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Losses of nitrogen in surface runoff from a plantation horticulture farm in coastal Queensland, Australia

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Abstract. Surface losses of nitrogen from horticulture farms in coastal Queensland, Australia, may have the potential to eutrophy sensitive coastal marine habitats nearby. A case-study of the potential extent of such losses was investigated in a coastal macadamia plantation. Nitrogen losses were quantified in 5 consecutive runoff events during the 13-month study.

Irrigation did not contribute to surface flows. Runoff was generated by storms at combined intensities and durations that were 20–40 mm/h for >9 min. These intensities and durations were within expected short-term (1 year) and long-term (up to 20 years) frequencies of rainfall in the study area. Surface flow volumes were 5.3 ± 1.1% of the episodic rainfall generated by such storms. Therefore, the largest part of each rainfall event was attributed to infiltration and drainage in this farm soil (Kandosol). The estimated annual loss of total nitrogen in runoff was 0.26 kg N/ha.year, representing a minimal loading of nitrogen in surface runoff when compared to other studies.

The weighted average concentrations of total sediment nitrogen (TSN) and total dissolved nitrogen (TDN) generated in the farm runoff were 2.81 ± 0.77% N and 1.11 ± 0.27 mg N/L, respectively. These concentrations were considerably greater than ambient levels in an adjoining catchment waterway. Concentrations of TSN and TDN in the waterway were 0.11 ± 0.02% N and 0.50 ± 0.09 mg N/L, respectively. The steep concentration gradient of TSN and TDN between the farm runoff and the waterway demonstrated the occurrence of nutrient loading from the farming landscapes to the waterway. The TDN levels in the stream exceeded the current specified threshold of 0.2–0.3 mg N/L for eutrophication of such a waterway. Therefore, while the estimate of annual loading of N from runoff losses was comparatively low, it was evident that the stream catchment and associated agricultural land uses were already characterised by significant nitrogen loadings that pose eutrophication risks. The reported levels of nitrogen and the proximity of such waterways (8 km) to the coastline may have also have implications for the nearshore (oligotrophic) marine environment during periods of turbulent flow.

Additional keywords: nitrate, ammonium, eutrophication, macadamia.

Introduction

The south-eastern and northern coastal regions of Queensland, Australia, border the world's largest expanse of protected marine habitat, known as the Great Barrier Reef World Heritage Area (GBRWHA). The ecosystem of this reef is sustained by an oligotrophic marine environment. Many studies show that elevated concentrations of nitrogen will be detrimental to the ecological balance of such an ecosystem. Nitrogen-induced eutrophication is linked to the decline of reefs, by favouring species and processes which lead to their de-calcification and the decline of seagrass populations (Fabricius 2005; Burkholder *et al*. 2007). Extreme eutrophication of marine habitats with nitrogen runoff from farming activities can also lead to hypoxia, resulting in fish and crustacean mortality (Ribaudo *et al*. 2005).

Annual nitrogen fertiliser expended in farming activities within the adjoining coastal belt of the GBRWHA was estimated at 86 kt in 2000–2001 (Menzies and Harper 2007). Modelled calculations have estimated that 20–67 kt N/year of anthropogenic nitrogen reaches the GBRWHA from coastal farming catchments (McKergow *et al*. 2005). Rising concern for threats to water quality in the GBRWHA, including that from nitrogen eutrophication, has led to the implementation of a nutrient management zone (NMZ) (Anon. 2007). Horticulture farming in the NMZ was assessed as an activity at high risk of nutrient loss into the GBRWHA (Anon. 2007).

Limited information is available on surface losses of nitrogen from horticulture farms in the NMZ or in similar agroecosystems worldwide. To obtain an initial estimate of the potential magnitude of losses from horticulture, our work focused on quantifying the escape of nitrogen from plantation horticulture in the NMZ for several reasons. Soil nitrogen concentrations have been reported to be highest in plantation horticulture farms when compared to other coastal farming industries in

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the NMZ (Menzies and Harper 2007). This industry uses a raised bed system of production, and plantations are often located on sloping landscapes adjacent to coastal streams and rivers which are within 50 km of the NMZ. A coastal macadamia farm was chosen as a representative model of such farming activity. The escape of nitrogen and its speciation in runoff from the farm were measured and compared with nitrogen in water and sediments of an adjoining catchment waterway.

Materials and methods

Location of study

Field research was carried out in the coastal Burnett catchment of South-East Queensland, ~24.866°S and 152.349°E. The area has a subtropical climate. Average maximum temperatures for the regional centre of Bundaberg vary from 22 to 30°C and long-term average rainfall is 1002 mm (SILO 2005).

Farm study

Nutrient runoff and soil concentrations of nitrogen were measured in a commercial macadamia plantation. The farm soil is gradationally textured and classified locally as a Kandosol and internationally as a Red Earth (Anon. 2004). Key physical and chemical properties of the soil are summarised in Table 1. The farm operated under a conventional regime of production. The macadamia trees were spaced at 3.9-m intervals lengthwise in bare-soil raised beds that were 3.9 m wide and 28 cm high at their crest. A 3.4-m grassed inter-row area separated adjacent beds. This configuration gave a planting density of 351 trees/ha. Trees were irrigated with micro-jet sprinklers that were spaced equidistant between trees and 30 cm above bed surfaces. A granular form of ammonium potassium sulfate fertiliser (14.7% N, 0% P, 11% K, 18.1% S) was mechanically broadcast onto these beds periodically.

Measurement of surface runoff at the study farm

A 0.24-ha catchment with a gradient of 3.1% was established on the farm in mid September 2005 to measure and sample surface runoff. This area consisted of 2 inter-rows, 165 m in length, containing 3 rows of 8-year-old macadamia trees. Surface flow exiting the area was contained by grassed embankments, ~15 m in length and 0.20 m high. They were constructed from soil in a shelter belt undisturbed by agricultural activity in close proximity to the block. The embankments formed a V-shape that directed flow into a San Dimas flume. This flume had an entrance width of 0.60 m, a throat height/width of 0.50/0.20 m, and length of 1.40 m. The flume was connected to automated flow-sensing equipment, a water sampler and a tipping bucket rain gauge (ISCO). This equipment was integrated to coordinate measurements of flow through the flume (L/s) and rainfall intensity (mm/min), and to sample and store the flow in glass containers. The last was at preset time intervals activated during events where flow exceeded a height of 5 mm in the throat of the flume, equivalent to an overland surface flow rate of 0.7 mm/h. Samples were retrieved within 12 h of a flow event and were maintained at 4°C in glass bottles until dispatch for analysis under ice. Data from 5 runoff events were collected between October 2005 and July 2006.

Table 1. Physical and chemical properties of the farm soil and sediment

	Sand >20 µm	Silt 2–20 µm	Clay <2 µm	OC[A]	TN[B]	BD[C] (g/cm^3)	pH[D]
	(%)						
	Farm soil						
0–0.10 m	85	9	5	1.3	0.07	1.5	7.9
	Stream sediment						
–	63	17	19	2.1	0.13	1.4	4.7

[A] Oxidisable carbon content soil.
[B] Total nitrogen.
[C] Bulk density of soil and sediment.
[D] 1 : 5 water.

Measurement of soil mineral nitrogen

During the study period, temporal and spatial changes in soil mineral nitrogen were measured in the 0.24-ha runoff block. Soil samples were extracted to a 50 mm depth using a 6-cm-diameter Riverside hand auger (Eijkelkamp). Within 2 h of all soil sampling, samples were placed in a forced-fan dehydrator and air-dried to constant weight at 40°C. Samples were then ground to pass through a 2-mm sieve before nutrient analyses.

Replicated temporal measurements of mineral nitrogen were obtained by sampling each of the 3 bare soil beds within the runoff catchment. Samples were removed at 2 sampling points equidistant between the crest and the edge of each bed. This was repeated 10 times at 16-m intervals, alternating between the left and right of the beds, along a 175 m length of each row (Fig. 1). The 20 cores derived from each row were bulked and stored in clean plastic containers. Sampling was

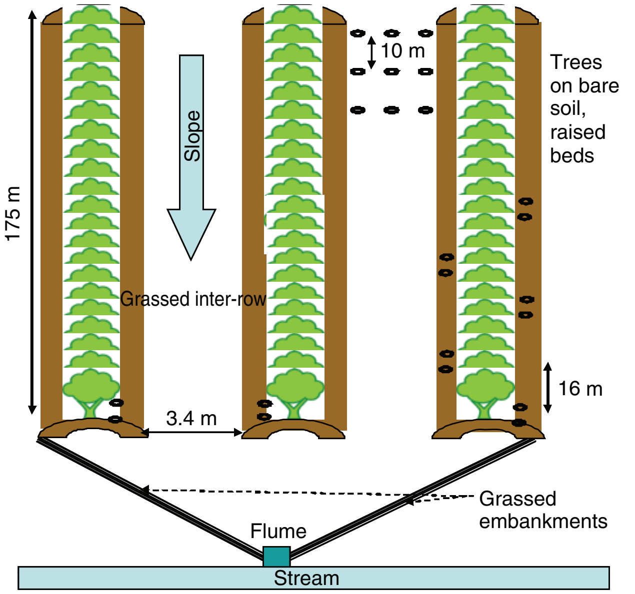

Fig. 1. Schematic of the 0.24-ha catchment that was monitored during the study. Examples of the soil sampling points (o) are indicated for both the grassed inter-row and the bare raised bed.

undertaken at approximate monthly intervals between October 2005 and July 2006 and at least 2 m from a previous sampling.

Spatial sampling of mineral nitrogen was obtained after the fourth runoff event in July 2006 from the 2 inter-rows within the runoff catchment. Samples were extracted from 3 equidistant points spaced across each 3.4 m grassed inter-row area and repeated at 10 m intervals along a 175-m length, from the crest to the bottom of the 0.24-ha block (Fig. 1). The 3 samples collected at each 10 m interval were bulked and stored in clean plastic containers. Both inter-row areas were sampled in this way, providing 2 replicated measurements for each 10 m interval.

Stream sediment sampling

Sediment and water samples were collected under quiescent conditions along ~5 km of stream. The runoff block was at the approximate midpoint of this stream length, which drained a catchment of ~7000 ha of mixed farmland. This waterway is located ~8 km from the coastline of the NMZ. The average width of the stream over this distance was ~6 m and the depth of sediment sampled was up to ~0.50 m. Sampling was undertaken in August 2006 at 10 different sampling locations spaced over the 5-km length. At each location, a 5-cm-diameter piston sampler (Enviroequip) was used to retrieve undisturbed sediment from 5 points within a 4-m^2 area of stream. The samples from each location were individually bulked in glass jars. A collection rod fitted with a 1-L bottle was used to collect water samples from a 10-m swathe at each sampling point. All samples were immediately stored under ice and transferred to a refrigerator about 2 h later and held at 4°C until analysis. The key physical and chemical properties of the sediment are listed in Table 1.

Nutrient analyses

Total soil nitrogen was quantified by Kjeldahl digestion (Bremner and Mulvaney 1982). The resulting conversion to ammonium in the extractant was determined colourimetrically by the procedures of Blakemore *et al*. (1987) and Searle (1984). Soil mineral N (nitrate-N and ammonium-N) was extracted from a 1 : 10 soil : solution of 2 M potassium chloride by procedure 7C2 described in Rayment and Higginson (1992). The mineral nitrogen in the extractant was quantified colourimetrically by the procedures of Searle (1984) and Best (1976). An automated Dumas combustion analyser was used to determine total organic carbon in soil samples by the method detailed in Yeomans and Bremmer (1991), following their pre-treatment with sulfurous acid to evolve any soil carbonate. Primary soil particle sizes were classified as coarse sand (200–2000 µm), fine sand (20–200 µm), silt (2–20 µm), and clay (<2 µm) after disaggregating soil samples with chemical reagents and mechanical dispersion.

Total Kjeldahl nitrogen (TKN) was determined in unfiltered water runoff samples and dissolved Kjeldahl nitrogen (DKN) was determined in filtered (45 µm) runoff by methods similar to those for soils, except a block digestion was used for water. Filtered (45 µm) runoff water samples were quantified colourimetrically for ammonium (NH_4) and oxidised nitrogen (NOx-N), the latter after cadmium reduction, using the same chemistry used for soil samples. NOx was >99.9 nitrate (NO_3^-) in water samples. Total suspended sediment (TSS) in water was quantified from a measured volume of a homogeneous runoff sample. The runoff was filtered through a weighed, glass, 45-µm fibre filter disc that had been rinsed and oven-dried (105°C) before filtration. The filter disc with the filtered residue was oven-dried and weighed again. The difference in weights of the filter disc gave the total suspended sediment content of the measured volume of sample.

Data analyses

Soil concentrations of nitrate and ammonium were converted to amounts per unit area (g/ha) using the bulk density and depth of soil. Concentrations in runoff waters were converted to amounts exported per unit area (g/ha) according to corresponding flow volumes (m^3/ha). Total nitrogen and its composition in runoff water were quantified according to the following calculations:

(i) Total nitrogen (TN) = TKN + NOx-N
(ii) Particulate nitrogen (PN) = TKN − DKN
(iii) Total dissolved nitrogen (TDN) = DKN + NO_3-N
(iv) Dissolved organic nitrogen (DON) = DKN − NH_4-N
(v) Dissolved inorganic nitrogen (DIN) = NOx-N + NH_4-N
(vi) Total sediment nitrogen (TSN) = PN/TSS.

The rainfall events that generated each occurrence of runoff at the study site were characterised by measurements of rainfall intensity recorded at 1-min intervals. Each event was then compared to published frequency-intensity-duration tables generated by the I-F-D Design Rainfall Program (WP Software 1988) to derive an indication of the frequency with which such an event might be expected in that locality.

Results

Temporal variation in soil mineral nitrogen at the study farm

Composite ammonium potassium sulfate fertiliser containing 29 kg N/ha at each fertilisation was applied to the macadamia beds on 5 occasions during the approximate 8-month monitoring period (Fig. 2), totalling 145 kg N/ha; the equivalent annual applied amount was 191 kg N/ha of bed-top or 543 g N/tree. Following the first soil sampling, average concentrations of ammonium and nitrate were 17 (±2) and 9 (±1) mg kg/soil, respectively, during this time (Fig. 2). These concentrations were equal to 8 (±1) and 4 (±1) kg/ha of ammonium and nitrate, respectively, within the 0–50 mm soil layer.

Rainfall, irrigation, and surface flows at the study farm

In the period when runoff events occurred, between 21 October 2005 and 28 July 2006 (Fig. 2), total rainfall and irrigation were 709 and 458 mm, respectively. Monitoring at the site continued until January 2007 but runoff events did not occur in the latter period due to the onset of a drought (data not displayed). Rainfall was most frequent during the storm season between October 2005 and March 2006 and totalled 446 mm during this time (Fig. 2). The majority of rainfall events during this time were episodes of ≤10 mm or ≤20 mm, representing 76% and 93% of all events, respectively. Irrigation applications of ~26 mm/event were also most frequent in this period, when the macadamia nuts were forming and maturing (Fig. 2), with

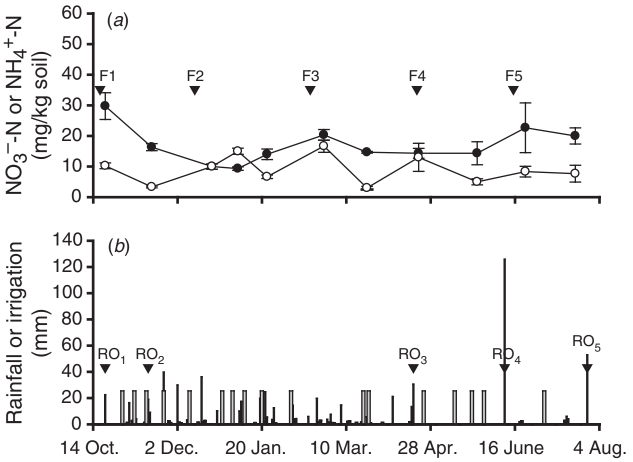

Fig. 2. (*a*) Temporal soil concentrations of nitrate (○) and ammonium (●) within 0–50 mm of macadamia beds and fertiliser applications (▼); and (*b*) corresponding total rainfall (black bars), irrigation (grey bars), and runoff events (▼) at the study farm. F1, 18 Oct. 2005; F2, 12 Dec. 2005; F3, 17 Feb. 2006; F4, 20 Apr. 2006; F5, 15 June 2006. RO_1, 21 Oct. 2005; RO_2, 15 Nov. 2005; RO_3, 18 Apr. 2006; RO_4, 10 June 2006; RO_5, 28 July 2006.

a total 305 mm applied. Total rainfall during runoff events on 21 October (RO_1) and 15 November (RO_2) 2005, and 18 April (RO_3), 10 June (RO_4), and 28 July (RO_5) 2006 amounted to 23, 19, 31, 126, and 53 mm, respectively (Fig. 2). These events were interspersed with episodes totalling 40, 30, 36, 20, 20, and 21 mm that did not produce runoff. There were several occasions when irrigation closely followed such rainfall episodes and a single runoff event (RO_2) eventuated under these conditions.

Rainfall intensities were recorded in 1-min intervals for all storm events during the monitoring period except RO_4. The last was due to equipment failure, and intensities in 30-min intervals from another weather station at the site were matched to RO_4 flow data (Fig. 3). Higher intensities that occurred in shorter time intervals were not captured at RO_4 and this event was therefore excluded from a comparative analysis of rainfall intensities.

Data for RO_1, RO_2, RO_3, and RO_5 showed that the duration of these rain events ranged between 0.5 and 8.3 h, and while peak intensities ranged between 257 and 64 mm/h, these peaks were rarely maintained for >2–3 min (Fig. 3). Peak intensities averaged over a 5-min period in these events ranged from *c*. 180 mm/h in RO_1 to 110 mm/h in RO_2 and 50–55 mm/h in RO_4 and RO_5. These events could be directly compared to the Bundaberg I-F-D data (Fig. 4), which indicated that while the intense RO_1 event would be expected to occur with a frequency of 1 in 5 years, all other events could be expected to occur at least on an annual basis. Similarly, when the average rainfall intensity during the whole of each rainfall event was calculated, all except RO_4 (126 mm over a 6-h period, i.e. 1-in-10-year event) would be expected to occur on an annual basis (WP Software 1988, data not shown).

Surface flows occurred when rainfall intensity exceeded 40 mm/h at RO_1, RO_2, and RO_3 and 20 mm/h at RO_5 and when this threshold intensity was sustained for >9 min (Fig. 3). These runoff-generating events would have been expected to occur at least on an annual basis (Fig. 4). Storm events that did not generate runoff did not reach these thresholds of intensity and duration (data not displayed). The total volume of surface flow during individual episodes of runoff amounted to 26, 6, 13, 87, and 45 m^3/ha at RO_1, RO_2, RO_3, RO_4, and RO_5, respectively. These flow volumes were strongly related to the total rainfall of these runoff events (Fig. 5), and they represented an average of 5.3 ± 1.1% of the total episodic rainfall received.

Nitrogen losses in surface flows at the study farm

The duration of surface flow at RO_1, RO_2, RO_3, RO_4, and RO_5 was 0.6, 0.4, 0.8, 4.1, and 2.6 h during runoff events, respectively (Fig. 3). The cumulative losses of TN during these events amounted to 76, 19, 38, 82, and 68 g N/ha, respectively (Fig. 3). Approximately 75% of the cumulative loss of TN occurred within the first quarter (RO_5) or within first half (RO_1, RO_2, RO_3, and RO_4) of the total period of surface flow at each event (Fig. 3). This trend showed that the entry of TN into surface flow during each runoff was initially rapid but diminished greatly in the larger timeframe of the latter stages of events (Fig. 3). The aggregate loss of TN and total surface flow volume at each runoff event also formed a similar relationship (Fig. 6). This defined an exponential relationship for TN lost in all events that suggested the loading of TN became limiting as total flow volumes increased (Fig. 6).

The TN in all runoff events consisted of an undissolved particulate fraction of nitrogen (PN) and DON and DIN fractions (Table 2). The fractions totalled 283 g N/ha, with PN accounting for 159 g/ha, which was higher than the combined amounts of DON and DIN, which totalled 124 g/ha (Table 2). The total DIN fraction consisted of near-equal quantities of ammonium and nitrate (Table 2). These amounts included 2 events where a proportionately greater amount of ammonium (at RO_1) or nitrate (at RO_3) dominated the DIN fraction (Table 2). The higher loading of ammonium corresponded to elevated surface soil ammonium at RO_1 but this was not true for nitrate at RO_3 (Table 2 and Fig. 2). Overall, there was little correspondence between the surface soil concentrations of ammonium or nitrate and their loadings in surface flows (Table 2 and Fig. 2).

Spatial variation in soil concentrations of mineral nitrogen at the study farm

Surface (0–50 mm) soil concentrations of ammonium and nitrate along a 175-m distance in the inter-row area, from the crest of the runoff block to within 15 m of the edge of a stream bordering the farm, are displayed in Fig. 7. Ammonium and nitrate concentrations did not show an increasing or decreasing trend along this gradient (Fig. 7). The average concentrations of ammonium-N and nitrate-N were 39 (±1) and 10 (±1) mg/kg soil, respectively, at this time. These concentrations were equal to 12 (±0.4) and 3 (±0.3) kg N/ha of ammonium and nitrate, respectively. Fertiliser was not applied in the inter-row area.

Nitrogen in water and sediments in the catchment stream and in farm runoff

Nitrogen fractions in quiescent water and in sediments of the catchment stream were measured at the end of the period of

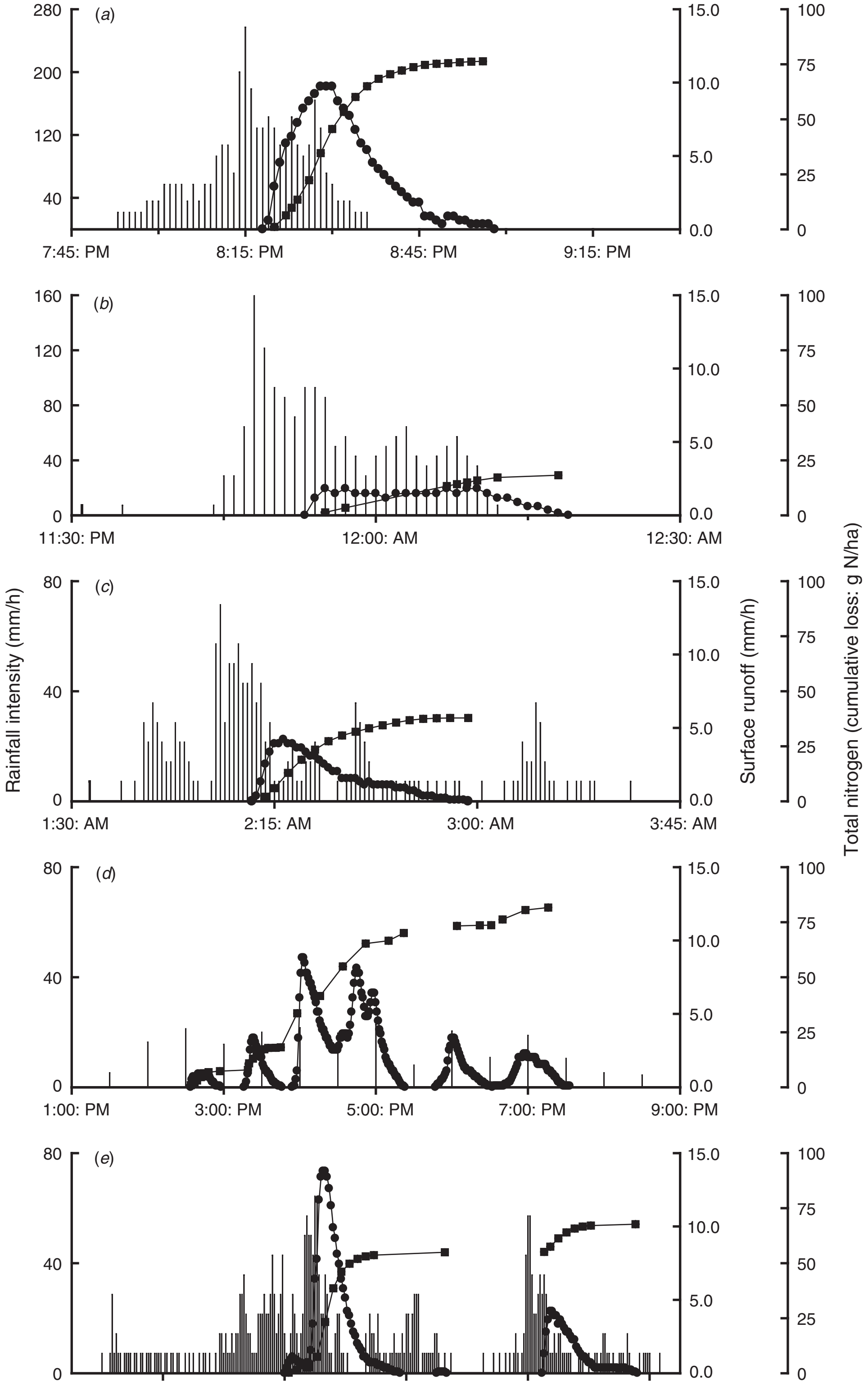

Fig. 3. Rainfall intensity (bars), surface runoff (●), and the cumulative loss of total nitrogen (■) during storm events at the study farm on (*a*) 21 Oct. 2005, (*b*) 15 Nov. 2005, (*c*) 18 Apr. 2006, (*d*) 10 June 2006, and (*e*) 28 July 2006.

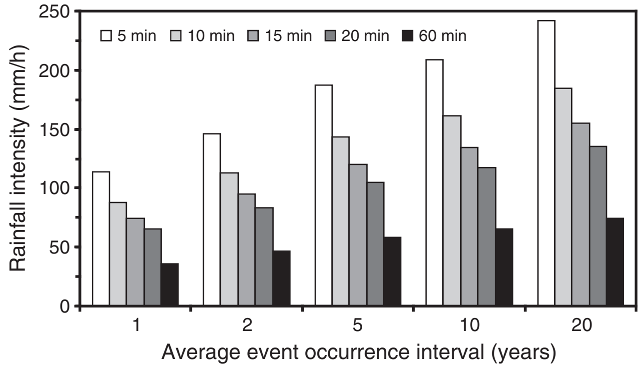

Fig. 4. Rainfall intensity-frequency-duration information (IFD) generated by the WP Software program for Bundaberg, Queensland.

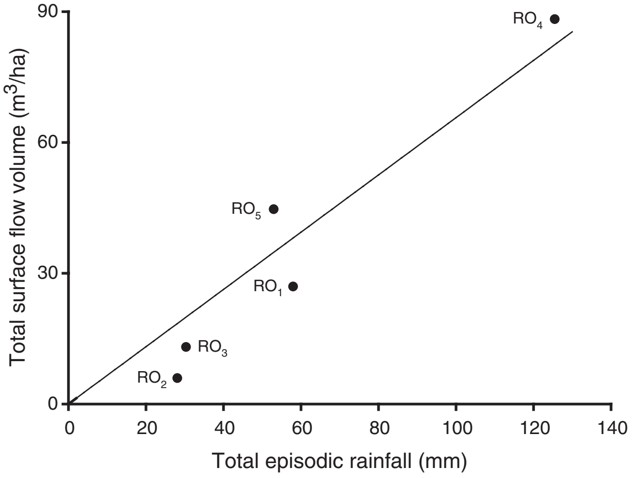

Fig. 5. Relationship between the total volume of surface flow (TSF) and total episodic rainfall (TER) during runoff events (●) at the study farm. The functional relationship of the regression was TSF = 0.657TER, $R^2 = 0.89$. Dates of runoff events RO$_1$ to RO$_5$ are identical to those detailed in Fig. 2.

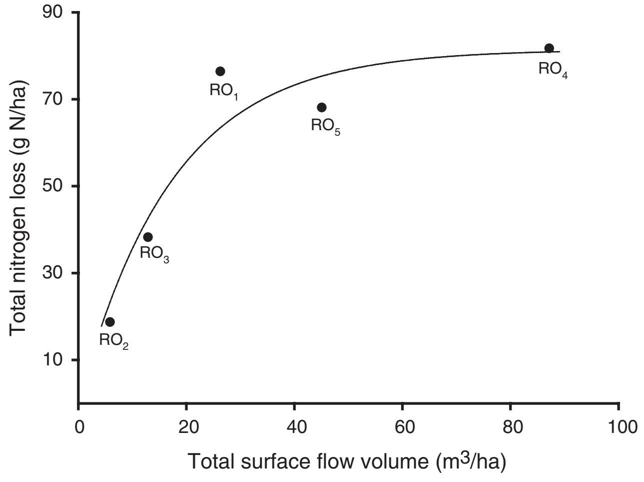

Fig. 6. Relationship between total nitrogen loss (TNL) and the total volume of surface flows (TSF) for runoff events at the study farm. The functional relationship of the fitted curve was TNL = 81.43(1 − exp(−0.0574TSF)), $R^2 = 0.91$. Dates of runoff events RO$_1$ to RO$_5$ are identical to those detailed in Fig. 2.

Table 2. Composition of total nitrogen lost in runoff at the study farm (g/ha)

PN, Particulate N; DON, dissolved organic N; DIN, dissolved inorganic N; total N for all runoff events (TN) = PN + DON + DIN = 283 g/ha; DIN = NH$_4$-N + NOx-N

Runoff event	PN	DON	DIN	NH$_4$-N	NOx-N
21 Oct. 05	42	14	20	13	7
15 Nov. 05	8	4	7	3	4
18 Apr. 06	20	8	10	2	8
10 June 06	51	11	19	9	11
28 July 06	39	13	16	7	10
Total	159	52	72	33	39

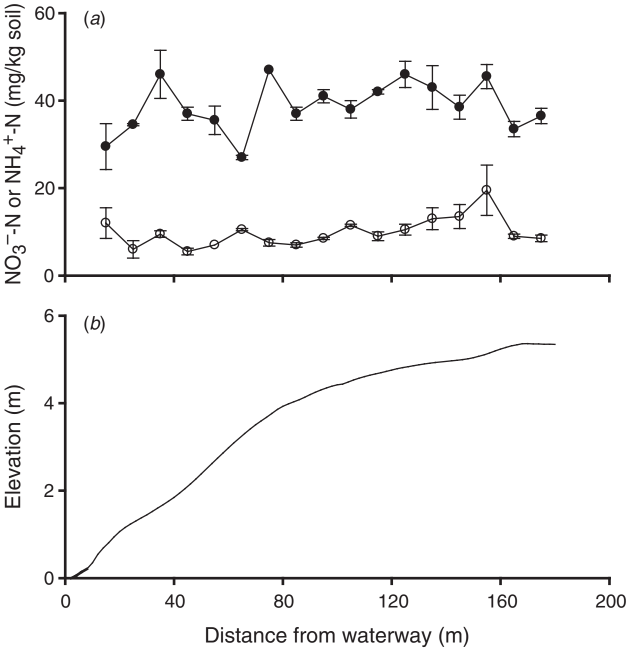

Fig. 7. (*a*) Spatial soil concentrations of nitrate (○) and ammonium (●) within 0–50 mm of the inter-row area of the macadamia study farm according to (*b*) the topography (—) of the plantation inter-rows. This data was collected on 24 July 2007 following RO$_1$, RO$_2$, RO$_3$, and RO$_4$.

monitoring farm runoff. They were compared with the weighted averages (average of total amounts/total flow volume or total sediment of all events) of DON, DIN, and TSN concentrations in farm runoff. The results showed that concentrations of DON in stream waters and farm runoff were identical (Table 3). This was in contrast to results for the DIN fraction, for which farm runoff was >20-fold higher than stream concentrations of DIN (Table 3). The individual components of DIN, ammonium, and nitrate, were 27- and 18-fold higher in farm runoff than stream waters (Table 3). The weighted average concentration of TDN (DON + DIN) was 1.10 ± 0.27 and 0.50 ± 0.09 mg N/L in farm runoff and stream water, respectively. TSN in farm runoff was 25-fold higher than TN in stream sediments (Table 3).

Table 3. Average concentrations of dissolved and sediment nitrogen fractions in runoff from the study farm and in the adjoining catchment stream

DON, Dissolved organic N; DIN, dissolved inorganic N; TSN, total sediment N. Standard errors of means are shown in parentheses

	Farm	Stream
DON (mg/L)	0.47 (±0.11)	0.47 (±0.08)
DIN (mg/L)	0.64 (±0.16)	0.03 (±0.01)
NH_4-N (mg/L)	0.27 (±0.08)	0.010 (±0.005)
NOx-N (mg/L)	0.37 (±0.11)	0.021 (±0.010)
TSN (%)	2.81 (±0.77)	0.11 (±0.02)

Discussion

Temporal variation in soil concentrations of mineral nitrogen at the study farm

Concentrations of soil ammonium were generally 2-fold higher than soil nitrate within 0–50 mm of macadamia beds during the study period and showed greater uniformity than nitrate. Lower surface soil nitrate was consistent with its greater leaching potential. Nevertheless, the combined concentration of mineral nitrogen (ammonium and nitrate) within the surface soil was not subject to significant shifts during the study period despite rainfall and irrigation totalling 1167 mm. This showed that the farm's fertiliser regime maintained a stable concentration range of mineral nitrogen in topsoil despite the influence of leaching and plant uptake. This was possibly achieved by a nitrogen fertiliser regime that was excessive. A 6-year study of mature bearing macadamia trees found that the optimum annual rate of nitrogen was 355 g/tree (Stephenson *et al.* 2000). At an annual application of 543 g N/tree, equivalent to 191 kg N/ha, the fertiliser regime on the farm was therefore 53% higher than the reported optimum. This annual rate of fertiliser application was not considered excessive in the district and was within current commercial guidelines (Stork *et al.* 2007).

The general trend of higher soil concentrations of ammonium and lower concentrations of nitrate in macadamia beds did not lead to higher ammonium and lower nitrate loadings in runoff, with the exception of RO_1 (Table 2 and Fig. 2). This was not unexpected, given the ability of soils to hold at least some ammonium on exchange surfaces, compared with nitrate which would be almost entirely in the soil solution.

Rainfall, irrigation, and surface flows at the study farm

Although 64% of episodic rainfall and irrigation occurred during the storm season between October and March, large episodes of runoff (RO_4 and RO_5) occurred outside this period. Surface flows occurred at total amounts of episodic rainfall that were either higher or lower than other episodes which did not generate runoff under similar seasonal conditions. In several instances, irrigations closely preceded such episodic rainfall but surface flow eventuated in only one such event (RO_2). Therefore, total amounts of episodic rainfall alone, or in combination with recent irrigation, did not predict runoff events. Rainfall episodes that caused surface flows were distinguished from other episodes by intensities and durations that were 20–40 mm/h for >9 min. In another farm study, in a Podosol soil, runoff occurred at rainfall intensities >20 mm/h when durations exceeded 26 min (Stork *et al.* 2008). The surface (0–50 mm) soil textures in both soils were similar but the site gradient in the Podosol was 1.4%, compared with 3.1% in the present study, indicating that catchment gradients may moderate the initiation of surface flow.

Results from the present study also revealed that total surface flow volumes were strongly related to total amounts of rainfall during runoff events, which concurred with findings from the Podosol. Total surface flow volumes accounted for ~5.3% of total precipitation during runoff events in the present study and 10.7% in the Podosol (Stork *et al.* 2008), suggesting that total flow volumes from soil in the present study (Kandosol) were reduced by higher rates of internal drainage. This is in agreement with field investigations of drainage characteristics of soils in the study region which found saturated hydraulic conductivities in Kandosols were 6-fold greater than a Podosol (Verburg *et al.* 2001). The high rates of internal drainage on these soils will have implications for drainage losses and associated nitrogen leaching. This issue is not covered in this paper.

Nitrogen losses in surface flows at the study farm

In the 9-month period between October 2005 and July 2006, the aggregate loss of TN was 0.28 kg/ha. The complete monitoring period spanned ~13 months and therefore the adjusted estimated annual loss of TN was 0.26 kg/ha.year. Reported annual losses of TN from field studies from fertilised agricultural activities under natural conditions of rainfall and irrigation are limited. A synthesis of runoff studies from dairy pastures showed that TN losses were 0.08–0.84 kg/ha.year in New Zealand farms and 0.2–2.35 kg/ha.year in Australian farms (Drewry *et al.* 2006). Total nitrogen losses in forest catchments in both regions were 0.2–3.7 kg/ha.year (Drewry *et al.* 2006), with the higher losses associated with disturbance (e.g. logging) or runoff events after fires. Runoff losses of TN in fertilised sugarcane catchments were 1–3.5 kg/ha.year in Mauritius (Ng Kee Kwong *et al.* 2002). In wheat–pea rotations in Oregon, USA, losses were 5–11 kg/ha. year (Douglas *et al.* 1998). The wide variation in these findings and contradictory results between disturbed and undisturbed catchments are possibly due to differences in gradients, drainage properties, climate, and seasons in the study catchments. However, these results combined generally indicate that the annual total losses from our study were comparatively small.

The limited TN losses at the study site were explained by the relationship between TN and flow volumes for all events by their derived exponential relationship, which showed that the loading of TN diminished as flow volumes increased. The exponential nature of the composite losses of TN in response to flow volumes was mirrored in individual flow events where loadings of ~75% of TN into surface flow occurred within the first half of the total duration of a runoff event. Collectively, these data showed that the loading of the surface store of TN into surface flows was rapidly exhausted during runoff events. This may indicate that the loadings of TN were largely derived from a finite source of detritus in surface soil rather than from the release of TN according to soil sorption equilibria governed by surface flow volumes. The lack of influence of surface soil ammonium and nitrate concentrations on loadings of DIN, as discussed previously, is consistent with this hypothesis.

As the majority of TN losses during runoff events occurred in the early period of surface flow, this would have ensured that the subsequent period of surface flow, which was at least of the same duration, would have provided the impulsion to evacuate all TN loadings off-farm and into the adjoining waterway.

Loadings of TN in each runoff event contained both undissolved (particulate) and dissolved fractions of nitrogen. The undissolved fraction, PN, accounted for 56% of all off-farm TN losses, while the dissolved fractions, DON and DIN, accounted for 18% and 26%, of the losses, respectively. Therefore, it could be expected that approximately half of the total losses, as PN, would settle into sediments of the adjoining catchment waterway as long as flow velocities and suspended material particle sizes were conducive to deposition. The remainder would be transportable in the water column and either wholly bioavailable (DIN), or potentially bioavailable in the short-medium term (DON), depending on chemical composition (Berman and Bronk 2003).

Spatial variation in soil concentrations of mineral nitrogen at the study farm

The average spatial concentration of ammonium in the inter-row area was 2-fold higher than the average temporal concentrations of ammonium within macadamia beds. Concentrations of nitrate were almost identical in both areas. As fertiliser was not applied in the inter-row area of the runoff catchment, this indicated that ammonium but not nitrate was sequestered in the inter-row area. Spatial differences in concentrations of ammonium and nitrate were not evident from the crest to the edge of the catchment waterway despite the suggestion of accumulation of ammonium in the inter-row area. Therefore, these results showed that a nutrient load did not accumulate at the base of the farming landscape as a consequence of periodic runoff events. The latter was consistent with surface flow characteristics that enabled the entire evacuation of nutrient loadings off farm during runoff events, as discussed in the preceding section.

Nitrogen in water and sediments in the catchment stream and in farm runoff

Concentrations of DON in runoff from pristine forest and ungrazed land in tropical Queensland were 0.015–0.25 mg/L in a range of studies (McKergow *et al*. 2005). The average concentration of DON in farm runoff and the catchment waterway were identical at 0.47 mg/L and were therefore 2–3-fold higher than the reported studies. The DIN concentration in the farm runoff was 21-fold higher than in the catchment stream, indicating the existence of a steep concentration gradient of biologically available nitrogen from the farming landscapes to the waterway. This export of DIN has the potential to stimulate bacterial and algal growth within the stream, which in turn could contribute to the high levels of DON observed in the stream compared with reported DON levels in pristine environments (McKergow *et al*. 2005). The indicative threshold values for nitrogen stress upon slightly disturbed aquatic ecosystems have been reported to be 0.2–0.3 mg N/L for tropical regions of Queensland, Australia (Mitchell *et al*. 2005). The combined concentration of DON and DIN in the catchment stream therefore exceeded this threshold by a factor of 1.7–2.6. This indicated that nutrient loading into the water column of the stream was likely to have caused eutrophication of the waterway beyond that resulting from pristine conditions.

The concentration of total sediment nitrogen in farm runoff (TSN) was 25-fold higher than that found in the stream, and as with the dissolved fractions, created a steep concentration gradient between the farming landscape and the catchment stream. The TSN in farm runoff represented the concentration of PN carried in surface sediments. The weighted average of TSN concentrations (2.81%) in runoff was high and generally within the normal range of plant nitrogen concentrations, suggesting that TSN was highly enriched with plant detritus. This would be consistent with the exponential nature of nitrogen loading into surface flows, as discussed in a preceding section where it was concluded that loadings were largely supplied from surface detritus. However, these concentrations are less consistent with the normally observed range for macadamia leaves (1.2–1.4% N; Stephenson and Gallagher 1989) than from the mown, vigorously growing grass pastures in the inter-row areas (2.0–3.5% N; Pinkerton *et al*. 1997).

Data are not available from other studies to assess the euptrophication potential of TSN in the waterway, although it is likely that the build-up of sediment nitrogen from farm runoff in the waterway would contribute to eutrophication. This would occur when the sediments are perturbed under conditions of turbulent flow, as has been demonstrated in simulation studies. Re-suspension of a 1-cm layer of near-shore sediment samples in a 10-cm interstitial water column caused an increase of 210–360% of suspended total nitrogen (Ullman and Sandstrom 1987).

Conclusion

Frequent applications of fertiliser maintained a stable concentration range of ammonium and nitrogen in topsoil on the study farm despite substantial inputs of rainfall and irrigation in this well-drained soil. Under this regime, runoff could only be predicted by combined information on threshold rainfall intensities and durations. Therefore, event-based episodic rainfall data is required to model nitrogen losses under such farming practices to estimate losses at the catchment scale. Strong functional relationships found between such thresholds for runoff and surface flow volumes and the latter with total nitrogen losses showed that farm-scale modelling of such losses is possible. Such modelling was beyond the scope of the present study.

The annual rate of surface losses of total nitrogen was relatively minor when compared to other studies, and appeared to be more likely related to management of the grassed inter-row areas than the macadamia rows. Nitrogen concentrations in the water column of an adjoining catchment stream clearly exceeded defined eutrophication thresholds of such waterways determined in other studies, although the source of the nitrogen in this stream could not be partitioned between macadamia and other land uses in the mixed farming landscape in which this study was conducted. Indeed given the well-drained soils in the catchment, the stream N may well have been augmented by groundwater transport of leached N which was not quantified during this study.

In addition to the risk posed by elevated nitrogen concentrations in the water column, further potential for eutrophication of the waterway would occur during the re-suspension of stream sediments. The potential for transport of nitrogen species in the water column and from re-suspension during flow events also presents a possible risk of nutrient loading to near shore areas of the GBRWHA, given the waterway's proximity (8 km) to the coastline.

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