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Performance of grass and rainforest riparian buffers in the wet tropics, Far North Queensland. 2. Water quality

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Abstract. Riparian lands have the potential to buffer streams from hillslope sediment and nutrient transport. Most research on buffers has been conducted under laboratory or manipulated field experimental conditions. Few quantitative data exist on buffer performance under natural field conditions. This study reports measured soil loss and evaluates the effectiveness of riparian buffers on planar and convergent slopes under field hydrological conditions in Far North Queensland. The conditions are extreme for testing the effectiveness of riparian buffers as the land is steep, intensely cropped and receives high intensity rainfall. Hillslopes cropped with bananas were monitored using paired flumes. Runoff, bedload, and suspended loads were measured leaving the crop (upper sites) and leaving the riparian buffers (lower sites). Highly variable hillslope soil losses of <1 to >70 t/ha per wet season were recorded. High rates of hillslope soil loss were from areas of steep gradient with little ground cover experiencing high rainfall intensity. On planar slopes, even with high soil loss, grass buffer strips were able to trap >80% of the incoming bedload. Total N (TN), total P (TP) and suspended sediment (SS) loads were reduced between 25 and 65% by the planar slope grass buffer and within the first 15 m of the moderately convergent grass buffer. Loads leaving the moderately convergent buffer were often higher than those delivered from the crop, due to seepage after prolonged or high frequency rainfall. Under these conditions the buffer's main function is to prevent erosion rather than trap sediment and nutrients. Results from a highly convergent 5-ha hillslope, suggest that for buffers to be more effective in such topography, they should also be placed at the end of the crop rows, where contributing areas are smaller. Flow was able to concentrate within the crop and on at least one occasion was able to scour a 30-cm-wide channel through the entire width of the buffer releasing previously trapped material and making the buffer ineffective. A remnant rainforest buffer, receiving runoff from a planar slope, acted as a temporary store of sediment and nutrients that were reworked during subsequent events. This study demonstrates both a need for managed buffer strips on sloping tropical cropped land and identifies limitations on their potential effectiveness.

Additional keywords: bedload, suspended sediment, phosphorus, nitrogen.

Introduction

There is general agreement that riparian buffers can significantly reduce sediment loads and concentrations from surface runoff (see overland flow, Goudie *et al*. 1994) in agricultural lands. Typically between 40 and 95% of the sediment load is retained, but the variability in performance is large (Peterjohn and Correll 1984; Dillaha *et al*. 1989; Arora *et al*. 1996; Daniels and Gilliam 1996; Patty *et al*. 1997; Barfield *et al*. 1998; Schmidt *et al*. 1999; Sheridan *et al*. 1999). Particulate or sediment-associated nutrients can also be removed from surface runoff, although trapping is generally lower than for sediment (Peterjohn and Correll 1984; Smith 1989). Loads of dissolved pollutants (e.g. nitrate, filterable reactive phosphorus) transported by surface runoff are reduced the least (Peterjohn and Correll 1984; Dillaha *et al*. 1989; Vought *et al*. 1991; Daniels and Gilliam 1996; Patty *et al*. 1997; Schmidt *et al*. 1999).

Buffers remove debris, sediment, and particulate nutrients from surface runoff through the processes of deposition, infiltration, and physical filtering. The buffer vegetation

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reduces the velocity of surface runoff, decreasing its sediment transport capacity. If the transport capacity is less than the incoming sediment load then sediment will be deposited. The reduction in flow velocity at the buffer edge results in a backwater, or area of slow moving water (Dabney *et al*. 1995; Karssies and Prosser 1999; Ghadiri *et al*. 2001), causing a splay of sediment to be deposited (e.g. Peterjohn and Correll 1984; Dillaha *et al*. 1989). Infiltration also reduces the sediment transport capacity by decreasing the surface runoff volume (Dillaha and Inamdar 1997). Dissolved pollutants and fine particles in surface runoff may also enter the soil with infiltrating water. Only the larger particles and aggregates are likely to be physically filtered from the runoff (Dillaha and Inamdar 1997) because of the higher sediment transport capacity and longer settling times for fine particles than coarse particles.

Many factors influence buffer performance, including sediment particle size and load, buffer width (downslope distance through the buffer), slope, slope length, vegetation type and density, flow rate, and flow conditions (Wilson 1967; Dillaha *et al*. 1989; Magette *et al*. 1989; Barfield *et al*. 1998). If conditions are not favourable then buffers will not achieve their function.

There are many conditions that may limit buffer effectiveness, for example concentration of flow and high erosion rates. Concentration of flow in rills, topographic hollows, or ephemeral gullies will all pose limitations to buffer performance. These situations usually occur in large fields where overland flow accumulates downslope. At the extreme, flow can have sufficient energy to not only transport sediment through a buffer but also scour a channel through the vegetation. Similarly, the high hillslope erosion rates in the field increase the risk of the buffer capacity being exceeded. Buffers have only a limited capacity to trap sediment, so if the incoming load fills the backwater at the buffer edge, or buries the grass, the flow will no longer be slowed and the buffer will be breached (Karssies and Prosser 1999).

Most research on sediment and nutrient filtering by riparian buffers has been conducted under laboratory or manipulated field experimental conditions (e.g. Dillaha *et al*. 1989; Magette *et al*. 1989; Barfield *et al*. 1998) and little quantitative data exists on buffer performance under natural field conditions. Although experimental studies are valuable for investigating processes, the conditions may not accurately represent natural conditions (Dillaha *et al*. 1989). Natural storm durations are often longer than in experimental studies, and in nature there are a range of vegetation and topographic conditions, not incorporated into many experimental designs, that can conspire to defeat sediment filtering. Given the many factors that contribute to buffer performance, and the range of performances observed, it is important to monitor buffer performance in a variety of field conditions.

This study reports on patterns of hillslope soil loss and sediment and nutrient trapping by riparian buffers under natural rainfall conditions in the Johnstone River catchment, part of the wet tropics of Far North Queensland. The wet tropics present extreme conditions for testing the effectiveness of riparian buffers, with intensively cropped land receiving high-intensity, long-duration rainfall. The potential of riparian buffers to reduce sediment and nutrient loads currently delivered to streams has not been previously investigated in this environment. Hillslope erosion is the predominant source of sediment in the region (NLWRA 2001), so filtering surface runoff has been identified as a key riparian buffer function and is one way to reduce the impact of significant erosion. Erosion has been recognised as a problem on cropped land in Queensland since the 1940s (Sloan 1947; Kerr 1937 cited in Sallaway 1979; Stephens 1945 in Prove *et al*. 1995). Traditional methods of erosion control, for example contour banks and grassed waterways, have been adopted in southern and central Queensland, but not in the north. Prove *et al*. (1995) attribute this to the difficulty in achieving workable farm layouts on steep and highly dissected topography.

The study investigates buffer effectiveness on hillslopes with differing slopes, contributing areas, and topographic convergence. Both grass and rainforest buffers were examined. The key questions addressed in this paper are (*i*) what are the conditions that lead to high sediment delivery from hillslopes, (*ii*) under what topographic and hydrological conditions are riparian buffers effective at reducing sediment and nutrient delivery to streams, and (*iii*) are grass buffers more effective than remnant rainforest at trapping sediment and nutrients. A companion paper explores the riparian hydrology (McKergow *et al*. 2004, this issue).

Materials and methods

Study sites

The study hillslopes are in the banana and sugarcane producing area of wet tropical Far North Queensland. They are part of the North Johnstone River catchment, which meets the coast at Innisfail (Fig. 1). Bananas are planted on steeper land in this region, while sugarcane is generally grown on the flatter land. The average rainfall at Innisfail is 3585 mm (station 032025, 101.9 years; Bureau of Meteorology 2001). Most of the annual total rainfall occurs in the wet season, December–April, and is characterised by long-duration, high-intensity storms.

Riparian buffers at 4 sites, across 2 properties, were monitored for this study (Table 1). Soils at the sites are krasnozems derived from basalt. Krasnozems are red to brown, acidic, strongly structured clay soils (50–70% clay) (Isbell 1994).

Two of the catchments were adjacent hillslopes on Gallagher's property, which have been cropped continuously for 20 years and were previously unfertilised pasture (Table 1, Fig. 1). Both hillslopes drained a 7% gradient, 200-m-long planar slope planted with bananas. The current crop of bananas was planted in May 1996, in double rows perpendicular to the contours. The mounds along the rows define the boundaries of the contributing area. There was little grass cover between the double rows of banana plants.

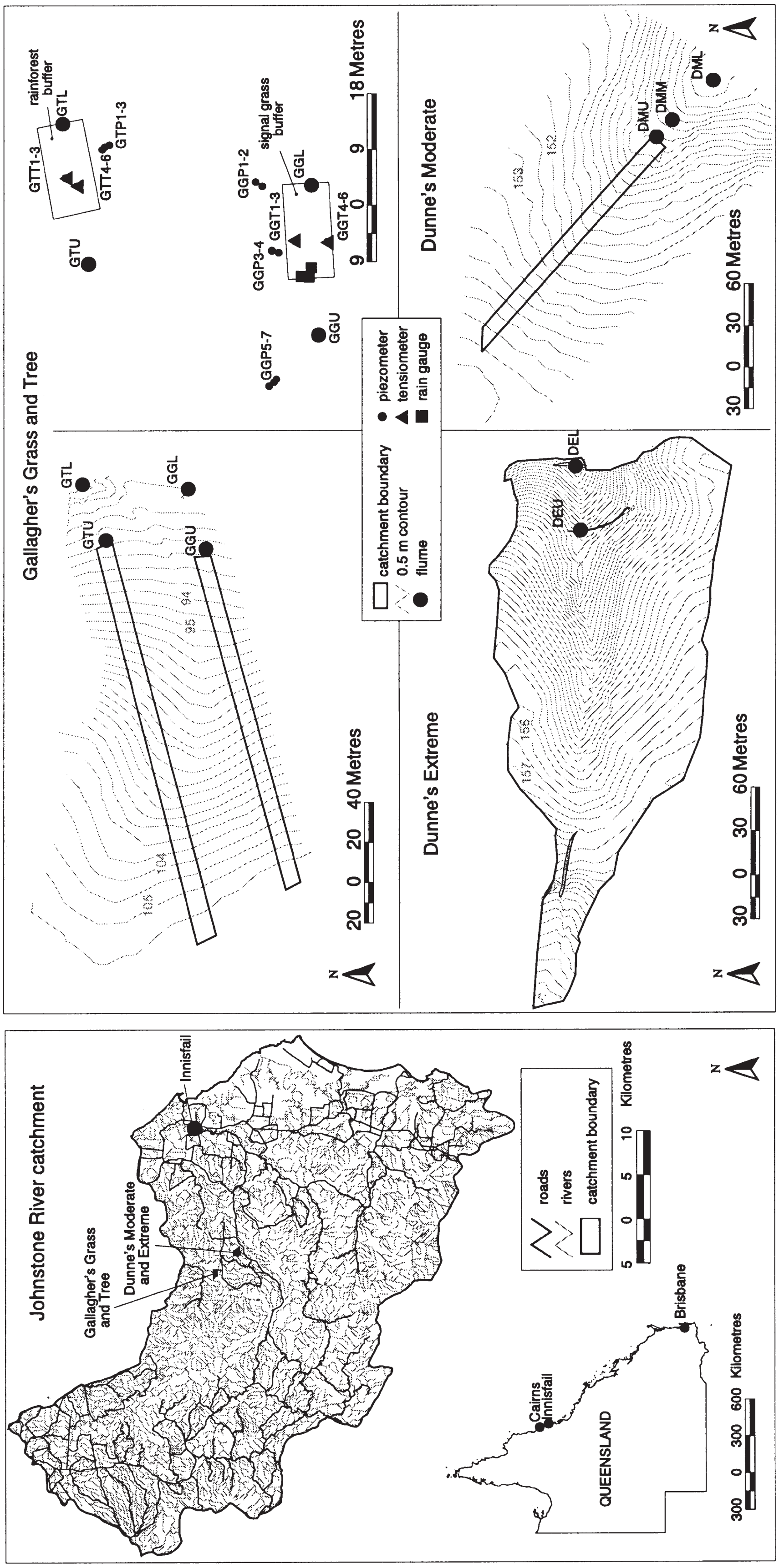

Fig. 1. Monitoring layouts at Gallagher's and Dunne's. Accompanying maps place the sites within the Johnstone River catchment and Queensland.

Table 1. Characteristics of monitored hillslopes and riparian buffers

Site	Hillslope			Riparian buffer	
	Slope (%)	Area (ha)	Form	Vegetation	Width (m)[A]
Gallagher's Grass	7	0.2	Planar	Signal grass	15
Gallagher's Tree	7	0.2	Planar	Remnant rainforest	15–20
Dunne's Moderate	3	0.3	Moderately convergent	Signal grass in hollow	60
Dunne's Extreme	13	5.0	Highly convergent	Steep hollow of signal grass with 4 vetiver grass hedges	50

[A]Downslope length of buffer.

The 15-m-wide riparian buffer at Gallagher's Grass (GG) was planted with signal grass (*Brachiaria decumbens*), a low-growing perennial, which forms a dense vegetation cover. The remnant rainforest riparian buffer, Gallagher's Tree (GT), was 15–20 m wide. The buffer had no understorey and some tree species had buttressed roots.

Two hillslope hollows, both draining into Berner Creek, were instrumented on Dunne's property (Table 1, Fig. 1). The names of these instrumented hillslopes reflect the degree of topographic convergence of flow. The hollow at Dunne's Extreme drained a 5-ha area with an average gradient of 13%. Deep soil fill has been placed in the riparian area of this small catchment. Double rows of bananas were planted perpendicular to the contours in 1994 and cropping continued across the upper part of the hollow. In May 1996 the riparian buffer was planted across the steeper foot of the hollow. A 50-m-wide signal grass buffer with 4 vetiver grass (*Vetiveria zizanioides* L.) hedges was established quickly and there was good grass cover throughout the investigation. The 4 vetiver grass hedges were located 5, 10, 25, and 45 m, respectively, below the upper flume.

Dunne's Moderate drained 0.3 ha with an average gradient of 3% and had dense signal grass cover along 60 m of gently sloping hollow (Fig. 1). The riparian buffer at Dunne's Moderate was planted in January 1996. Dunne's Moderate was ploughed in 1996, and in 1997 double rows of bananas were planted perpendicular to the contours. Good grass cover was established in the inter-rows.

The signal grass buffers were all mown regularly during each wet season to prevent the clump-forming guinea grass (*Panicum maximum*) from dominating. The signal grass height varied throughout the monitoring period and between the 4 sites, but was generally 10–40 cm high.

Bananas receive a range of fertilisers in fortnightly or monthly applications depending on rainfall. Fertiliser is either applied via irrigation (dissolved) or to the surface in solid form. Common fertilisers are superphosphate (8.8% P), muriate of potash (50% K), Nitram (34% N as ammonium nitrate), and urea (46% N). The plant is harvested at 10 months and subsequent ratoons at 10–12-month intervals. There are usually 5–6 ratoons per crop, i.e. a 4–5-year cycle.

The Queensland Department of Primary Industries monitored fertiliser application at Dunne's between 1995 and 1998. During the monitoring period the crop received 432 kg N, 20 kg P, and 957 kg K/ha.year. In addition, organic fertilisers were applied as a soil improver. Gallagher's farm has been under bananas for 20 years almost continually and was previously unfertilised cattle paddocks. For the last 12 years the bananas have been fertilised at 6–8-week intervals at 360 kg/ha of a 13 N:2.5 P:23 K blend, which is equivalent to 346 kg N, 67 kg P, and 1092 kg K/ha.year.

Methods

This study is based on sampling of sediment bedload, suspended sediment and nutrient loads over 4 wet seasons (October 1996 to May 2000).

Sampling methods

Runoff volumes and water quality leaving the crop (Upper site, U) and leaving the riparian buffer (Lower site, L) on each hillslope were monitored using identical San Dimas flumes (Wilm *et al*. 1938), fitted with bedload traps, water level recorders and automatic water samplers (Fig. 1). Riparian buffer trapping was calculated for loads using: trapping = (upper load – lower load)/upper load. An additional middle flume at Dunne's Moderate allowed comparisons between the upper and middle flumes, and middle and lower flumes to be made.

During large events the lower flumes at Gallagher's, particularly in the grass buffer were submerged by streamflow. During such events, analysis was restricted to the periods before and after the flume was flooded.

To measure bedload transport, each San Dimas flume was fitted with a trap that diverted a known proportion of sediment (3–13%) into a storage drum. Each bedload trap consisted of a 20-mm-wide slot, flush with the flume concrete apron that diverted material from the flume to a storage drum. Runoff was dispersed over a concrete apron after flowing through the flume and the remaining sediment was able to continue moving through the riparian zone. The term 'bedload' therefore has an operational definition in this paper (i.e. material that enters the bedload trap). The storage drums were emptied periodically. Subsamples were collected and taken to the laboratory for oven drying (at 65°C for at least 7 days), and the oven-dry mass of sediment was converted to equivalent soil loss (kg/ha). Subsamples were analysed to determine the attached nutrient load.

Each flume was also fitted with an automatic water sampler (ISCO Model 3700), which was triggered by a float switch. Samples were collected at 10–30-min intervals depending on the expected event size.

Water and sediment quality analysis

A single flow-weighted composite of surface runoff was prepared per event and sent to the lab for analysis. Samples were analysed for suspended sediment (SS; APHA 1995, method reference 2540 with 0.7-μm Whatman GFF filter paper), total Kjeldahl N (TKN; APHA 1995, method reference 4500-N_{org} B), total Kjeldahl P (TP; APHA 1995, method reference 4500-P), and oxidised N (OxN; Griess-Ilosvay reaction following cadmium reduction; APHA 1995). Total nitrogen (TN) was determined by summing TKN and OxN. Detection limits were 0.001 mg/L for OxN, 0.01 mg/L for TP, 0.03 mg/L for TKN, and 0.001 g/L for SS analyses. During the 1996–97 wet season, samples from Dunne's Extreme were also analysed for ammonium (APHA 1995, method reference 4500-NH_3 H) and reactive P (RP; APHA 1995; method reference 4500-P F). Organic N (OrgN) was calculated by subtracting ammonium from TKN. Composite samples were quality coded, and if errors were discovered in discharge estimation, sample times, representativeness of samples or sample identification, the results were not used in subsequent analysis.

Bedload samples were also analysed for nutrients. Total Kjeldahl N (Bremner 1965) and TP were determined on dried, finely ground samples pelletised onto a boric acid backing and analysed by X-ray fluorescence spectroscopy.

Sample turbidities were measured from December 1998 with a turbidity meter (Hach 2100P; 0–1000 NTU). Samples with turbidities exceeding 1000 NTU were diluted until a value could be obtained. Diluted samples were scaled up linearly, for example, a 10:1 diluted sample with an NTU of 850 was evaluated as 8500 NTU.

A regression relationship was developed between turbidity and SS concentration to produce instantaneous SS concentration during events. This method has been used to estimate SS concentrations using both continuously recorded and laboratory turbidity data (Gippel 1995; Grayson *et al*. 1996). In this study turbidity could not be monitored continuously as flow only occurred when there was sufficient rainfall. Data from all sites were lumped into a single model, as there were no apparent differences between the 2 farms. A linear regression model was developed using 101 samples and the final model was SS (mg/L) = 0.6Turbidity (NTU) + 43.6 ($r^2 = 0.96$).

During the 1999–2000 wet season, the turbidity–SS relationship was used to estimate flow weighted mean concentrations (FWMC) for each event. Analysis of composite and FWMC SS concentrations analysed during the 1998–99 wet season confirms that the methods yield similar results. The correlation coefficient between the SS concentrations estimated by the two methods was 0.93 ($P < 0.001$) and the medians were not significantly different (Mann Whitney, $P = 0.234$).

Trapping efficiencies were calculated for paired events (i.e. with good quality upper and lower data), while concentration data is presented for all events with good quality samples. Concentration and load data presented for Dunne's Extreme do not include the 1999–2000 season, as the side embankment of the buffer was breached and runoff from part of the banana crop entered the buffer between the flumes. Total load results (i.e. bedload + suspended load) are not presented, as the runoff in many events was not adequately sampled. However, assessments are made of the ratios of bedload to suspended load over entire wet seasons and large events. Non-parametric statistical measures and tests were used and a substitution of 0.5 detection limit (DL) was made for values below the DL for load calculations and plotting.

Results and discussion

The results and discussion are presented in 2 sections; the first deals with bedload and associated nutrient delivery from hillslopes, and the second with buffer effectiveness.

Bedload loss from hillslopes

Bedload is defined here as material entering the bedload traps, and is made up of water-stable soil aggregates of clay and silt, predominantly 2–4 mm in diameter. Table 2 shows high spatial and temporal variability in sediment delivery of bedload from hillslopes over 3 of the monitored wet seasons. Bedload soil loss varied from <1 to >70 t/ha per wet season. As described later, bedload transport dominates the total soil loss in the events that produce the most erosion. Significant bedload transport only occurs sporadically and while it is not possible to decipher the precise causes of erosion, because more than one factor tends to vary between sites, some patterns do emerge.

The highest bedload losses occur during formation of rills in large storms on poorly covered sloping land. By far the highest soil losses were measured at the Gallagher's sites in the second wet season, when 1280 mm of rain fell over 12 days during 2 cyclones. Rill erosion was observed in the inter-row areas and crop rows upslope of the rainforest buffer. Upslope of the grass buffer, rills only formed in the crop rows, as there was good grass cover in the inter-row areas. The erosion in this period accounted for the high total bedload yield for the season. On both sampling occasions the upper bedload drums at Gallagher's Tree overflowed, and so the soil loss rate was >70 t/ha.

No other major episodes of rill erosion were recorded in the study. The highest bedload yield from Dunne's Extreme was in the first wet season (Table 2), probably from modification of an existing rill that had eroded along the hollow axis at Dunne's Extreme prior to monitoring. The bed and banks of this rill were composed of cohesive clay and the high intensity runoff during subsequent wet seasons was unable to further erode the rill. This reflects observations of earlier work (Prove *et al*. 1997) that bedload transport, and total sediment yield, declines with plantation age due to a depletion of readily erodible soil. For example, new rills formed in a freshly planted paddock adjacent to Dunne's Extreme in the second wet season, when there was little sediment loss from the older Dunne's Extreme paddock.

Ploughing, grass cover, and low gradient appear to result in low bedload transport. The effect of ploughing is contrary to expectation. The soils at Gallagher's and Dunne's Moderate were deep ripped across the contour prior to the first wet season and very few surface runoff events or erosion were recorded in the first season. It appears that the ripping interrupted flow paths and increased infiltration capacities. For example, peak discharges were <200 L/min at Dunne's Moderate during a cyclone in March 1997. During later cyclones, maximum discharges were >6000 L/min.

Dunne's Moderate is an example of a low-gradient, well-grassed site, and it failed to yield significant bedload in any season (Table 2). The only time Dunne's Moderate yielded well over 10 kg of bedload was in the third year when a cyclone severely damaged the crop. In addition to the bedload reported in Table 2, a deposit (approx. 1 m^3) was observed upslope of Dunne's Moderate upper flume after the cyclone. Higher hillslope losses were possible because there was low grass cover in the inter-row areas and soil was exposed after the crop was damaged.

Even the highest bedload yields of 40 and 70 t/ha measured at the Gallagher's sites are significantly lower than those quoted in the literature for soil loss from sugarcane in this region. Prove *et al*. (1995) reported soil losses from plot studies on conventionally cultivated ratoon cane lands in the Johnstone River catchment of 47–505 t/ha.year. The average loss was 148 t/ha.year and no-tillage practices reduced this value to <15 t/ha.year. Mathews and Makepeace (1981) reported a soil loss of 382 t/ha.year for conventionally cultivated sugarcane on a 16% slope. This soil loss was measured during a wet season that included a record

Table 2. Bedload data from the upper (U) and lower (L) bedload traps at Gallagher's Grass (GG), Gallagher's Tree (GT), Dunne's Extreme (DE), and Dunne's Moderate (DM) for 3 wet seasons: sediment total (kg) and loss (t/ha); total Kjeldahl N and total P (kg) and loss (kg/ha)

Italicised loads are estimated using the median content for the site

Site	1996–97		1997–98		1998–99	
	Total	Loss	Total	Loss	Total	Loss
			Sediment			
GGU	145	0.76	7860	41.15	81	0.42
GGL	24		>8		40	
GTU	18	0.10	>13 455	>70.45	805	4.21
GTL	37		>392		283	
DEU	8189	1.76	1429	0.31	4375	0.94
DEL	9810		927		6949	
DMU	5	0.02	11	0.04	56	0.18
DMM	3		6		22	
DML	4		24		46	
			Total Kjeldahl N			
GGU	0.55	2.9	23.2	121	*0.28*	*1.5*
GGL	0.1		>0.04		*0.27*	
GTU	0.07	0.4	41.9	219	*3.7*	*19.4*
GTL	0.16		>1.0		*1.0*	
DEU	22.2	4.8	7.4	1.6	*18.3*	*3.9*
DEL	28.5		5.1		*22.9*	
DMU	0.03	0.1	0.1	0.3	*0.61*	*2.0*
DMM	0.01		0.04		*0.14*	
DML	0.02		0.14		*0.26*	
			Total P			
GGU	0.56	2.9	23.6	124	*0.24*	*1.3*
GGL	0.08		>0.02		*0.16*	
GTU	0.06	0.3	40.0	209	*2.66*	*14*
GTL	0.13		1.16		*0.93*	
DEU	21.6	4.6	3.8	0.8	*11.4*	*2.4*
DEL	26.5		2.6		*19.5*	
DMU	0.02	0.07	0.05	0.2	*0.36*	*1.2*
DMM	0.01		0.02		*0.1*	
DML	0.02		0.1		*0.19*	

2742 mm of rain in a single month. Conventional cane-growing practices and banana land use practices have much in common. They both involve intensive cultivation and there is considerable bare ground between the crop, particularly early in the crop rotation. Thus, we might expect similar sediment yields from the 2 land uses, a result found by Walton and Hunter (1997) based upon in-stream sediment loads.

Using caesium-137 as a tracer (Loughran 1989; Walling and Quine 1991), long-term soil loss rates at Dunne's Extreme and Gallagher's Grass were 14–25 t/ha.year (P. J. Wallbrink, pers. comm.). The sediment budget calculations of Prosser (1999) for the whole catchment also point to such soil loss rates for the catchment sediment budget to balance. Thus, these results suggest that the published figures of >100 t/ha.year are too high to be used as hillslope averages over longer time periods and across the whole catchment. The earlier results tended to include higher-than-average rainfall intensities, steeper-than-average slopes, and measurement at less than hillslope scale, all of which would over-estimate sediment delivery potential to streams. Our results show that despite the extreme rainfall, there are a range of conditions that give quite low soil loss on cultivated land in the wet tropics. These include good grass cover, deep ripping across the contour, low slope gradient, and cohesive subsoils that limit continuing rill erosion.

Nutrient contents of bedload samples (expressed as a %) were analysed for samples collected prior to June 1998. Both TKN and TP bedload generally reflect bedload sediment delivery (Table 2), as any variability in nutrient content is much lower than the variation in bedload mass. The highest bedload losses were at Gallagher's during the second wet season, and the corresponding nutrient losses were 121 and 219 kg TKN/ha and 124 and 209 kg TP/ha at Gallagher's

Grass and Gallagher's Tree, respectively. Bedload nutrient delivery was low at both Dunne's sites and during the first wet season at Gallagher's (Table 2).

Buffer effectiveness

Riparian buffer effectiveness can be evaluated using either pollutant concentrations or loads, and trapping efficiencies can be reported for either individual events or entire monitoring periods. In this study, emphasis was placed on the reductions in bedload and suspended loads captured during the monitoring period. The variability in trapping between events was examined to gain insight into factors influencing riparian buffer performance, such as riparian hydrology and event size. Concentration and load data are reported for suspended material to help identify key trapping mechanisms.

Bedload trapping

The riparian buffers have significant bedload trapping ability but not under all conditions (Table 2).

The dense grass buffer receiving runoff from a planar slope performed consistently (Gallagher's Grass, Table 2), and was tested by several large events. In one event only 4 kg of the 4161 kg of bedload passing through the upper flume reached the lower flume. Data gaps prevent an overall trapping estimate, but up to the middle of the second wet season >80% of bedload was trapped. Trapping cannot be calculated for the later part of the second wet season as the storage drums at both lower sites at Gallagher's were forced out of the ground (by positive pore water pressures) during a cyclone. Trapping during the third wet season was not as high (50%), but this was the season of lowest input.

The bulk of the bedload were transported as soil aggregates, 2–4 mm in diameter, which fall out of suspension easily, thereby assisting trapping. The focus of bedload deposition was at the upper edge of the buffer, consistent with deposition in a backwater (Karssies and Prosser 1999). A dense grass buffer <15 m wide may therefore be able to trap significant quantities of bedload from planar slopes. Farm management practices that maintain aggregate structure, and therefore encourage backwater deposition, will ensure high trapping under conditions of high bedload delivery.

Despite trapping considerable quantities of sediment, the grass buffer at Gallagher's showed no signs of a long-term decline in performance. The deposits were rapidly colonised by grass and the sediment permanently trapped. This finding contrasts with that of Dillaha *et al.* (1989), who observed accumulations of sediment at the field–buffer interface, which later became dikes and diverted runoff from the buffers. Our study suggests that sediment removal may not be required at the buffer–crop interface if good grass cover is maintained.

Data and observations for the rainforest buffer show that during some events bedload was deposited; however, the sediment was re-suspended and transported during subsequent events. During the low intensity runoff of the first wet season, the rainforest buffer was a source of sediment (Gallagher's Tree, Table 2). Data gaps prevent calculation of trapping for the entire second wet season, but data for a cyclone in late December 1997 suggest that significant amounts of bedload were trapped within the buffer. However, this bedload was reworked in later storms and was not permanently retained by the buffer. Rills were observed in the deposited sediment, particularly near buttressed tree roots, which help concentrate surface runoff.

At both Dunne's sites scour occurred within the grass buffers, and the lower flumes generally recorded higher bedload than the upper flumes (Table 2). At Dunne's Extreme, scour occurred within the axis of the hollow. For example, a cyclone during the third wet season resulted in a 30-cm-wide channel through the entire width of the buffer, including the vetiver grass hedges. This erosion and the release of previously trapped sediment increased the bedload between the upper and lower flumes by 60%. These results from the highly convergent Dunne's Extreme site, with a contributing catchment area of 5 ha, suggests, buffers should *also* be placed at the end of the crop rows, where contributing areas are smaller to reduce the risk of channelised flow and scour.

At Dunne's Moderate, seepage was often observed at the lower flume and this may have reduced the soil strength. The sediment trapped at the lower flume is likely the result of scour within the lower section of the buffer, as bedload trapping occurred between the upper and middle flumes (Table 2).

Suspended material

Dense grass buffers on the planar and moderately converging slopes can trap significant amounts of suspended material. The buffer at Gallagher's Grass trapped SS (46%), TN (26%), and TP (40%) during the monitored events (Tables 3, 4). Similar sediment trapping occurred at Dunne's Moderate, but nutrient trapping was higher with 45% TN and 64% TP reductions in the total load between the upper and lower flumes for the paired events (Tables 3, 4). Trapping was at the lower end of the range previously reported for buffers below cropped land monitored under natural rainfall conditions (Arora *et al*. 1996; Daniels and Gilliam 1996; Patty *et al*. 1997; Sheridan *et al*. 1999). This is most likely due to the extreme conditions, including the magnitude of runoff and steeper slopes, compared with previous studies.

Nitrogen transport was dominated by TKN (OrgN and ammonium) at all sites, with OxN generally making up <25%. The additional data from Dunne's Extreme shows that OrgN dominated TKN, with a median OrgN : TKN ratio of 0.92 (IQR = 0.19, n = 55). The dominance of OrgN probably

Table 3. Total runoff volume (m^3), sediment load (SS, kg), and % reductions for all paired events at Gallagher's Grass, Gallagher's Tree, Dunne's Extreme, and Dunne's Moderate

		No. of events	Upper	Lower	% Reduction
Gallagher's Grass	Runoff	32	681	822	–20
	SS	32	297	159	46
Gallagher's Tree	Runoff	26	414	449	8
	SS	26	189	287	–51
Dunne's Extreme	Runoff	21	3248	2447	24
	SS	21	2233	1388	37
Dunne's Moderate	Runoff	12	412	446	–3
	SS	12	79	48	39

Table 4. Total runoff volume (m^3), nutrient loads (kg), and % reductions for all paired events at Gallagher's Grass, Gallagher's Tree, Dunne's Extreme, and Dunne's Moderate

TN, total N; TKN, total Kjeldahl N; OxN, oxidised N; TP, total P

	No. of events	Upper	Lower	% Reduction
		Gallagher's Grass		
Runoff	34	713	868	–22
TN	34	1.6	1.19	26
TKN	34	1.31	0.93	29
OxN	34	0.29	0.26	10
TP	34	1.0	0.6	40
		Gallagher's Tree		
Runoff	26	558	456	18
TN	26	1.22	1.74	–43
TKN	26	10.3	1.57	–52
OxN	26	0.19	0.18	6
TP	26	0.69	0.92	–33
		Dunne's Extreme		
Runoff	19	2883	2156	25
TN	19	9.72	7.34	24
TKN	19	6.4	5.1	20
OxN	19	3.3	2.13	36
TP	19	3.8	2.77	27
		Dunne's Moderate		
Runoff	13	434	515	–7
TN	13	1.38	0.65	45
TKN	13	1.22	0.61	50
OxN	13	0.16	0.15	5
TP	13	0.78	0.28	64

reflects the use of urea fertiliser. The additional first wet season data from Dunne's Extreme suggested that >90% of P is moving associated with particles >0.45 µm. The median RP : TP ratio was 0.06 (IQR = 0.17, $n = 55$).

Trapping was extremely variable at all sites for individual events. Many factors may have influenced trapping, including riparian hydrology, buffer vegetation condition, incoming load, and sediment particle size. For example, at Gallagher's Grass (Fig. 2), SS trapping varied between –175% and 92% and the median trapping efficiency was 39% (IQR = 60%). The buffer trapped TP consistently, and this is likely to reflect the dominance of sediment-associated P (Fig. 2). For TN, trapping varied between –300 and 80%, and the buffer was typically a TN source area when exfiltration occurred.

When infiltration was recorded in the grass buffer, with less runoff at the lower flume than the upper flume (Fig. 2), SS trapping efficiencies were high (median = 45%, IQR = 22%). Negative SS trapping efficiencies were only measured at Gallagher's Grass for events with small loads (typically <10 kg SS) and were more likely when exfiltration (or return flow; Chorley 1978) occurred (Fig. 2). During small events it is likely that less sediment, with smaller particle sizes will be entrained and trapping will be less effective.

Exfiltration also occurred at Dunne's Moderate and loads leaving the bottom of the buffer were often higher than the hillslope delivered. The focus of trapping in this buffer was between the upper and middle flumes (SS 36%, TN 40%, TKN 42%, OxN 32%, TP 52%). Exfiltration and seepage were observed in the lower section of the Dunne's Moderate buffer (DMM to DML) after prolonged or high-frequency rainfall. Sediment and nutrient concentrations were low, but the runoff volumes were significant. For example, an additional 12% (6 kg) of SS left the buffer during the 12 paired events evaluated between the middle and lower flumes. During the majority of these events, exfiltration occurred in the buffer and 134 m^3 (–36%) more runoff left the buffer than entered it.

Buffers where exfiltration occurs are seldom reported in the literature and most studies with natural rainfall report reductions in runoff within riparian buffers (e.g. Arora *et al.* 1996; Patty *et al.* 1997). Exfiltration was measured at 2 of our sites, Gallagher's Grass and Dunne's Moderate. Under these runoff conditions, the buffers were more likely to be pollutant source areas, and the buffer's main function is to prevent erosion rather than trap sediment and nutrients. If the riparian lands were cropped, instead of being protected by good grass cover, a higher erosion hazard would exist. Positive pore water pressures accompanying exfiltration and seepage may reduce soil strength. In the most extreme cases this can lead to mass soil failure and rill and gully erosion (Huang and Laften 1996; Bryan *et al.* 1998).

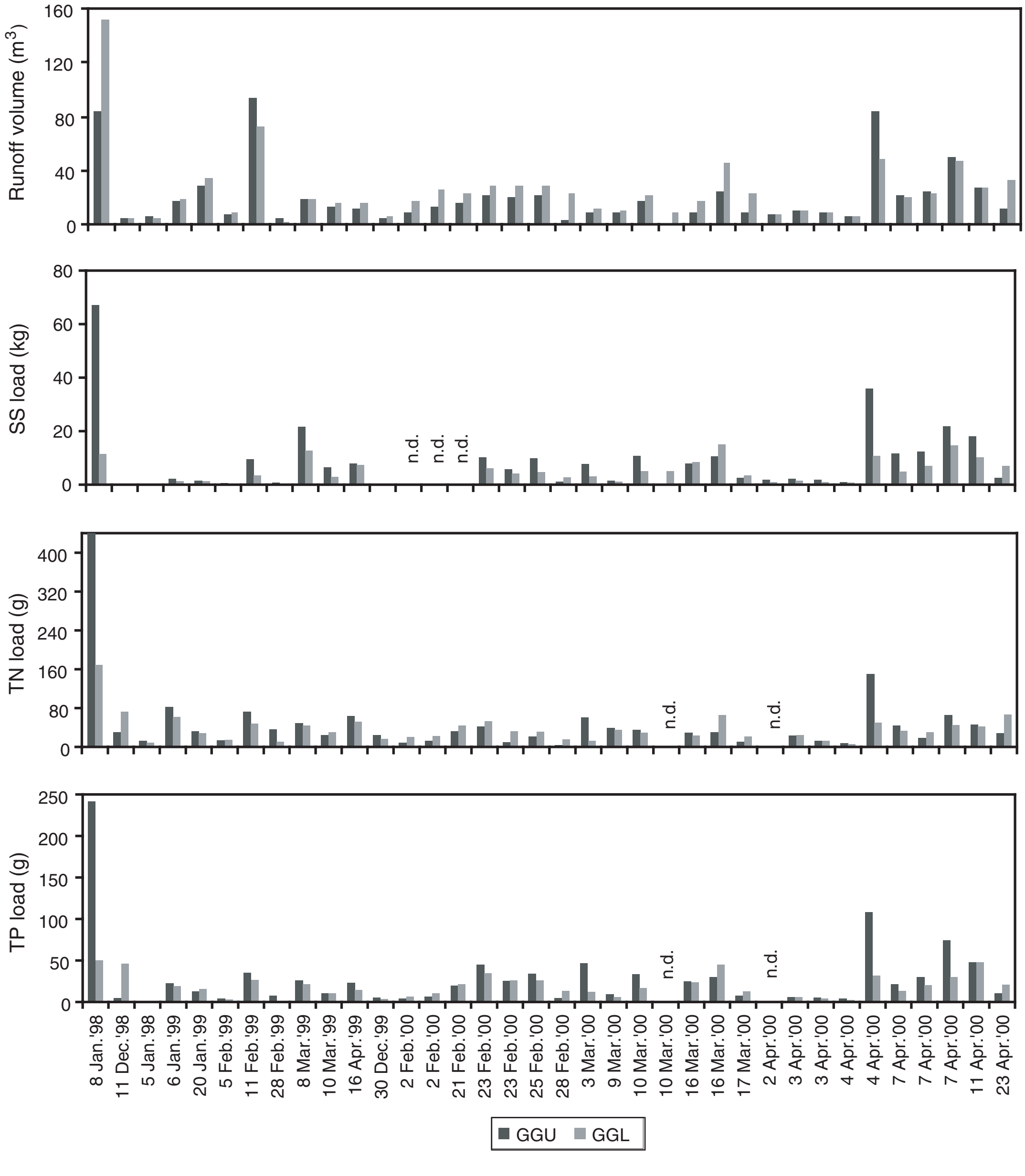

Fig. 2. Runoff volumes and suspended material loads at Gallagher's Grass Upper (GGU) and Lower (GGL) flumes for each of the paired events (summarised in Tables 3, 4); n.d., no data.

Concentration and load data can be used to identify trapping mechanisms. For example, if both concentrations and loads are reduced then deposition is likely to be the key removal mechanism. If infiltration is accompanied by deposition there will be a load reduction (due to the decrease in runoff volume) but the concentration would not alter. If infiltration is not accompanied by deposition, the load would remain unaffected and the concentration would rise.

The data suggest that deposition was the key SS and TP removal mechanism at Gallagher's Grass, as the buffer reduced both concentrations and loads. For example, the SS load was reduced 45% (Table 3) and the median SS concentration decreased by 46% between the upper and lower sites, from 0.277 to 0.150 g/L (Fig. 3; Mann Whitney, $P = 0.003$). When deposition is the key removal processes, trapping of sediment associated pollutants (e.g. TP) is likely to be less than SS trapping because they have an affinity for finer particles, which settle less easily.

Despite receiving channelised flow, the grass buffer at Dunne's Extreme generally reduced suspended material loads and concentrations. Infiltration occurred during all of the paired events and appears to be the key removal process at Dunne's Extreme. Overall, the buffer trapped SS (37%), TN (24%), and TP (27%) from the incoming loads for the

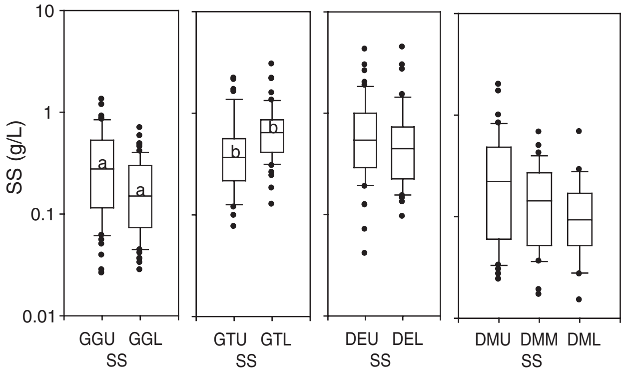

Fig. 3. Suspended sediment concentrations for all composite, flow weighted mean concentration and individual samples analysed for the Upper (U) and Lower (L) sites at Gallagher's Grass (GG), Gallagher's Tree (GT), Dunne's Extreme (DE), and Dunne's Moderate (DM). Note only one sample per event. Box represents the median with 25th and 75th percentiles, whiskers are the 10th and 90th percentiles and outliers are dots. Medians with the same letter are significantly different ($P < 0.05$).

paired events evaluated (Tables 3, 4). For the 21 individual events the SS trapping efficiencies varied between –73 and 90% (median 23%, IQR = 36%). The riparian buffer was a SS source area during 5 of the 21 paired events. Total N trapping for the individual events varied from –96 to 74% and TP trapping ranged from –150 to 78%. There were no significant differences in median concentrations between the upper and lower sites for any of the parameters measured (Figs 3, 4, 5). The reduction in loads but not concentration suggests that trapping in this buffer was primarily due to infiltration, most likely due to the presence of deep soil fill.

The rainforest buffer was a source area for suspended material with very low or negative trapping (Tables 3, 4). The total SS, TN, and TP loads for 26 paired events increased by 30–50% despite a reduction in runoff volume (Table 3). Suspended sediment was only trapped during 7 events of the paired events (Fig. 6), when infiltration occurred in the buffer. Trapping during these events ranged between 9 and 88%.

Concentrations increased between the upper and lower sites in the rainforest buffer for all parameters analysed (Figs 3, 4, 5). For example, the median SS concentration increased from 0.37 to 0.65 g/L (Mann Whitney, $P < 0.001$; Fig. 3), and the median TKN concentration increased by 76%, from 1.61 to 2.83 mg/L (Mann Whitney, $P < 0.001$; Fig. 4).

The increase in TN, TKN, and TP concentrations and loads between the upper and lower flumes in the rainforest

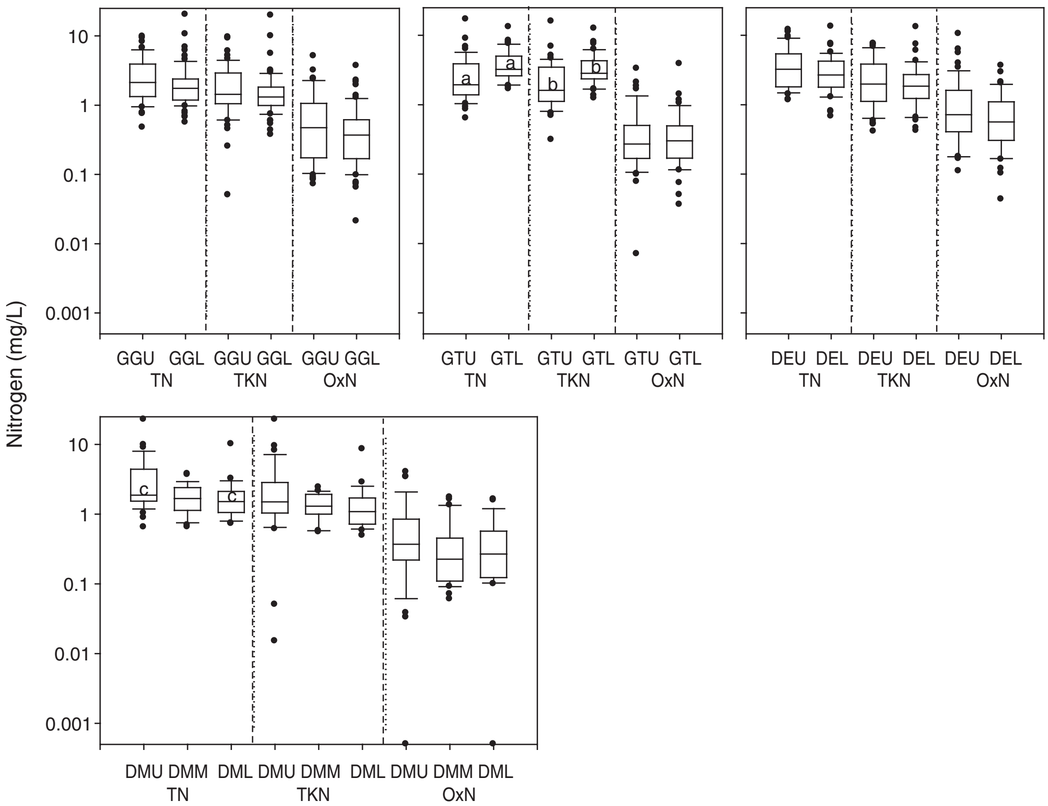

Fig. 4. Nitrogen concentrations for all composite and individual samples analysed for the Upper (U) and Lower (L) sites at Gallagher's Grass (GG), Gallagher's Tree (GT), Dunne's Extreme (DE), and Dunne's Moderate (DM). Medians with the same letter are significantly different ($P < 0.05$).

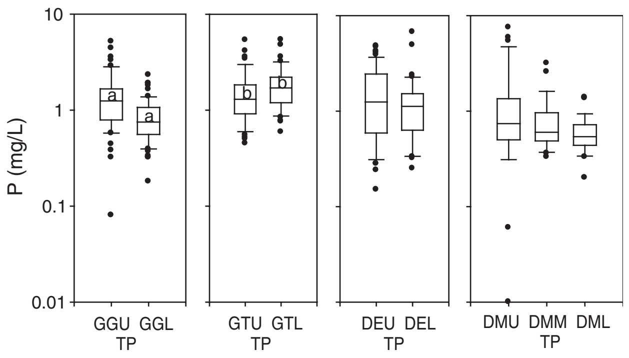

Fig. 5. Phosphorus concentrations for all composite and individual samples analysed for the Upper (U) and Lower (L) sites at Gallagher's Grass (GG), Gallagher's Tree (GT), Dunne's Extreme (DE), and Dunne's Moderate (DM). Medians with the same letter are significantly different ($P < 0.05$).

buffer suggests there are additional nutrient sources within the buffer. Possible sources include leaf litter and sediment. Annual litterfall in rainforest in Gadgarra State Forest (50 km NW of our site) was 10 t/ha.year, and was 1% N and 0.1% P (Brasell *et al*. 1980), which equates to 100 kg N and 10 kg P ha/year. The rainforest buffer has an area of around 0.02 ha and so the annual nutrient inputs from litterfall may be in the order of 2 kg N and 0.2 kg TP. Annual runoff volumes were around 1000 m^3 and so the potential increase in flow-weighted concentrations attributable to litterfall are 2 mg N and 0.2 mg P/L. The N increases were smaller than this estimate (Fig. 4), so litterfall is a possible TN source. The median TP concentration increased by 0.4 mg/L (Fig. 5), so litterfall cannot account for the increase in concentration. Bedload deposited within the rainforest buffer is reworked during subsequent events and SS, N, and P may be released during this process.

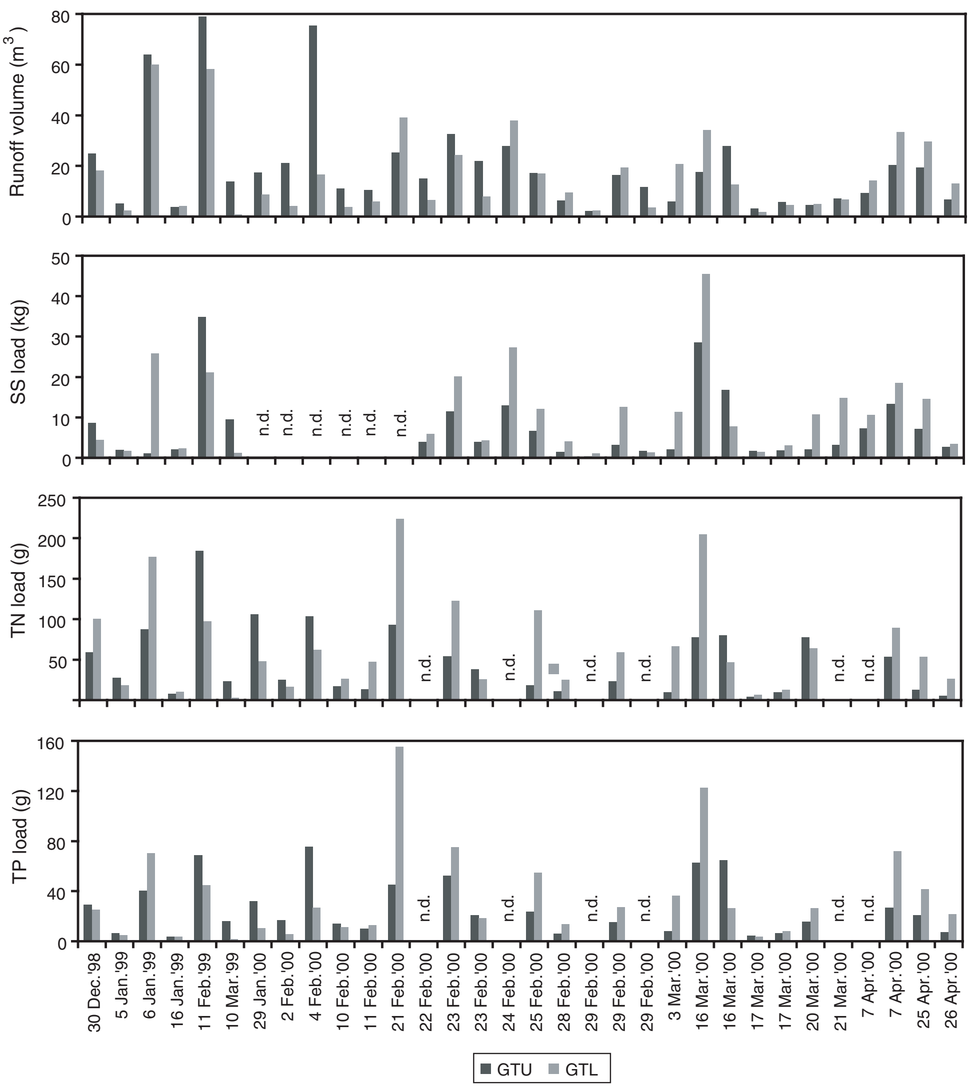

Fig. 6. Runoff volumes and suspended material loads at Gallagher's Tree Upper (GTU) and Lower (GTL) flumes for each of the paired events (summarised in Table 3, 4); n.d., no data.

Rainforest or tree buffers may be important from an ecological perspective to help maintain stream ecosystem health (Bunn *et al.* 1999). Our results indicate that rainforest buffers in this region should consist of 2 zones: a managed grass buffer to trap sediment and associated pollutants exiting from the cropped area upslope of any rainforest buffer.

Bedload v. suspended load

The fraction of material moving as bedload or suspended load will influence grass buffer performance. While the bedload was sampled continuously, the suspended load was not, due to the difficulty of sampling extreme events. For annual load comparisons the suspended load can be estimated by combining total runoff volumes for wet seasons with continuous records (pressure transducer records at Gallagher's Grass) and median concentrations.

The total upper flume runoff volume at Gallagher's Grass for the third wet season was 1800 m^3 and the median concentrations were 0.28 g SS/L, 2.13 mg TN/L, and 1.25 mg TP/L, so the third wet season suspended load estimates are 500 kg SS, 3.8 kg TN, and 2.2 kg TP. During the same wet season only 81 kg of bedload was measured and the median nutrient contents were 0.39% TKN and 0.33% TP, giving loads of around 0.3 kg for both TN and TP, and so the suspended material dominated transport.

However, previous work in the catchment (Prove *et al.* 1997) and visual observation indicate that the proportion of total load that is transported as bedload increases with the total load of the event. For example, at Gallagher's around 13300 kg of sediment and 40 kg of sediment-associated TKN and TP passed through the upper flume as bedload during two cyclones in a 12-day period in the second wet season. This load is well in excess of any suspended load passing through the flumes during the same period. Water quality samples were not taken during all runoff events, but using the maximum flow-weighted composite concentration analysed during the period, a maximum load of 700 kg SS and around 5 kg TN and TP have been estimated. The suspended SS load was therefore around 5% of the total sediment load and the suspended nutrient loads were around 12% of the total nutrient load. During this event sediment trapping was extremely high, with only 0.1% of the total bedload passing through the upper flume reaching the lower flume. In addition, during one 4-h event with paired upper and lower samples on 8 January 1998 the buffer trapped 83%, 79%, and 62% of the SS, TP, and TN loads, respectively, despite the fact exfiltration was occurring with 80% more runoff at the lower flume. The flow-weighted composite SS concentration also decreased by an order of magnitude, from 0.8 to 0.08 mg/L, between the upper and lower flumes.

During some wet seasons, particularly when inter-row grass cover was low and the crop was young, bedload dominated the total sediment load. Under these circumstances, the grass buffer at Gallagher's was able to trap considerable amounts of sediment. During later wet seasons, when the suspended sediment load dominated the total sediment load trapping was not as high, but neither were the incoming loads.

While riparian buffers can prevent significant amounts of sediment and nutrients from entering streams, additional management practices, such as on-site erosion and nutrient control, which reduce pollutant generation at the source, must also be implemented in this environment. On-site conservation practices keep the soil and nutrients on the productive hillslopes, while riparian buffers can only trap some of the sediment and nutrients before they enter streams.

Conclusion

The study was conducted under extreme conditions—steep, intensely cropped land subject to high rainfall intensities. High hillslope soil losses were measured on steep slopes with little inter-row grass cover. Low gradients and good inter-row grass cover present little erosion hazard. Slopes are most at risk of erosion in the first wet season of a crop. The results suggest that soil loss at the hillslope scale was lower than previously reported in the literature, but was still high.

The results show that dense grass riparian buffers on planar and moderately converging slopes may be effective at trapping sediment and nutrients in these extreme conditions. Bedload trapping was consistently high at Gallagher's Grass and deposition was focused in a backwater at the upper edge of the buffer. Deposits were quickly colonised by couch grass and were not reworked. This suggests that a dense grass buffer, <15 m wide, may still be able to trap significant quantities of bedload from planar slopes. Overall, trapping of suspended material varied between 25 and 65%. Trapping was variable on an individual event basis and was generally superior when infiltration occurred.

Several factors were identified that limit riparian buffer performance, including exfiltration, flow channelisation, scour, and low vegetation density. Exfiltration was measured at 2 sites with grass buffers and generally reduced the effectiveness of the buffers.

In a 5-ha highly convergent catchment with a dense grass buffer, flow channelisation reduced bedload trapping and resulted in scour of the buffer. Surface runoff was able to infiltrate into the buffer and as a result 20–50% reductions in the SS, TN, TKN, and TP loads occurred. For the buffer to be more successful it should extend up the hollow to the end of the crop rows, where gradient and discharge are less.

The riparian rainforest buffer performed poorly due to low vegetation density and lack of understorey. Bedload was deposited during several events, but the material was not permanently trapped and was reworked during subsequent events. The remnant rainforest buffer was a source area of suspended material. Rainforest buffers should therefore consist of two zones, a grass buffer upslope of a rainforest buffer.

This study demonstrates both a need for managed buffers on sloping, tropical, cropped land and identifies limitations on their potential effectiveness. Land managers adopting riparian buffers as a water quality management tool should also work to limit sediment and nutrient delivery from hillslopes.

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