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### **Author**

Newham, Michael J, Fellows, Christine S, Sheldon, Fran

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# **Functions of riparian forest in urban catchments: a case study from sub-tropical Brisbane, Australia**

Michael J. Newham<sup>1</sup>, Christine S. Fellows and Fran Sheldon<sup>2</sup>.

Australian Rivers Institute, Griffith University, Nathan, Queensland, Australia 4111

<sup>1</sup> Email addresses: [m.newham@griffith.edu.au](mailto:m.newham@griffith.edu.au)

<sup>2</sup> [f.sheldon@griffith.edu.au](mailto:f.sheldon@griffith.edu.au)

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**Abstract :**

Riparian forests are vital for maintaining healthy stream ecosystems; acting as buffers against nutrient and contaminant inputs, contributing energy subsidies and providing favorable instream habitat conditions. In urban catchments riparian forests are often degraded or cleared, removing the ecosystem functions the forest provides. Intact riparian forest along urban waterways, may mitigate some aspects of degradation associated with an urbanized catchment. In Bulimba Creek, an urbanized catchment in southeast Queensland, Australia, we investigated some ecosystem functions provided by riparian forest. We found that during baseflow periods a forested riparian corridor provided energy subsidies to the stream through litterfall and had a controlling influence on instream production through shading. Denitrification potential of benthic sediments increased with increasing levels of woody debris and organic matter, deposited from riparian vegetation. Denitrification was nitrate limited, indicating some potential to reduce nitrate loads in the stream. Riparian soils also showed moderate denitrification potential; which, through management strategies, could be utilized to reduce excess nitrate loads. These results suggest that riparian forests provide important functions for urban streams; highlighting the importance of conserving forest remnants in urban landscapes and the usefulness of replanting degraded riparian forest to enhance stream health and habitat condition.

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## Introduction

Riparian forests provide essential functions for healthy streams which regulate nutrient and contaminant inputs, maintain microclimate and low light levels, and provide energy subsidies for instream organisms and microbial processes (see Naiman  
25 and Decamps 1997 for review). The riparian zones of urban catchments are often degraded or even totally cleared of forest, often with engineered channels, removing the beneficial processes that these forests may provide. In addition, streams in urbanized catchments often suffer extensive degradation from contaminants and altered hydrology (Walsh et al. 2005). While not addressing issues of altered  
30 hydrology, the presence of riparian forest may mitigate some level of degradation in urban streams.

The capacity of riparian zones to reduce nutrient and contaminant loads to streams was established in the seminal paper by Peterjohn and Correll (1984). In the  
25 years since, an ever growing body of literature supports, and further elaborates, on both the contaminant buffering capacity and nutrient removal processes which occur  
35 in riparian zones; of these special attention has been given to denitrification (Ambus and Lowrance 1991; Hill 1996; Groffman et al. 2002; Sabater et al. 2003).

Denitrification is an anaerobic, microbial metabolic process that permanently removes nitrogen from stream systems by reducing oxidized forms of nitrogen to gaseous  
40 products ( $N_2O$  and  $N_2$ ) which are released into the atmosphere. Riparian zones can provide conditions favorable for denitrification including moisture, soils high in organic carbon and through-flowing surface- and sub-surface water laden with nitrate. In catchments with high nitrate levels denitrification in riparian soils has been found to remove over 90% of nitrate content in sub-surface flow before it reaches the stream  
45 channel (see Hill 1996 for review). Instream denitrification can also act as a self-

purification mechanism, but mass rates are often less than that in soils and dependent upon biofilms and organic matter storage in the stream channel (McClain et al. 2003).

Riparian forests provide many functions for maintaining stream health and favorable habitat conditions (Gregory et al. 1991). The riparian forest canopy provides shade for stream channels and assists in reducing instream temperature fluctuations (Rutherford et al. 2004) and, by limiting light reaching the stream, controls instream primary production (Bunn et al. 1999; Mosisch et al. 2001). Riparian forests also provide allocthonous inputs of organic carbon to stream channels through wood and litter fall. Although this terrestrial carbon may not be a major contributor to stream foodwebs (Bunn et al. 1999), it is a basis for many microbial processes (Findlay and Sinsabaugh 1999) within stream ecosystems. When accumulated in large volumes (eg. debris dams), riparian litter (leaves, wood, bark) forms 'hot-spots' of microbial nutrient processing, particularly for denitrification (McClain et al. 2003).

Urban streams face particular degradation effects as a result of large impervious catchments, where rainfall is efficiently converted to runoff, along with the added impact of stormwater flows from these impervious areas being piped directly to stream (Paul and Meyer 2001; Walsh et al. 2005). Through the stormwater pipe network, larger stormflows and their associated contaminants are delivered directly to the stream channel, bypassing the riparian zone and its buffering capacity (Groffman et al. 2002). The efficient conversion of rainfall to runoff means even small rainfall events may generate high flows in urban streams (Walsh et al. 2005), resulting in highly incised and eroded stream channels with limited capacity to retain organic matter and form the debris dams that are important for instream nutrient processes (Groffman et al. 2005). Increased nutrient concentrations from greater

catchment loads, combined with a reduced removal capacity, can lead to increased primary production, higher abundance of nuisance algae and dominance of macrophytes, particularly where riparian shading is reduced (Chessman et al. 1992; Murdock et al. 2004; Taylor et al. 2004; Meyer et al. 2005).

75            Previous studies have examined ecosystem processes, which may be influenced by riparian condition in urban catchments, and shown relationships with metrics of urbanization (Walsh et al. 2001, Meyer et al. 2005). However, these studies have not attempted to use “riparian condition” at the study site as a descriptive variable in their analysis of ecosystem processes (but see Roy et al. 2005). In urban  
80 streams, the general conclusion is that the presence of riparian vegetation alone is not enough to fully protect their biotic integrity, given the range of other disturbances associated with urbanization. While not disputing this, we suggest that the degree of degradation to stream processes caused by urbanization may be mitigated to some degree by the functions of the riparian forest. In this study, we attempt to quantify  
85 some instream processes and investigate the effect, if any, which the presence and condition of the surrounding riparian forest has on these processes. The processes investigated were nutrient retention (denitrification), instream production (algal biomass) and organic matter deposition (litter fall and presence of organic debris); while riparian condition was assessed as percentage riparian canopy cover and  
90 through the use of a rapid appraisal method.

## Methods

### *Study area*

Bulimba Creek is an urban stream located in the lower Brisbane River catchment, Southeast Queensland, Australia. The area has a sub-tropical climate and experiences summer dominated rainfall, with 55% of annual rainfall occurring between December and March when the monthly average can exceed 150 mm. Lowest rainfall occurs from June to September with an average rainfall of less than 70 mm per month. Therefore, streams experience an extended period of stream baseflow conditions during the cooler winter months. Over the winter period when sampling occurred the average temperature range is 11 - 22°C.

The Bulimba Creek catchment covers 122 km<sup>2</sup>, which is about 10% of the Brisbane City area. Much of the land around Bulimba Creek was initially cleared for rural development of pasture and crops 100 years ago but has been progressively converted to residential areas, which now house over 120 000 people. Today, only small pockets of active rural industry remain, although much of the eastern catchment retains a low impervious surface area with low density residential development.

Nine study sites were located along 2<sup>nd</sup> to 4<sup>th</sup> order reaches of the stream, with the most downstream site at the boundary of tidal influence (Figure 1). These sites were selected to be at least 1 km apart by stream distance and in reaches that do not experience total drying. All sampling was conducted during the winter baseflow period between May and August 2006, and occurred no less than one week following a rain event.

115 *Stream characteristics*

Total catchment imperviousness, riparian canopy cover and streamwater nutrient content were assessed as potential influences on stream ecosystem processes.

Catchment imperviousness was estimated by methods based on those of Walsh et al. (2001) using satellite imagery of the catchment. Riparian canopy cover over the

120 stream at each study site was measured by fish-eye lens hemispherical photography, using a Nikon D70 digital camera, and image analysis using WINPHOT software (Ter Steege 1994, Bunn et al. 1999). Physical habitat characteristics of the stream and riparian zone were described and classified using a modified version of the RARC (Rapid Appraisal of Riparian Condition: Jansen et al. 2004) assessment systems

125 (Costelloe, 2005). The RARC (Jansen et al. 2004) collect data on indicators of functional features of the riparian zone, including habitat (width and continuity), cover, debris (ground and dead trees), percentage native vegetation and regeneration features. The modified version used here (Costelloe 2005) takes into account reduced riparian width within the scoring system, which we thought important given that

130 Bulimba Creek was an urban catchment with restricted, non-natural, riparian widths. The RARC score varies between 0 and 1, with lower values indicative of poor riparian condition, and higher values better riparian condition. Conductivity (TPS Model WP-84), dissolved oxygen and temperature (TPS Model WP-82Y) measurements were made at each site to characterize water quality.

135 A water sample (50mL) was collected from each site for dissolved nitrogen and carbon concentrations, samples were filtered in the field using 0.45 µm syringe filters and frozen until analyzed. Analysis for nitrate plus nitrite (hereafter referred to collectively as nitrate) and ammonium was performed on a LACHAT Instruments Flow Injection Analyser (Lachat Instruments, Loveland, Colorado) using QuikChem



140 Method 31-107-04-1-D and a modification of QuikChem Method 10-107-06-4 which  
excluded the dialysis procedure. Total nitrogen (TN) was determined by a persulfate  
digestion followed by nitrate analysis as described above (Hosomi and Sudo 1986).  
Dissolved organic carbon (DOC) analysis was conducted using a Shimadzu TOC  
analyser (TOC-VCSH, Shimadzu Corporation, Kyoto, Japan).

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#### *Denitrification potential*

Denitrification potential of shallow riparian soil and instream sediment was analyzed  
by collecting eight samples each of riparian soil and instream sediment from each site.  
Sample collection and analysis occurred between 3 and 9 May 2006. Riparian soil  
150 was collected to 30cm using a hand auger within 3 m of the stream bank. Instream  
sediments were collected to a depth of 3 cm in areas of sand or silt, which were  
common substrate types at all sites. Soil and sediment samples were homogenized  
prior to removing subsamples for analysis. Sample preparation began within 6 hours  
after the first sample was collected.

155 Denitrification potential was measured using the acetylene block method  
(Balderston et al. 1976). Two treatments were used, a control with ambient nutrient  
conditions and a nitrate-spiked sample with an additional 5 mg N L<sup>-1</sup>. The moisture  
content of the soil and sediment samples was visually estimated to determine the  
amount of water required to produce a sediment slurry with an approximate 1:1 ratio  
160 of dry sediment to water. The actual moisture content was determined by drying a  
small amount of sediment at 70°C overnight, which was then used in subsequent  
calculations. ‘Dummy’ slurries were prepared as for analyzed samples, but were  
sacrificed to get a measure of initial nitrate concentration in the prepared slurries.  
Treated sediment slurries were incubated in 250 mL sample bottles, with anoxic

165 conditions achieved by flushing headspace with N<sub>2</sub> gas for 2 minutes, and with 10%  
of the headspace replaced with acetylene gas. A gas chromatograph with an electron  
capture detector (Agilent 6890 micro ECD; methane/argon carrier gas; HP Gas Plot  
Pro column) was used to measure nitrous oxide accumulation. A Bunsen coefficient  
of 0.6 at 295°K was used to estimate the amount of nitrous oxide dissolved in the  
170 slurry water. The total moles of nitrous oxide per bottle was plotted against time.  
The production rate of N<sub>2</sub>O was calculated using linear regression and a ratio of 2:1  
was used to convert N<sub>2</sub>O-N produced to NO<sub>3</sub>-N consumed in units of mg N kg dry  
soil<sup>-1</sup> day<sup>-1</sup>.

175 *Benthic algal biomass*

The chlorophyll-a content of benthic sediments was assessed at each study site as an  
indicator of the benthic algal biomass. Samples were collected in conjunction with  
sediment sampling for denitrification analysis. Three benthic sediment core samples  
were collected from random positions at each study site to a depth of 2 cm using a  
180 cut-off syringe (i.d. 29 mm). Sediment cores were stored in plastic vials and frozen  
until analysis. Chlorophyll-a was extracted from the sediments using 90% acetone for  
24 hours at 4 °C. Samples were acidified with 2N HCl to correct for phaeophytin.  
Calculations of chlorophyll-a concentrations followed that of Lorenzen (1967).

185 *Contribution of organic matter from riparian vegetation*

Litter fall rate in the riparian zone immediately adjacent to the creek was used as a  
proxy for direct measurement over the creek. Different methods were used to  
measure litter fall at sites with forested riparian vegetation and dead biomass  
accumulation at sites dominated by grass and groundcovers. Methods used for litter

190 collection were designed to remain inconspicuous in the urban setting to avoid  
unwanted attention and vandalism. This sampling was conducted in June and July of  
2006.

The rate of litter fall in forested riparian zones was determined using  
collection quadrats. Each site had four quadrats of 0.36 m<sup>2</sup>. However, site three had  
195 very different riparian vegetation on each bank, so three quadrats were installed on  
either side of the creek and were analyzed separately as sites 3a and 3b. The standing  
stock of litter within each quadrat was collected and returned to the lab for drying and  
weighing when the quadrats were installed and again five weeks later to calculate a  
rate of litter fall. Following each collection, leaf litter was dried at 70°C for at least 48  
200 hours, then cooled to room temperature in a dessicator. The dry weight was recorded  
either as standing stock weight in the first case, or as a rate in the second case and  
expressed in units of g m<sup>-2</sup> day<sup>-1</sup>.

At sites with tall stands of grass (sites 7 and 9) a biomass accumulation  
method similar to that of Dugas et al. (1999) and Frank and Dugas (2001) was used.  
205 In four quadrats (each 0.09m<sup>2</sup>) per site, grass was cut and collected along with leaf  
litter that had accumulated within the standing grass. In the laboratory, the leaf litter  
and dead grass was separated from the samples and the living grass was removed and  
discarded. Processing of samples followed that described above for leaf litter. Five  
weeks later, a second collection was undertaken using the same procedure in new  
210 quadrats located less than 2 m from those used for the first collection. The initial  
mean weight was used as the standing stock weight and the difference between this  
and the second mean weight was recorded as the rate of dead biomass accumulation  
(g m<sup>-2</sup> day<sup>-1</sup>).

Riparian litterfall and accumulated biomass were assessed for carbon and  
215 nitrogen content using a continuous flow-isotope ratio mass spectrometer (Micromass  
Isoprime Euro Vector EA 300, Manchester, UK) at Griffith University. From each  
collection quadrat a third sample of leaf litter, excluding large sticks, was collected  
following the litterfall investigation. At grassy sites, samples of dead grass were  
collected from the second quadrats which were used for rate calculation. This was  
220 returned to the lab and dried for 48 hours at 60°C. The samples of litter were ground  
into a homogenous powder and analyzed for carbon and nitrogen content. The carbon  
and nitrogen content was calculated using the %C and %N contents by mass and  
multiplying by the total mass of litter as rate or standing stock. C:N ratios were  
calculated using the atomic weights of C and N.

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#### *Data analysis*

Linear regression was used to investigate the relationships between ecosystem process  
measures and local- and catchment-scale environmental factors. Environmental  
variables were selected *a priori* as those expected to influence the processes. For  
230 benthic algal biomass the variables selected were canopy cover, instream nitrate  
concentration and instream habitat complexity. Nitrate concentrations, organic matter  
content of sediments and vegetation cover were chosen for denitrification potential.  
Instream denitrification potential was also analyzed for relationships with 'habitat  
complexity' and 'debris' scores (between 0 and 1) from RARC. Litterfall rates and  
235 standing stock were regressed with variables of vegetation and canopy cover. All  
processes were investigated with respect to catchment imperviousness and catchment  
area. A p value < 0.05 was considered significant for the regression analysis.  
Differences in denitrification potentials across the nine sites were assessed using

ANOVA performed in SAS version 9.0 (SAS Institute Inc, Cary, NC). The two-  
240 factor design used sample location (instream sediment or riparian soil) and treatment  
(nitrate spiked or control) as the independent variables. Mean values of denitrification  
potential for each location and treatment grouping within each of the nine sites were  
analyzed providing a total of 36 observations with four observations from each site.  
In the case of a significant ANOVA result, Tukey's studentized range (HSD) test was  
245 used to determine where significant differences lay.

## **Results**

### *Stream and Catchment Characteristics*

Canopy cover at the sites ranged from 26.7 to 79.3 % with all but two sites having  
250 greater than 50 % cover (Table 1). Although this is an urbanized catchment, the creek  
flowed through an almost continuous corridor of green space, which varied in width  
from 50 to over 200 m. On-ground observation showed that riparian forest was  
present at most sites and made up much of the area of the green space corridor. The  
riparian health indicator (RARC Score, Table 1) showed only moderate levels of  
255 riparian health at most sites, despite even high levels of riparian cover. This was due  
to low scores for channel stability and abundance of native vegetation.

The range of land use activities within the Bulimba Creek catchment was  
reflected in the pattern of catchment imperviousness (Fig. 1, Table 1). At the time of  
study the catchment was heavily urbanized on the western side with imperviousness  
260 of up to 80 % in some areas. The eastern catchment tended to have much less  
impervious surface area with less intensive development. Catchment imperviousness  
increased dramatically in the first 3 sites from 25 to 57 % as the drainage area first

covered mainly forested headwaters, then heavily urbanized sections of the catchment. From site 4 onwards, the catchment imperviousness remained between 45 and 50 %.

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### *Denitrification potential*

Denitrification potentials differed significantly between sediment type ( $F_{1,32} = 7.55$ ;  $p < 0.01$ ) and nitrate treatment ( $F_{1,32} = 12.78$ ;  $p < 0.01$ ) while the interaction was not significant ( $F_{1,32} = 0.12$ ;  $p = 0.73$ ). The Tukey *post-hoc* groupings for these

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significant factors showed that denitrification potential of riparian soil was greater than that of instream sediments and that samples receiving added nitrate were greater than control samples (Fig. 2). Control instream sediments had the lowest

denitrification potentials, with all values less than  $2 \text{ mg N kg}^{-1} \text{ day}^{-1}$ . The addition of nitrate to instream sediments increased the denitrification potentials by as much as  $8 \text{ mg N kg}^{-1} \text{ day}^{-1}$ , although in most cases the rate increased by  $2\text{-}3 \text{ mg N kg}^{-1} \text{ day}^{-1}$ .

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Addition of nitrate to soil slurries also increased denitrification rates, though in most cases to a lesser extent than for stream sediments. Across both instream sediments and riparian soils, except for two cases, denitrification potential was nitrate limited.

A significant relationship was found in the control treated instream sediments between initial nitrate concentration and denitrification potential ( $R^2 = 0.65$ ,  $p < 0.01$ ), though the degree of variance between the replicates makes conclusions tenuous.

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This relationship would be expected due to the low nitrate concentrations limiting the possible rate of denitrification. Similar relationships were not found with sediments treated with additional nitrate nor in the riparian soils. However, denitrification

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potential of riparian soil was related to its organic matter content for both control ( $R^2 = 0.81$ ,  $p < 0.001$ ) and nitrate ( $R^2 = 0.87$ ,  $p < 0.001$ ) treatments (Fig. 3).

Regression analysis revealed that only the control treated instream sediments showed significant relationships with measures of stream condition. Instream denitrification potential had significant relationships with ‘habitat complexity’ ( $p < 0.05$ ) and ‘debris’ ( $p < 0.01$ ), which both indicate the degree of instream habitat heterogeneity and storage of organic matter. The ‘debris’ score explained 71% of the variation in instream denitrification, while ‘habitat complexity’ explained 53% of the variation.

### 295 *Benthic algal biomass*

There were no significant relationships between benthic chlorophyll-a concentration and measured environmental variables, but a trend of increasing chlorophyll-a concentration with decreased canopy cover was suggested (Fig. 4). There are two apparent outliers in the data at approximately 50 % and 80 % canopy cover (Fig. 4). These two sites had channel morphologies vastly different to other sites. The low chlorophyll-a concentration at 50 % canopy cover could be attributed to a channel depth of over 80 cm, limiting benthic light penetration. The site at 80 % canopy cover had a water depth of approximately 10 cm and channel width of 11 m, providing good light conditions for algal growth despite the high canopy cover. Other sites tended to have water depth ranges from 10-30 cm and width of 2-3 m. When the two outlying sites are removed from the regression of benthic chlorophyll-a with canopy cover the result becomes significant and explains 90 % of the variation ( $R^2 = 0.90$ ,  $p < 0.05$ ). Benthic chlorophyll-a concentration was not significantly correlated with streamwater nitrate concentration (which ranged from 0.34 – 0.97 mg N L<sup>-1</sup>), measures of stream condition (habitat complexity and debris) or the degree of catchment imperviousness.

### *Contribution of organic matter from riparian vegetation*

Standing stock of leaf litter and rates of litter fall in the riparian zone tended to be similar between sites, although some large variations due to vegetation management activities were observed. Most sites had standing stocks of litter between 300 and 500 g m<sup>-2</sup> of litter with litter fall rates of 1 to 5 g m<sup>-2</sup> day<sup>-1</sup> (Fig. 5). Site 3a is a notable exception where regular mowing and maintenance of lawn in the riparian zone limited the accumulation of litter. Sites 7 and 9, where the grass collection method was employed, had litter accumulation of greater than 10 g m<sup>-2</sup> day<sup>-1</sup>. Standing stocks, however, were comparable to those at other sites. Assuming a constant standing stock of litter, this indicates a much faster turnover rate of litter in grassed riparian zones.

Leaf litter samples across the nine sites had a mean carbon content of 48.3% by weight with a range from 44.7 to 51.4%. Mean nitrogen content was 1.1% by weight with a range from 0.9 to 1.4%. Combined with standing stock values, this revealed that the riparian zone stores about 100 to 200 g of carbon and 2 to 6 g of nitrogen per square meter as leaf litter on the soil surface (Table 2). Accumulation rate of carbon varied between 0.5 and 7 g m<sup>-2</sup> day<sup>-1</sup> and nitrogen accumulated at a rate of up to 0.06 g m<sup>-2</sup> day<sup>-1</sup>.

Riparian litterfall did not display significant linear relationships with site characteristics that were expected to influence, or be influenced by, leaf litter dynamics, possibly indicating complex interactions beyond the scope of this study. For example, there were no significant relationships between litterfall rate, or litter standing stock, and soil organic matter content. The characteristic ‘vegetation cover’ did not display any significant relationships with litterfall standing stock or accumulation. The soil organic matter content was also not significantly related to the ‘vegetation cover’ score.



## **Discussion**

Although highly urbanised, Bulimba Creek does not have an ‘engineered’ or concrete  
340 channel devoid of natural structure typical of many urban creeks; rather, it is  
characterised by an intact riparian forest along much of its length. This contrast to the  
usual view of urban creeks as being little more than drains, possibly reflects the sub-  
tropical climate of south-east Queensland, with high rates of vegetation growth and  
variable flashy flooding which prohibits construction and urbanisation too close to the  
345 channel. The presence of the intact riparian forest meant that common attributes of  
urban streams, such as high stream temperatures and high algal biomass were not  
observed in this creek, as riparian shading acts to reduce both instream temperature  
fluctuations and algal production (Bunn et al., 1999). The degrading influences on  
Bulimba Creek, therefore, may be related more to changes in hydrology through both  
350 higher runoff from upstream impervious area and piped stormwater flows containing  
contaminants (see Walsh et al. 2005) rather than degraded riparian conditions.

### *Denitrification*

The relatively low rates of denitrification observed in this study, when compared to  
355 other studies in urbanized catchments, suggest that Bulimba Creek may not be  
severely impacted by nitrate contamination, since the denitrifying community does  
not appear to be as abundant as reported elsewhere (Groffman et al. 2002; Inwood et  
al. 2005; Inwood et al. 2007). However, across much of the Bulimba Creek  
catchment, stream sediments and the associated riparian soils tended to be sandy,  
360 which could also contribute to the relatively low denitrification rates, as sandy soils  
will limit the organic matter content of the soil and moisture retention would be lower.

This is reflected in our results where the highest riparian denitrification potentials are found with high organic matter content, which occurs at sites with finer textured soils. Denitrification potentials of Bulimba Creek, when compared to literature values, were  
365 more similar to potentials reported for less impacted streams than other urban areas. For example, Inwood et al. (2005) found along a gradient of urbanization, increasingly higher instream denitrification potentials in a gradient from forested, agricultural then urban catchments, without additional nitrate treatment. In that study, the mean denitrification potential for instream sediments from the urban catchment  
370 was 15 mg N kg<sup>-1</sup> day<sup>-1</sup>. This is a much higher potential than that found in our study of 0-2 mg N kg<sup>-1</sup> day<sup>-1</sup>. Our values are more similar to the reported values from forest 1.5 mg N kg<sup>-1</sup> day<sup>-1</sup> (Inwood et al. 2005). In Bulimba Creek we did observe a relationship between denitrification potential at ambient nitrate loading and measures of channel 'debris' and 'habitat complexity'. These measures are indicative of the  
375 amount of woody debris and leaf litter accumulated in the stream channel, and reflect overall riparian condition. Although we found no significant relationship between denitrification and organic matter content of instream sediment, the abundance of woody debris was a factor in promoting higher denitrification potential. Therefore, in this urban stream the riparian forest provides woody debris and organic matter to form  
380 debris dams and organic matter accumulations which provide conditions for higher denitrification potential.

Denitrification potentials of riparian soils of Bulimba Creek were also more similar to forested catchments than urbanized catchments. Groffman et al. (2002), using a denitrification enzyme activity method involving addition of nitrate and  
385 carbon, found denitrification potentials of urban riparian soils (5-30cm depth) in Baltimore, U.S.A., were greater than 10 mg N kg<sup>-1</sup> day<sup>-1</sup> while the forested and low

density urban catchments in this study had rates of 0.7-2.3 mg N kg<sup>-1</sup> day<sup>-1</sup>.

Comparatively, the riparian sediments at a similar depth range (0-30 cm) in Bulimba Creek had denitrification potentials between 2 and 10 mg N kg<sup>-1</sup> day<sup>-1</sup>, which makes  
390 then more similar to the low density – forested soils of the Baltimore study.

Denitrification potential of riparian soils therefore appears to reflect both the density of urbanisation and the prevalence of available nitrate. This was further confirmed by the addition of nitrate to the Bulimba Creek riparian soils, which suggested their denitrification potential was nitrate limited, and indicates that even though the sandy  
395 sediment and soils may limit denitrification potential across much of the Bulimba Creek catchment, the system may retain a buffering capacity against increases in nitrate load.

#### *Contribution of organic matter from riparian vegetation*

400 Mean riparian litter fall along Bulimba Creek (1 to 5 g m<sup>-2</sup> day<sup>-1</sup>) is greater than litter fall within Toohey Forest, a forest reserve within the Bulimba Creek catchment (0.9 g m<sup>-2</sup> day<sup>-1</sup>) (Birk 1979). The greater litterfall along Bulimba Creek may be a result of greater vegetation density and production rates associated with riparian conditions (Naiman and Decamps 1997), a trend found by Catterall et al. (2001) between upland  
405 and riparian sites within Toohey forest. Assuming a constant rate throughout the year, litter fall into the Bulimba Creek channel and riparian zone equates to approximately 350 g to 1500 g m<sup>-2</sup> year<sup>-1</sup>, about half of which is carbon and 1% is nitrogen. On the riparian soil, assuming relatively stable standing stocks of about 300g m<sup>-2</sup>, the turnover rate of litter could be from 1 year in forested sites to as little as 10 weeks in  
410 grassy areas, some of which would be incorporated as soil organic matter. The deposition rates presented here for the forested sites are likely underestimates of

organic matter deposition to the stream channel. Along with direct litterfall to the channel, litterfall in the riparian zone will also move towards the channel by wind-throw and repositioning by flooding. This is the case for all forested sites, however, 415 cleared sites had large accumulation rates of organic matter ( $> 12 \text{ g m}^{-2} \text{ day}^{-1}$ ), which consisted mainly of grasses, and as such would not provide the same delivery of coarse material to the stream channel as forested sites. Instead of coarse particulate matter coming from these cleared sites there is likely to be higher rates of dissolved organic carbon in their runoff, leached from the large decomposing biomass. This 420 precludes the formation of organic debris accumulations in these reaches which can be important for instream food resources and nutrient processing.

#### *Benthic algal biomass*

Riparian shading may be limiting benthic algal growth in Bulimba Creek. The 425 influence of shading on instream production obscured any effects that nutrient concentration may have had, as shading seemed to limit primary production to below a level where nutrient availability would be a limiting factor. This result is in contrast to other studies of urban streams and algal production that showed strong correlation between chlorophyll-a concentration and measures of urban density or nutrient 430 concentration (Chessman et al. 1992, Taylor et al. 2004). However, Roy et al. (2005) found that in paired sites of urban streams, those with riparian shading had reduced algal biomass compared with those without riparian forest cover. This result again reflects the fact that Bulimba Creek flows through a green space corridor that provides significant shading over much of the stream, compared to a more 'typical' urban 435 stream that lacks riparian forest. For example, in urban catchments of Melbourne, Australia, which had high benthic light levels, benthic algal biomass was positively

correlated with urban density and most strongly with drainage connection, which provided phosphorus to the stream (Taylor et al. 2004). Chessman (1985) found that in human impacted sections of the La Trobe River, chlorophyll-a concentrations  
440 peaked with peaks in nitrate concentration in late winter and spring, which is also the time of year of greatest runoff in that region (Lake 1995). In Bulimba Creek during baseflow sampling, nitrate concentration in the creek did not exceed  $1 \text{ mg N L}^{-1}$  and benthic chlorophyll-a did not relate to nutrient concentrations, but appeared to be limited by available light. During periods of increased runoff in summer, nutrient  
445 concentrations could increase, although it is expected that shading would be a dominant controlling factor year-round. Further investigation of chlorophyll-a concentrations and stream nutrient concentrations year-round would be required to determine the effects of streamflow and nutrients on seasonal variation of algal growth.

450

#### *Riparian vegetation*

The measured stream characteristics of benthic algal biomass and leaf litter fall showed ties with the nature of the riparian forest of Bulimba Creek. Benthic algal biomass was limited by the low light environment produced by shading riparian trees.  
455 The input of organic matter to the stream and riparian soil, especially during baseflow conditions when stormwater drainage to the creek is minimal, is dependent on local vegetation condition. Denitrification in riparian soils, although having a high potential, is possibly restricted by a limited interaction between groundwater and shallow soils. As a management tool, the denitrification potential of shallow riparian  
460 soils could be utilized by managing urban stream hydrology to connect nitrate-laden water with riparian soils through the construction of riparian wetlands and detention

basins for surface runoff (Groffman et al. 2002). Our findings support these management options as riparian denitrification rates were found to be much higher than those of instream sediments per kilogram of soil. High stormflow events in urban catchments may engage shallow soil denitrification by raising streamwater levels to flood the surrounding riparian area and promote bank storage (Rassam et al. 2006). This process could be enhanced through the previously mentioned management options of riparian wetland construction. Deep-rooted riparian vegetation can aid in the removal of nitrate and other nutrients from groundwater by direct uptake, and can account for substantial removal in the absence of conditions that favour denitrification (Schade et al. 2005).

This urban riparian forest was found to provide important, although limited, nutrient processing functions for Bulimba Creek. Restoration of a more natural hydrograph and increasing hydrologic interaction with riparian soils is vital for improving urban stream health, yet where degraded riparian conditions exist in urban catchments, revegetation may be a useful method to return some degree of stream health to these reaches.

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**Table 1:** Stream characteristics for each study site. Streamwater nitrate content was sampled at time of denitrification assay. Catchment Imp. is total catchment imperviousness. CC - canopy cover.

Site No.	Instream Sediments	Riparian Soils	Conductivity ( $\mu\text{S cm}^{-1}$ )	Streamwater Physicochemical Parameters				NO <sub>3</sub> -N (mg L <sup>-1</sup> )	CC (% $\pm$ SE)	Dominant Riparian Vegetation	RARC Score	Catchment Imp. (%)	Catchment Area (km <sup>2</sup> )
				DO 24hr Max (ppm)	DO 24hr Min (ppm)	Water Temp 24hr Max (°C)	Water Temp 24hr Min (°C)						
1	Silty	Silty clay	411	4.05	3.07	18.2	16.1	0.43	53.8 $\pm$ 1.7	<i>Melaleuca quinquenervia</i> , <i>Brachiaria mutica</i>	0.416	25.6	3.0
2	Sandy gravel	Sandy loam	381	5.81	2.95	16.9	15.2	0.34	53.6 $\pm$ 3.0	<i>M. quinquenervia</i> , <i>Casuarina glauca</i>	0.432	49.5	7.2
3	Sandy gravel, some fine sand	Clay to sandy clay	423	9.70	8.78	16.7	14.9	0.44	34.8 $\pm$ 7.1	<i>Cynodon dactylon</i> , <i>Eucalyptus spp.</i>	0.461	57.2	16.2
4	Sandy, some exposed bedrock	Fine sand	297	9.88	8.23	16.9	15.0	0.97	65.0 $\pm$ 2.0	<i>M. quinquenervia</i> , <i>Cinnamomum camphora</i>	0.471	46.5	38.7
5	Sandy	Fine sand	375	8.76	6.62	16.2	15.5	0.67	77.1 $\pm$ 3.3	<i>C. camphora</i> , <i>Lomandra longifolia</i>	0.515	46.0	40.0
6	Sandy with areas of silt	Sandy loam	367	10.01	7.08	17.2	15.6	0.61	64.2 $\pm$ 2.0	<i>C. camphora</i> , <i>C. glauca</i>	0.463	48.3	44.0
7	Sandy	Sandy loam	385	10.14	7.46	16.6	14.8	0.47	64.1 $\pm$ 2.0	<i>C. camphora</i> , <i>Acacia concurrens</i>	0.535	47.6	46.5
8	Sandy	Sandy loam	375	9.91	6.72	16.7	15.2	0.69	79.3 $\pm$ 3.0	<i>C. camphora</i> , <i>Eucalyptus spp.</i>	0.481	49.4	50.9
9	Clay	Clay	405	9.84	9.21	20.6	17.3	0.65	26.7 $\pm$ 5.0	<i>B. mutica</i> , <i>C. camphora</i>	0.272	49.4	60.6

**Table 2:** Mass of carbon and nitrogen in standing stocks and accumulated leaf litter.

‘\*’ indicates sites where grass collection method was used.

Site No.	Standing Stock (g m <sup>-2</sup> )		Fall Rate (g m <sup>-2</sup> day <sup>-1</sup> )		C:N molar ratio
	Carbon	Nitrogen	Carbon	Nitrogen	
1	219.0	4.94	0.9	0.02	51.7
2	192.1	3.63	1.7	0.03	61.8
3a	13.5	0.39	1.3	0.04	40.2
3b	202.9	5.95	2.1	0.06	39.8
4	95.6	2.23	1.3	0.03	50.0
5	146.6	2.73	1.1	0.02	62.6
6	193.0	3.85	0.6	0.01	58.6
7*	151.5	2.85	5.8	0.11	62.0
8	199.7	5.18	1.0	0.03	45.0
9*	128.5	4.22	5.6	0.18	35.5

**Fig. 1:** Bulimba Creek catchment showing location of study sites.

**Fig. 2:** Denitrification potential mean and SE for each site and nitrate treatment (n=4). Sites are arranged from 1 to 9, left to right within each treatment. Stippled bars represent control treatments while solid bars represent samples that received additional nitrate.

**Fig. 3:** Mean (+SE) denitrification potential (a), organic matter content (b) and slurry nitrate concentration before spike (c) of instream sediments (spotted bars) and riparian soil (solid bars) from 9 reaches of Bulimba Creek. Denitrification potential is that with additional nitrate treatment.

**Fig. 4:** Relationship between canopy cover and benthic chlorophyll-a concentration. Points are means  $\pm$  SE (n=3).

**Fig. 5:** Leaf litter standing stocks in riparian zones and the accumulation rate from litter fall traps. Site 3a is managed parkland that is frequently mown. Site 3b is the opposite bank that has thick brush to 3 m with overstory trees. Bars and points are means  $\pm$  SE (n=4). Calculation of accumulation rate at grassy sites (Sites 7 and 9) did not contain replication to provide standard error.

Figure 1

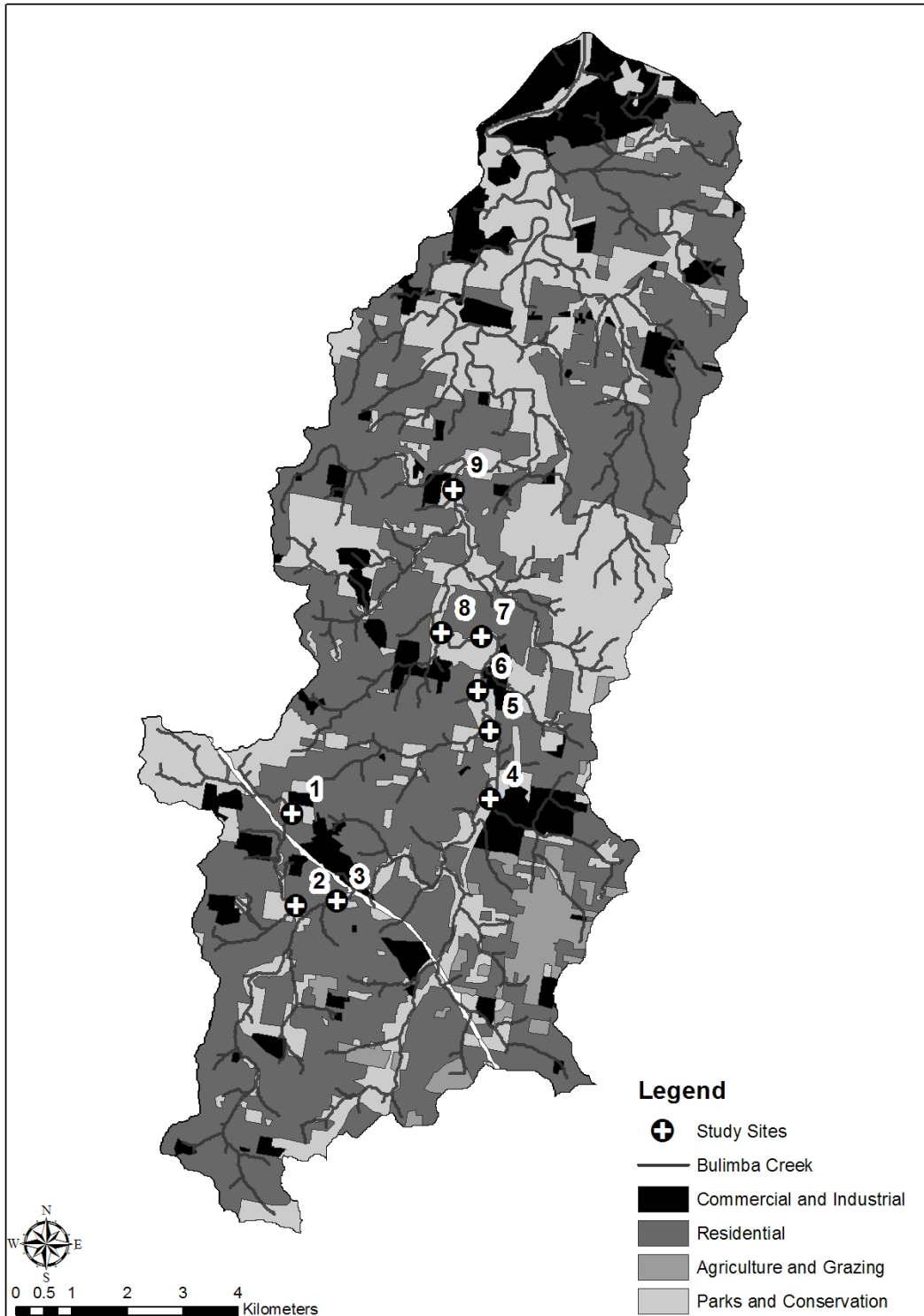




Figure 2

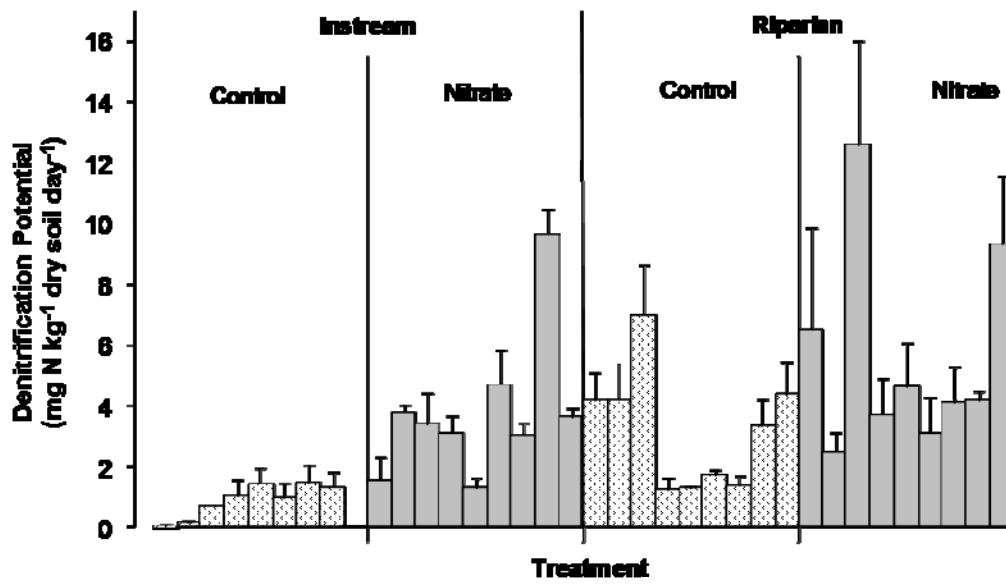


Figure 3

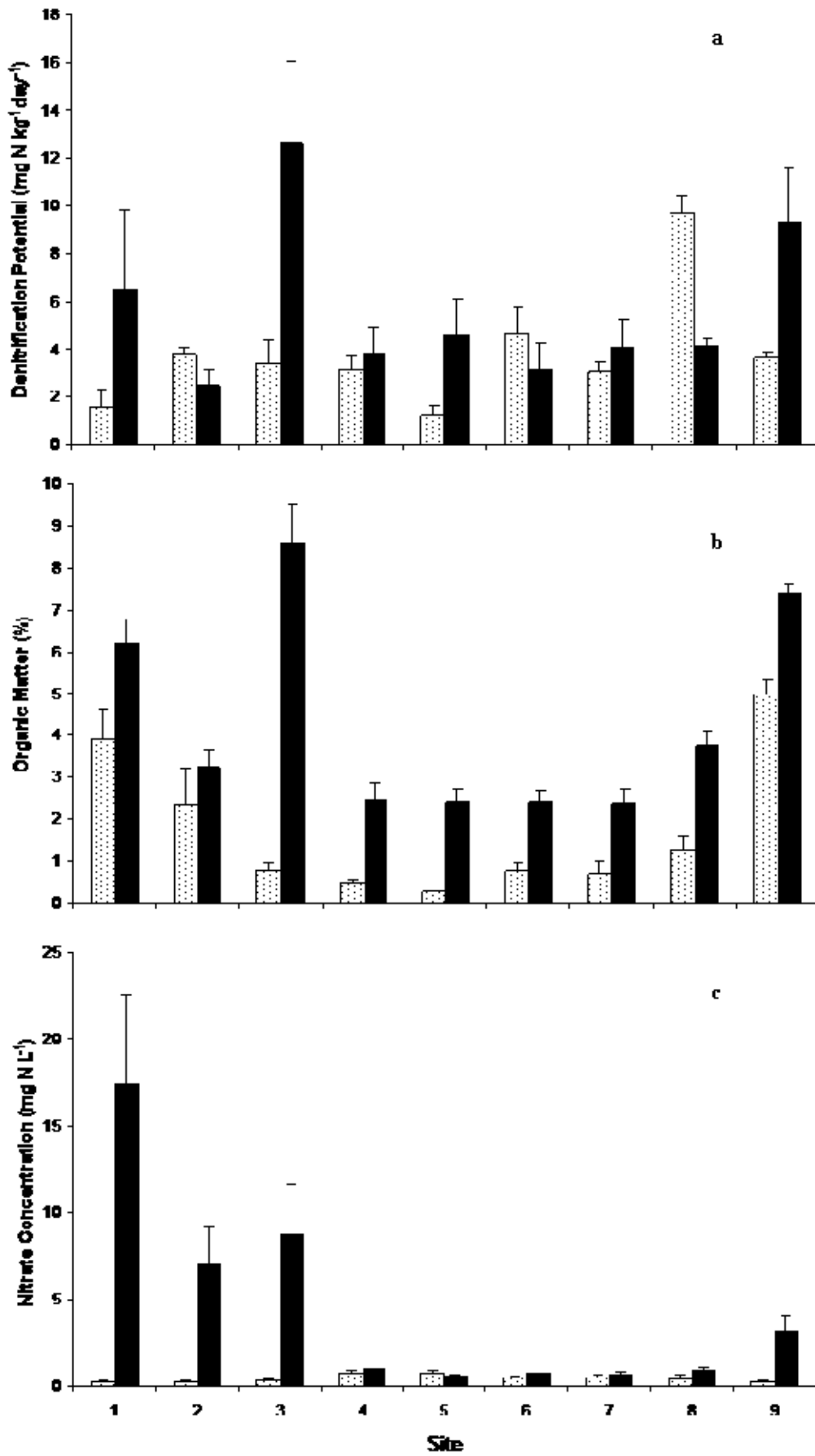


Figure 4

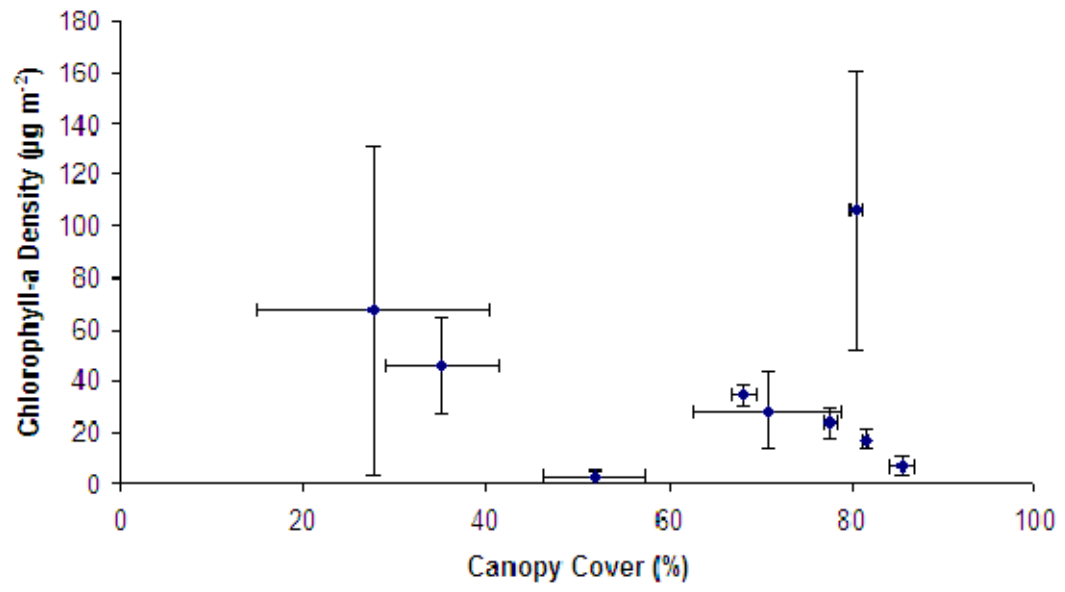


Figure 5

