns	Kuambit (18%)	=	ARM450 (0%)
<i>Oxyeleotris herwerdinii</i>	1	-	-	ARM450 (53%)	=	Kuambit (0%)
<i>Terapon lacustris</i>	1	-	-	ARM450 (0%)	=	Kuambit (0%)
<i>Thryssa scratchleyi</i>	1	-	-	ARM450 (0%)	=	Kuambit (0%)

Interestingly, the halfbeak *Zenarchopterus novaeguineae* showed a progressive change in percent algal carbon at ARM 450 with life stage from 2% in larval/very juvenile to 42% in adults, indicating a likely dietary switch with age. The single Archerfish *Toxotes chatareus* showed a

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very strong algal signature (78%), however, this species, as well as ingesting aquatic insects and small fish, also consumes terrestrial insects, and the apparent high algal carbon signature could reflect terrestrial insects with a C₄ grass signature (i.e. grasshoppers feeding on grasses).

Table 4. Species of fish recorded only from either ARM450 or Kuambit, giving sample size and mean percentage carbon derived from algal sources.

ARM450

A. berneyi (n = 6, 27%), *A. macrorhynchus* (n = 2, 43%), *C. danielsi* (n = 2, 37%), *S. krefftii* (n = 5, 1%), *T. chatareus* (n = 1, 78%), *Z. novaeguinea* – adults (n = 2, 42%), - sub-adults (n = 2, 40%), - juvenile (n = 4, 17%), - very juvenile (n = 2, 2%).

Kuambit

C. papuensis (n = 1, 15%), *D. quadrifasciatus* (n = 1, 0%), *L. calcarifer* (n = 10, 1%), *P. gulliveri* (n = 1, 0%), *P. meraukensis* (n = 1, 0%).

4.3. Comparison with 1998 $\delta^{13}\text{C}$ data from Kawok

Comparisons were made between the same sources and consumers collected from Kawok in October 1998 and ARM450 in late September 2003. The two locations are relatively close to each other, Kawok being at ARM440 versus ARM450 sampled in the current study, and sampling occurred at approximately the same season (late dry season), therefore minimizing the potential effects of location and season on isotopic signatures of sources, leaving the main potential effect being time, with samples collected five years apart. Comparisons were made using mean (and range) values from Bunn *et al.* (1999), with data separated into primary sources, primary/secondary consumers and higher consumers.

Initial comparison of potential primary carbon sources showed very strong concordance between the two studies for most sources, with almost identical $\delta^{13}\text{C}$ values for C₃ riparian vegetation (rainforest), benthic detritus, and C₄ grasses (*Saccharum*) (Table 5). There was a large difference in the $\delta^{13}\text{C}$ values of algal sources between the two studies, however, with algal sources more depleted than riparian sources for the Kawok 1998 dataset, but more enriched than riparian sources for the current study (Table 5). This is a relatively large difference in algal signatures between the two studies, but not totally unexpected, since algal carbon signatures are known to vary spatially and temporally, an issue discussed by Bunn *et al.* (1999). The implication of this difference for further comparisons between the two studies means that it is not relevant to compare directly the $\delta^{13}\text{C}$ values of the various consumers in each study, but it is more

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appropriate to compare percent algal carbon as determined by mixing models, as undertaken in section 4.2 to compare ARM450 and Kuambit.

Table 5. Mean stable carbon isotope signatures of major primary sources sampled at Kawok in 1998 (Bunn *et al.*, 1999) and at ARM450 in 2003 (this study).

Source	Kawok (1998)	ARM450 (2003)
Epiphyton/periphyton	-33.4‰	-25.9‰
Seston/plankton	-32.7‰	-29.8‰
C3 Riparian vegetation	-29.8‰	-29.9‰
Benthic detritus	-29.1‰	-29.5‰
C4 plants (<i>Saccharum</i>)	-12.4‰	-11.2‰

Therefore, data on mean percent algal carbon for each species were extracted from Bunn *et al.* (1999) and tabulated against percent algal carbon for the same species collected from ARM450 in 2003. There were five primary and secondary consumers collected both in 1998 and 2003 (Table 5), and 12 higher consumers collected in both studies (Table 6). Data from Bunn *et al.* (1999) separated consumers into habitats (adjacent to *Saccharum* stands or adjacent to rainforest), and Bunn *et al.* (1999) ran mixing models on two algal endpoints (phytoplankton and periphyton) giving a range of possible percent algal contributions, depending on which was the dominant algal source in the diet of the selected consumer.

Comparisons of primary and secondary consumers indicated relatively high disparity in percent algal carbon between the two studies, with the same species having quite different percentages. For example, *Plethanogesia* mayflies varied from 97 – 100% algal carbon (1998; larvae) to 1% (2003; adults), Odonate larvae from 86 – 100% (1998) to 0% (2003), and *M. rosenbergii* from 0% (1998) to 48% (2003). In many instances sample sizes were small, and this makes comparisons problematic, however, some of the differences were apparently large, and this may reflect temporal differences in the signature of algal sources.

Similarly, comparisons of higher consumers indicated relatively high disparity in percent algal carbon between the two studies, with the same species again having quite different percentages. For example, *A. agrammus* varied from 100% algal carbon (1998) to 0% (2003), *A. leptaspis* from 0% (1998) to 45% (2003), *M. splendida* from 0% (1998) to 37% (2003), *Nematalosa*, 100% (1998) to 0% (2003), and *O herwerdenii*, 0-8% (1998) to 53% (2003). Some species, however, had comparable values for percent algal carbon, for example, *G. aprion* with 14-33% (1998) and 8% (2003), *L. goldiei*, 8 – 28% (1998) and 0% (2003), and *N. ater*, 54-67% (1998)

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and 60% (2003) As for primary and secondary consumers, in many instances sample sizes were small, and this makes comparisons problematic, however, some of the differences were apparently large, and this most likely reflects temporal differences in the signature of algal sources.

Table 6: Comparison of percent algal carbon in primary and secondary consumers at Kawok (1998) and ARM450 (2003), presenting mean percent algal carbon for ARM450, and likely minimum/maximum percent algal carbon for Kawok (ref. Bunn *et al.* 1999) (for Kawok data, 'S' = from Saccharum stands, 'F' = adjacent to riparian forest) (number of replicate samples of each species analysed are in parentheses).

Method/Consumer	Kawok	ARM450
	% algal C	% algal C
Primary consumers		
Zooplankton	22-42 (1)	
Atyidae	100 (5)	
Chironomidae – grabs	61-97 (3)	
<i>Plethanogesia</i> mayflies	97-100 (5)	1 (10)
Orthoptera (Site 3)	- (1)	
Trichoptera adults (on ship)	- (1)	0 (1)
Coleoptera (adults)		
Coleoptera (larva)	0 (1)	65 (1)
Secondary consumers		
Odonata (larvae)	86-100 (7)	0 (3)
Hydrobiosidae	100 (1)	
<i>M. handschini</i>	0-9 (6)	
<i>M. lorentzi</i> * (S)	53-60 (5)	
<i>M. lorentzi</i> * (off logs)	25-37 (9)	
<i>M. lorentzi</i> * (F)	0-12 (10)	
<i>M. rosenbergii</i> (S)	0-7 (2)	
<i>M. rosenbergii</i> (F)	0 (6)	48 (1)
<i>M. weberi</i> (S)	0 (3)	
<i>M. weberi</i> (F)	0 (1)	
Macrobrachium sp.		26 (8)
Macrobrachium sp. Nov.1		23 (6)

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Table 7: Comparison of percent algal carbon in higher consumers at Kawok (1998) and ARM450 (2003), presenting mean percent algal carbon for ARM450, and likely minimum/maximum percent algal carbon for Kawok (ref. Bunn *et al.* 1999) (number of replicate samples of each species analysed are in parentheses).

Method/Taxon	Kawok % algal C	ARM450 % algal C
Gill/seine nets		
<i>Ambassis agrammus</i>	100 (3)	0 (5)
<i>Amniataba percooides/affinis</i>	100 (3)	
<i>Arius berneyi</i>		27 (6)
<i>Arius latirostris</i>	0 (6)	
<i>Arius leptaspis</i>	0 (7)	45 (2)
<i>Arius macrorhynchus</i>		43 (2)
<i>Cinetodus crassilabris</i>	0-39 (1)	
<i>Cochlefelis danielsi</i>		37 (2)
<i>Craterocephalus randi</i>	0-8 (1)	
<i>Glossogobius sp.</i>	100 (2)	
<i>Glossomia aprion</i> (>170 mm)	14-33 (10)	8 (3)
<i>Hephaestus roemeri</i>	0-3 (1)	
Larval fish		6 (13)
<i>Lutjanus goldiei</i>	8-28 (1)	0 (1)
<i>Liza diadema</i>	0-19 (1)	
<i>Melanotaenia splendida</i> (juvenile)		7 (3)
<i>Melanotaenia splendida</i> (adult)	0 (1)	37 (3)
<i>Nematalosa sp</i> (99- 125 mm)	100 (8)	
<i>Nematalosa sp</i> (>145 mm)	100 (10)	0 (5)
<i>Neosilurus ater</i>	54-67 (10)	60 (1)
<i>Nibeia soldado</i>		0 (1)
<i>Oxyleotris herwerdenii</i>	0-8 (5)	53 (1)
<i>Parambassis gulliveri</i>	0 (5)	
<i>Plotosus papuensis</i>	0-19 (5)	
<i>Porochilus meraukensis</i>	100 (1)	
<i>Scleropages jardini</i>	6-25 (2)	
<i>Strongylura krefftii</i>	69-89 (3)	1 (5)
<i>Thryssa scratchleyi</i>	0-19 (9)	0 (6)
<i>Toxotes chatareus</i>	0 (7)	78 (1)
<i>Variichthys lacustris</i>	100 (10)	0 (1)
<i>Zenarchopterus novauguineae</i> (<60 mm)		10 (6)
<i>Z. novauguineae</i> (>68 mm)		41 (4)
Saccharum -sweeps		
<i>Craterocephalus randi</i> (larvae)	100 (10)	
<i>C. randi</i> (<20mm)	78-97 (7)	
<i>C. randi</i> (<40 mm)	92-100 (9)	
<i>C. randi</i> (41-55 mm)	100 (10)	
<i>C. randi</i> (> 60 mm)	56-75 (10)	
<i>Glossogobius sp</i>	0 (2)	
<i>Glossomia aprion</i> (<40mm)	100 (3)	
<i>G. aprion</i> (< 50 mm)	97-100 (10)	
<i>G. aprion</i> (>75 mm)	67-86 (5)	
<i>Melanotaenia splendida</i> (< 50 mm)	86-100 (10)	
<i>M. splendida</i> (<65mm)	100 (9)	
<i>M. splendida</i>	47-67 (10)	
<i>Toxotes chatareus</i>	0 (1)	
<i>Variichthys lacustris</i>	78-97 (1)	
<i>Zenarchopterus novauguineae</i> (<60 mm)	0-8 (5)	
<i>Z. novauguineae</i> (>68 mm)	3-22 (10)	

5. DISCUSSION

5.1. Comparison of carbon sources

Samples collected in this study indicate that the aquatic food web in the river channel downstream of the mine (Kuambit) has a much reduced contribution of algal carbon compared with the food web upstream of the mine (ARM450). Comparisons at the species level were constrained by there being few species occurring at both sites. Even so, those species taken from both sites consistently had a greater algal carbon contribution at ARM450 than at Kuambit. Similarly, for species that occurred only at one site, those at ARM450 consistently had a greater percent algal carbon contribution than species taken from Kuambit.

Interestingly, Bunn *et al.* (1999) noted that fish sampled from Kuambit by Power *et al.* (1995) had higher $\delta^{13}\text{C}$ signatures compared with data collected from Kawok in 1998. It was hypothesized that fish at Kuambit were more dependent upon forest inputs, having lost their algal inputs, however, Power *et al.* (1995) did not sample primary sources at Kuambit and so it was not possible to exclude a temporal shift (*viz.* enrichment) in the algal signature, but with no effective difference in the percent algal contribution. The current study tends to support the initial contention that algal sources were reduced at Kuambit.

As noted above, data were standardized using two-point mixing models as per Bunn *et al.* (1999) prior to analysis to allow for between-site differences in the $\delta^{13}\text{C}$ signature of the algal sources; riparian sources had the same signatures, however algal sources had significantly different $\delta^{13}\text{C}$ signatures across sites. The difference in algal signatures across sites is not readily explicable, apart from an effect due to the mine or source of carbon assimilated.

Photosynthesis in aquatic plants (algae, macrophytes etc) utilises dissolved CO_2 which is obtained from a range of sources, including weathering of carbonate rock, mineral springs, the atmosphere or from respired organic matter. Variation in sources of CO_2 causes widely varying $\delta^{13}\text{C}$ values in algae, which, as a result may be subject to site specific and seasonal variations (Peterson and Fry 1987). Differences in algal signatures between Kuambit and ARM450 may reflect a difference in the dominant source of dissolved carbon available for assimilation during photosynthesis. As part of mine environmental management, limestone is continually fed into the waste rock stream to mitigate ARD risk in the mine area creeks, and this also influences buffering capacity in the Ok Tedi and middle Fly. The input of limestone may well result in a different carbonate content in the river downstream of the mine compared with that coming

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from the upper Fly, which would likely exhibit a greater influence from respired organic matter. This may be sufficient to modify the carbon signature of algae downstream of the mine. Alternatively, samples of algal at Kuambit were collected from higher on the banks than at ARM450 due to there being no visible algae in the water column or on the lower banks. Algae at Kuambit would therefore experience less frequent inundation, and as a result, algae at Kuambit may depend more on atmospheric CO₂, compared with populations at ARM450 which were inundated, and therefore exposed to dissolved sources of carbon. This aspect requires further investigation to determine reasons for differences in algal signatures and an indication of temporal variability.

In the current study, algal signatures were more enriched than C3 plants from the same site, however, Bunn *et al.* (1999) reported algal signatures as more depleted than C3 plants, which is a relatively large temporal shift and a fundamental change for the same site, particularly in a tropical system without a strong seasonal signal to influence growth rates, respiration rates, sources of carbon etc. Interestingly, data collected for OTML from floodplain sites in February 2005 (AW Storey, unpub. dat.) showed carbon signatures of algal and plankton sources to be more enriched than C3 plants, supporting the current study. This aspect requires further investigation, to better determine temporal variability in δ¹³C signatures of algae.

Table 8. Mean δ¹³C signatures of primary producers and consumers collected during the current study at Kuambit (FLY10) and ARM450, and from Lake Murray by Bowles *et al.* (in prep; 2001). Data for Lake Murray provided by Simon Apte (CSIRO).

Species	Lake Murray	ARM450	Kuambit
Algae	-21.3	-23.8	-20.5
Seston	-29.8	-29.8	
<i>Nematalosa</i>	-31.5	-34.4	-34.7
<i>A. berneyi</i>	-28.6	-28.0	
<i>S. krefftii</i>	-29.2	-30.9	
<i>T. chatareus</i>	-25.9	-24.8	
<i>T. scratchleyi</i>	-30.1	-36.1	-34.0
<i>L. calcarifer</i>	-28.2		-31.0

As well as data collected from the Fly River by Bunn *et al.* (1999), and in the current study, data for the Strickland River were provided by Simon Apte (CSIRO) from an independent study undertaken on the food web of Lake Murray (Bowles *et al.* in prep.; Bowles *et al.* 2001). Although no attempt has been made to standardize data for differences in algal and riparian sources, the data showed strong consistency in δ¹³C signatures for primary producers, seston and for species of fish that were recorded across studies (Table 8). This tabulation indicates that if

short-term temporal variability in algal signatures was ignored, and it was assumed that primary and higher consumers integrated any short-term variations into an averaged algal signature, the consumers listed in Table 8 essentially have the same $\delta^{13}\text{C}$ signatures. The consistency across study sites provides confidence in the approach, whereby species from Lake Murray appear to be assimilating carbon from comparable energy sources. Similarly, although there was a greater diversity of consumers at ARM450 than at Kuambit in the current study, especially those with a relatively high algal $\delta^{13}\text{C}$ contribution, higher consumers at both sites had similar $\delta^{13}\text{C}$ signatures prior to any standardization using mixing models, but differences in algal signatures influenced how the data were interpreted. Therefore, temporal variability in algal signatures (riparian signatures appear very stable in time) needs further investigation.

5.2. Site conditions

Whilst collecting samples for the current study, a difference in the availability of algae was very apparent between ARM450 and Kuambit, and this supports findings from data analyses. At ARM450, algal growth was apparent along most of the exposed banks and into the water, with algal growth observable into the water column to a depth of 30 – 40 cm along the edge of the channel. Similarly, algae were present on exposed unconsolidated mud banks, and on objects floating close to the water surface and within the photic zone (i.e. stems of floating grasses and on woody debris). However, at Kuambit there was no observable algal growth on areas of exposed unconsolidated mud banks, floating objects also were devoid of algae, and on the banks there were small patches of algae only higher up the banks, but further from the waters edge. In fact, there was an apparent ‘tide’ line reflecting a recent drop in water level, with no visible algal growth below the upper water level. Although not measured, the photic zone at Kuambit would have been much less (i.e. maximum photic zone likely only several cm) than at ARM450 due to the high levels of TSS. This, in itself would likely limit algal growth to a very narrow strip along the waters edge.

Bunn *et al.* (2003) studied a naturally highly turbid arid zone river system in western Queensland, Australia, characterized by zero flows in the dry season, but constant high turbidity in permanent river pools, presumably from suspended colloidal clays. They observed a narrow but very productive band of algal growth in the very restricted photic zone along the margins of the pools, and this band was sufficient to drive much of the aquatic food web (i.e. give an algal signature to higher consumers). This phenomenon was referred to as the bathtub ring concept, whereby a narrow band of algal growth around the margins could drive a food web. The upper Fly River

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likely would have a lower turbidity than pools studied by Bunn *et al.* (2003), and therefore a greater photic zone with greater potential for algal production. As such, the role of algal carbon in food webs observed in this study, and by Bunn *et al.* (1999) is not unexpected. Based on observations of Bunn *et al.* (2003), it could be expected that there would still be a narrow band of algal growth in the river channel downstream of the mine, even though the photic zone was much reduced. This would lead to a greater than currently observed contribution of algal carbon to the downstream food web. Therefore, the loss of algal carbon downstream of the mine suggests that factors other than high turbidity/reduced photic zone are playing a role.

As discussed above, considering the results of toxicity tests, increased TSS, and the observations from the baseline stable isotope study conducted in 1998 (Bunn *et al.*, 1999), it was hypothesised that the component of the riverine food web downstream of the mine dependent upon organic carbon derived from algae could be at risk due to direct effects to algae from one or a combination of factors including:

- ◆ chronic toxicity of algae (i.e. growth retardation) from labile dCu,
- ◆ abrasion of algae due to increased TSS,
- ◆ limited primary production due to a reduced photic zone, and,
- ◆ physical smothering of algal biofilm and microhabitats by silt.

Inference from Bunn *et al.* (2003) would suggest that algae may survive under conditions of high turbidity (suspended colloidal clays) giving a low photic zone. The Fly River downstream of the mine has a reduced photic zone, but as a result of high total suspended sediment load, which, although related to turbidity, is not directly equivalent. Therefore, although reduced photic zone may not be as important as previously postulated, the effects of chronic toxicity from metals, abrasion from high TSS and smothering/siltation of growth surfaces may still be important mechanisms for loss of algal growth below D'Albertis Junction.

5.3. Concepts of river function

Understanding how rivers function often assists in understanding how stressors affect aquatic systems. Existing models of ecological processes differ in the interaction between a river and its catchment, particularly in the sources and delivery of organic carbon that supports food webs. The River Continuum Concept (RCC) (Vannote *et al.* 1980) emphasizes an upstream-downstream linkage in energy flow, whereby organic carbon derived from forested headwater regions supports downstream ecosystems. Fine particulate organic matter (FPOM) from terrestrial vegetation is the

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principal carbon source for food webs in downstream reaches, and much of this is derived from upstream input and downstream movement following physical and biological “processing”.

The Flood Pulse Concept (FPC) (Junk *et al.* 1989) emphasizes river-floodplain interactions in some large (floodplain) rivers, and proposes that riverine food webs are driven by production from the floodplain rather than by organic matter transported from upstream areas. These links occur during flood events and material from the floodplain is transported back into river channels when floods recede.

A third concept for carbon fluxes in some large rivers is the River Productivity model (RPM; Thorp & DeLong 1994). This model emphasizes the importance of local carbon inputs in providing energy (carbon) to the system. These inputs consist of in-stream primary production (phytoplankton, benthic algae, and other aquatic plants) and local inputs of carbon (i.e. leaf litter, terrestrial insects) from the adjacent riparian zone.

The Fly River system likely functions through a combination of all three models. There is downstream transport of coarse and fine particulate organic matter (woody debris, leaf litter and finer material) from forested headwaters, there is transport of organic matter off the floodplain and into the channel as floods recede (direct wash-out as well as return of foraging fish/invertebrates into the channel), and there are local carbon inputs in the form of in-stream production (algae observed along banks) and riparian inputs (local inputs of leaf litter, fruits and woody debris). Bunn *et al.* (1999) calculated that approximately 40% of fish biomass in the river channel had an algal carbon signature, but noted that the proportion of algal carbon derived from riverine versus floodplain production was unknown. The current study does not, and was not intended to elucidate this issue further, however, based on field observations (presence of algal in the channel) and the biology of the species of fish involved (i.e. *Nematalosa* herrings being predominantly a floodplain species), the source of the algal carbon is likely a mixture of riverine and floodplain production. Although floodplain production can not be discounted in the upper forested reaches of the Fly, the open water habitat is relatively minor compared with the open, grassed floodplain in the middle/lower Fly, and it is likely that in-stream production may be the major source of algal carbon to the food web in the upper Fly.

The importance of in-stream production by algae to riverine food webs was recently acknowledged by Douglas *et al.* (2005), who proposed five general principles for how tropical

rivers of northern Australia function, one of which was that riverine and wetland food webs are strongly dependent on algal production. They argued that identifying the sources of organic matter that support aquatic fauna is of fundamental importance in understanding how rivers and wetlands function as ecosystems, and that microalgae play a disproportionately important role in food webs relative to other aquatic plants. The review by Douglas *et al.* (2005) highlights the importance of understanding the relative contributions of algal and riparian carbon to the aquatic food webs of the Fly River, and the potential effects of mine impacts through modifying availability of these carbon sources. This study supports the above contention that algae are important, and loss of this carbon source has occurred, with implications for ecosystem function.

High turbidity, smothering by sediment, and labile dissolved copper, are factors likely to have influenced the composition and productivity of algal assemblages in the channel. As noted by Bunn *et al.* (1999), changes in algal species composition may have cascading effects on grazers (e.g. because of differences in palatability). Reductions in algal productivity will ultimately result in reduced secondary production. This will translate into reduced population sizes, reduced growth rates and/or loss of fish species dependent on algal food sources. These effects together help account for observed changes in fish catch and populations downstream of the mine, although the magnitude of potential mine-related impacts on the algal carbon pathway is likely to depend on whether most of the production occurs within the river channel (e.g. on logs or trailing vegetation) or in associated floodplain wetlands that are less likely to be impacted by high TSS and copper. However, as also shown by Storey & Marshall (2003), loss of habitat for fish and other fauna is likely a factor, directly influencing fish catch and assemblages, and therefore, not all ecological changes observed in the river channel downstream of the mine can be attributed to loss of algae as a carbon source to food webs.

6. RECOMMENDATIONS

1. This study indicated a reduction in algal carbon in the riverine food web downstream of the mine, however, it did not attempt to determine the mechanism for the loss. It is recommended that studies are implemented to differentiate between the effects of the main stressors of concern to in-stream epiphytic algae, namely abrasion from TSS, chronic toxicity from dissolved metals, reduced photic zone and loss/smothering of habitat. This will likely require controlled experiments under laboratory conditions to separate the effects of the different factors.

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2. Studies in 1998 (Bunn *et al.* 1999), 2003 (this study) and data collected in 2005 (A.W. Storey, unpub. dat.) indicated temporal variability in in-stream algal carbon signatures. This variability makes data interpretation problematic. It is recommended that regular sampling of in-stream algae is undertaken for a set period to track temporal variability. This would involve collection of algae off available surfaces at a control location on a regular basis (i.e. weekly or monthly), with subsequent determination of $\delta^{13}\text{C}$ to determine temporal variability in carbon signatures.
3. Field observations, coupled with food web analysis indicated that algae had been lost from downstream of the mine. However, algae are technically difficult to sample, particularly unicellular algae that are not readily observable due to being actively cropped/grazed. In-stream productivity measurements should be conducted to compare algal growth (production of carbon per m^2 per day) above and below D'Albertis Junction to quantify the loss of algal growth (*viz.* production) due to mine impacts. This information will also provide input to the Bayesian Networks model currently under construction on algal growth/availability. In-stream productivity measurements should also incorporate transplanting "quadrats" of 'healthy' algae from upstream of D'Albertis Junction to areas downstream of the mine and measuring response in algal production against control areas (i.e. 96 hr exposure trials).

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9. APPENDICES

Appendix 1. $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ signatures of all primary producer and consumers collected from ARM450 and Kuambit in September/October 2003, grouped by site, sample type and taxon/species. Percent of assimilated carbon derived from algal sources is also indicated for all consumers, as derived from the two-point mixing model using riparian vegetation and algal signatures as end points.

Site	Group	Taxa/species	$\delta^{15}\text{N}$	$\delta^{13}\text{C}$	% C from algae
ARM450	Algae	Algae - filamentous	3.77	-28.78	
ARM450	Algae	Algae - filamentous	0.39	-30.00	
ARM450	Algae	Algae - filamentous	2.82	-33.75	
ARM450	Algae	Algae off mud	2.29	-20.75	
ARM450	Algae	Algae off mud	0.17	-23.10	
ARM450	Algae	Algae off mud	1.59	-23.85	
ARM450	Algae	Algae off mud	1.08	-24.19	
ARM450	Algae	Algae off mud	1.85	-24.38	
ARM450	Algae	Algae off mud	3.04	-24.75	
ARM450	Algae	Algae off mud	0.14	-25.68	
ARM450	Bugs - aquatic	Dragonfly nymphs	2.14	-31.80	0.000
ARM450	Bugs - aquatic	Dragonfly nymphs	2.35	-32.23	0.000
ARM450	Bugs - aquatic	Dragonfly nymphs	1.11	-34.15	0.000
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	2.82	-29.62	0.029
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	2.97	-29.65	0.024
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	2.97	-29.73	0.011
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	3.00	-29.86	0.000
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	2.86	-29.98	0.000
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	2.85	-29.98	0.000
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	3.06	-30.04	0.000
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	3.03	-30.09	0.000
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	3.23	-30.11	0.000
ARM450	Bugs - aquatic	Plethogenesia mayfly - adults	3.39	-30.26	0.000
ARM450	Bugs - terrestrial	Riparian bug - Carabidae adult beetle	1.82	-25.78	0.650
ARM450	Bugs - terrestrial	Riparian bug - black orb-type spider	2.33	-26.75	0.493
ARM450	Bugs - terrestrial	Riparian bug - centipede	1.84	-19.52	1.000
ARM450	Bugs - terrestrial	Riparian bug - Cicada	2.52	-30.07	0.000
ARM450	Bugs - terrestrial	Riparian bug - grasshopper	4.09	-12.79	1.000
ARM450	Bugs - terrestrial	Riparian bug - grasshopper	3.40	-18.46	1.000
ARM450	Bugs - terrestrial	Riparian bug - grasshopper	2.56	-23.28	1.000
ARM450	Bugs - terrestrial	Riparian bug - grasshopper	1.34	-30.58	0.000
ARM450	Bugs - terrestrial	Riparian bug - spider-olive	7.38	-29.98	0.000
ARM450	Bugs - terrestrial	Trichoptera - adults	1.92	-30.73	0.000
ARM450	C3 grass	Phragmites karka	1.50	-26.78	
ARM450	C3 grass	Phragmites karka	-0.11	-27.62	
ARM450	C3 grass	Phragmites karka	-3.15	-28.09	
ARM450	C4 grass	Cooch grass	8.09	-11.50	
ARM450	C4 grass	Cooch grass	-2.09	-11.72	
ARM450	C4 grass	Saccharum	8.06	-10.68	
ARM450	C4 grass	Saccharum	1.84	-10.70	
ARM450	C4 grass	Saccharum	30.64	-11.15	
ARM450	Fish	A. berneyi	11.17	-26.44	0.478
ARM450	Fish	A. berneyi	9.40	-26.78	0.423
ARM450	Fish	A. berneyi	10.73	-27.08	0.375
ARM450	Fish	A. berneyi	9.69	-27.78	0.262
ARM450	Fish	A. berneyi	8.85	-28.98	0.068
ARM450	Fish	A. berneyi	8.66	-31.23	0.000
ARM450	Fish	A. leptaspis	9.28	-26.08	0.537

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Site	Group	Taxa/species	del ¹⁵ N	del ¹³ C	% C from algae
ARM450	Fish	A. leptaspis	9.59	-27.18	0.359
ARM450	Fish	A. macrorhyncus	5.36	-26.50	0.501
ARM450	Fish	A. macrorhyncus	7.03	-27.44	0.349
ARM450	Fish	Ambassis agrammus	7.16	-30.37	0.000
ARM450	Fish	Ambassis agrammus	6.95	-31.55	0.000
ARM450	Fish	Ambassis agrammus	7.16	-31.79	0.000
ARM450	Fish	Ambassis agrammus	6.76	-33.57	0.000
ARM450	Fish	Ambassis agrammus	9.14	-34.52	0.000
ARM450	Fish	C. danielsi	9.10	-26.47	0.474
ARM450	Fish	C. danielsi	10.12	-27.80	0.259
ARM450	Fish	Fish - sp.1 beach seine	7.72	-26.81	0.451
ARM450	Fish	Fish - sp.1 beach seine	7.05	-27.75	0.299
ARM450	Fish	Fish - sp.1 beach seine	7.18	-27.82	0.288
ARM450	Fish	Fish - sp.1 beach seine	7.60	-27.88	0.278
ARM450	Fish	Fish - sp.1 beach seine	7.55	-27.97	0.263
ARM450	Fish	Fish - sp.1 beach seine	8.39	-28.70	0.145
ARM450	Fish	Fish - sp.1 beach seine	7.95	-29.74	0.000
ARM450	Fish	Fish - sp.1 beach seine	7.93	-30.04	0.000
ARM450	Fish	Fish - sp.1 beach seine	9.40	-30.27	0.000
ARM450	Fish	Fish - sp.1 beach seine	8.92	-31.13	0.000
ARM450	Fish	Fish - sp.2 beach seine	8.57	-31.19	0.000
ARM450	Fish	Fish - sp.2 beach seine	8.33	-33.34	0.000
ARM450	Fish	Fish - sp.3 beach seine	9.02	-32.76	0.000
ARM450	Fish	G. aprion	6.72	-29.14	0.074
ARM450	Fish	G. aprion	8.10	-29.59	0.001
ARM450	Fish	G. aprion	5.79	-28.51	0.176
ARM450	Fish	L. goldeii	10.48	-29.60	0.000
ARM450	Fish	Larval fish	7.22	-30.65	0.000
ARM450	Fish	Larval fish	7.15	-32.52	0.000
ARM450	Fish	N. ater	7.62	-25.86	0.605
ARM450	Fish	Nematolsa	6.11	-31.89	0.000
ARM450	Fish	Nematolsa	5.28	-31.93	0.000
ARM450	Fish	Nematolsa	7.80	-35.23	0.000
ARM450	Fish	Nematolsa	6.70	-35.33	0.000
ARM450	Fish	Nematolsa	8.02	-37.48	0.000
ARM450	Fish	N. soldado	9.77	-30.00	0.000
ARM450	Fish	O. herwerdinii	7.43	-26.33	0.529
ARM450	Fish	Rainbow - juvenile	6.89	-28.50	0.178
ARM450	Fish	Rainbow - juvenile	7.22	-29.33	0.043
ARM450	Fish	Rainbow - juvenile	6.48	-31.00	0.000
ARM450	Fish	Rainbow - adult	6.96	-27.04	0.414
ARM450	Fish	Rainbow - adult	7.40	-27.34	0.365
ARM450	Fish	Rainbow - adult	8.65	-27.62	0.320
ARM450	Fish	S. krefftii	11.43	-29.09	0.050
ARM450	Fish	S. krefftii	11.11	-29.63	0.000
ARM450	Fish	S. krefftii	11.57	-31.39	0.000
ARM450	Fish	S. krefftii	11.14	-31.60	0.000
ARM450	Fish	S. krefftii	9.39	-32.85	0.000
ARM450	Fish	T. chatereus	6.94	-24.79	0.778
ARM450	Fish	T. lacustris	8.68	-34.66	0.000
ARM450	Fish	T. scratchleyi	9.03	-30.16	0.000
ARM450	Fish	T. scratchleyi	9.41	-37.03	0.000
ARM450	Fish	T. scratchleyi	10.00	-37.20	0.000
ARM450	Fish	T. scratchleyi	9.40	-37.78	0.000
ARM450	Fish	T. scratchleyi	9.92	-38.74	0.000

Comparison of carbon sources supporting riverine food webs

Site	Group	Taxa/species	del ¹⁵ N	del ¹³ C	% C from algae
ARM450	Fish	T. scratchleyi	9.41	-35.67	0.000
ARM450	Fish	Zenarchopterus - adult	7.27	-26.91	0.435
ARM450	Fish	Zenarchopterus - adult	6.42	-27.07	0.409
ARM450	Fish	Zenarchopterus - juvenile	5.94	-27.66	0.314
ARM450	Fish	Zenarchopterus - juvenile	6.44	-28.22	0.223
ARM450	Fish	Zenarchopterus - juvenile	6.81	-28.83	0.124
ARM450	Fish	Zenarchopterus - juvenile	5.74	-29.40	0.032
ARM450	Fish	Zenarchopterus - medium	6.28	-26.95	0.428
ARM450	Fish	Zenarchopterus - medium	6.21	-27.25	0.380
ARM450	Fish	Zenarchopterus - very juvenile	6.06	-29.32	0.045
ARM450	Fish	Zenarchopterus - very juvenile	5.96	-29.84	0.000
ARM450	POM	CPOM	-1.18	-29.25	0.121
ARM450	POM	CPOM	-0.62	-29.46	0.087
ARM450	POM	CPOM	-4.26	-29.78	0.035
ARM450	POM	FPOM	-0.22	-29.46	0.087
ARM450	POM	FPOM	-2.61	-29.48	0.084
ARM450	POM	FPOM	0.69	-29.82	0.029
ARM450	POM	MPOM	-0.55	-29.50	0.081
ARM450	POM	MPOM	-1.36	-29.55	0.073
ARM450	POM	MPOM	0.16	-29.67	0.053
ARM450	Prawns	Macrobrachium rosenbergii	8.09	-26.61	0.483
ARM450	Prawns	Macrobrachium sp.	8.17	-25.90	0.598
ARM450	Prawns	Macrobrachium sp.	7.30	-26.39	0.519
ARM450	Prawns	Macrobrachium sp.	6.87	-26.62	0.482
ARM450	Prawns	Macrobrachium sp.	7.88	-28.43	0.189
ARM450	Prawns	Macrobrachium sp.	8.35	-28.53	0.173
ARM450	Prawns	Macrobrachium sp.	6.58	-28.90	0.113
ARM450	Prawns	Macrobrachium sp.	7.96	-29.60	0.000
ARM450	Prawns	Macrobrachium sp.	6.90	-29.84	0.000
ARM450	Prawns	Macrobrachium sp. Nov.1	6.88	-27.98	0.262
ARM450	Prawns	Macrobrachium sp. Nov.1	6.25	-28.11	0.241
ARM450	Prawns	Macrobrachium sp. Nov.1	7.04	-27.55	0.331
ARM450	Prawns	Macrobrachium sp. Nov.1	6.62	-28.41	0.192
ARM450	Prawns	Macrobrachium sp. Nov.1	5.82	-28.45	0.186
ARM450	Prawns	Macrobrachium sp. Nov.1	7.00	-28.49	0.179
ARM450	Riparian	Ficus adornasperma	0.95	-28.20	
ARM450	Riparian	Ficus adornasperma	0.50	-30.01	
ARM450	Riparian	Ficus adornasperma	-8.12	-30.45	
ARM450	Riparian	Ginger sp.	-1.38	-28.09	
ARM450	Riparian	Ginger sp.	-3.34	-28.19	
ARM450	Riparian	Ginger sp.	-5.06	-29.60	
ARM450	Riparian	Moss	1.45	-29.92	
ARM450	Riparian	Moss	1.25	-31.18	
ARM450	Riparian	Moss	0.28	-31.77	
ARM450	Riparian	Pandanus aquaticus	8.95	-31.72	
ARM450	Riparian	Pandanus aquaticus	2.18	-32.35	
ARM450	Riparian	Pandanus aquaticus	5.96	-32.72	
ARM450	Riparian	Piper sp. (mustard)	-1.59	-28.53	
ARM450	Riparian	Piper sp. (mustard)	-3.47	-31.22	
ARM450	Riparian	Piper sp. (mustard)	-0.91	-31.29	
ARM450	Riparian	Myristica sp. (V1)	-5.53	-30.87	
ARM450	Riparian	Myristica sp. (V1)	-2.15	-33.20	
ARM450	Riparian	Myristica sp. (V1)	-2.36	-33.65	
ARM450	Riparian	Ipomoea hederifolia (V10)	1.83	-29.13	
ARM450	Riparian	Ipomoea hederifolia (V10)	4.09	-29.63	

Comparison of carbon sources supporting riverine food webs

Site	Group	Taxa/species	del ¹⁵ N	del ¹³ C	% C from algae
ARM450	Riparian	Ipomoea hederifolia (V10)	-1.96	-30.05	
ARM450	Riparian	Diplazium sp. (V11)	-5.01	-28.35	
ARM450	Riparian	Diplazium sp. (V11)	-1.96	-28.54	
ARM450	Riparian	Diplazium sp. (V11)	-3.91	-29.45	
ARM450	Riparian	Macaranga aleuritoides (V12)	-5.72	-26.88	
ARM450	Riparian	Macaranga aleuritoides (V12)	2.39	-28.45	
ARM450	Riparian	Macaranga aleuritoides (V12)	-1.82	-30.27	
ARM450	Riparian	Atractocarpus sessilis (V2)	1.03	-27.57	
ARM450	Riparian	Atractocarpus sessilis (V2)	0.55	-30.51	
ARM450	Riparian	Atractocarpus sessilis (V2)	-1.28	-32.12	
ARM450	Riparian	Pouteria sp. (V3)	-1.75	-28.78	
ARM450	Riparian	Pouteria sp. (V3)	-2.24	-31.22	
ARM450	Riparian	Pouteria sp. (V3)	-2.56	-31.43	
ARM450	Riparian	Derris sp. (V4)	-0.43	-27.87	
ARM450	Riparian	Derris sp. (V4)	-0.62	-29.22	
ARM450	Riparian	Derris sp. (V4)	-2.99	-30.64	
ARM450	Riparian	Nauclea orientalis (V5)	-0.45	-27.59	
ARM450	Riparian	Nauclea orientalis (V5)	0.75	-28.31	
ARM450	Riparian	Nauclea orientalis (V5)	3.52	-29.87	
ARM450	Riparian	Dictyoneura sp (V6)	-6.35	-31.60	
ARM450	Riparian	Leea indica (V7)	-15.08	-30.55	
ARM450	Riparian	Leea indica (V7)	-0.01	-30.76	
ARM450	Riparian	Leea indica (V7)	-3.53	-31.51	
ARM450	Riparian	Glochidion sp. (V8)	1.32	-32.52	
ARM450	Riparian	Dendrocnide sp. (V9) (stingy)	-4.04	-27.47	
ARM450	Riparian	Dendrocnide sp. (V9) (stingy)	-1.13	-28.22	
ARM450	Riparian	Dendrocnide sp. (V9) (stingy)	-3.35	-30.24	
ARM450	Riparian	Rattan (wait awhile)	4.76	-26.56	
ARM450	Riparian	Rattan (wait awhile)	0.48	-29.95	
ARM450	Riparian	Rattan (wait awhile)	0.02	-31.74	
ARM450	Seston	Seston >110 um	-0.67	-29.60	0.032
ARM450	Seston	Seston >110 um	-0.97	-29.81	0.000
ARM450	Seston	Seston >110 um	-1.80	-29.89	0.000
Kuambit	Algae	Algae off mud	-0.47	-16.37	
Kuambit	Algae	Algae off mud	-1.36	-19.00	
Kuambit	Algae	Algae off mud	-1.24	-20.35	
Kuambit	Algae	Algae off mud	-1.26	-23.47	
Kuambit	Algae	Algae off mud	-1.33	-18.60	
Kuambit	Algae	Algae off mud	-1.89	-20.06	
Kuambit	Algae	Algae off mud	1.04	-22.14	
Kuambit	Algae	Algae off mud	-0.53	-22.97	
Kuambit	Algae	Algae off mud	-1.15	-23.39	
Kuambit	Algae	Algae off mud	-0.65	-18.79	
Kuambit	Bugs - terrestrial	Riparian bug - Cicada	4.20	-27.67	0.204
Kuambit	Bugs - terrestrial	Riparian bug - Cricket burrowing	4.67	-27.76	0.195
Kuambit	Bugs - terrestrial	Riparian bug - grasshopper	3.05	-25.15	0.470
Kuambit	Bugs - terrestrial	Riparian bug - grasshopper	0.19	-27.71	0.200
Kuambit	Bugs - terrestrial	Riparian bug - grasshopper	4.03	-29.12	0.052
Kuambit	Bugs - terrestrial	Riparian bug - grasshopper	0.68	-29.27	0.036
Kuambit	Bugs - terrestrial	Riparian bug - water spiders	7.08	-27.81	0.190
Kuambit	C3 grass	Phragmites karka	3.33	-26.61	
Kuambit	C3 grass	Phragmites karka	1.04	-27.31	
Kuambit	C3 grass	Phragmites karka	2.98	-27.91	
Kuambit	C4 grass	Cooch grass	2.21	-11.85	
Kuambit	C4 grass	Cooch grass	0.80	-11.89	

Comparison of carbon sources supporting riverine food webs

Site	Group	Taxa/species	del ¹⁵ N	del ¹³ C	% C from algae
Kuambit	C4 grass	Cooch grass	1.95	-12.06	
Kuambit	C4 grass	Saccharum	4.03	-11.01	
Kuambit	C4 grass	Saccharum	4.72	-11.24	
Kuambit	C4 grass	Saccharum	2.15	-11.40	
Kuambit	Fish	A. leptaspis	9.94	-28.67	0.057
Kuambit	Fish	A. leptaspis	11.30	-29.11	0.010
Kuambit	Fish	A. leptaspis	10.78	-30.30	0.000
Kuambit	Fish	A. leptaspis	10.14	-30.38	0.000
Kuambit	Fish	A. leptaspis	11.07	-31.05	0.000
Kuambit	Fish	A. leptaspis	9.92	-31.31	0.000
Kuambit	Fish	A. leptaspis	11.60	-31.38	0.000
Kuambit	Fish	A. leptaspis	10.81	-31.38	0.000
Kuambit	Fish	A. leptaspis	11.22	-31.54	0.000
Kuambit	Fish	A. leptaspis	10.70	-31.66	0.000
Kuambit	Fish	A. leptaspis	10.77	-32.43	0.000
Kuambit	Fish	Ambassis agrammus	7.60	-35.89	0.000
Kuambit	Fish	Ambassis agrammus	9.11	-31.67	0.000
Kuambit	Fish	Ambassis agrammus	9.34	-33.30	0.000
Kuambit	Fish	Ambassis agrammus	9.72	-34.01	0.000
Kuambit	Fish	Ambassis agrammus	8.65	-34.25	0.000
Kuambit	Fish	Ambassis agrammus	8.49	-35.31	0.000
Kuambit	Fish	Ambassis agrammus	9.45	-35.63	0.000
Kuambit	Fish	Ambassis agrammus	10.41	-35.84	0.000
Kuambit	Fish	Ambassis agrammus	9.17	-36.30	0.000
Kuambit	Fish	Ambassis agrammus	8.62	-39.22	0.000
Kuambit	Fish	Clupeoides papensis	7.15	-27.96	0.153
Kuambit	Fish	D. quadrifasciatus	10.12	-29.34	0.000
Kuambit	Fish	L. calcarifer	10.27	-28.77	0.046
Kuambit	Fish	L. calcarifer	10.62	-30.10	0.000
Kuambit	Fish	L. calcarifer	11.24	-30.49	0.000
Kuambit	Fish	L. calcarifer	10.55	-30.80	0.000
Kuambit	Fish	L. calcarifer	10.73	-31.54	0.000
Kuambit	Fish	L. calcarifer	10.78	-31.55	0.000
Kuambit	Fish	L. calcarifer	10.59	-31.60	0.000
Kuambit	Fish	L. calcarifer	10.53	-31.73	0.000
Kuambit	Fish	L. calcarifer	11.14	-31.83	0.000
Kuambit	Fish	L. calcarifer	10.04	-32.08	0.000
Kuambit	Fish	L. goldeii	10.92	-28.99	0.023
Kuambit	Fish	L. goldeii	10.43	-29.07	0.015
Kuambit	Fish	L. goldeii	10.67	-30.53	0.000
Kuambit	Fish	Larval fish	8.21	-35.29	0.000
Kuambit	Fish	N. ater	7.10	-30.91	0.000
Kuambit	Fish	N. ater	9.02	-35.25	0.000
Kuambit	Fish	N. ater	6.79	-36.21	0.000
Kuambit	Fish	N. soldado	10.56	-26.08	0.330
Kuambit	Fish	N. soldado	10.64	-28.93	0.029
Kuambit	Fish	Nematolsa	5.68	-32.94	0.000
Kuambit	Fish	Nematolsa	6.26	-33.38	0.000
Kuambit	Fish	Nematolsa	5.56	-33.47	0.000
Kuambit	Fish	Nematolsa	4.92	-33.94	0.000
Kuambit	Fish	Nematolsa	5.73	-34.07	0.000
Kuambit	Fish	Nematolsa	6.46	-34.30	0.000
Kuambit	Fish	Nematolsa	6.48	-34.64	0.000
Kuambit	Fish	Nematolsa	6.93	-35.19	0.000
Kuambit	Fish	Nematolsa	5.61	-35.64	0.000

Comparison of carbon sources supporting riverine food webs

Site	Group	Taxa/species	del ¹⁵ N	del ¹³ C	% C from algae
Kuambit	Fish	Nematolsa	8.95	-37.05	0.000
Kuambit	Fish	Nematolsa	7.55	-37.35	0.000
Kuambit	Fish	O. herwerdinii	10.43	-31.70	0.000
Kuambit	Fish	P. gulliveri	9.16	-31.51	0.000
Kuambit	Fish	Porochilus maurekensis	8.30	-34.06	0.000
Kuambit	Fish	Rainbow - adult	7.58	-26.04	0.355
Kuambit	Fish	Rainbow - adult	7.67	-27.54	0.197
Kuambit	Fish	Rainbow - adult	9.48	-27.90	0.159
Kuambit	Fish	Rainbow - adult	8.05	-29.82	0.000
Kuambit	Fish	Rainbow - juvenile	7.79	-27.89	0.160
Kuambit	Fish	Rainbow - juvenile	7.77	-31.88	0.000
Kuambit	Fish	Rainbow - juvenile	7.45	-32.84	0.000
Kuambit	Fish	Rainbow - juvenile	8.68	-31.24	0.000
Kuambit	Fish	T. lacustris	8.78	-34.80	0.000
Kuambit	Fish	T. scratchleyi	11.65	-31.04	0.000
Kuambit	Fish	T. scratchleyi	10.42	-34.86	0.000
Kuambit	Fish	T. scratchleyi	10.46	-34.97	0.000
Kuambit	Fish	T. scratchleyi	8.59	-35.06	0.000
Kuambit	POM	CPOM	-0.31	-28.03	0.188
Kuambit	POM	CPOM	-1.09	-28.68	0.119
Kuambit	POM	CPOM	-0.87	-29.50	0.033
Kuambit	POM	FPOM	-2.33	-28.98	0.087
Kuambit	POM	FPOM	-1.38	-29.11	0.074
Kuambit	POM	FPOM	-2.05	-29.14	0.071
Kuambit	POM	MPOM	-2.14	-28.85	0.101
Kuambit	POM	MPOM	-1.90	-28.85	0.101
Kuambit	POM	MPOM	-1.57	-28.93	0.093
Kuambit	Prawns	Macrobrachium rosenbergii	7.79	-27.08	0.246
Kuambit	Prawns	Macrobrachium rosenbergii	8.32	-26.21	0.337
Kuambit	Prawns	Macrobrachium rosenbergii	6.35	-26.94	0.260
Kuambit	Prawns	Macrobrachium rosenbergii	7.61	-27.52	0.199
Kuambit	Prawns	Macrobrachium rosenbergii	7.11	-28.28	0.119
Kuambit	Prawns	Macrobrachium rosenbergii	5.50	-30.56	0.000
Kuambit	Prawns	Macrobrachium sp.	7.10	-26.40	0.317
Kuambit	Prawns	Macrobrachium sp.	7.80	-27.01	0.253
Kuambit	Prawns	Macrobrachium sp.	7.53	-27.07	0.247
Kuambit	Prawns	Macrobrachium sp.	8.51	-27.14	0.239
Kuambit	Prawns	Macrobrachium sp.	6.44	-27.27	0.226
Kuambit	Prawns	Macrobrachium sp.	6.70	-28.41	0.105
Kuambit	Prawns	Macrobrachium sp.	8.12	-25.71	0.390
Kuambit	Prawns	Macrobrachium sp.	8.82	-27.61	0.190
Kuambit	Prawns	Macrobrachium sp.	6.45	-27.44	0.208
Kuambit	Prawns	Macrobrachium sp. Nov.1	5.74	-26.00	0.359
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.38	-26.54	0.302
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.14	-27.38	0.214
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.93	-28.22	0.125
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.14	-28.27	0.120
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.48	-27.48	0.203
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.13	-27.65	0.185
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.84	-28.08	0.140
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.10	-28.13	0.135
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.69	-28.55	0.091
Kuambit	Prawns	Macrobrachium sp. Nov.1	7.94	-28.64	0.081
Kuambit	Prawns	Macrobrachium sp. Nov.1	6.37	-28.72	0.073
Kuambit	Riparian	Ficus adornasperma	-0.28	-29.77	

Comparison of carbon sources supporting riverine food webs

Site	Group	Taxa/species	del ¹⁵ N	del ¹³ C	% C from algae
Kuambit	Riparian	Ficus adornasperma	0.04	-29.79	
Kuambit	Riparian	Ficus adornasperma	-1.07	-30.00	
Kuambit	Riparian	Ginger sp.	-3.62	-29.37	
Kuambit	Riparian	Ginger sp.	-1.07	-30.14	
Kuambit	Riparian	Ginger sp.	-3.37	-31.23	
Kuambit	Riparian	Pandanus aquaticus	3.07	-30.55	
Kuambit	Riparian	Pandanus aquaticus	4.94	-30.56	
Kuambit	Riparian	Pandanus aquaticus	6.05	-31.18	
Kuambit	Riparian	Piper sp. (mustard)	-1.89	-30.81	
Kuambit	Riparian	Piper sp. (mustard)	-2.90	-31.33	
Kuambit	Riparian	Piper sp. (mustard)	-1.51	-31.55	
Kuambit	Riparian	Myristica sp. (V1)	0.17	-31.01	
Kuambit	Riparian	Myristica sp. (V1)	1.93	-31.47	
Kuambit	Riparian	Myristica sp. (V1)	-0.86	-33.93	
Kuambit	Riparian	Diplazium sp. (V11)	-2.79	-27.81	
Kuambit	Riparian	Diplazium sp. (V11)	-3.43	-28.63	
Kuambit	Riparian	Diplazium sp. (V11)	2.81	-28.86	
Kuambit	Riparian	Macaranga aleuritoides (V12)	-2.37	-27.66	
Kuambit	Riparian	Macaranga aleuritoides (V12)	-3.33	-28.72	
Kuambit	Riparian	Macaranga aleuritoides (V12)	-1.81	-30.33	
Kuambit	Riparian	Faradaya splendida (V13)	3.25	-29.21	
Kuambit	Riparian	Derris sp. (V4)	-0.43	-26.86	
Kuambit	Riparian	Derris sp. (V4)	-0.96	-28.15	
Kuambit	Riparian	Derris sp. (V4)	0.15	-30.03	
Kuambit	Riparian	Nauclea orientalis (V5)	3.41	-26.30	
Kuambit	Riparian	Nauclea orientalis (V5)	5.88	-29.58	
Kuambit	Riparian	Nauclea orientalis (V5)	4.41	-30.25	
Kuambit	Riparian	Leea indica (V7)	-3.54	-27.75	
Kuambit	Riparian	Leea indica (V7)	-2.20	-30.16	
Kuambit	Riparian	Leea indica (V7)	-0.54	-31.67	
Kuambit	Riparian	Dendrocnide sp. (V9) (stingy)	1.02	-29.40	
Kuambit	Riparian	Dendrocnide sp. (V9) (stingy)	3.37	-29.78	
Kuambit	Riparian	Dendrocnide sp. (V9) (stingy)	-0.29	-32.52	
Kuambit	Riparian	Rattan (wait awhile)	4.40	-28.19	
Kuambit	Riparian	Rattan (wait awhile)	0.00	-28.96	
Kuambit	Riparian	Rattan (wait awhile)	3.03	-29.09	
Kuambit	Riparian	Rattan (wait awhile)	2.57	-30.15	
Kuambit	Seston	Seston >110 um	-1.51	-28.80	0.085
Kuambit	Seston	Seston >110 um	-0.90	-28.86	0.079
Kuambit	Seston	Seston >110 um	-0.79	-28.87	0.078