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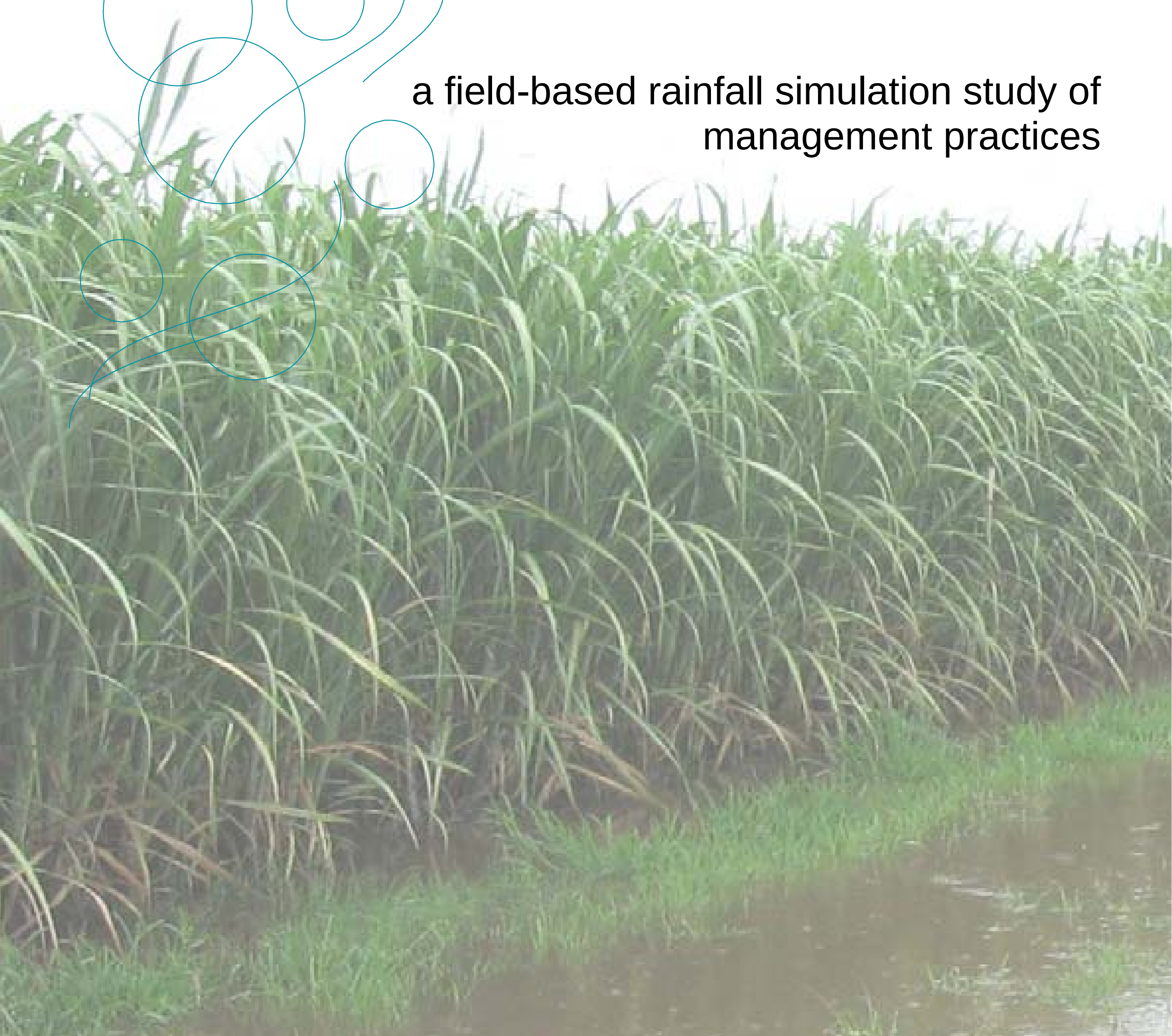
a field-based rainfall simulation study of management practices



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a field-based rainfall simulation study of management practices

May 2008

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List of Acronyms

ACTFR	Australian Centre for Tropical Freshwater Research
ARI	Average return interval
BoT	Back on Track program
BSES Ltd	Bureau of Sugar Experimental Stations
CC	Conventional cultivation
CEC	Cation exchange capacity of soil
CP	Current Practice
CTF	Controlled Traffic Farming
DIN	Dissolved Inorganic Nitrogen (sum of ammonia and NO_3)
DON	Dissolved Organic Nitrogen
DOP	Dissolved Organic Phosphorus
EMC	Event Mean Concentration
FRP	Filterable Reactive Phosphorus
GBR	Great Barrier Reef
Kd	Linear distribution coefficient for partitioning in soil-water (L/kg)
Koc	Linear distribution coefficient for partitioning in soil organic-water (L/kg) (Kd normalised for soil organic carbon content)
LCMS	Liquid Chromatography and Mass Spectrometry
LOR	Limit of Recording
MWNRM	Mackay Whitsunday Natural Resource Management Group
N	Nitrogen
NO_x	Nitrate plus Nitrite
NRW	Queensland Department of Natural Resources and Water
OC	Organic carbon content of soil (%)
P	Phosphorus
PN	Particulate Nitrogen
PP	Particulate Phosphorus
QHSS	Queensland Health Scientific Services
TFN	Total Filterable Nitrogen
TFP	Total Filterable Phosphorus
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
WQ	Water Quality
WQIP	Water Quality Improvement Plan

Units of Measure

dS/m	deciSiemen per metre
g/cm^3	Grams per cubic centimetre
g/g	Grams per gram
g/ha	Grams per hectare
g/kg	Grams per kilogram
g/L	Grams per litre
g N/ha	Grams of nitrogen per hectare
g P/ha	Grams of phosphorus per hectare
kg	Kilogram
kg/ha	Kilograms per hectare
km^2	Square kilometres
L	Litre
L/s	Litres per second
m	Metre
m^2	Square metres
meq/100g	Milliequivalents per 100 grams
mg	Milligram (one-thousandth of a gram)
mg/kg	Milligrams per kilogram
mg/L	Milligrams per litre
mg N/L	Milligrams of nitrogen per litre
mg P/L	Milligrams of phosphorus per litre
mm	Millimetre (one-tenth of a centimetre)
mm/hr	Millimetres per hour
t/ha	Tonnes per hectare
µm	Micrometre
µg	Microgram (one-millionth of a gram)
µg/L	Micrograms per litre

EXECUTIVE SUMMARY

Diffuse source pollutants from agricultural landuse, such as excessive sediments, nutrients, and herbicides entering waterways and the Great Barrier Reef (GBR) lagoon threaten inshore reefs and ecosystems. The Mackay Whitsunday Natural Resource Management Group has developed a regional Water Quality Improvement Plan (WQIP) which identifies priority agricultural management practices aimed at reducing water quality decline, and sets adoption targets and methods to implement these practices. The validation of management practices, particularly for cane farming, that are intended to improve water quality is a major focus throughout the development of the Mackay Whitsunday region's WQIP. This report is a supporting document of the plan, and outlines the results and main findings of a water quality study of runoff from selected cane farming management practices.

The study consisted of both plot and paddock-scale water quality monitoring trials. The core component was the plot-scale study, which involved a series of rainfall simulation trials. This permitted a reliable and consistent comparison of each management practice under investigation, without the need to depend on highly variable wet season falls. The paddock-scale study involved the installation of two flumes and automatic samplers to collect natural rainfall runoff to complement plot-scale trials.

The aim was to assess the runoff and water quality of two farming systems (row/bed/traffic treatments), including:

1) Current practice (CP) with 1.5 m wide beds and a single row of sugarcane in the centre of the bed
2) Controlled traffic farming (CTF) with dual sugarcane rows (0.8 m apart) in permanent 2 m beds

Both were no-till green harvested and had 90-100% cover

Each system was treated with two different nitrogenous fertilisers and methods of residual herbicide application. These were paired as:

1) Surface application of *Liquid One Shot* (dunder) and broadcast application (100% coverage) of residual herbicides,
2) Sub-surface split stool application of *Nitra King S* (granular) and banded application (50-60% coverage) of residual herbicides (on the centre of bed only)

The herbicides applied included *Gesapax Combi Flowable* (ametryn and atrazine) and *Velpar* (diuron and hexazinone).

An additional 'replant' treatment was also assessed. This involved raking and burning the trash blanket after harvest followed by conventional cultivation, resulting in <2% cover. There was no application of fertiliser or herbicides.

The plot-scale rainfall simulation study involved the scenario of a 10-year average recurrence interval (ARI) storm occurring before (i.e. no application), 1 day and 21 days after the application of fertilisers and herbicides. A storm of this size is anticipated to be more than sufficient to generate runoff that would export to the fresh and marine water environments. A storm at one day after application would be considered *catastrophic* (Wauchope 1978) and of high risk to waterways, but not unlikely in a tropical environment with high intensity, low frequency events. This was to assess runoff from practices in the high risk period after application. Simulations at day 21 were considered *critical* events (Wauchope 1978) and were to assess a more likely scenario of rainfall after application when concentrations of fertilisers and herbicides are still high and potentially available for export in runoff.

For each treatment discrete water samples were taken at regular intervals during runoff flow (hydrograph). Water samples were analysed for total sediment, nutrients (total and dissolved) and herbicides, and event mean concentrations and total load in runoff were calculated. The total amount of runoff, peak runoff rate and time to runoff was also determined.

Soil bulk density samples were collected in the furrow, mid-section and centre of beds for both CP and CTF treatments, to assess the impact of harvester/haulout compaction on the soil.

Results showed that CTF treatments had significantly less runoff (43%) and lower peak runoff rates (46%) than CP treatments, when 67 mm of simulated rainfall was applied at 100 mm/hr (1 in 10 year ARI storm) at the plot-scale. This was also maintained in natural rainfall events on the paddock-scale during the wet season, although differences were smaller (30% less runoff for CTF).

Lower runoff was achieved on CTF treatments as they were less compacted compared to CP treatments, therefore improving infiltration. CP treatments had higher bulk densities on the mid-section of the bed compared to CTF treatments. This was a result of compaction from the straddling effect of uncontrolled traffic and non-matching axle widths of harvester/haulout machinery. This increased runoff and resulted in higher losses of associated total sediment, nutrients and herbicides.

Total sediment loads were reduced by 44% on CTF treatments compared to CP treatments. However total sediment losses from both these treatments were negligible compared to conventional cultivation replant treatments. This treatment produced the highest sediment event mean concentration and load, which was 46 times that measured from CP and CTF treatments. This was a result of low ground cover.

Total nitrogen loads from surface applications of dunder (Liquid One Shot) and sub-surface applications of granular (Nitra King S) fertiliser were similar, as both were applied at the same rate (160 kg N/ha). Granular applications had greater loads of nitrate at day 1 and day 21 than dunder, with losses being reduced on CTF treatments compared to CP treatments. However, dunder applications had greater amounts of ammonia, especially at day one, compared to granular treatments. This loss was greatest on CP treatments. Loads declined considerably by day 21, highlighting the greatest risk to loss of ammonia, as well as total nitrogen and nitrates, in runoff in the first three weeks after application.

Careful consideration and planning should be made on placement (with respect to waterways) and timing (with respect to significant rainfall) of surface applications of dunder. It is likely that sub-surface applications of dunder would reduce this loss. Avoiding dunder application within at least three weeks of the onset of significant rainfall will reduce the risk of ammonia loss in runoff by 44% on CP treatments and 29% on CTF treatments.

The urea/dunder mixing process for Liquid One Shot production needs to be refined to improve consistency in nitrogen content and therefore application rates.

Losses of phosphorus, in particular FRP in runoff were evident at days 1 and 21 for both fertilisers. Highest loads were from granular application on CP treatments at day one. CTF treatments effectively reduced runoff loads for all species of P, especially for day one. Losses of phosphorus were also observed before to the application of fertilisers suggesting soils were elevated in phosphorus reserves from prior mill mud applications.

Rainfall one day after the broadcast applications of ametryn, atrazine, diuron and hexazinone on CP treatments produced the highest herbicide event mean concentrations and loads. The highest risk to herbicide loss in runoff was within a few weeks after application with percentage losses for all herbicides >2% in runoff one day after application. Avoiding application within at least three weeks of heavy rainfall will reduce the risk of herbicide loss in runoff by an order magnitude for ametryn and atrazine, and by approximately half for diuron and hexazinone.

Event mean concentrations from all herbicides applied by broadcast were more than double those for banded applications in runoff one day after rainfall. Further reductions in runoff loads were made from applications on CTF treatments compared with CP treatments. "Runoff-available-herbicide" half-lives calculated from event mean concentrations were 6-9 days for ametryn and atrazine and 8-11 days for diuron and hexazinone. Herbicides were detected in runoff at the paddock scale up to 123 days after application.

There were strong relationships between herbicide load on the trash and event mean concentration in runoff, for all four herbicides. This, and the strong relationships between event mean concentration and time after application, suggests that relatively simple models for herbicide runoff could be derived for cane trash blanket systems.

In summary, the recommended best practice for management of water quality in cane farming is no-till green harvested controlled traffic farming, with fertilisers and herbicides applied as early as possible before the onset of the wet season. Residual herbicides should be banded on centres of beds only and fertilisers applied sub-surface.

1 INTRODUCTION

Diffuse source pollutants from agricultural landuse, such as excessive sediments, nutrients, and herbicides entering waterways and the Great Barrier Reef (GBR) lagoon threaten inshore reefs and ecosystems (Queensland Department of the Premier and Cabinet 2007). One approach to reduce diffuse source pollutants from agriculture is to define and adopt a set of improved or "best" management practices for the industry (Rolfe *et al.* 2007). The Mackay Whitsunday Natural Resource Management Group has developed a regional Water Quality Improvement Plan (WQIP) which identifies priority management practices aimed at reducing water quality decline and sets adoption targets and methods to implement these practices (Drewry *et al.* 2008).

The validation of management practices, particularly in cane farming, that are intended to improve water quality is a major focus throughout the development of the Mackay Whitsunday region's WQIP (Drewry *et al.* 2008). This report is a supporting document of the plan, and outlines the results and main findings of a plot and paddock-scale water quality study of runoff from selected cane farming management practices. It also forms a component of the *Mackay Whitsunday Healthy Waterways Integrated Monitoring Program.* Other components of this program and the WQIP, reported separately, include the event-based water quality monitoring (Rohde *et al.* 2008), ambient community volunteer network monitoring (Galea *et al.* 2008a), and monthly baseline monitoring (Galea *et al.* 2008b).

In 2005 approximately 114,880 ha of sugarcane was grown in the Mackay Whitsunday region (CANEGROWERS 2006), accounting for 19% of the land area (Drewry *et al.* 2008). Sugarcane is the major intensive landuse and has been identified as the predominant diffuse source of the nutrient and herbicide water quality pollutants (Drewry *et al.* 2008). The highest risk to off-farm transport of these pollutants is early in the wet season in high intensity rainfall-runoff events. In these events, sugarcane dominated subcatchments have been found to export high concentrations of nutrients, particularly dissolved inorganic nitrogen (DIN) and filterable reactive phosphorus (FRP), and herbicides, including ametryn, atrazine, diuron and hexazinone (Rohde *et al.* 2008). High nutrient concentrations in the resulting flood plumes have produced massive phytoplankton blooms in coastal waters, and the persistence of herbicides, particularly diuron, in these flood plumes indicates that offsite transport from agricultural catchments poses a significant risk to the health of inshore corals, seagrasses and mangroves (Rohde *et al.* 2008).

The sugarcane industry has invested substantial resources into the identification and adoption of improved management practices that will benefit productivity, efficiency and sustainability. Considerable effort has been placed on assessing the productivity and efficiency of many of these practices, for example the "Back on Track" program which assessed the viability of controlled traffic farming (CTF) systems (Morris 2005). However less effort has been focused on quantifying possible water quality benefits that may also be associated with adoption. Understanding the relative impacts of current and improved management practices, such as CTF, are vital in the planning and implementation of management interventions that improve water quality.

One of the major disadvantages of the current cropping system is that the standard 1.5 m row spacing configuration does not match the 1.83 m harvester and haulout track width (Braunack and McGarry 2006). This has a straddling effect whereby wheel traffic overlaps the edges of each bed resulting in at least 61% of the area being compacted (Price *et al.* 2004). The 1.5 m row spacing produces eight times the compactive loading on the soil compared to the production of a cereal grain crop (Price *et al.* 2004). This has important implications for runoff as soil compaction reduces infiltration capacity (Li *et al.* 2001; Silburn and Glanville 2002).

Since the 1960s CTF has been advocated by scientists in a number of countries and environments as the solution to soil compaction, however large-scale adoption has been rare (Tullberg *et al.* 2007). At present approximately 8% of farms in the Mackay Whitsunday region have adopted controlled traffic practices (Rolfe *et al.* 2007). The principle behind CTF is to restrict wheel traffic to a narrow interspace by matching the track of harvesting and haulout machinery with the row spacing. Row and axle width are usually increased from 1.5 m to 2 m, which also allows for a second row of sugarcane and the establishment of permanent beds (Figure 1). The 2 m row spacing conversion results in a minimum of 26% of the area compacted (Price *et al.* 2004).

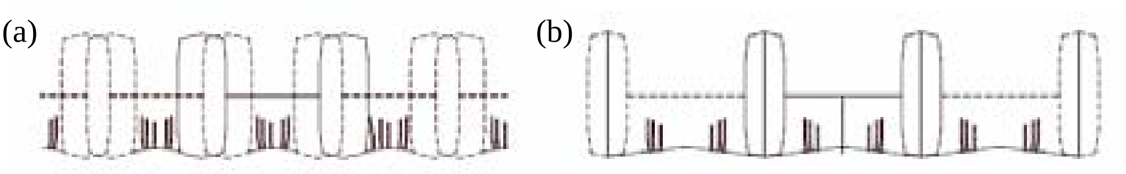

Figure 1. (a) 1.5 m row spacing with 1.83 m harvester/haulout track width, and (b) 2.0 m row spacing and dual rows (0.8 m crop spacing) with 2 m harvester/haulout track width (Price *et al.* 2004).

Tullberg *et al.* (2001) demonstrated a large and consistent increase in runoff associated with wheeled compared to non-wheeled plots with broadacre grain. Silburn and Glanville (2002) also observed greater total runoff from wheel tracks than from non-wheeled tracks in cotton fields. It therefore seems likely that CTF principles will reduce runoff for the sugar cane industry. However, this has not been quantified and the effects on potential losses of fertilisers and herbicides in runoff are unknown.

Recent surface water quality studies have focused on the effect of fertiliser rate on nutrient losses in runoff (e.g. Bartley *et al.* 2005). However, less is understood on how different fertiliser types and their current placement methods impact on nutrient concentrations and composition in runoff. Two fertiliser practices used in the district include sub-surface placement of granular fertiliser and surface placement of *Liquid One Shot* (at same rate as granular). Both are considered current practice (Rolfe *et al.* 2007), however sub-surface placement of fertilisers is preferred as they are more readily available for plant uptake and less available for runoff and volatilisation.

Once applied to the field, fertilisers are exposed to a variety of chemical, physical and biological processes which change their form and availability in the system over time. Uptake by the plant, volatilisation, nitrification, as well as leaching and runoff processes all affect the quantity and form of nitrogen and phosphorus in the soil. Therefore not only is the rate of fertiliser application important for managing losses of nitrogen and phosphorous in runoff, but also the type of fertiliser used, its placement and the application time in respect to rainfall, especially the first significant rainfall event after application.

In a similar manner, herbicides are also exposed to a variety of processes, and possess different properties that affect their availability for runoff. The ability to adsorb to soil and organic matter, dissolve in water, and break down over time varies greatly from product to product and in different environments. The breakdown processes can usually be summarised as dissipation, with the decline over time defined as a "half-life". A half-live is the amount of time in days taken for the initial concentration of herbicide (e.g. in soil, trash or water) to reduce by half due to natural degradation. Therefore, as for fertiliser, herbicide product selection is an important consideration, including its placement and the application time with respect to rainfall. Current practice for residual herbicide application is by broadcast (100% coverage) on plant cane and ratoons. One method of reducing the use of these residual herbicides is to target their application to the areas immediately surrounding the plant (i.e. ~50% banding on the centre of the bed) and using knock down herbicides, such as glyphosate, to control weeds in the furrows.

A useful method of assessing water quality of runoff from these management practices is by artificially generating runoff under the controlled conditions with a rainfall simulator. Artificial rainfall is applied in known quantities, at a constant intensity to a small land area (normally several m^2) until runoff occurs for a given amount of time. Rainfall simulation methods have been used successfully in the cotton industry to study management practices for the control of runoff losses (Silburn and Glanville 2002; Silburn *et al.* 2002). With the highly variable nature of wet season rainfall in tropical areas such as the Mackay Whitsunday region, this method permits a reliable and consistent comparison of each treatment under investigation. However, it is recognised that rainfall simulation studies complement, rather than replace, field studies under natural rainfall (Silburn and Kennedy 2007).

The aim of this study was to assess the relative impact on the water quality of surface runoff of different fertiliser and herbicide application methods on current cropping and CTF practices, from simulated and natural rainfall events. This was achieved with the use of a rainfall simulator and a paired flume trial on the Deguara "Back on Track" BSES Ltd project site in the Sandy Creek catchment in 2006 to 2007.

The objective of the field-based plot-scale rainfall simulation study was to assess the difference in water quality of runoff from a simulated 1 in 10 year (average return interval) storm event. This was achieved by:

- Applying rainfall at different stages before and after the application of nitrogenous fertilisers and residual herbicides, on current practice and CTF plots,
- Measuring runoff and collecting samples for sediment, nutrient and herbicide analysis, and
- Calculating and comparing total runoff, runoff rate, time to runoff and event mean concentrations and loads of sediment, nutrients and herbicides from each treatment.

The objective of the paddock-scale paired flume study was to:

- Monitor the water quality of runoff from natural rainfall on two of the practice treatments studied in the plot-scale study,
- Determine total runoff, runoff rate, time to runoff and event mean concentrations and loads of sediment, nutrients and herbicides from each event monitored,
- Compare results between treatments and with plot-scale results and determine the decline in nutrient and herbicide availability since application.

2 METHODS

The core component of the project was the plot-scale study, which involved a series of rainfall simulation trials. The paddock-scale study involved the installation of two flumes and automatic samplers to collect runoff from natural rainfall to complement plot-scale trials. Flood-event samples were also collected during the 2006/07 wet season 16 km downstream of the field site from Sandy Creek at Homebush (NRW Gauging station 126001A, 21^{o} 16’ 59”S 149^{o} 01’ 22”E) within the Sandy Creek catchment, as part of the Healthy Waterways Event Monitoring Project. These results are reported in full in Rohde *et al.* (2008). This information provided further understanding of the water quality at the catchment scale compared to the nested-plot and paddock trials.

2.1 Site details

The study was carried out on a cane farming property in North Eton, SW of Mackay (21^{o} 12’ 46’’S 148^{o} 57’ 7’’E) (Appendix 8.1). The site was located on one of the controlled traffic productivity trials for the “Back on Track” (BoT) program with the BSES Ltd and Mackay Sugar (Morris 2005). This productivity trial was situated on a 5.13 ha block with 0.25% slope and was planted with the sugarcane variety Q135 on 30th July 2002. Mill mud was applied to the paddock at approximately 150-200 t/ha at planting. The paddock was irrigated, cut green and trash blanketed. Fertiliser and water application rates remained unchanged throughout the BoT study (2002-2005). There was no irrigation during the plot and paddock-scale monitoring (2006-2007).

The area has a humid tropical climate with a mean annual rainfall of 1600 mm, but ranges from 1200 to 2500 mm (Brodie 2004). Approximately 75% of rainfall is in summer between December and April (Brodie 2004). Rainfall is highly variable from year to year, with tropical cyclones and depressions having major influences on rainfall intensity and duration.

The soil is a duplex derived from quaternary alluvium and has been identified as mapping unit “Ma1” (Marian, yellow B horizon variant) (Holz and Shields 1984), which is a brown Chromosol (Australian Soil Classification, Isabell 1996) and Db2.32/ Dy3.32 (Northcote 1979).

Duplex soils represent 28% of the sugarcane growing area in the Mackay district, with Marian soils (Ma and Ma1) occupying 6% (Holz and Shields 1985). In the Proserpine district approximately 16.7% of the sugarcane area are brown Chromosols and 3% are Marian soils (Schroeder *et al.* 2006).

The soil across the paddock can be generally described as a 0.3 m deep, dark to very dark brown (sometimes greyish) heavy clay loam with a fine sandy A horizon; there is a sharp change to a dark to yellowish or greyish brown medium clay B horizon with a strongly prismatic structure. The surface condition of the soil is hard setting, imperfect drainage and slow permeability. Surface soil properties are shown in Table 1.

Table 1. Selected surface soil (0-10 cm) properties averaged across the site (4 profiles)

pH (H_20 1:5)	CEC[A] (meq/100g)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)
6.0	6.5	14	51	18	17

Ammonia (mg/kg), NH_4-N (KCl)	Nitrate (mg/kg), NO_3-N (KCl)	Phosphorus (mg/kg), P bicarb Colwell	Organic Carbon (%)	Cl^- (mg/kg)	EC (dS/m)
8	7	45	1.4%	75	0.10

[A] CEC values estimated from sum of cations. Full description (1.5 m depth) is in Appendix 8.2.

2.2 Treatments

The treatments studied included two row/bed/traffic treatments, with the application of two fertiliser and two herbicide treatments which were paired for the study. One replant treatment was also studied without the application of fertiliser or herbicide treatments.

The row/bed/traffic treatments included, (1) current practice with 1.5 m wide beds and a single row of sugarcane in the centre of the bed, and (2) controlled traffic farming beds with dual sugarcane rows 0.8 m apart in permanent 2 m beds (Table 2; Figure 2). Both were no-till green harvested and had 90-100% groundcover.

Table 2. Row/bed/traffic treatments

Sugarcane rows	Bed width	Cultivation	Traffic	Green harvest
Current Practice (CP) treatment				
Single (centred)	1.5 m	No-till	Uncontrolled	Yes
Controlled Traffic Farming (CTF) treatment				
Dual (0.8 m apart)	2 m	No-till	Controlled	Yes

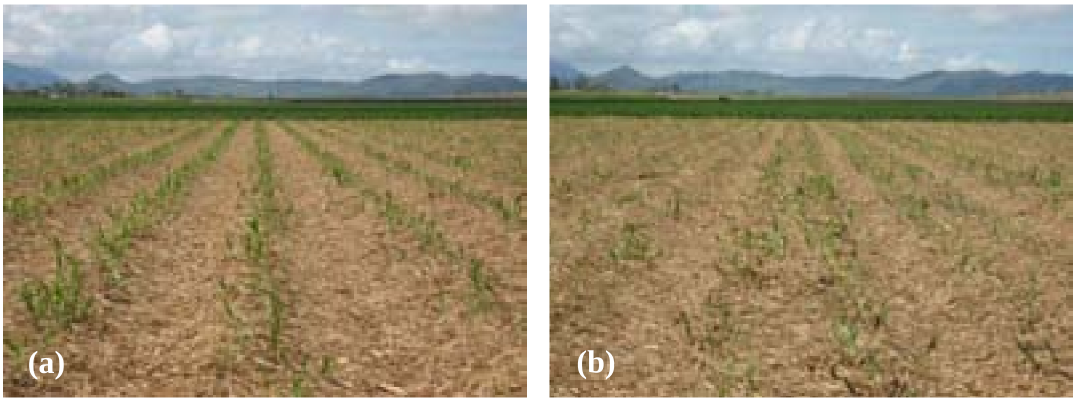

Figure 2. (a) Single sugarcane rows in 1.5 m beds with uncontrolled traffic, and (b) 2 m controlled traffic beds with dual row cane 0.8 m apart

The fertiliser/herbicide treatments included, (1) the surface application of Liquid One Shot (dunder) and broadcast of residual herbicides, and (2) the sub-surface split stool application of Nitra King (S) (granular) and the banding residual herbicides (on the centre of bed only) (Table 3; Appendix 8.3).

Replant treatments included raking and burning of the trash blanket (after harvest), and the conventional cultivation of the paddock ready for planting. Cover was <2%.

Table 3. Fertiliser/herbicide application treatments

Treatment	Application Description	Product	Product application rate	Herbicide product applied	Active ingredient rate
Dunder/broadcast treatment					
Fertiliser	Surface (Centre of bed)	Liquid One Shot (dunder)	3.4 m^3/ha		160 kg N/ha
Residual herbicides	Surface (100% coverage, bed & furrow)	Velpar (Diuron & Hexazinone)	0.3 g/m^2	3 kg/ha	Table 4
		Gesapax Combi *Flowable* (Ametryn & Atrazine)	0.6 mL/m^2	6 L/ha	Table 4
Granular/banded treatment					
Fertiliser	Sub-surface (Stool split, centre of cane rows)	Nitra King (S) (granular)	590 kg/ha		160 kg N/ha
Residual herbicides	Surface (50-60% coverage[A], centre of bed)	Velpar (Diuron & Hexazinone)	0.3 g/m^2	1.5-1.8 kg/ha	Table 4
		Gesapax Combi *Flowable* (Ametryn & Atrazine)	0.6 mL/m^2	3-3.6 L/ha	Table 4

[A] Application rate for the treated area of banded treatments is the same as broadcast treatments, however covering 50-60% of the area rather than 100%. This results in lower application per hectare on banded treatments than broadcast treatments. CTF treatments received 50% coverage and CP treatments received 60% coverage.

The BoT experimental design comprised four replications of the two row/bed/traffic treatments overlaid with three replications of the two fertiliser/herbicide treatments for our study (Figure 3). Replicated rainfall simulation data were obtained from these treatments at three stages (pre fertiliser/herbicide application, 1 and 21 days after application). Replications were obtained at the same stage by staggering fertiliser and herbicide applications and the simulations over a period of 6 days. Application rates were adjusted for bed width to obtain the same overall rate per hectare.

In summary, treatments included rainfall simulation on:

1) *Current Practice (CP)* row/bed/traffic treatment, with fertiliser/herbicide applications:
    i. *No application* of fertiliser or herbicide
    ii. *Dunder fertiliser/broadcast herbicide* (1 and 21 days after application)
    iii. *Granular fertiliser/banded herbicide* (1 and 21 days after application)

2) *Controlled Traffic Farming (CTF)* row/bed/traffic treatment, with fertiliser/herbicide applications:
    i. *No application* of fertiliser or herbicide
    ii. *Dunder fertiliser/broadcast herbicide* (1 and 21 days after application)
    iii. *Granular fertiliser/banded* herbicide (1 and 21 days after application)

3) *Conventional Cultivation (CC)* replant treatment, with
    i. *No application* of fertiliser or herbicide

2.2.1 *Fertilisers*

Liquid One Shot consists of the sugar mill by-product, dunder, premixed with urea (3.5%-8.5% w/v). It has no added phosphorus (P, <1% w/v). There can be considerable variability between each truck mix of Liquid One Shot. Nitra King (S) consists primarily of urea (24.4% w/w) and ammonium nitrate (2.8% w/w). Phosphate salts are listed in the composition, however information for quantity or form is not provided. Both products are considered mainly as a source of nitrogen (N) (i.e. but still contain some P). Application rates were determined by local soil-specific nutrient management guidelines for sugarcane production (Schroeder *et al.* 2006), which recommend 160 kg N/ha annually for Marian soils.

2.2.2 *Herbicides*

The residual herbicide products applied included *Velpar* (Diuron and Hexazinone) and *Gesapax Combi* (Ametryn and Atrazine) (Appendix 8.4). These products are not usually used together and this was only done for the purposes of this study. Gramoxone (1 L/ha) was also applied with the herbicide mix. This was to "burn" the cane leaves slightly and prevent the "cocktail" of herbicides from affecting the cane plant. Selected herbicide properties are shown in Table 4.

Table 4. Selected properties of herbicides studied (ANZECC and ARMCANZ 2000; Montgomery 1993; Wauchope *et al.* 1992)

Common name	Group	Solubility in water (mg/L)	Soil sorption Koc (mL/g)	Soil half-life [A] (days)	Active ingredient in product
Diuron	Substituted Urea	42	480	30-365	468 (g/kg)
Hexazinone	Triazine	33000	173	30-180	132 (g/kg)
Ametryn	Triazine	185	300	70-250	250 (g/L)
Atrazine	Triazine	33	100	12-213	250 (g/L)

[A] Soil half-life depends on soil type and climate. Information provided is general and not specific to brown Chromosols.

Broadcast application had 100% coverage of herbicides to the bed and furrow. Banded application treatments targeted application to the top of the bed only, reducing coverage to a 50-60% band. Both treatments were applied at the same rate, with application speed (7 km/hr) and pressure (240 kPa, 35 psi) kept constant. All herbicide applications were made directly onto the trash blanket cover. The nozzle spacing on the herbicide boom spray was not adjustable between treatments. As a result the CP treatment received a 60% band from banded applications, whilst the CTF treatment received a 50% band. Herbicides were applied as per BSES Ltd and label recommendations. Note that banded application of residual herbicides was always paired with sub-surface applications of granular fertiliser.

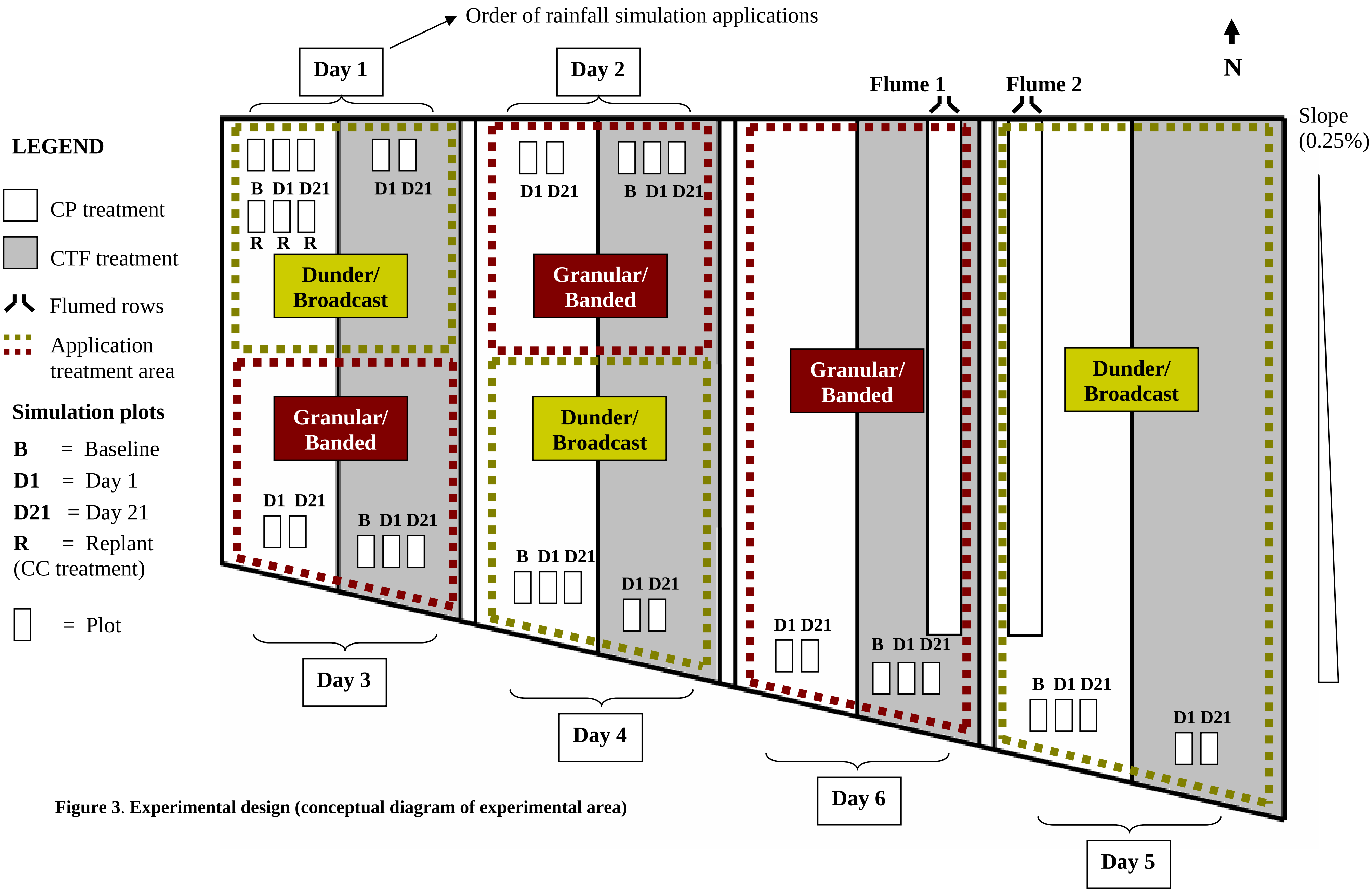

Figure 3. Experimental design (conceptual diagram of experimental area)

2.3 Plot-scale rainfall simulation trials

2.3.1 *Experimental design*

A series of rainfall simulation trials were conducted (Figure 4) within a randomised complete block design (Figure 3) at four stages in the cycle of sugarcane production:

1) *Baseline simulations* (after green harvest, no applications)
2) *Day 1 simulations* (one day after the application of treatments)
3) *Day 21 simulations* (21 days after the application of treatments)
4) *Replant simulations* (conventional cultivation, no applications)

Each set of simulations was replicated three times on both CP and CTF treatments, excluding replant simulations which was the conventional cultivation of CP treatments only.

The first series of simulations were an initial baseline assessment shortly after harvest and before the application of treatments. The paddock was harvested in two parts. Three-quarters of the cane was cut on the 22 October 2006 whilst the remainder was cut on the 3 November. The first two rainfall simulations for the baseline trial were conducted on the freshly cut beds, with 100% cover of cane trash.

The second series of simulations were conducted one day after the application of fertilisers and herbicides and less than one week after the baseline trials. The third series of simulations were conducted (on fresh sites) 21 days after the application of treatments. Cover from trash averaged 1.1 kg/m^2 dry matter for both CP and CTF treatments. Sub-surface applications of fertiliser did produce some inconsistencies in cover in parts of the paddock (Appendix 8.3), however all simulations were conducted on plots with minimal disruption (i.e. 90-100% surface cover). For both day one and day 21 simulations, two simulations were conducted on any given day; a CP plot and a CTF plot with the same treatment.

Prior to the final day of simulations on day 21, a 70.5 mm storm was experienced. These plots were covered with tarpaulins for protection. However, rainfall was sufficient to penetrate underneath the tarpaulins via runoff from the furrow up slope. The top ~10 cm of the profile on the beds (where fertiliser and herbicide treatments were) remained dry, thus creating a unique situation within the study. Results from these plots are excluded from calculations of means, but they are still considered important results within the study.

The final simulations were conducted almost one year later, after the following harvest. The cane was harvested on 9 July 2007. The western CP bay (Figure 3) was then raked and burnt (trash blanket), offset-ploughed twice, and rotary-hoed leaving no surface cover (<2%). This section of the paddock was treated the year previously with surface Liquid One Shot dunder and broadcast herbicide. The day before the first simulation the plots were cultivated with a planter to represent conventional planting of CP (1.5 m rows - cane was not actually planted). Rainfall simulations for two of the three replant replications were interrupted with power failures. Once the problems were rectified, simulations were resumed until a total of 40 min in runoff was collected.

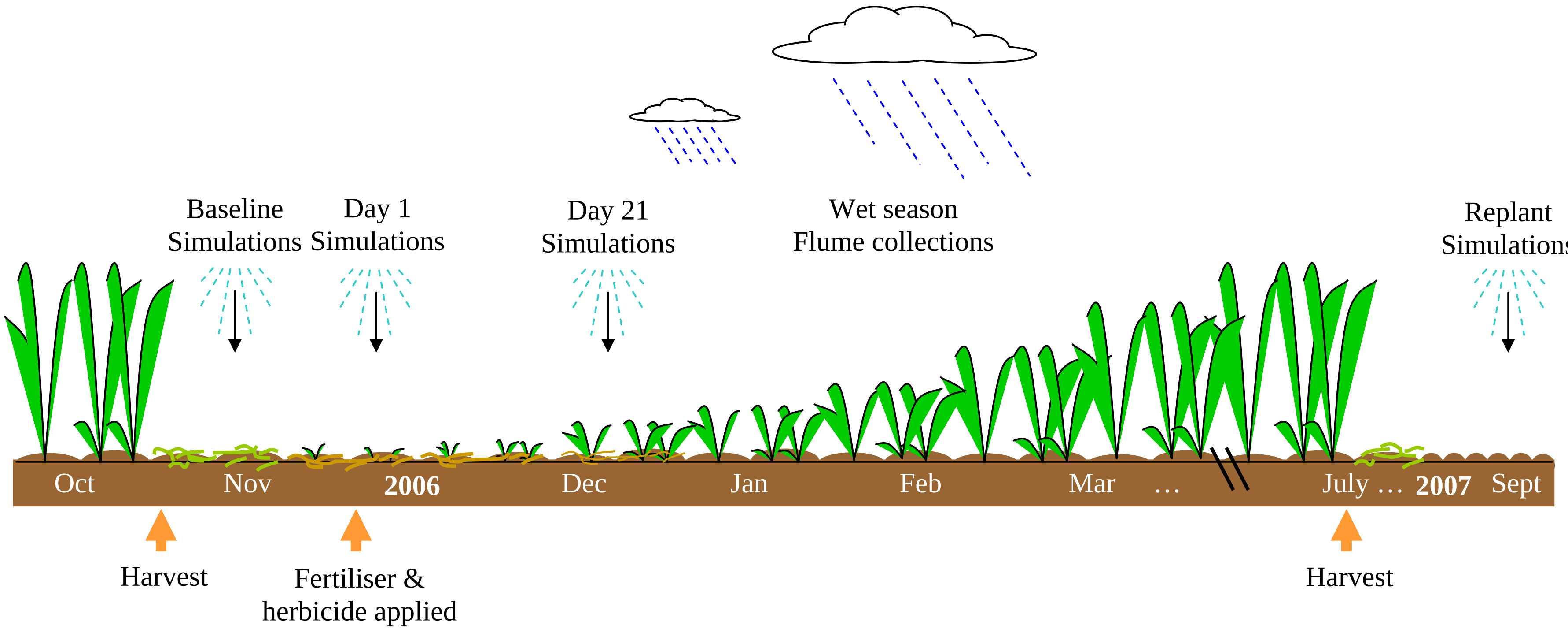

Figure 4. **Timeline of project**

2.3.2 *Rainfall simulator and plot setup*

The rainfall simulator consists of a mobile six piece modular A-frame. Along the apex is an oscillating manifold with a series of Veejet 80100 nozzles set downward and powered by an automotive windscreen wiper motor. Rainfall is delivered to the plot in an intermittent sweeping motion which controls the intensity of the rainfall. At the end of each sweep excess rainwater is captured in trays and recycled back to the supply tank and through the system.

Duncan (1972) reported these nozzles produce a droplet size and kinetic energy (29.49 J/m^2.mm) suitable for use in the simulation of intense natural rainfall above 40 mm/hr in eastern Australia (Rosewell 1986). Further details of the rainfall simulator, including its extensive use through southern and central Queensland and New South Wales, are outlined in Loch *et al.* (2001).

For the purposes of this study only three modules of the rainfall simulator were used (Figure 5). Prior to use, it was calibrated to deliver 100 mm/hr using a three-second sweep delay. The rainfall simulator was assembled over one bed (plot) at a time. Each rainfall simulation plot was 7 m long and centred over the bed extending from the furrow centres each side (either a total of 1.5 m (CP & CC) or 2 m (CTF) wide). The edges of the plots were bound by metal plates driven approx 5 cm into the soil and extending 5 cm above the soil. Runoff was routed through a metal gutter (protected with a canopy) and a ~30 cm long PVC outlet pipe, cut into the top of the bed (approximately level with the bottom of the furrows).

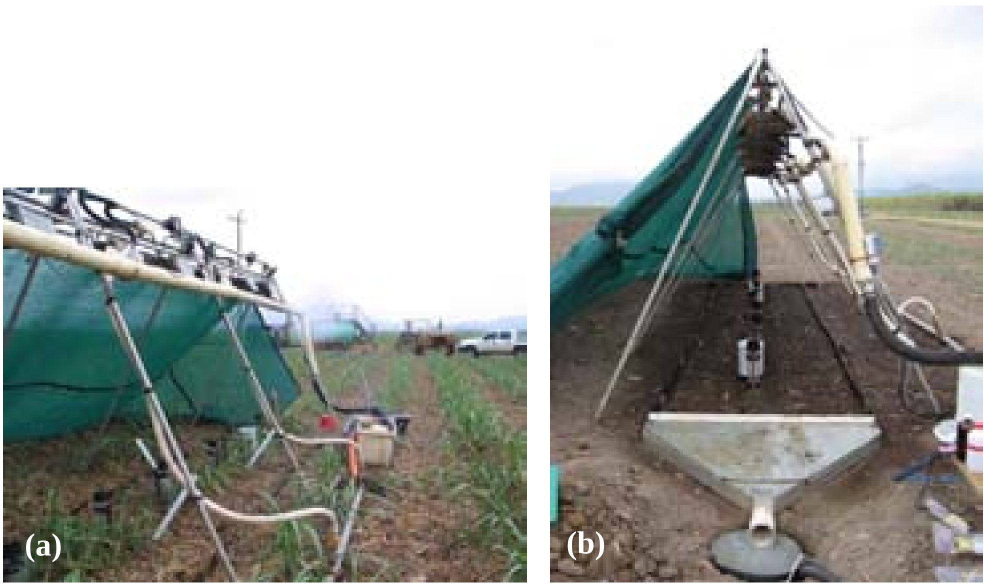

Figure 5. Rainfall simulator on (a) CP treatment at day 21, and (b) CC treatment.

2.3.3 *Simulation and runoff sampling*

Runoff, as well as sediment, nutrient and herbicide concentrations were determined for each set of simulations. For the replant (conventional cultivation) simulations, only runoff and sediment results are reported.

Rain was applied at 100 mm/hr until 40 minutes of runoff was generated. The runoff rate was measured manually at the simulator plot outlet, every 4 minutes (2 minutes at initial and tail flows). Discrete samples for total sediment (includes suspended sediment, bedload and organic matter i.e. cane trash), herbicides and nutrients (total and filtered) were collected every 8 minutes (4 minutes on tail flows). Nutrient samples were filtered immediately after simulations through 0.45 μm cellulose acetate Ministat micro-pore filters. For the second and third simulation replicates, herbicide sampling was limited to the initial, peak and tail of flows to reduce the cost in analysis. A sample of source water was taken for herbicide and nutrient analysis for each simulation trial.

Samples for herbicides (~500 mL) were collected in 1 L glass amber bottles with teflon lids. Total sediment samples were collected in 1 L detergent-washed polypropylene bottles, and samples for total and filtered nutrients were collected in 60 mL and 10 mL polyethylene vials (one use only), respectively. All samples were placed in an esky with ice immediately after collection and chilled (total sediment and herbicides) or frozen (nutrients) at the end of each day. Samples were transported in eskies with ice to laboratories for analysis. Samples were sent within a few days of each set of simulations.

For the purposes of this study, event mean concentrations (EMC) (flow weighted mean concentration) and loads per ha, for each water quality parameter, were calculated for the *first 40 minutes (or 67 mm)* of the rainfall simulation (as different treatments had different start times and therefore different amounts of rainfall to generate 40 minutes of runoff). This is equivalent to a 10 year average annual recurrence interval (ARI) for the Mackay region (Jenkins 2001). Total runoff, time and rain to runoff, and peak runoff rate (for 67 mm) are also presented.

2.3.4 *Quality of source water*

Water for the rainfall simulator was sourced from a 23 m deep bore on site and was the only reasonable source for the study. Analysis of the source water revealed concentrations of nitrate that are similar to those in other tropical groundwaters (Table 5) (median 0.01 – 1.5 mg NO_x-N/L, Rasiah *et al.* 2005) and N loads were small in comparision to the nutrient applications. There were low levels of most of the herbicides under investigation (Table 6). The same source water was used for all treatments. Simulations conducted before the application of fertiliser/herbicides provide a good comparison to simulations conducted post the application of fertilisers and herbicides.

Table 5. Nutrient concentrations and loads (per ha) from 67 mm source water for rainfall simulator (averaged across each trial)

	Total Nitrogen	Ammonia	Nitrate	DIN	Total Phosphorus	FRP
(mg N/L, P/L)	2.69	0.03	2.26	2.29	0.06	0.004
(kg/ha)	1.8	0.02	1.51	1.53	0.04	0.026

Table 6. Herbicide concentrations and loads (per ha) from 67 mm of source water for rainfall simulator (averaged across each trial)

	Ametryn	Atrazine	Desethyl Atrazine [A]	Desisopropyl Atrazine [A]	Diuron	Hexazinone
(μg/L)	<0.01	0.16	0.20	0.01	0.06	0.05
(g/ha)	<0.01	0.11	0.13	0.01	0.04	0.03

[A] Proportion of Atrazine to its break down products Desethyl Atrazine and Desisopropyl Atrazine suggest these herbicides are not from recent contamination.

2.3.5 *Soil and cane trash sampling*

Soil samples were collected prior to each simulation for measurement of soil moisture, nutrient (0-10 cm) and herbicide content (0-2.5 cm). Samples were taken close to plots (two in the centre and two on the edges of the beds). The soil samples were bulked to produce one composite sample for each plot treatment. Samples for herbicides were stored in glass jars with teflon lids, placed on ice immediately and then chilled before transport over night on ice to the laboratory. Samples for nutrient and moisture determination were stored in plastic disposable containers.

Samples of cane trash were also collected prior to the simulations for the day 1 and day 21 trials. The samples were collected directly above 0-2.5 cm soil sample collection points from the area of four 25 cm x 25 cm quadrats. Samples were bulked, wrapped in aluminium foil, sealed with plastic, stored on ice, chilled and transported overnight in eskies with ice to the laboratory for dry matter and herbicide analysis.

Soil cores for bulk density were taken from the furrow bottom, mid-slope of the edge of the bed and centre of the bed (Figure 6) from three CP and CTF from random locations across the study site. Cores were taken using a 10 cm diameter thin walled hydraulically pushed tube. Each core was cut into increments (0-5, 5-10, 10-20, 20-30, 30-45 and 45-60 cm) using thin wire and accurately measured for length.

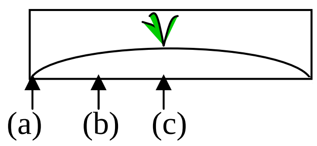

Figure 6. (a) Furrow bottom, (b) mid-slope, and (c) centre of the bed

2.4 Paddock-scale flume trials

2.4.1 *Experimental design*

Paddock-scale flume trials were set up on two different row/bed/traffic and fertiliser/herbicide treatments studied in the rainfall simulation trials (Figure 3) to monitor runoff from rainfall events through the succeeding wet season (Figure 4). Each treatment (not replicated) consisted of three rows 180 m long. These included:

1) CP row/bed/traffic treatment with dunder/broadcast application treatments (catchment area 810 m^2)

2) CTF row/bed/traffic treatment with granular/banded application treatments (catchment area 1080 m^2)

2.4.2 *Instrumentation and measurements*

Runoff was measured from each treatment with a 300 mm San Dimas flume (Figure 7). Water height in the flume was recorded at one minute intervals with a pressure transducer height recorder and stored on a Macquarie data logger, or using an ISCO Flow Bubbler Module. Water height was converted to discharge using the standard discharge equation for a San Dimas Flume:

$$a = 0.110925b^{1.286}$$

where a = Discharge (L/s)
b = Water height (mm)

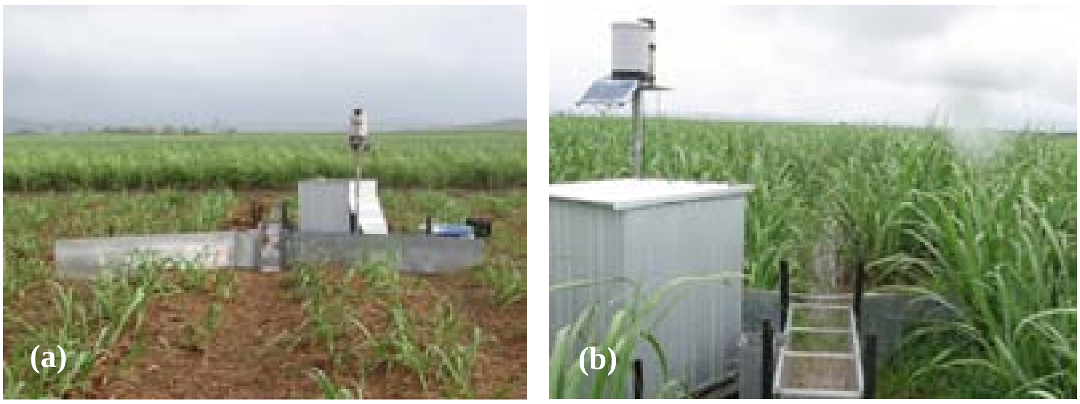

Figure 7. Flume set up on CTF treatment (a) shortly after the first event, and (b) later in the wet season.

Rainfall was measured with a standard rain gauge and a tipping bucket pluviometer. Rainfall intensity was recorded at one minute intervals. ISCO automatic pumping samplers were installed at each flume with sampling arms located at the flume outlets. Bedload traps were installed at the entry to each flume but due to the lack of bedload accumulation, no samples were collected.

2.4.3 *Events and runoff sampling*

Due to several equipment faults with the data logger and pressure transducer height recorder only five events were sampled adequately to determine runoff, EMC and loads (Table 7).

Table 7. Events and number of samples collected in flumes

Event	Date	No. samples collected		Rainfall	
		CP	CTF	(mm)	Max (mm/hr)
1	10/12/06	0	1 (composite)	70.5	115
2	24/01/07	1	8	80.2	112
3	27/01/07	4	4	24.5	62
4	30/01/07	3	6	41.2	75
5	21/03/07	0	3	45.4	87

The first natural rainfall event to be triggered by the samplers (Table 7) occurred on the final day of simulations at day 21 (granular/banded treatment), and was similar to that used to determine EMC and loads in the plot-scale trials. During this event a composite sample from the CTF treatment was collected. This provided a unique opportunity to compare samples at paddock and plot scales, at the same time frame after fertiliser and herbicide applications, and after a similar amount and intensity of rainfall.

Subsequent events through the wet season were sampled discretely through the hydrograph in 1 L glass jars. Sampling intervals were equivalent to 15 mm of runoff (12,150 L for the CP treatment and 16,200 L for the CTF treatment). This was adjusted from 5 mm early in the wet season. Water samples were retrieved as soon as possible after the event. Each 1 L sample was manually shaken to ensure mixing and resuspension of particulate material, and then manually split for total sediment, herbicide and nutrients (total and filtered) analyses. Each sample was refrigerated before overnight transport on ice to laboratories.

2.5 Water, soil and cane trash analysis

All herbicide analyses (source and runoff water, soil and cane trash) were conducted at Queensland Health Scientific Services (QHSS), Brisbane. Samples with low herbicide levels were fully extracted using routine procedures and analysed by liquid chromatography and mass spectrometry (LCMS). As herbicide levels in day 1 and day 21 samples were high, full extraction of the sample would mean multiple dilutions and increased probability of analytical errors. Therefore these samples were analysed by *direct injection of a filtered 1mL sub-sample (0.45 μm filter)* into the LCMS. The limit of recording (LOR) for direct injection is 1 μg/L. If samples were found to contain <1 μg/L a full extraction was conducted. For soil and cane trash samples, results were reported on a dry weight basis.

Total sediment and nutrients in source and runoff water were analysed by the Australian Centre for Tropical Freshwater Research (ACTFR) Water Quality Laboratory, James Cook University, Townsville. Samples for total sediment analyses were filtered though pre-weighed GF/C 1.2 μm membranes and dried at 103-105°C for 24 hours and reweighed to determine the dry total sediment weight.

Nutrient analysis included total nitrogen (TN) and phosphorus (TP), total filterable nitrogen and phosphorus, ammonia, NO_x (nitrate + nitrite) and filterable reactive phosphorus (FRP). Samples for total and filtered nutrients were digested in an auto-clave using a alkaline persulfate technique (modified from Hosomi and Sudo (1987)) and the resulting solution simultaneously analysed for NO_x and FRP by segmented flow auto-analysis using an ALPKEM Flow Solution II (Alpkem Corporation, Wilsonville, Oregon, USA). The analyses of NO_x, ammonia and FRP were also conducted using standard segmented flow auto-analysis techniques following standard methods (APHA 1998). Particulate nutrient concentrations (PN and PP) were estimated by the subtraction of the total filterable nutrient from the total nutrient concentrations. Similarly, filterable organic nitrogen or phosphorus (referred as Dissolved Organic Nitrogen or Phosphorus, DON or DOP) was estimated by the subtraction of NO_x and ammonia (for nitrogen) or FRP (for phosphorus) from total filterable nitrogen or total filterable phosphorus concentration.

General soil analyses (standard profiling and nutrients) were conducted by the Natural Resource Sciences (NRSc) laboratory, Queensland Department of Natural Resources and Water, Indooroopilly.

Soil moisture samples and bulk density samples were dried at 105°C to constant weight to give a dry mass of soil in a known volume. The volume of bulk density samples were calculated using the area of the tip of the thin walled tube and the length of each sample.

2.6 Statistical analyses

All runoff data (total runoff, rain/time to runoff, peak runoff rate, EMC and loads) were analysed with analysis of variance (ANOVA) using the statistical package SPSS, release 15.0 (SPSS 2006). General linear models were used to determine differences between means for main treatments (row/bed/traffic treatment and fertiliser/herbicide treatment) at a given time (before application, day 1 and day 21 post application). For interactions found not to be significant, main treatments were pooled. Logarithmic transformations were used to stabilise variance in data where appropriate. Statements of significance in the text are based on $P<0.05$, unless stated otherwise (where values of $P<0.10$ were found these were also presented and considered significant). Pair-wise multiple comparisons were conducted by least significant difference, at the 5% level of significance, to determine grouping of treatment means (represented by different letters after the treatment mean for significant differences). Regression analysis was used to determine relationships between concentrations in cane trash and runoff event mean concentrations, and decline of herbicide concentrations over time.

3 RESULTS

Total sediment, nutrients and herbicide results are expressed as event mean concentrations and loads for 67 mm rainfall (100 mm/hr). Mean values and values of significance are presented for parameters for each treatment simulated. Graphs of these tabulated data have also been presented to highlight findings. The concentration of herbicides refers to the concentrations in the dissolved phase (herbicides transported in solution, not on sediment, i.e. samples were filtered through a 0.45 μm filter).

3.1 Soils

3.1.1 *Bulk density*

The CP and CTF treatment bulk densities were not significantly different within furrows or within the centre of the bed (Figure 8). The CTF treatments maintained similar bulk densities from the centre to the midsection of the bed. However, the bulk density of CP treatments were significantly higher (and hence more compact) in the top 30 cm of the midsection. This reflects the straddling effect of uncontrolled traffic and therefore greater area of compaction under CP compared to CTF. The farmer also reported greater ease in ploughing the CTF beds (after the completion of the study) compared with the compacted CP beds (N Kallaghan 2008, pers. comm.).

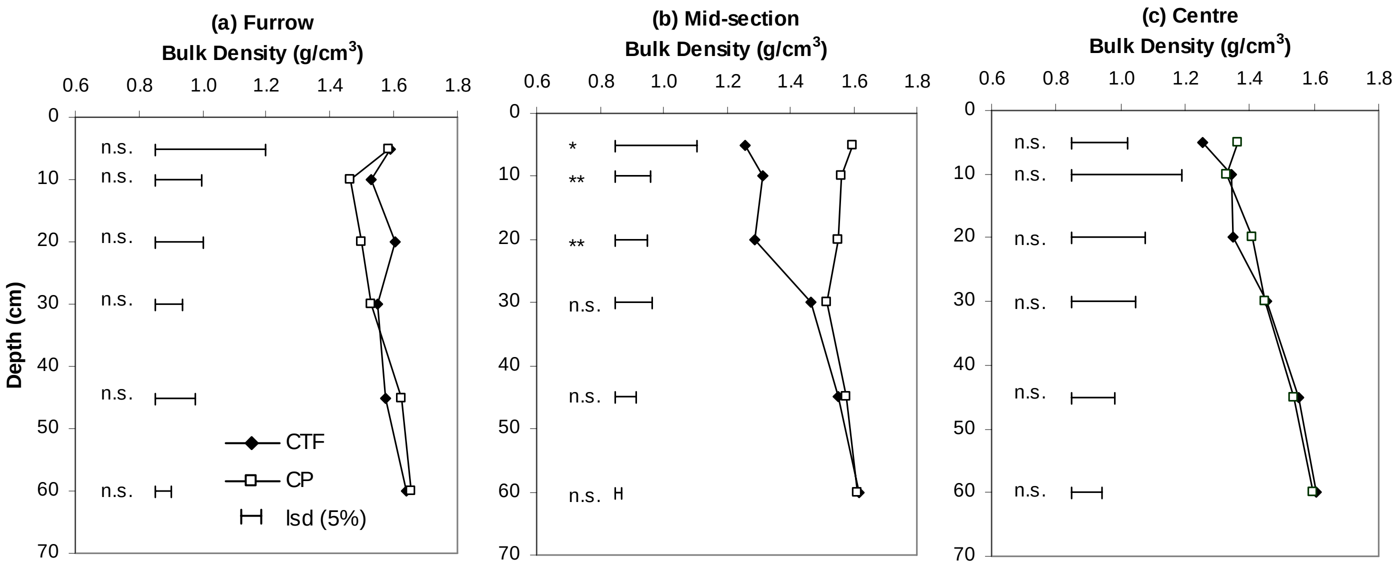

Figure 8. Bulk density of (a) furrow, (b) mid-section, and (c) centre of beds for CP and CTF treatments

n.s. = not significant; *P<0.05; **P<0.01

3.1.2 *Surface soil moisture*

There were no significant differences in mean surface soil moisture (0-10 cm) prior to rainfall simulations between CP treatments and CTF treatments at baseline, day one and day 21 simulations. A decrease in mean surface soil moisture was observed from baseline (0.16 g/g, P<0.05, s.e.d. = 0.008) and day one simulations (0.16 g/g, P<0.05, s.e.d. = 0.007) to day 21 simulations (0.12 g/g) (excluding treatments which received natural rainfall). The CC treatments (0.07 g/g) were drier than all other treatments due to cultivation and lack of a trash blanket (P<0.05).

3.1.3 *Surface soil nutrient concentrations*

Prior to simulations ammonia concentrations in the soil surface (0-10 cm) increased more than ten-fold one day after application of fertiliser compared with concentrations before fertiliser application (Table 8). At day 21, concentrations for granular applications increased to 232 mg/kg compared with dunder applications which had declined to 46.3 mg/kg. Nitrate concentrations remained somewhat constant before and one day after fertiliser application for both treatments, but concentrations increased by more than five-fold by day 21.

Phosphorus concentrations in soil surface (0-10 cm) prior to rainfall simulation did not show large increases like nitrogen 1 or 21 days after application (Table 8). Dunder treatments were lower than granular treatments at day 1 and day 21.

Table 8. Mean soil concentrations for nutrients before rainfall simulation (0-10 cm) (CP and CTF treatments combined)

Timing	Treatment	Ammonia (mg/kg) NH_4-N (KCl)	Nitrate (mg/kg) NO_3-N (KCl)	Phosphorus (mg/kg) P bicarb Colwell
Baseline	None	6.3	8.7	54
Day 1	Granular	65	7.5	59
	Dunder	89	8.5	32
Day 21	Granular	232	51	49
	Dunder	46	48	37

3.2 Plot-scale rainfall simulation trials

3.2.1 *Runoff and sediment loss*

3.2.1.1 *Total runoff and peak runoff rate*

There was significantly less total runoff from CTF treatments compared to CP treatments (Table 9). This was equivalent to 23% and 13% rainfall as runoff for CP and CTF treatments, respectively. The difference in total runoff between CP and CTF treatments increased over longer durations of rainfall (>67 mm) (Figure 9). This suggests that CTF treatments have a greater potential to reduce runoff during storm events greater than the 1 in 10 year storm applied in this study.

Conventional cultivation (CC) and granular/banded treatments (at day 1 and 21) produced greater total runoff compared to dunder/broadcast or no application treatments (Table 9). The granular/banded treatment had the shortest start to runoff time (8 minutes). This consequently led to greater total runoff from these treatments during the 40 minute duration (67 mm) of the simulated storm. The CC treatments had a longer mean start time (13 minutes) but still produced the highest runoff total (24 mm).

The no application treatments (baseline) produced the least total runoff as a result of extended start to runoff times on two CTF plots (28 and 36 minutes). These were the longest start times of the study. Total runoff from the no application treatments was not significantly different compared to the dunder/broadcast treatments (at day one and 21) (Table 9). Overall start to runoff times were longer on CTF treatments, but this was not significantly different to CP treatments.

The peak runoff rate of CP treatments (44 mm/hr) was almost twice that of CTF treatments (24 mm/hr) (Table 9). The CC treatments had the highest peak runoff rates of the study (68 mm/hr). Thus the final infiltration rates were highest for CTF, intermediate for CP and lowest for CC.

The largest total runoff value measured was 44 mm (65 %) from a CP plot at day 21 (excluded from means in Table 9), which received 70.5 mm of natural rainfall the night before simulation. This plot had a peak runoff rate of 87 mm/hr and the shortest time to runoff (4 minutes). The CTF plot, which was also affected by the same natural storm event, produced only 31 mm (46 %) runoff and a peak runoff rate of 82 mm/hr, with 6 minutes to runoff. Both of these plots had received a granular/banded application.

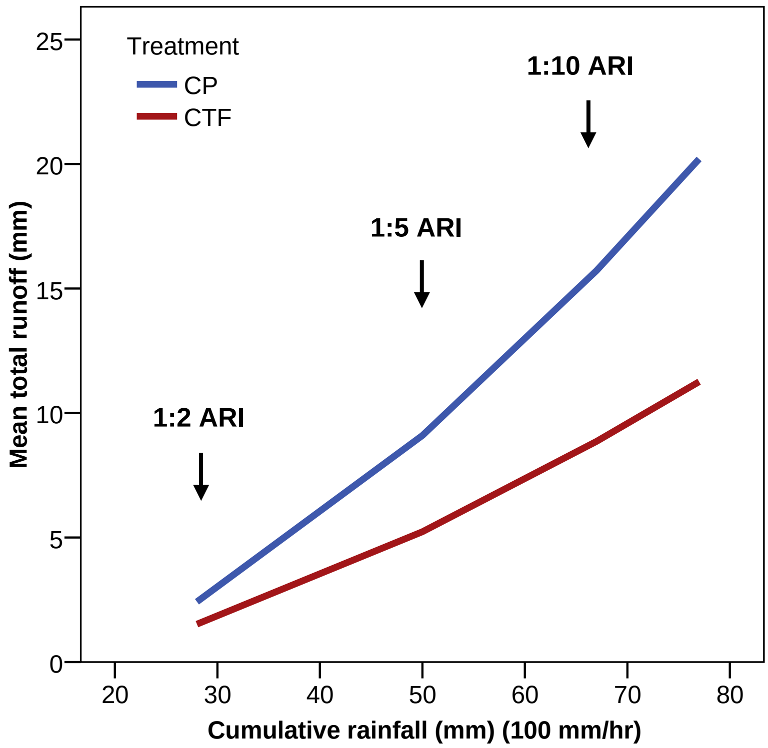

Figure 9. Effect of row/bed/traffic practice on total runoff for cumulative rainfall
Storms approximating three average annual return intervals (ARI) for 100 mm/hr at Mackay are indicated (28, 50 and 67 mm of rain). Application treatments pooled with day 1 and day 21 results combined.

Table 9. Runoff and total sediment (TS) loss during 67 mm simulated rainfall at 100 mm/hr, averaged for application & replant treatments and row/bed/traffic treatments.
Values followed by the same letter are not significantly different (at *P*>0.05) within treatments. Day 1 and day 21 results for dunder/broadcast and granular/banded treatments are combined as there was no significant effect of day on runoff and sediment loss.

Treatment	n	Surface cover (%)	Total runoff (mm)	Time to runoff (minutes)	Rain to runoff (mm)	Peak runoff rate (mm/hr)	Log_{10} (TS, mg/L)	Total sediment (mg/L)	Log_{10} (TS, kg/ha)	Total sediment (kg/ha)
Application and replant treatments										
No application	6	100	6.4a	19.7	31.1	24.1a	2.202a	(159.2)	0.712a	(5.2)
Dunder/broadcast	12	100	11.1a	10.7	15.6	31.6ab	2.069a	(117.2)	1.073ab	(11.8)
Granular/banded	10	90 - 100	17.2b	8.0	16.4	43.2b	2.003a	(100.7)	1.212b	(16.3)
CC	3	<2	23.8b	13.0	21.1	68.0c	3.561b	(3639.2)	2.881c	(760.3)
Significance			**	n.d.	n.d.	***	***		***	
l.s.d. (5%) [A]			6.0			12.7	0.269		0.387	
Row/bed/traffic treatment										
CP (all, excl. replant)	14	100	15.7a	9.9a	16.4a	44.2a	2.084a	(121.3)	-	20.9a
CTF (all)	14	100	8.9b	13.0a	21.6a	24.1b	2.099a	(125.6)	-	11.6b
Decrease from CP			43.3%	-	-	45.5%	-			44.4%
Significance			**	n.s.	n.s.	***	n.s.			*
l.s.d. (5%)			4.6	5.1	8.4	9.7	0.269			8.4

n = number of plots; n.s. = not significant; *$P<0.05$; **$P<0.01$; ***$P<0.001$; n.d. = not determined
[A] l.s.d. not adjusted unequal sample size (lowest value presented)
Log_{10} and back transformed values (in parentheses) for total sediment are presented

3.2.1.2 *Total sediment loss*

The highest total sediment event mean concentration and load was generated from CC treatments (<2% cover), with 3640 mg/L and 760 kg/ha respectively (Table 9; Figure 10). This was more than 46 times the average of other treatments (90-100% cover). Event mean concentrations for all other treatments were not significantly different. A slight increase in total sediment load was observed from granular/banded treatments compared to dunder/broadcast and no application treatments. Overall, total sediment load was lower in CTF treatments (12 kg/ha) than CP treatments (21 kg/ha) (Table 9).

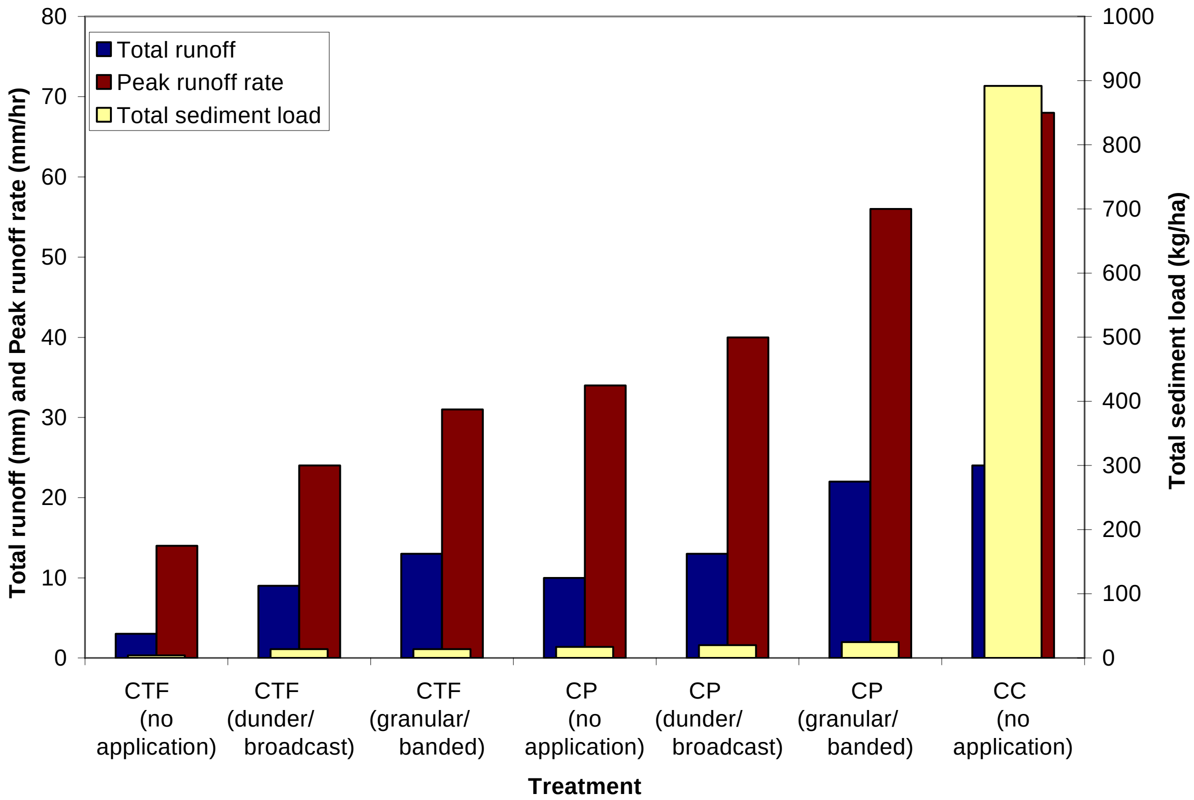

Figure 10. Mean total runoff, peak runoff rate, and total sediment load from all treatments (day 1 and day 21 data combined).

3.2.2 *Nitrogen loss in runoff*

Fertiliser/herbicide application treatments in this section are referred to individually as dunder or granular treatments (without reference to the paired herbicide treatment).

3.2.2.1 *No fertiliser application*

There was no significant difference in event mean concentrations between CP and CTF treatments for TN, ammonia, nitrate and DIN before the application of fertilisers (Table 10). Total N and ammonia loads were lower from CTF treatments (Table 11), a result of a delayed start to runoff in the CTF treatments. Nitrate and DIN loads from CTF treatments were also lower, though not significantly different.

Event mean concentrations were similar to rainfall simulation source water concentrations suggesting that the primary source of N was from the source water, rather than the soil or trash blanket.

Table 10. Nitrogen EMC before fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TN (mg N/L)	Ammonia (mg N/L)	Nitrate (mg N/L)	DIN (mg N/L)
			No application		
CP	3	4.44a	0.023a	2.65a	2.69a
CTF	3	5.37a	0.020a	3.77a	3.81a
Significance		n.s.	n.s.	n.s.	n.s.
l.s.d. (5%)		2.45	0.022	3.64	3.64

n = number of plots; n.s. = not significant

Table 11. Nitrogen loads before fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TN (g N/ha)	Ammonia (g N/ha)	Nitrate (g N/ha)	DIN (g N/ha)
			No application		
CP	3	446a	2.3a	256a	260a
CTF	3	139a	0.3b	90a	91a
Significance		$P<0.10$	***	n.s.	n.s.
l.s.d. (5%)		400	0.7	410	411

n = number of plots; n.s. = not significant; ***$P<0.001$

3.2.2.2 *One day after fertiliser application*

Total N and ammonia one day after fertiliser application showed substantial increases in event mean concentration from baseline simulations (Table 12; Figure 11). However, this was not as prominent for nitrate and DIN event mean concentrations.

Dunder treatments had significantly greater TN event mean concentration (12 mg N/L) than granular treatments (6 mg N/L) for simulations conducted one day after fertiliser application (Table 12; Figure 11). Concentrations were lower from CTF treatments than CP treatments although there was no significant interaction between application treatment and row/bed/traffic treatment for TN. Dunder treatments also produced greater event mean concentrations of ammonia in runoff than granular treatments. There was a significant application and row/bed/traffic treatment interaction ($P<0.10$), with dunder applications on CP treatments producing the highest concentration (1.09 mg N/L) and granular application on CTF treatments producing the lowest concentration (0.06 mg N/L). Nitrate and DIN event mean concentrations were not significantly different for all treatments.

CP treatments had significantly greater losses of TN, ammonia, nitrate and DIN loads than CTF treatments (Table 13; Figure 12). The N loads from no application treatments would primarily account for N in the source water rather than fertilisers. Therefore loads measured above the no application treatment results would most likely reflect actual loss from fertilisers applied.

Table 12. Nitrogen EMC one day after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TN (mg N/L)	Ammonia Log_{10}	Ammonia (mg N/L)	Nitrate (mg N/L)	DIN (mg N/L)
			1 day after application			
Dunder (CP)	3	14.66a	0.005a	(1.01)	3.62a	4.72a
Dunder (CTF)	3	9.25ab	-0.510b	(0.31)	3.78a	4.11a
Granular (CP)	3	6.43b	-0.670b	(0.21)	3.83a	4.10a
Granular (CTF)	3	6.05b	-1.221c	(0.06)	3.79a	3.86a
Significance		*	**		n.s.	n.s.
l.s.d. (5%)		5.59	0.468		0.92	1.31
Dunder (all)	6	11.96a	-0.253a	(0.56)	3.72a	4.41a
Granular (all)	6	6.23b	-0.960b	(0.11)	3.79a	3.99a
Significance		*	***		n.s.	n.s.
l.s.d. (5%)		4.46	0.321		0.62	0.90

n = number of plots; n.s. = not significant; **P*<0.05; ***P*<0.01; ****P*<0.001
Log_{10} and back transformed values (in parentheses) for ammonia are presented

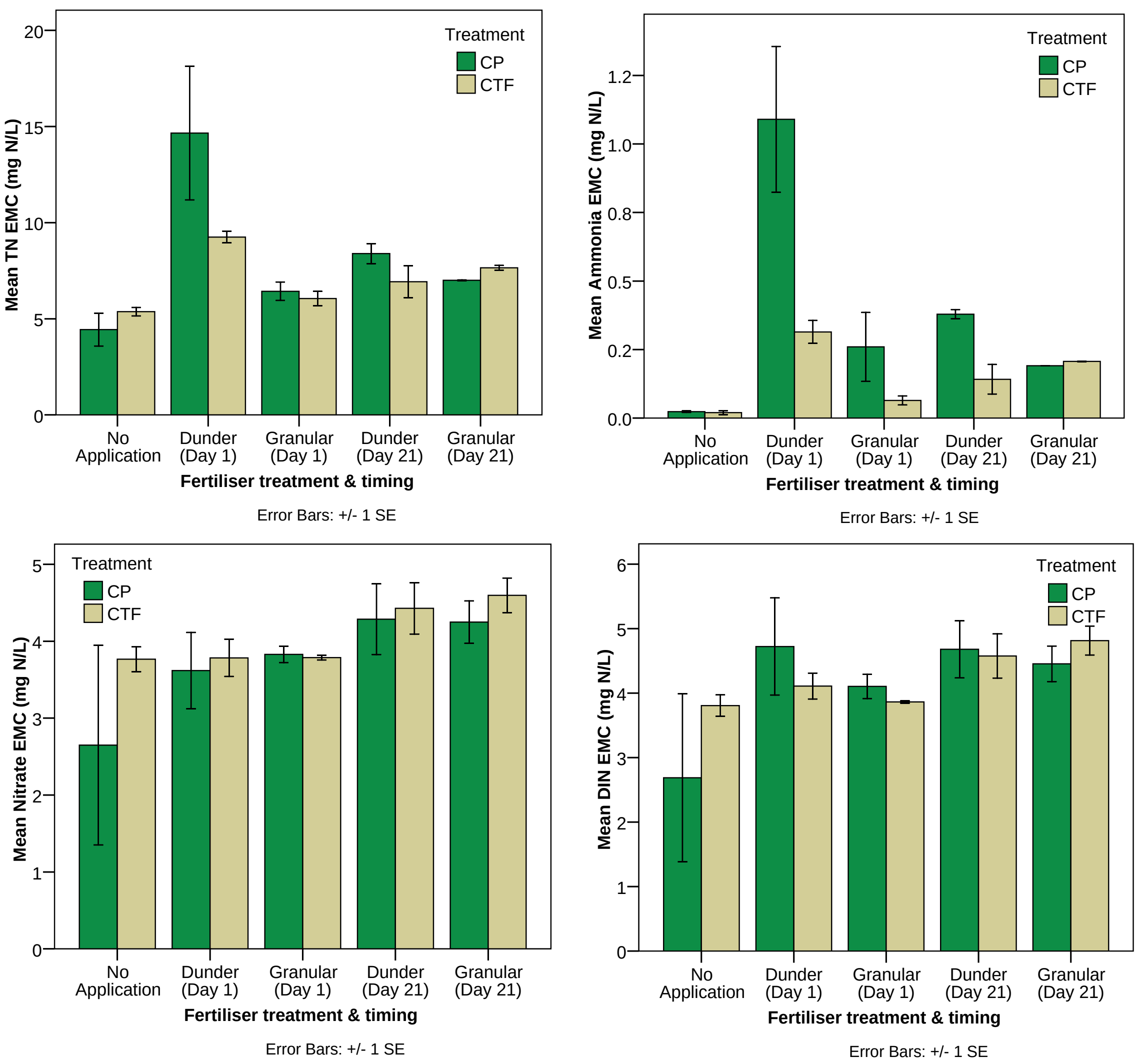

Figure 11. Nitrogen EMC before, 1 day and 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr.

Table 13. Nitrogen load one day after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TN Log_{10}	TN (g N/ha)	Ammonia Log_{10}	Ammonia (g N/ha)	Nitrate (g N/ha)	DIN (g N/ha)
			1 day after application				
Dunder (CP)	3	3.304a	(2014)	2.171a	(148.3)	539a	706ab
Dunder (CTF)	3	2.860b	(764)	1.384bc	(24.2)	312a	339b
Granular (CP)	3	3.198ab	(1578)	1.693ab	(49.3)	959b	1035a
Granular (CTF)	3	2.847b	(703)	0.845c	(7.0)	441a	451b
Significance		*		**		**	*
l.s.d. (5%)		0.318		0.579		288.3	390
CP (all)	6	3.3a	(1995)	1.932a	(85.5)	749a	870a
CTF (all)	6	2.6b	(398)	1.115b	(13.0)	377b	395b
Significance		**		**		**	**
l.s.d. (5%)		0.223		0.397		196	267

n = number of plots; *P<0.05; **P<0.01

Log_{10} and back transformed values (in parentheses) for TN and ammonia are presented.

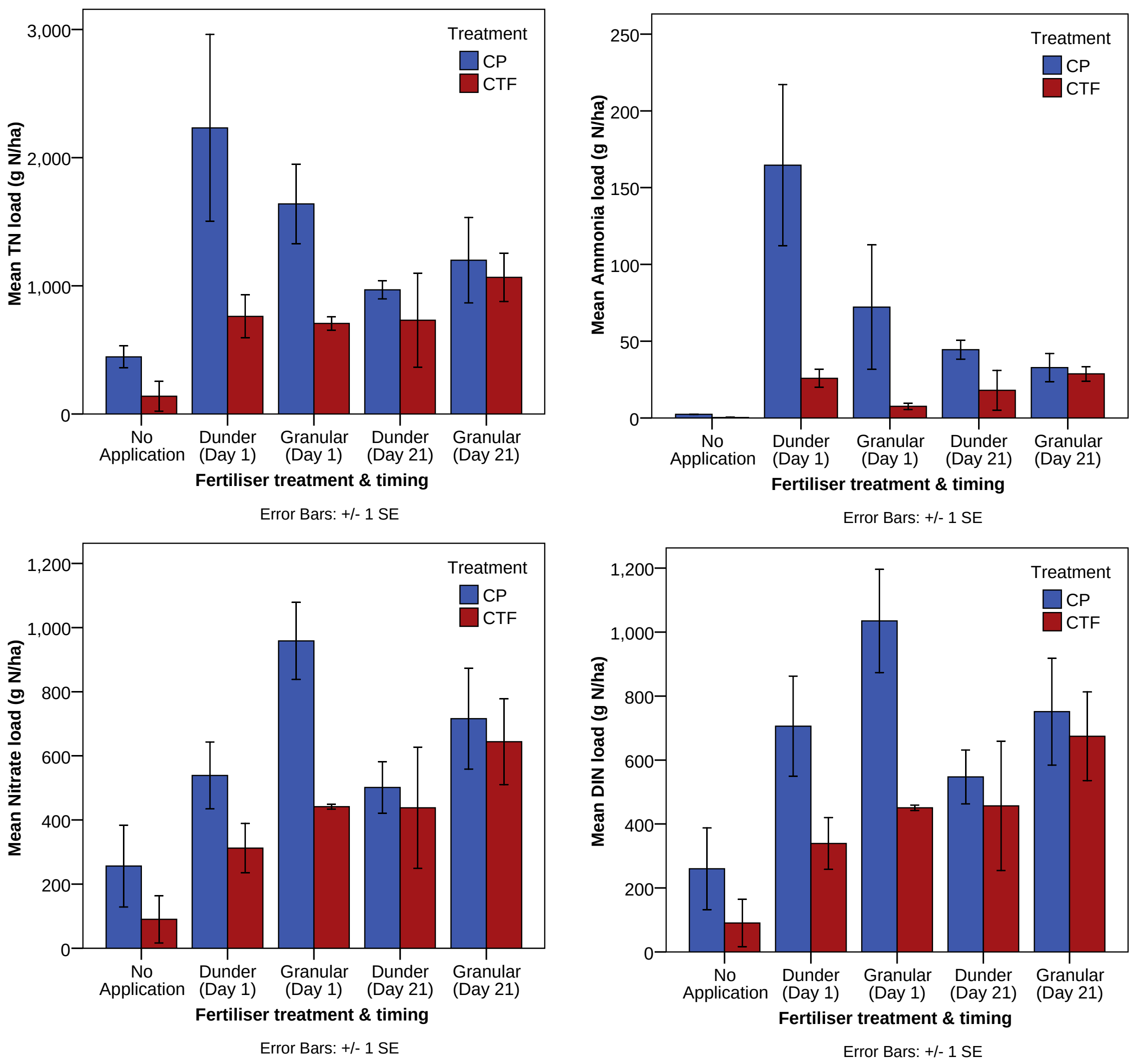

Figure 12. Nitrogen loads before, 1 day and 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr.

3.2.2.3 *21 days after fertiliser application*

There were no differences between treatments in event mean concentrations for TN, nitrate and DIN at day 21 (Table 14; Figure 12). There were some differences between treatments for ammonia event mean concentrations, with dunder application on CP treatments (0.38 mg N/L) greater than dunder application on CTF treatments (0.14 mg N/L), but not significantly different from granular treatments.

The CP treatments had higher N loads than CTF treatments at day 21 and granular more than dunder however the differences were not significant (Table 15).

Table 14. Nitrogen EMC 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr.

Treatment	n	TN (mg N/L)	Ammonia (mg N/L)	Nitrate (mg N/L)	DIN (mg N/L)
			21 days after application		
Dunder (CP)	3	8.39a	0.38a	4.29a	4.68a
Dunder (CTF)	3	6.93a	0.14bc	4.43a	4.58a
Granular (CP)	2	7.00a	0.19ac	4.25a	4.46a
Granular (CTF)	2	7.65a	0.21ac	4.60a	4.82a
Significance		n.s.	*	n.s.	n.s.
l.s.d.[A] (5%)		1.97	0.11	1.21	1.19

n = number of plots; n.s. = not significant; *$P<0.05$
[A] l.s.d. not adjusted unequal sample size (lowest value presented)

Table 15. Nitrogen loads 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TN (g N/ha)	Ammonia (g N/ha)	Nitrate (g N/ha)	DIN (g N/ha)
			21 days after application		
Dunder (CP)	3	969a	44.5a	501a	547a
Dunder (CTF)	3	732a	18.0a	438a	457a
Granular (CP)	2	1201a	32.8a	716a	751a
Granular (CTF)	2	1067a	28.7a	644a	675a
Significance		n.s.	n.s.	n.s.	n.s.
l.s.d.[A] (5%)		868	31.1	475	504

n = number of plots; n.s. = not significant
[A] l.s.d. not adjusted unequal sample size (lowest value presented)

3.2.2.4 *Nitrogen fractions in runoff over time*

The distribution of N species in runoff over time is shown in Figure 13. Total N event mean concentrations prior to the application of fertilisers ranged from 2.76 to 5.72 mg N/L. This range increased to 8.22 to 20.16 mg N/L for dunder treatments at day one compared to 5.54 to 7.18 mg N/L for granular treatments. Total N at day 21 did not vary substantially from day one granular treatments.

In general TN consisted primarily of nitrate and nitrite (NO_x) and to a lesser extent PN, DON and ammonia. DON was also a primary contributor to TN from dunder treatments at day one. DON loads at day one were also large as a result of large DON event mean concentrations on CP treatments compared to CTF treatments (Figure 14).

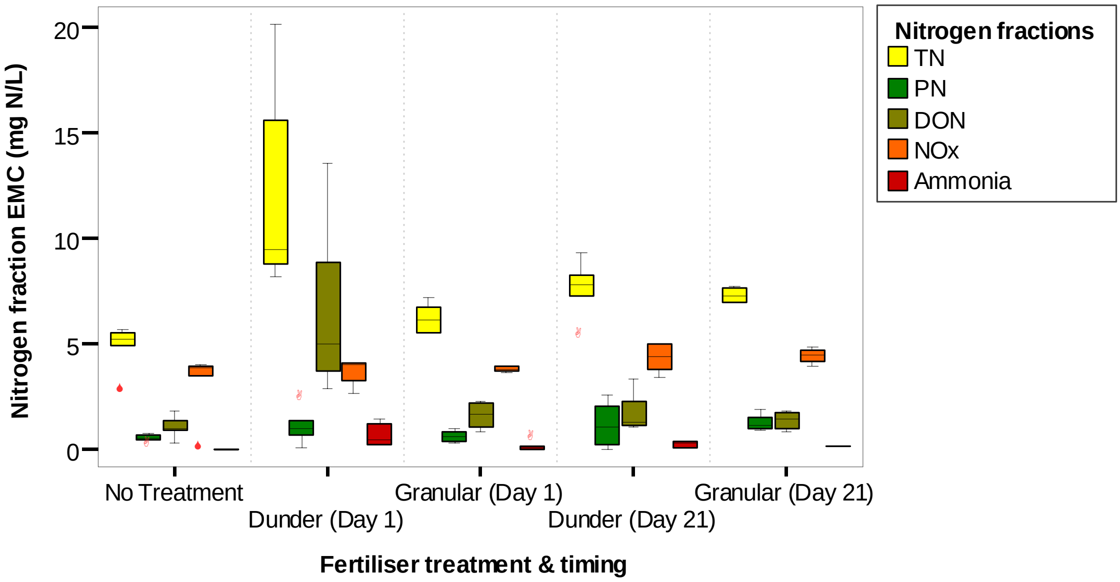

Figure 13. The range of Nitrogen EMC fractions for treatments over time (CP and CTF treatments pooled). Nitrate and nitrite shown as NOx.

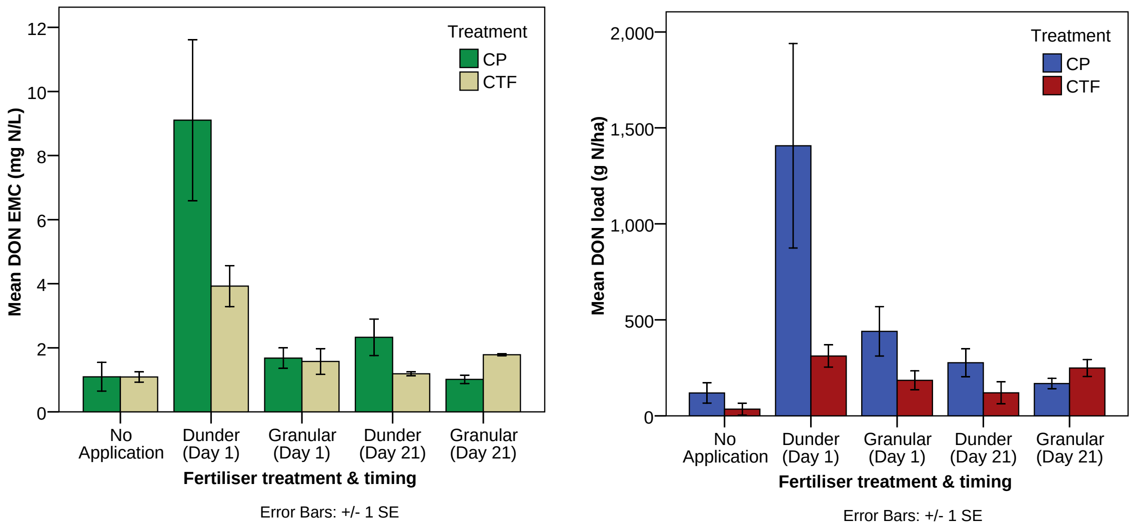

Figure 14. Dissolved Organic Nitrogen EMC and loads before, 1 day and 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr.

3.2.3 *Phosphorus loss in runoff*

Fertiliser/herbicide application treatments in this section are referred to individually as dunder or granular treatments (without reference to the paired herbicide treatment).

3.2.3.1 *No fertiliser application*

There was no significant difference in event mean concentrations between CP and CTF treatments for TP, PP and FRP before the application of fertilisers (Table 16). The CP treatments had significantly greater PP and FRP loads than the CTF treatment at $P<0.10$ (Table 17). Total P load from CTF treatments was also less but not significantly different.

Unlike N results, event mean concentrations were higher than rainfall simulation source water concentrations suggesting that the primary source of P was from the soil or trash blanket, rather than source water.

Table 16. Phosphorus EMC before fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TP (mg P/L)	PP Log_{10}	PP (mg P/L)	FRP Log_{10}	FRP (mg P/L)
			No application			
CP	3	0.48a	-0.940a	(0.11)	-0.553a	(0.28)
CTF	3	0.54a	-0.867a	(0.14)	-0.487a	(0.33)
Significance		n.s.	n.s.		n.s.	
l.s.d. (5%)		0.27	0.450		0.353	

n = number of plots; n.s. = not significant
Log_{10} and back transformed values (in parentheses) for PP and FRP are presented.

Table 17. Phosphorus loads before fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TP (g P/ha)	PP Log_{10}	PP (g P/ha)	FRP (g P/ha)
			No application		
CP	3	31.9a	1.309a	(20.4)	31.6a
CTF	3	11.9a	0.148a	(1.4)	7.6a
Significance		n.s.	$P<0.10$		$P<0.10$
l.s.d. (5%)		50.8	1.185		30.0

n = number of plots; n.s. = not significant
Log_{10} and back transformed values (in parentheses) for TP and PP are presented.

3.2.3.2 *One day after fertiliser application*

There were no significant differences in P event mean concentrations between fertiliser treatments one day after application (Table 18; Figure 15). There were increases in TP and FRP concentrations from no application treatments, although fertilisers reported primarily N constituents. CTF treatments had significantly less P load compared to CP treatments (Table 19; Figure 16). The granular applications on CP treatments had greater TP (209 g P/ha) and FRP loads (155 g P/ha) compared to all other treatments.

Table 18. Phosphorus EMC one day after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TP (mg P/L)	PP (mg P/L)	FRP (mg P/L)
		1 day after treatment		
Dunder (CP)	3	0.82a	0.09a	0.58a
Dunder (CTF)	3	0.66a	0.11a	0.47a
Granular (CP)	3	0.84a	0.09a	0.62a
Granular (CTF)	3	0.81a	0.07a	0.59a
Significance		n.s.	n.s.	n.s.
l.s.d. (5%)		0.30	0.09	0.24

n = number of plots; n.s. = not significant

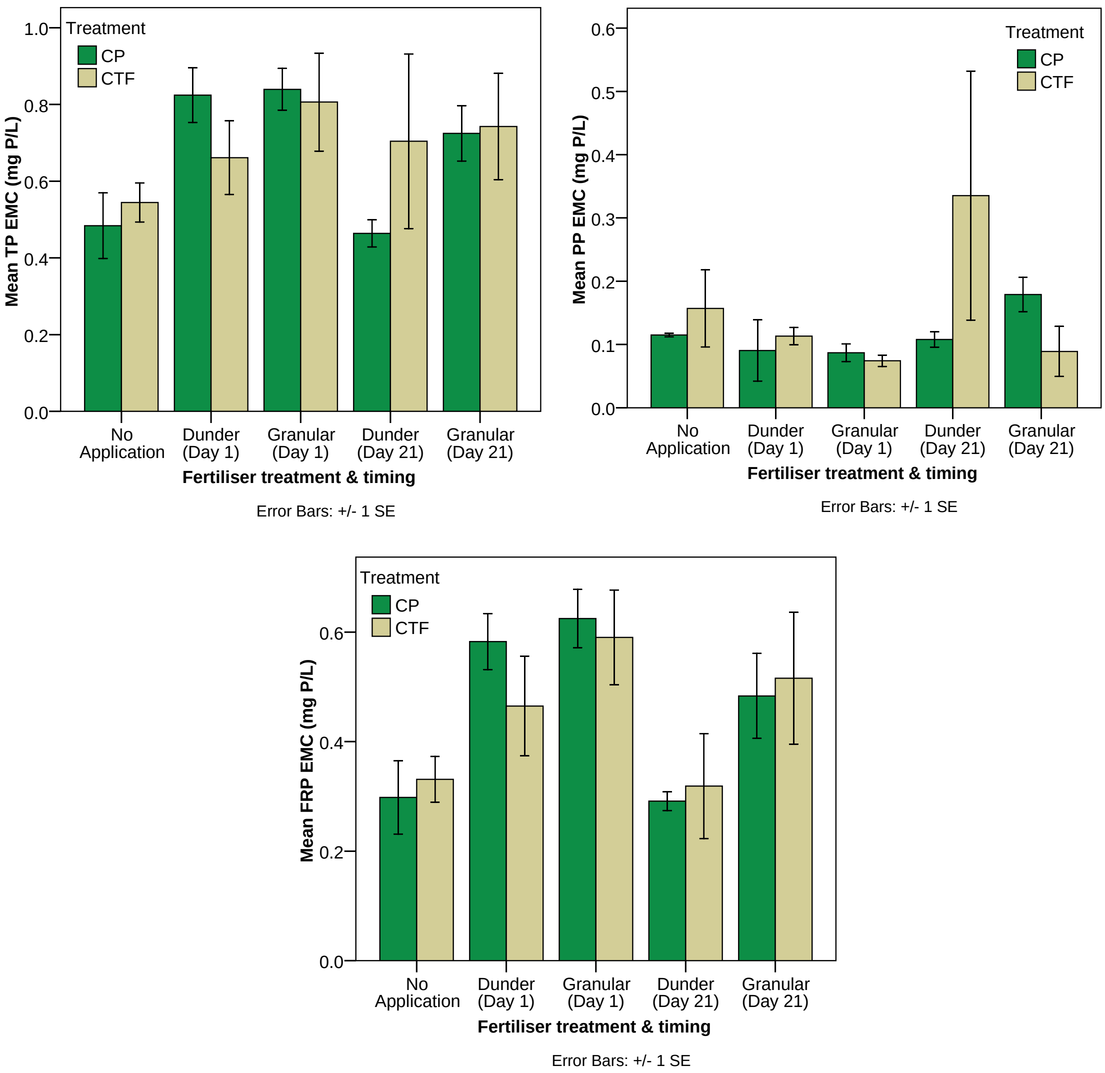

Figure 15. Phosphorus EMC before, 1 day and 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr.

Table 19. Phosphorus loads one day after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TP (g P/ha)	PP (g P/ha)	FRP (g P/ha)
		1 day after application		
Dunder (CP)	3	124.6a	11.9a	88.5a
Dunder (CTF)	3	56.7a	9.5a	39.9a
Granular (CP)	3	209.3b	21.7a	154.9b
Granular (CTF)	3	94.4a	8.6a	69.1a
Significance		**	n.s.	*
l.s.d. (5%)		72.6	11.8	70.6
CP (all)	6	170.0a	16.8a	121.7a
CTF (all)	6	75.6b	9.1a	54.5b
Significance		**	*P*<0.10	**
l.s.d. (5%)		49.7	8.3	35.6

n = number of plots; n.s. = not significant; **P*<0.05; ***P*<0.01

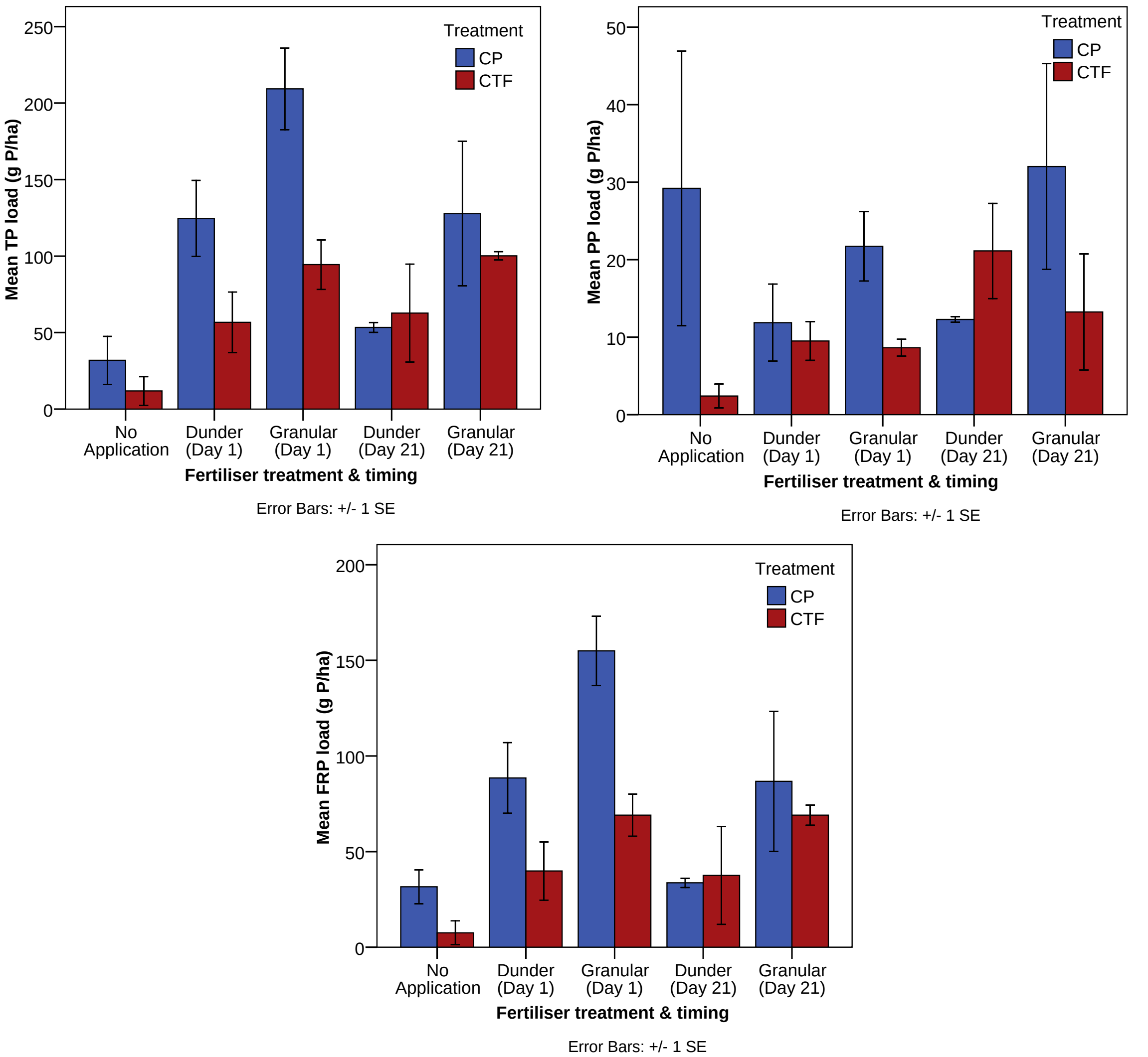

Figure 16. Phosphorus loads before, 1 day and 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr.

3.2.3.3 *21 days after fertiliser application*

There were no significant differences in event mean concentrations between treatments for TP and PP 21 days after the application of fertilisers (Table 20). Combined granular treatments had a significantly greater FRP event mean concentration than dunder treatments at *P*<0.10. There was no significantly different P load for all treatments (Table 21).

Table 20. Phosphorus EMC 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TP (mg P/L)	PP (mg P/L)	FRP (mg P/L)
		21 days after application		
Dunder (CP)	3	0.46a	0.11a	0.29a
Dunder (CTF)	3	0.70a	0.34a	0.32a
Granular (CP)	2	0.72a	0.18a	0.48a
Granular (CTF)	2	0.74a	0.09a	0.52a
Significance		n.s.	n.s.	n.s.
l.s.d.[A] (5%)		0.49	0.40	0.26
Dunder (all)	6	0.73a	0.22a	0.30a
Granular (all)	4	0.58a	0.13a	0.50a
Significance		n.s.	n.s.	*P*<0.10
l.s.d.(5%)		0.39	0.31	0.20

n = number of plots; n.s. = not significant
[A] l.s.d. not adjusted unequal sample size (lowest value presented)

Table 21. Phosphorus loads 21 days after fertiliser application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	TP Log_{10}	TP (g P/ha)	PP (g P/ha)	FRP Log_{10}	FRP (g P/ha)
			21 days after application			
Dunder (CP)	3	1.726a	(53.2)	12.3	1.523a	(33.3)
Dunder (CTF)	3	1.687a	(48.6)	21.1	1.361a	(22.9)
Granular (CP)	2	2.075a	(118.9)	32.0	1.896a	(78.7)
Granular (CTF)	2	2.001a	(100.2)	13.2	1.838a	(68.9)
Significance		n.s.		n.d.	n.s.	
l.s.d.[A] (5%)		0.475			0.642	

n = number of plots; n.s. = not significant; n.d. = not determined
Log_{10} and back transformed values (in parentheses) for TP and FRP are presented.
[A] l.s.d. not adjusted unequal sample size (lowest value presented)

3.2.3.4 *Phosphorus fractions in runoff over time*

The distribution of P species in runoff over time is shown in Figure 17. In general TP was comprised primarily of FRP and to a lesser extent PP and DOP. Total P event mean concentrations prior to the application of fertiliser ranged from 0.32 to 0.62 mg P/L. This range increased to 0.51 to 1.02 mg P/L for dunder and granular treatments at day one. This was also within the range of TP event mean concentrations at day 21.

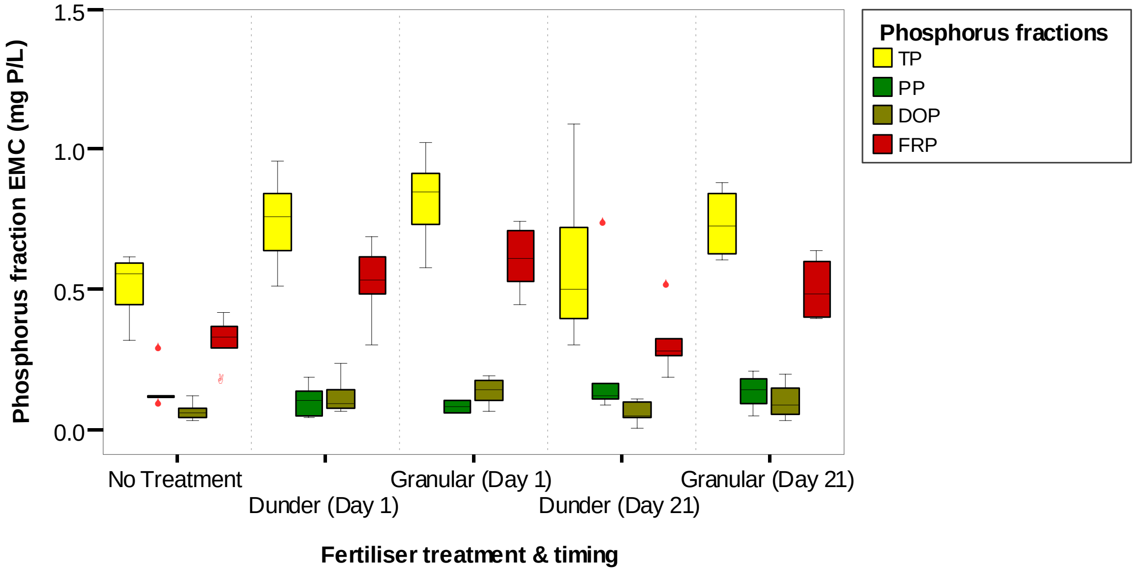

Figure 17. The range of Phosphorus EMC fractions for treatments over time (CP and CTF treatments pooled).

3.2.4 *Herbicide loss in runoff*

Fertiliser/herbicide application treatments in this section are referred to individually as broadcast or banded treatments (without reference to the paired fertiliser treatment).

3.2.4.1 *No herbicide application*

Concentrations of atrazine, diuron and hexazinone in runoff prior the application of herbicides were greater than detection limits (Table 22). Atrazine (0.14 µg/L) and hexazinone concentrations (0.08 µg/L) were similar to those levels reported for source water (0.16 µg/L and 0.05 µg/L respectively; Table 6). However, diuron (0.33 µg/L) was more than 5 times higher in the runoff than source water (0.06 µg/L). Cane trash samples were not collected for herbicide analysis prior to application. However, two surface soil samples (0-2.5 cm) collected before the simulations revealed diuron concentrations of 21 mg/kg (CTF) and 25 mg/kg (CP). It is likely that the high concentrations of diuron were from residues from the previous season as it has been detected in soils up to one year after application (Table 4). The most likely source of atrazine and hexazinone in runoff is the source water as concentrations of these herbicides were similar in the source water and runoff, and they were not detected in the soil samples.

Table 22. Herbicide EMC and loads prior to herbicide application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	Ametryn		Atrazine		Diuron		Hexazinone	
		(µg/L)	(g/ha)	(µg/L)	(g/ha)	(µg/L)	(g/ha)	(µg/L)	(g/ha)
				No applications					
CP	3	<0.01	0.0	0.14	0.01	0.28	0.03	0.07	0.01
CTF	3	<0.01	0.0	0.14	0.00	0.37	0.01	0.09	0.00

n = number of plots

3.2.4.2 *One day after herbicide application*

Banded applications had less than half the event mean concentrations of broadcast applications for ametryn, atrazine, diuron and hexazinone (range 39-44%, Table 23; Figure 18). Results indicated no significant application treatment by row/bed/traffic treatment interaction for event mean concentration. It is noteworthy that the banded applications received 50-60% of the herbicide rate that was applied to the broadcast applications.

For pooled data, CP treatments had significantly higher loads for both banded and broadcast treatments compared with CTF treatments (Table 24; Figure 19). Loads of each herbicide more than doubled in runoff from CP treatments compared with CTF treatments. There was no significant interaction between application and row/bed/traffic treatments.

Table 23. Herbicide EMC one day after herbicide application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	Ametryn (μg/L)	Atrazine (μg/L)	Diuron (μg/L)	Hexazinone (μg/L)
		1 day after application			
Broadcast (CP)	3	519.0a	771.1a	569.0a	262.0a
Broadcast (CTF)	3	318.4ab	544.4ab	418.5a	187.8ab
Banded (CP)	3	199.1b	306.4b	198.7b	104.8b
Banded (CTF)	3	151.3b	267.4b	191.2b	94.5b
Significance		*P*<0.10	*	**	*
l.s.d. (5%)		273.3	315.0	219.3	96.4
Broadcast (all)	6	418.7a	657.7a	493.7a	225.0a
Banded (all)	6	175.1b	286.9b	195.0b	99.6b
Significance		*	**	*	**
l.s.d. (5%)		186.7	215.2	143.7	65.7

n = number of plots; **P*<0.05; ***P*<0.01

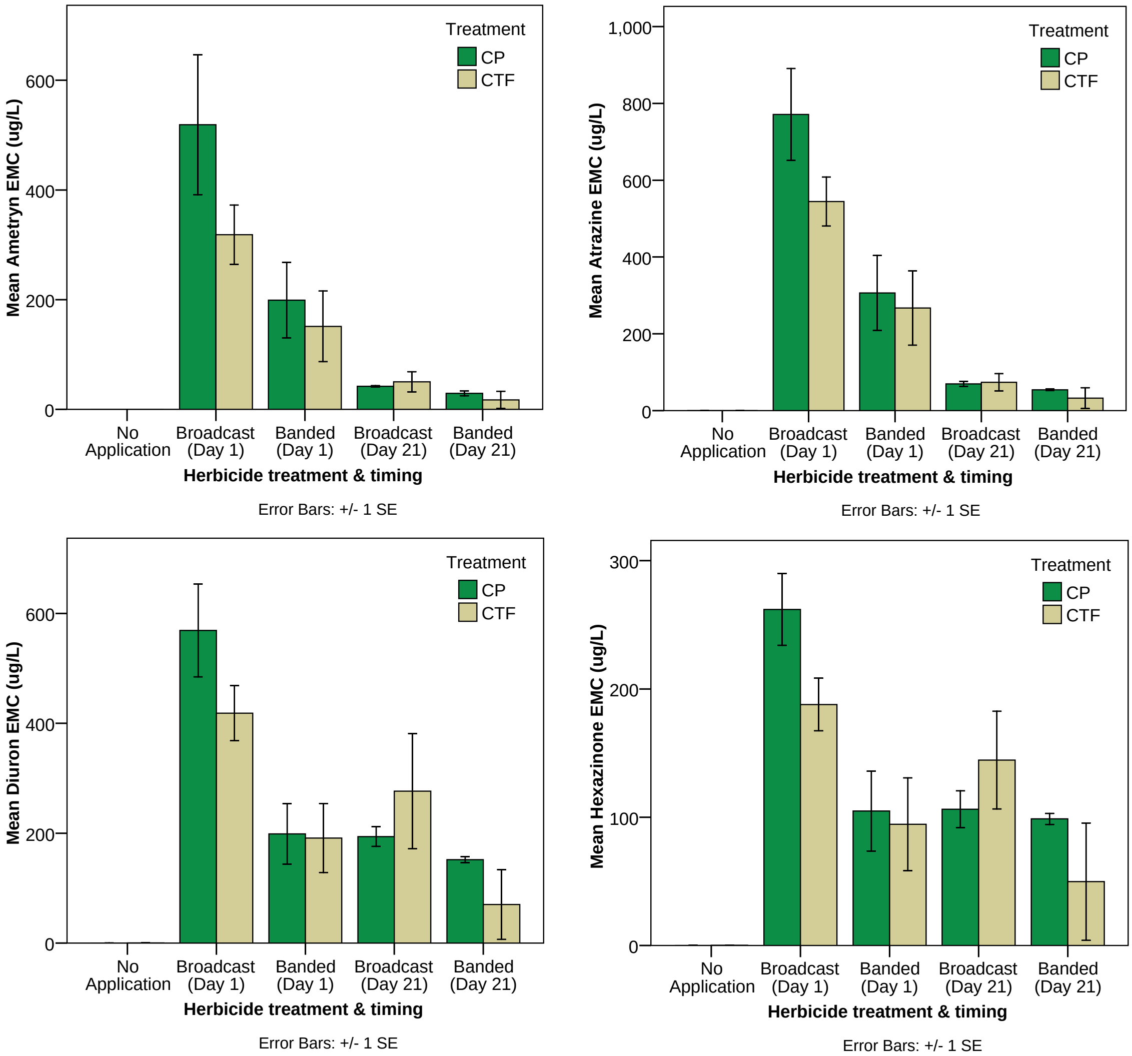

Figure 18. Herbicide EMC before, 1 day and 21 days after herbicide application, from 67 mm of simulated rainfall at 100 mm/hr.

Table 24. Herbicide loads one day after herbicide application, from 67 mm of simulated rainfall at 100 mm/hr

Application Row	n	Ametryn (g/ha)	Atrazine (g/ha)	Diuron (g/ha)	Hexazinone (g/ha)
		1 day after application			
Broadcast (CP)	3	80.5a	118.2a	87.8a	40.1a
Broadcast (CTF)	3	27.6a	45.5a	36.1ab	16.0b
Banded (CP)	3	51.5a	78.9a	50.6ab	26.4ab
Banded (CTF)	3	17.7a	31.2a	22.3b	11.0b
Significance		n.s.	n.s.	*P*<0.10	*P*<0.10
l.s.d. (5%)		63.2	79.3	53.5	23.1
CP (all)	6	66.0a	98.6a	69.2a	33.2a
CTF (all)	6	22.7b	38.3b	29.2b	13.4b
Significance		*P*<0.10	*	*	*
l.s.d. (5%)		43.0	54.1	39.0	15.8

n = number of plots; n.s. = not significant; *$P<0.05$

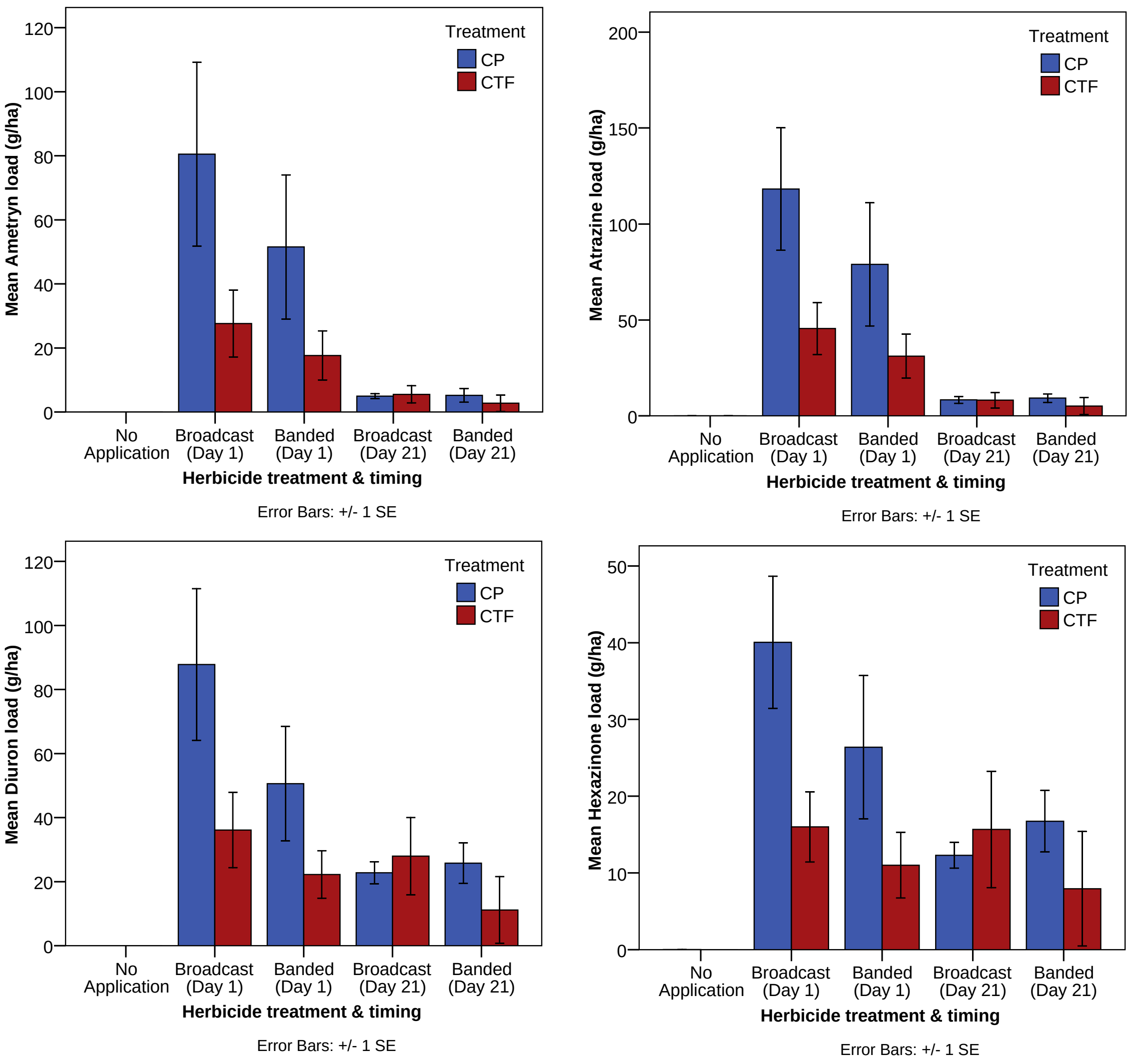

Figure 19. Herbicide loads before, 1 day and 21 days after herbicide application, from 67 mm of simulated rainfall at 100 mm/hr.

3.2.4.3 *21 days after herbicide application*

Although the differences were not significant, pooled event mean concentrations at day 21 for broadcast treatments were approximately twice those of banded treatments (Table 25; Figure 18).

Table 25. Herbicide EMC 21 days after herbicide application, from 67 mm of simulated rainfall at 100 mm/hr

Treatment	n	Ametryn (μg/L)	Atrazine (μg/L)	Diuron (μg/L)	Hexazinone (μg/L)
		21 days after application			
Broadcast (CP)	3	41.9a	69.8a	194.0a	106.2a
Broadcast (CTF)	3	50.2a	73.8a	276.5a	144.5a
Banded (CP)	2	29.1a	54.5a	151.8a	98.7a
Banded (CTF)	2	17.2a	32.6a	70.3a	49.8a
Significance		n.s.	n.s.	n.s.	n.s.
l.s.d.[A] (5%)		41.4	56.5	224.9	97.1
Broadcast (all)	6	46.1a	71.8a	235.2a	125.4a
Banded (all)	4	23.2a	43.6a	111.0a	74.2a
Significance		*P*<0.10	n.s.	n.s.	n.s.
l.s.d. (5%)		27.9	38.3	160.4	72.1

n = number of plots; n.s. = not significant
[A] l.s.d. not adjusted unequal sample size (lowest value presented)

3.2.4.4 *Herbicides in runoff over time*

Event mean concentrations for ametryn and atrazine at day 21 (Table 25) were an order of magnitude lower than at day one (Table 23), whereas diuron and hexazinone concentrations had approximately halved (Figure 18). Event mean concentrations show a good relationship (particularly for ametryn and atrazine) between cane trash herbicide concentrations on day one and day 21 (Figure 20).

Loads for all herbicides had also decreased by day 21, with ametryn and atrazine declining most (Figure 19). Unlike day one, event mean concentrations and loads from the broadcast application on CTF treatments were greater in comparison to CP treatments, although this was not significant.

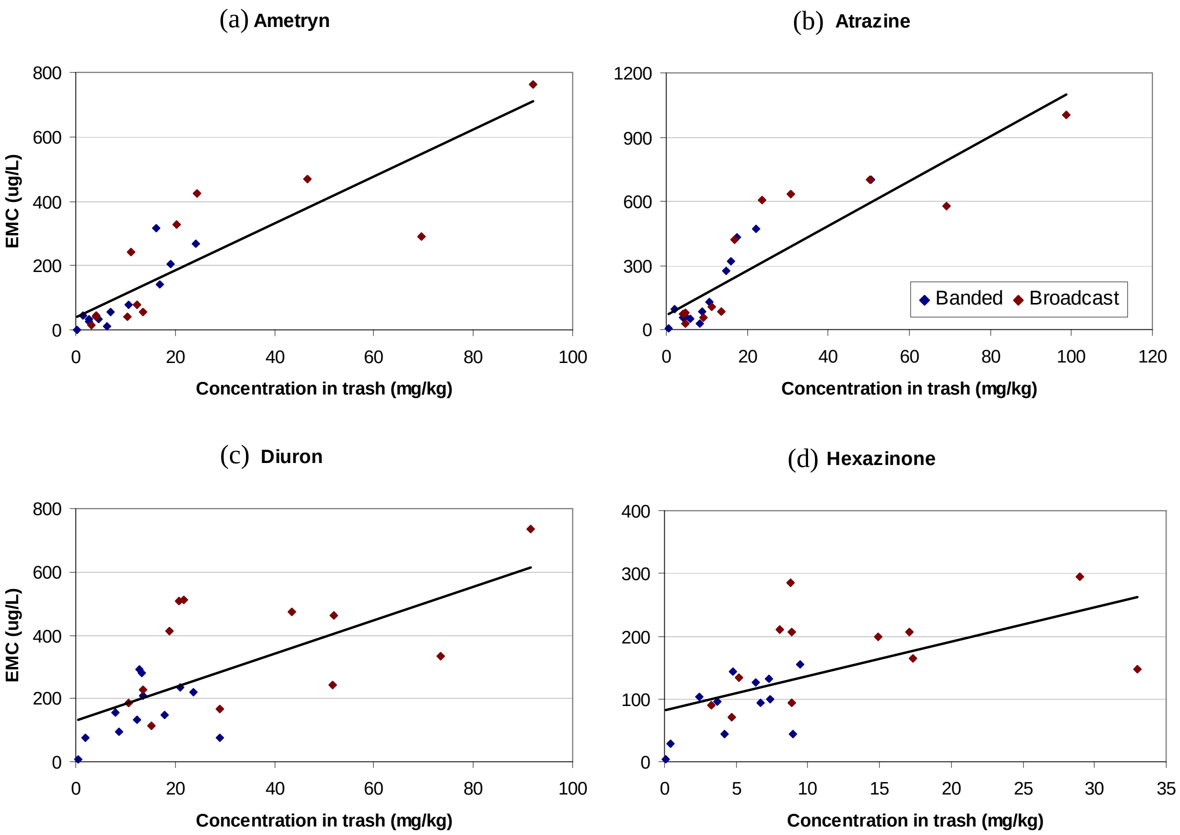

Figure 20. Relationship between herbicide concentration on cane trash (prior to simulation) and EMC for a 67 mm rainfall event.
Graphs include both day 1 and day 21 results. Regression equations for each plot are below.

Herbicide	**Regression**	**R^2**
Ametryn	y = 7.32x + 37.5	0.74
Atrazine	y = 10.42x + 69.3	0.77
Diuron	y = 5.28x + 129.4	0.45
Hexazinone	y = 5.49x + 81. 8	0.35

3.3 Paddock-scale flume trials

Runoff and water quality data were collected from five runoff events between December 2006 and March 2007 (Table 26). Runoff comparisons across treatments can be made from four of these (24, 27 and 30 January, and 21 March), and water quality comparisons between only two (27 and 30 January). The event on 10 December allowed a comparison with the day 21 plot-scale rainfall simulation data. Only TN and TP nutrient results are presented for nutrients.

3.3.1 *Runoff and sediment loss*

Total runoff from individual events from the CTF treatment averaged 30% less than from the CP treatment (Table 26) at the paddock-scale. Runoff from the CTF treatment was delayed by ~ 5 minutes compared with the CP treatment, and the peak runoff rate was ~30% lower, all contributing to reduced runoff.

On average the CTF treatment generated 50% less total sediment load than the CP treatment (65 kg/ha cf. 33 kg/ha) due to reduced runoff and lower EMC.

Table 26. Mean rainfall, runoff, and total sediment EMC and loads at the plot-scale and rainfall events sampled at the paddock-scale

Event	Date	Rainfall (mm)	Rainfall Max (mm/hr)	Treatment [C]	Runoff (mm)	Runoff Max (mm/hr)	Total sediment EMC (mg/L)	Total sediment Load (kg/ha)
Day 1 simulations (15-20/11/06)		67	100	CP	20	53	167	23
				CTF	10	26	110	13
Day 21 simulations [A] (5-9/12/06)		67	100	CP	14	39	154	23
				CTF	11	28	97	15
Day 21 simulation [B] (10/12/06)		67+	100	CTF	31	82	147	45
1	10/12/06	70.5	115	CP	No data		No samples	
				CTF	43	11	312	134
2	24/01/07	80.2	112	CP [D]	67	55	52	35
				CTF	40	30	126	50
3	27/01/07	24.5	62	CP	1.1	2.0	1112	13
				CTF	1.4	1.3	364	5.0
4	30/01/07	41.2	75	CP	30	19	175	52
				CTF	26	29	107	28
5	21/03/07	45.4	87	CP	28	32	No samples	
				CTF	21	8.8	271	57

[A] Means excludes simulation after natural rainfall event. [B] CTF simulation after natural rainfall event on the 10 December. [C] CP treatment includes dunder/broadcast application and CTF treatment includes granular/banded application. [D] One sample collected for CP treatment.

3.3.2 *Nitrogen loss in runoff*

The paddock-scale results showed higher TN event mean concentrations from dunder (CP) treatments compared to granular (CTF) treatments (Table 27). The lower runoff from the CTF treatment also led to a ~20% reduction in TN load. Over time TN showed a general decline in event mean concentration (Figure 21), which is attributed to crop N uptake of nutrients over the growing season. The granular treatment did show an initial increase in TN at day 21 most likely due to gradual break down and release of N.

Table 27. Mean rainfall, runoff, and TN and TP EMC and loads at the plot-scale and rainfall events sampled at the paddock-scale

Event	Date	Rainfall (mm)	Max (mm/hr)	Treatment [C]	TN EMC (mg N/L)	TN Load (g/ha)	TP EMC (mg P/L)	TP Load (g/ha)
Day 1 simulation (15-20/11/06)		67	100	CP	14.66	2233	0.82	125
				CTF	6.05	707	0.81	94
Day 21 simulation [A] (5-10/12/06)		67	100	CP	8.39	969	0.46	54
				CTF	7.65	1067	0.74	100
Day 21 simulation [B] (10/12/06)		67+	100	CTF	15.70	4800	0.41	127
1	10/12/06	70.5	115	CP	No samples		No samples	
				CTF	2.97	1280	0.43	430
2	24/01/07	80.2	112	CP [D]	1.79	1200	0.24	160
				CTF	2.84	1130	0.37	150
3	27/01/07	24.5	62	CP	2.54	30	0.78	9
				CTF	1.71	20	0.65	9
4	30/01/07	41.2	75	CP	1.59	470	0.36	110
				CTF	1.45	370	0.40	100
5	21/03/07	45.4	87	CP	No samples		No samples	
				CTF	1.21	260	0.24	50

[A] Means excludes simulation after natural rainfall event. [B] CTF simulation after natural rainfall event on the 10 December. [C] CP treatment includes dunder/broadcast application and CTF treatment includes granular/banded application. [D] One sample collected for CP treatment.

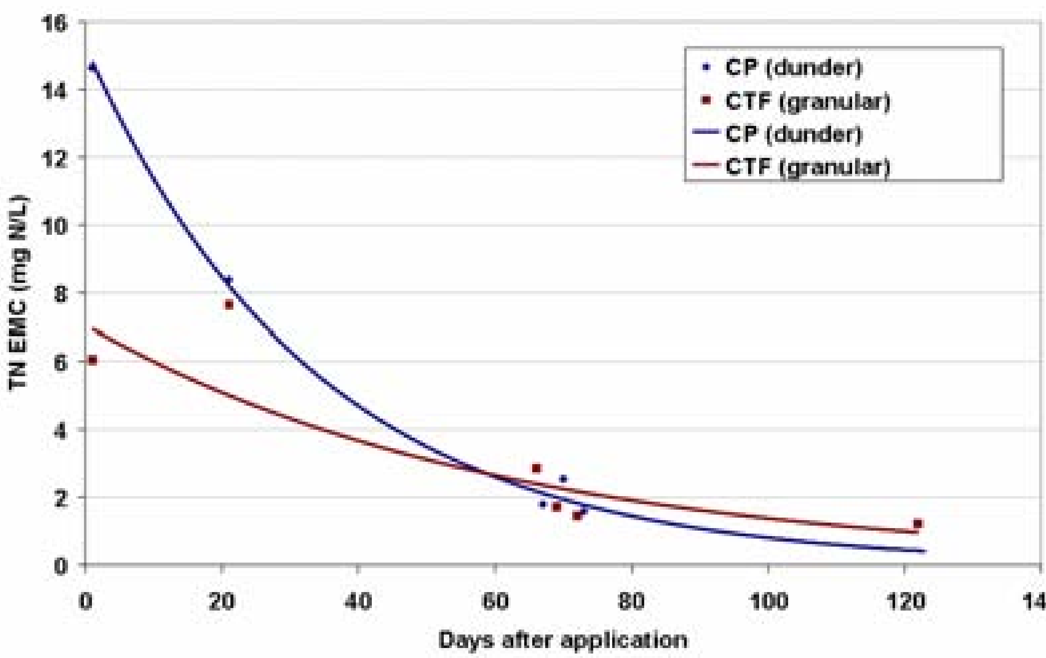

Figure 21. Relationship between Total N EMC in runoff and time after application
Note: Results from 1 and 21 days after application are from the simulator plot trials, and after that from the paddock trials.
CP (dunder) $y = 15.28e^{-0.03x}$ $R^2 = 0.97$
CTF (granular) $y = 7.07e^{-0.02x}$ $R^2 = 0.82$

3.3.3 *Phosphorus loss in runoff*

Event mean concentrations and loads of TP at the paddock-scale were similar for CP and CTF treatments (Table 27).

3.3.4 *Herbicide loss in runoff*

Event mean concentrations for all herbicides were higher from CP (broadcast) treatments than CTF (banded) treatments. Herbicide concentrations in runoff were related to the time that had elapsed between the herbicide application and the runoff event (Figure 22).

In the 10 December event herbicide EMC at the paddock-scale (15 µg ametryn/L, 44 µg atrazine/L, 107 µg diuron/L, and 59 µg hexazinone/L) were within 25-70% of the plot-scale event mean concentration from the simulation undertaken on the same day, but were within the range of values from the three plot-scale replications.

Herbicides were still detected in runoff 123 days after application (21 March 2007), despite 1140 mm of total rainfall. Ametryn (EMC 0.01 µg/L) and atrazine (EMC 0.03 µg/L) were detected at similar concentrations which were lower than the concentrations of diuron (EMC 0.10 µg/L) and hexazinone (EMC 0.09 µg/L).

3.4 Sandy Creek catchment comparison

A comparison can be made between the results of the 24 January 2007 event at the paddock and catchment scales (1080 m^2 vs. 326 km^2). Only one sample was collected for the CP treatment during the event. Therefore comparison is only made with CTF treatment results. The Sandy Creek catchment has 46% of its area in cane farming. Table 28 shows the total sediment, nutrient and herbicide event mean concentrations at these two scales. Total sediment and TN concentrations were slightly higher (18% and 12%, respectively) at the paddock scale, whereas TP was lower. Herbicide concentrations were highly variable between the paddock and catchment scale, but were generally of the same order.

Table 28. Total sediment, TN, TP and herbicide EMC at the paddock and catchment scale for the 24 January 2007 event

Parameter	Paddock scale (CTF granular/banded)	Catchment scale [A] (Sandy Creek)
Total sediment (mg/L)	126	107
TN (mg N/L)	2.84	2.53
TP (mg P/L)	0.37	0.51
Ametryn (µg/L)	0.25	0.05
Atrazine (µg/L)	0.33	1.75
Diuron (µg/L)	2.1	5.05
Hexazinone (µg/L)	1.0	1.81

[A] EMC calculated from 8 samples for total sediment, TN and TP, and 5 samples for herbicides.

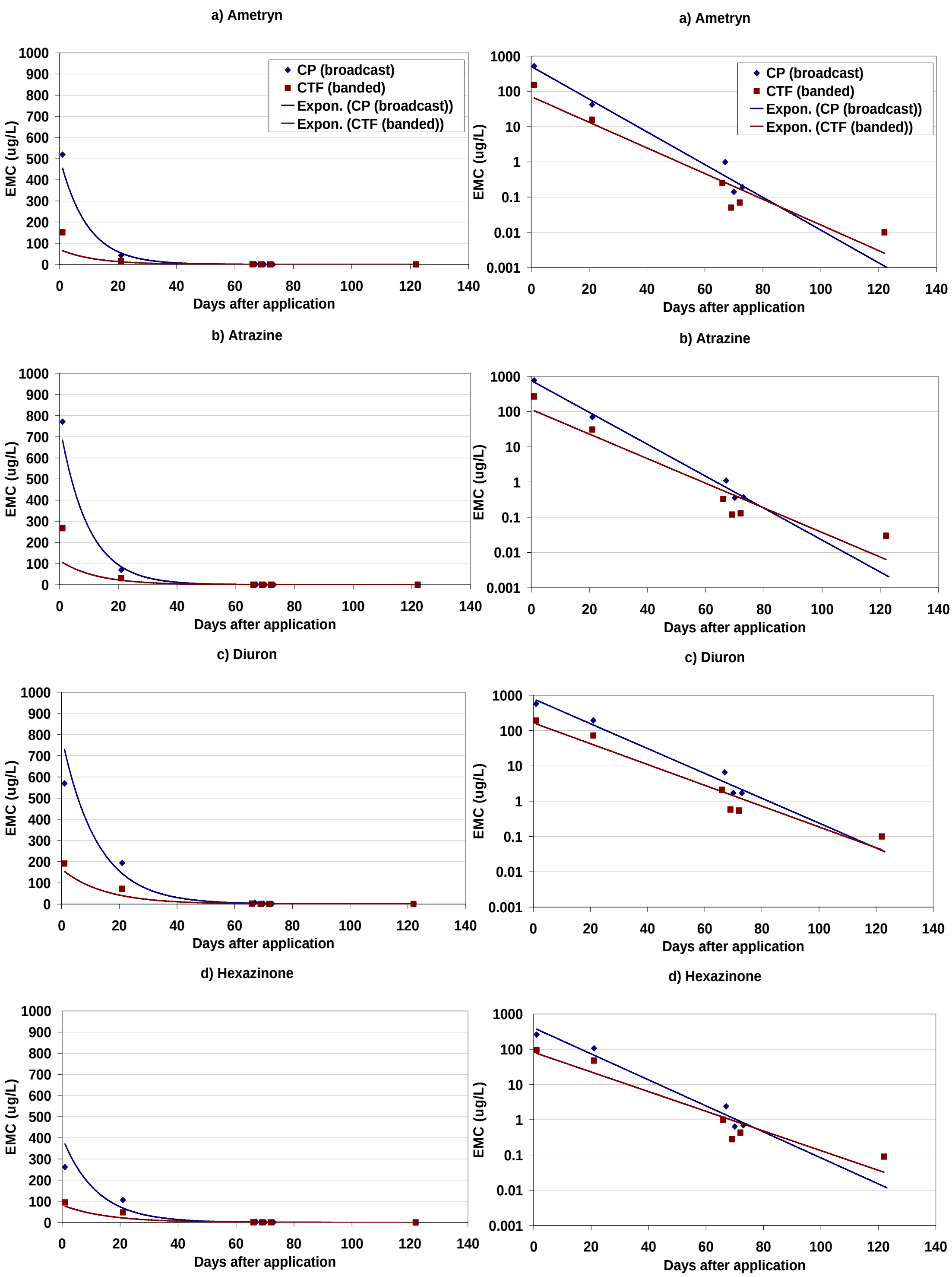

Figure 22. Relationship between herbicide EMC in runoff and time after application, plotted on a linear scale (left) and logarithmic scale (right)

Note: Results from 1 and 21 days (means) after application are from the simulator plot trials, and after that from the paddock trials. Regression equations for each plot are below.

Herbicide	CP (broadcast) Regression	CP (broadcast) R^2	CTF (banded) Regression	CTF (banded) R^2
Ametryn	$y=506.24e^{-0.11x}$	0.97	$y=70.57e^{-0.08x}$	0.92
Atrazine	$y=759.19e^{-0.10x}$	0.99	$y=114.44e^{-0.08x}$	0.90
Diuron	$y=791.95e^{-0.08x}$	0.97	$y=164.90e^{-0.07x}$	0.94
Hexazinone	$y=404.23e^{-0.08x}$	0.97	$y=81.93e^{-0.06x}$	0.91

4 DISCUSSION

The plot-scale rainfall simulation trails in this study represent the scenario of the first substantial rainfall runoff event occurring prior to, 1 day after or 21 days after the application of fertilisers and herbicides. These provide information on the differences in runoff from the treatments applied. The paddock-scale trials also monitored the first natural runoff event at 21 days after application (on CTF granular treatment) as well as selected consecutive runoff events throughout the wet season. These illustrate the decline in nutrients and herbicides in runoff over time.

4.1 Effect of wheel traffic on runoff

The most significant finding is that controlled traffic farming (CTF) treatments reduced total runoff compared to current practice (CP) and conventional cultivation (CC). This consequently reduced sediment, nutrient and herbicide loads in runoff. The difference in runoff between CP and CTF is not as large on wetter soils (such as throughout the wet season) compared to the dry soils in the rainfall simulation study, however a difference would be maintained. Runoff averaged 43% less from CTF treatments compared to CP treatments for rainfall simulations on dry soil, to 30% less on wetter soils in rainfall simulations (from the plots that received natural rainfall the night before simulation) and paddock-scale monitoring. This is to be expected as runoff is affected by soil water deficit (Sallaway *et al.* 1990).

Tullberg *et al.* (2001) also demonstrated that wheeling (uncontrolled traffic) on heavy clay soil with broadacre grain produced a large and consistent increase in runoff compared with non-wheeling. Results were similar to this study with wheeled plots producing 44% greater mean annual runoff than controlled traffic plots. Treatment effects were also greater on dry soil, but were maintained in large and intense rainfall events on wet soil (Tullberg *et al.* 2001).

CTF treatments also reduced peak runoff rate, which is considered a major predictor of soil erosion from rainstorms (Williams 1975; Onstad and Foster, 1975). Ground cover is a dominant factor in affecting peak runoff rate (Sallaway *et al.* 1990), due to the effect of cover on infiltration rates. This may explain why CC treatments (<2% cover) had the highest peak runoff rate compared to CP (35% less runoff rate) and CTF (65% less runoff rate) treatments. The difference in CP and CTF treatments, both with 90-100% groundcover, is likely attributed to the reduction in compaction of CTF treatments. Like total runoff, the decrease in soil moisture deficit through the season decreased the difference in peak runoff rate between CP and CTF treatments (45% to 36%).

The difference in start time to runoff for CTF treatments compared with CP treatments was not great enough to determine a significant difference at plot-scale. However the observation of delayed start times for CTF treatments at a paddock-scale are consistent with reduced compaction and improved infiltration. Silburn and Glanville (2002) showed increasing ground cover significantly increased the amount of time required to cause runoff under a 95 mm/hr rain storm on cotton furrows on a black Vertosol. This was also shown to be more effective in delaying start times on cotton furrows that have not received wheel traffic.

4.2 Factors affecting total sediment in runoff

Total sediment event mean concentrations for CP treatments (121 mg/L) and CTF treatments (126 mg/L) were not significantly different. This was expected as the main factors controlling sediment erosion are tillage and ground cover (Connolly *et al.* 1997; Prove *et al.* 1995; Silburn and Glanville 2002). In the context of agricultural erosion, these are quite low concentrations, as would be expected with 100% cover. The decrease in total runoff from reduced compaction of CTF treatments resulted in the significant reduction in total sediment load (44% plot scale, 50% paddock scale) compared with CP treatments. Rainfall simulation studies on loam soils have also demonstrated permanent controlled traffic wheeltracks produce more than twice the runoff and soil loss of non-wheeled areas (Young and Voorhees 1982).

Prove *et al.* (1991) measured annual erosion rates for conventional cultivation in the range of 47-505 t/ha, with an average of 148 t/ha in steep sugarcane land (5-18% slope) in the South Johnstone area. This was reduced by 90% to <15 t/ha on no-till green cane harvest practice. Similar reductions (97%) were measured from conventional cultivation (760 kg/ha) to CP treatments (no-till green cane harvest) (21 kg/ha) with minimal slope (0.25%) in this study. The absolute amounts are much lower due to the low slope of the study field.

Total sediment concentrations were higher from the paddock-scale natural rainfall event (roughly equivalent to rainfall simulations) on 10 December 2006 (312 mg/L) than the plot-scale (169 mg/L). Observations of the composite sample suggested that the high sediment result was not from sediment alone, but also fine particulate organic matter (Figure 23). No rilling was observed from this runoff event, but the increased erosive power at the paddock-scale (maximum discharge of 7 L/s for the paddock compared to 0.3 L/s for the plot-scale) may have led to erosion of the decomposing trash blanket.

Figure 23. The composite sample from the 10 December 2006 runoff event showing the stained runoff water from organic material

Total sediment concentrations at the catchment scale at Sandy Creek on 27 January 2007 event were slightly lower than at the paddock scale. However, both concentrations are very low compared to runoff from fields with low cover. Although a variety of other land uses also come into effect at the catchment scale, the tendency for sediment concentrations to decrease with increasing scale has also been measured in sugarcane catchments in Mauritius as a result of deposition (Ng Kee Kwong *et al.* 2002) and presumably dilution.

4.3 Factors affecting nutrients in runoff

4.3.1 *Nitrogen concentrations and loads in runoff*

Total N loads from dunder and granular applications were similar at the plot-scale, which was expected as both fertilisers were applied at the same rate (160 kg N/ha). However the fractionation of nitrogen in runoff was substantially different between fertiliser treatments and day of rainfall after application.

The greatest impact on loss of nitrogen at day one was the row/bed/traffic treatment, with reduced runoff from CTF treatments reducing loads for all species of nitrogen. Therefore substantial reductions in overall nitrogen loss in runoff shortly after application can be made by CTF practices alone, without a reduction in fertiliser rate. If CTF practices are adopted and current recommended rates for N refined this will see even further reductions in potential losses of N.

Large variations in TN and ammonia even mean concentrations from dunder treatments on day one most likely reflect the variation in Liquid One Shot urea/dunder truck mixes for each application. This is an important consideration, as more focus is being placed on N fertiliser management the ability to budget for N input rates is limited by inconsistent urea/dunder mixes. This process should be refined to deliver a product with a more consistent percentage of nitrogen.

Disproportionately high losses of ammonia and potentially DON from dunder applications at day one are of concern. Event meant concentrations were reduced by 3.5 times if applied on CTF treatments, presumably as a result of a larger watershed of the 2 m bed and improved infiltration capacity. However, this did not seem to play a role in reducing nitrate and DIN concentrations. Ammonia concentrations and loads were substantially lower in day 21 runoff. This reduction in runoff is a result of reduction in ammonia present on cane trash and soil from losses through volatilisation (due to surface application), nitrification, and plant uptake. Avoiding application within the onset of significant rainfall within at least three weeks will reduce the risk of ammonia loss in runoff by 44% on CP treatments and 29% on CTF treatments. Irrigation or rainfall of less than 25 mm (no runoff) after dunder application may be beneficial, as watering urea with irrigation or applying before rainfall has been found to promote early entry into soil and rapid uptake by roots (Reghenzani and Armour 2002). Caution should be exercised on fields in close proximity to waterways where dunder is applied.

Nitrate and DIN event mean concentrations were relatively similar for all treatments at day one. However, the loads however were much higher from granular (1 kg N/ha DIN) compared with dunder (0.7 kg N/L DIN) applications on CP treatments. This is likely a result of higher total runoff for granular treatments (17.2 mm) compared with dunder treatments (11.1 mm). At day 21 nitrate and DIN loads were higher for granular treatments, which would be a result of the breakdown and release from fertiliser granules. However nitrate soil concentrations of nitrate-N for dunder and granular treatments were similar. Elevated concentrations of ammonia were present in surface soils for granular treatments at day 21, which may have contributed to nitrate concentrations through nitrification during runoff. It should be noted that there were only two replicates of the granular treatments after the exclusion of plots which received that natural rainfall event on 10 December 2006. This may have reduced the ability to detect a significant difference in loads at day 21 unlike day one.

Nitrate concentrations in soils increased from day 1 to day 21 for both granular and dunder treatments, reflecting the release from of the granular fertiliser and transport of liquid dunder from the trash blanket into surface soils. Interestingly, concentrations of ammonia in surface soils (0-10 cm) for granular treatments on day 21 were markedly higher than soil concentrations for all other treatments. However, this was not reflected in ammonia runoff. This may suggest that sub-surface granular applications are less likely to lose ammonia in runoff compared to surface applications of dunder.

Total N event mean concentrations were 2.6 times higher at the plot-scale than at the paddock scale in the natural rainfall event monitored on the 10 December 2006 (7.7 mg/L cf. 3.0 mg/L). This difference maybe due to a combination of sampling times and/or the difference in runoff scale. Runoff began after 45 mm of rain at the paddock scale compared to 10 mm at the plot scale. There was also 16 mm of runoff occurring before the first sample was collected in the flume compared to 3.2 mm under rainfall simulation. Peak runoff at the paddock scale was 11 mm/hr compared to 88 mm/hr at the plot scale.

4.3.2 *Phosphorus concentrations and loads in runoff*

High levels of TP and FRP were detected in runoff prior to the application of fertilisers, although rainfall simulator source water levels of P were low. Phosphorus levels in soils before fertiliser application (54 mg/kg; Table 8) were high in comparison to post application. Sugarcane soils often have substantial soil reserves of P as a result of fertiliser and mill mud inputs over previous seasons (Simpson *et al.* 2001a). Unlike forms of N, the loss of P from soils depends on the degree of sorption to soil and organic particles, as a result reducing P application rates only slowly changes total soil reserves and export rates (Reghenzani and Armour 2002). It is therefore likely that the region's cane growing soils have P levels above requirements (Rolfe *et al.* 2007). This suggests the soil and the application of mill mud (at planting in 2002 and possibly applications previously) may have contributed to elevated P levels in runoff prior to fertiliser application for this study.

Rainfall one day after fertiliser application at the plot-scale produced event mean concentrations above those reported for baseline conditions (no treatment), although both fertilisers advertised no substantial amounts of P. The greatest loss of TP was from granular application on CP treatments. For all treatments on day one, TP consisted primarily of FRP (~72%) with lesser amounts of PP and DOP.

The greatest impact on P load at day one was the reduced runoff from CTF treatments which reduced loads for all species of P. Therefore substantial reductions in overall phosphorus loss in runoff shortly after application can be made by CTF practices alone, without a reduction in fertiliser rate. This is particularly beneficial in reducing P loss in runoff in this case, when it is not the intention to add P to the crop.

Total P and FRP event mean concentrations declined by day 21 for dunder applications however granular applications maintained levels similar to those recorded for dunder at day one. It is likely that this is a result of higher P concentrations in Nitra King S compared with Liquid One Shot.

Similar to N, loads of P species at day 21 did not differ significantly for treatments as they did for some at day one. This again may be a result of the exclusion of two banded treatments (CP and CTF) because of the rainfall experienced on the last day, which consequently reduced replicates and confidence in statistical analysis.

Total P event mean concentrations were higher at the plot-scale (0.74 mg P/L) than at the paddock-scale (0.43 mg P/L) in the natural rainfall event monitored on the 10 December 2006. Despite this, the TP event mean concentration from the single rainfall simulation trial undertaken on the same plot and day as this runoff event was similar (0.41 mg P/L). The main difference in plot and paddock-scales in this event was the high proportion of FRP at the plot-scale compared to PP at the paddock-scale. This is likely due to increases in total sediment at the paddock scale.

4.4 Factors affecting herbicides in runoff

4.4.1 *Herbicide concentrations in runoff*

As expected these rainfall simulation studies showed that reducing the amount of herbicide applied by banding reduced the amount of herbicide available to runoff. Interestingly the 10% difference in coverage between banded CTF treatments and CP treatments was not detectable (significant). This could suggest large application differences are needed to detect a difference in herbicide amount in runoff, or more replicates are required to enable detection of differences.

Differences in event mean concentrations between banded and broadcast treatments were evident at day 21, but the differences were not significant (with the exception of ametryn, $P<0.1$). Herbicide runoff results from this study were highly variable and with the exclusion of two banded applications on CP and CTF treatments because of the rainfall experienced on the last day, this consequently reduced replicates and confidence in statistical analysis.

CTF treatments may also play a role in reducing herbicide event mean concentrations in runoff. Although differences are not significant this was observed between CP and CTF results with broadcast herbicide application on day one. This could be a result of delayed time to runoff and higher infiltration for CTF treatments which would result in more herbicide transported deeper into the soil profile beneath the zone available for runoff.

In other work, avoiding wheel traffic gave 20-30% lower concentrations in runoff (ground cover 1-52%) for Endosulfan sulphate, Trifluralin and Prometryn in black Vertosol under rainfall simulation (Silburn *et al.* 2002). It is therefore a possibility that controlling traffic may also provide a role in reducing herbicide concentrations in runoff and may warrant further investigation. If so it is likely to provide more impact on drier soils.

Silburn and Kennedy (2007) simplified a quantitative framework by Silburn (2003) (inspired by Leonard *et al.* 1979) for understanding the transport of herbicides from a range of studies, including rainfall simulators and catchments. This can apply to the runoff of herbicides from the cane trash layer in this study. There are three concepts to the framework (adapted from Silburn and Kennedy 2007):

1) Herbicides in runoff are extracted from the trash blanket (and from a shallow soil depth usually 0-25 mm or 0-10 mm).

2) The concentration on the trash (and in soil surface layer) is a function of application rate, initial loss and dissipation rate (half-life). Concentrations of herbicides on trash and soil can vary by several orders of magnitude after application, resulting in variation in runoff concentrations.
3) A large proportion of the variation in herbicide runoff is related to the concentration in the cane trash and soil surface at the time of the rainfall event (Figure 20 for cane trash).

The simplified framework above predominately explains herbicides that are transported in the water (dissolved) phase. To further understand the transport of herbicides that are sorbed to particulate matter it is also important to consider sediment load (Silburn and Kennedy 2007; Wauchope and Leonard 1980) which was not considered in this study, as it focused on herbicides in the filtrate.

4.4.2 *Herbicide loads in runoff*

Applications of both herbicide treatments on CTF treatments reduced the runoff load compared to those on CP treatments at day one. This is result of the reduced runoff from CTF treatments and therefore the amount of dissolved herbicides transported in the runoff. Therefore CTF treatments combined with the reduced rate of herbicide application of banded treatments provided the greatest reduction in load at day one and at the paddock scale. Day 21 results still did not provide clear differences like day one. As explained above, this may due to the exclusion of two banded treatments (CP and CTF) as a result of the natural event experienced on the last day. This consequently led to fewer replicates reducing the power of the experiment to detect significant differences.

4.4.3 *Time of rainfall after application*

The greatest amount of herbicide lost in runoff was from rainfall one day after application. The percentage loss of herbicide applied was greatest from broadcast applications on the CP treatment with 10% (hexazinone), 8% (atrazine), 5% (ametryn) and 3% (diuron). This compared to 6% (hexazinone), 4% (atrazine) and 2% (ametryn) 3% (diuron) for banded applications on CTF treatments. Wauchope (1978) reported that single-event runoff losses in the range of 1-2% are not uncommon, however losses greater than this are a result of extreme conditions. Events with losses of >2% were termed *catastrophic*. These are usually the result of small plot simulation studies, such as this, but can be on larger fields under natural conditions; generally being the first event to occur after application (Wauchope 1978). Although the probability of such losses is lower on a catchment scale the validity of plot-scale simulations give realistic results (Wauchope 1978).

Wauchope (1978) defines rainfall events within an approximate two week period of application as *critical*. This is when a majority of losses of herbicide residues occur. Timing chemical applications in relation to the prediction of high rainfall within a three week time frame can be difficult and therefore losses measured under rainfall simulation at day 21 are more likely to reflect typical field situations. Wauchope (1978) also notes that simulation losses can over-predict long term losses by a factor of two. However, Silburn (2003) would argue that losses from rainfall simulations plots and fields can be generally shown to be consistent, once such factors as storm duration, time after application, differences in sediment loads and deposition are taken into account.

4.4.3.1 *Herbicide half-life*

The use of herbicide half-lives in soil for the estimation of herbicide residues available for runoff as a function of time after application is complicated (Wauchope 1978). Various processes are not always accounted for, such as the herbicide availability and breakdown (volatilisation and photodegradation) on the surface of foliage and ground cover residues (Wauchope 1978). Therefore "half-lives" based on concentration decline in runoff over time can give more realistic values, as they incorporate all sources of herbicide. These can be referred to as "runoff-available-herbicide" half-lives. Based on the regression equations of Figure 22, the half-lives of herbicides in runoff for the CP treatments with broadcast application are 6 days for ametryn and atrazine, and 8 days for diuron and hexazinone. The half-lives from the CTF treatments with banded application was 2-3 days longer than the CP broadcast treatment for each herbicide. Although the runoff-available-herbicide half-lives of herbicides increased under CTF banded practice the initial concentrations are less than half those of CP broadcast treatments, thus reducing the potential of herbicide runoff if rain is received in first few weeks after application.

Studies reported by Wauchope (1978) for runoff-available-herbicide half-lives for atrazine were 7-10 days, slightly longer than the 6 days calculated in our study, and much shorter than half-lives in soil reported in the literature (Table 4). Silburn (2003) determined half-life in soil (0-2.5 cm) for diuron as 20 days for black Vertosols, which was also longer than half-life reported for diuron in this study. This has been reported to increase to >250 days for red Ferrosols (Krasnozem) (Isbell 1996) near Bundaberg (Simpson *et al.* 2001b). Field dissipation rates for herbicides in other soil types in Bundaberg studied by Simpson *et al*. (2001b) showed quite rapid half-lives for ametryn, atrazine and diuron (Table 29), which are normally considered relatively persistent. However, dissipation half-lives from studies in Mauritius were longer than these.

Table 29. Soil dissipation rates (DT_{50}) for ametryn, atrazine and diuron in Bundaberg soils (0-2.5 cm) (Simpson *et al.* 2001b), Mauritius (Umrit *et al.* 2001) and runoff-available-herbicide half-lives for brown Chromosols of Mackay (this study).

Soil	pH	OC (%)	Clay (%)	Half-life Atrazine	Ametryn	Diuron	Hexazinone
Bundaberg					*(DT_{50} days)*		
Grey Kandosol	7.2	0.80	3	3 - 13	3.5	13	-
Redoxic Hydrosol	7.1	0.72	8	2.5 - 27.5	2	15.5	-
Red Ferrosol	6.0	1.23	63	1 - 7	14.5	>250	-
Yellow Chromosol	5.1	0.95	6	2.5	4	-	-
Mauritius	-	-	-	10-12	-	14-19	17-29
Mackay					*(Runoff, days)*		
Brown Chromosol	6.0	1.4	17	6-9	6-9	8-11	8-11

The understanding of herbicide loss in catastrophic and critical events, or the 'risk window' (Simpson *et al.* 2001b), and persistence in the system (half-life) provide important knowledge for herbicide management including product selection and timing of applications. Avoiding application within at least three weeks of heavy rainfall will reduce the risk of herbicide loss in runoff by an order magnitude for ametryn and atrazine, and by approximately half for diuron and hexazinone.

4.4.4 *Paddock and catchment scales*

The runoff event on 24 January 2007 (measured on CTF treatment at the paddock and catchment scale) was 66 days after the application of herbicides at the paddock scale, and herbicide concentrations in runoff were approximately 1% of the concentrations one day after application. Herbicide concentrations were highly variable (though of the same order) between the paddock and catchment scale. Concentrations at the catchment scale were smaller for some herbicides and greater for others. This highlights the widespread use of these herbicides across the catchment, the variable timing of these applications and the variable source area within the catchment. At a catchment scale the herbicide application times can vary substantially depending on the stage in the crop cycle individual paddocks within each farm. Velpar (K4) (diuron and hexazinone) is used on pre-plant, post-plant pre-emergence, and pre- out-of-hand (when cane is too tall to pass with machinary), and also in all stages of ratoon (immediate post-harvest, ratoon post emergence and ratoon out-of-hand) (Appendix 8.5). Gesapax Combi (atrazine and ametryn) (or other products with these active ingredients) are used on post-plant pre-emergence, spiking plant cane, and plant to 3-leaf, and also on ratoons (post-emergence and out-of-hand). Therefore the window of application for these products is across a broad range of crop growth stages, increasing the window of risk to runoff and the likelihood in any given event there will be high concentrations at the catchment scale.

4.5 Moving from current practice to controlled traffic farming

An important principle of controlled traffic farming is no or minimum till. Because the bed soil structure is not compacted by traffic there in no need for deep cultivations before planting. Under current practice ratoons are replanted every 3-4 years, which can involve conventional cultivation. Therefore each year there is still approximately 10% of the cane farm still under fallow or conventional cultivation (W Higham 2006, pers. comm.). A shift to CTF would reduce this percentage by maintaining permanent beds. However in the transition the initial establishment of permanent beds will require deep cultivation to remove the compaction of current practice beds. This will increase the risk to elevated total sediment concentrations and associated nutrients in runoff during the transition period throughout the catchment. This is an important consideration that would need to be included in management and planning.

With the reduction in runoff from CTF treatments the improved infiltration capacity could pose an increased risk to the drainage below the root zone of highly soluble forms of N, such as nitrate, and herbicides with high solubilities and low soil sorption (K_{oc}), such as atrazine. In sugarcane paddocks (Ferrosols) of the wet tropics nitrate leaching below the crop root-zone is a major pathway for N loss (Rasiah and Armour 2001). Baskaran *et al.* (2002) also found high levels of nitrates in groundwater associated with cane lands in the Pioneer Valley (Mackay region), as did this study (Table 5). This would also be an important factor to incorporate in management plans involving a shift to controlled traffic farming.

5 CONCLUSIONS

Controlled traffic farming practice, with no till green harvest on 2 m wide beds and dual row sugarcane (0.8 m apart) had significantly less runoff (43%) and lower peak runoff rates (46%) than current practice with uncontrolled traffic on no till green harvest 1.5 m beds and single row sugarcane, when 67 mm of simulated rainfall was applied at 100 mm/hr (1 in 10 year average recurrence interval storm) at the plot-scale. This was also maintained in natural rainfall events on the paddock-scale during the wet season, although differences were smaller (30% less runoff for CTF).

Lower runoff was achieved on CTF treatments as they were less compacted compared to CP treatments, therefore improving infiltration. CP treatments had higher bulk densities on the mid-section of the bed compared to CTF treatments. This was a result of compaction from the straddling effect of uncontrolled traffic and non-matching axle widths of harvester/haulout machinery. This increased runoff and resulted in higher losses of associated total sediment, nutrients and herbicides.

Total sediment loads were reduced by 44% on CTF treatments compared to CP treatments. However total sediment losses from both these treatments were negligible compared to conventional cultivation replant treatments. This treatment produced the highest sediment event mean concentration and load, which was 46 times that measured from CP and CTF treatments. This was a result of low ground cover.

Total nitrogen loads from surface applications of dunder (Liquid One Shot) and sub-surface applications of granular (Nitra King S) fertiliser were similar, as both were applied at the same rate (160 kg N/ha). Granular applications had greater loads of nitrate at day 1 and day 21 than dunder, with losses being reduced on CTF treatments compared to CP treatments. However, dunder applications had greater amounts of ammonia, especially at day one, compared to granular treatments. This loss was greatest on CP treatments. Loads declined considerably by day 21, highlighting the greatest risk to loss of ammonia, as well as total nitrogen and nitrates, in runoff in the first three weeks after application.

Careful consideration and planning should be made on placement (with respect to waterways) and timing (with respect to significant rainfall) of surface applications of dunder. It is likely that sub-surface applications of dunder would reduce this loss. Avoiding dunder application within the onset of significant rainfall within at least three weeks will reduce the risk of ammonia loss in runoff by 44% on CP treatments and 29% on CTF treatments.

The urea/dunder mixing process for Liquid One Shot production needs to be refined to improve consistency in N content and therefore application rates.

Losses of P, in particular FRP in runoff were evident at days 1 and 21 for both fertilisers. Highest loads were from granular application on CP treatments at day one. CTF treatments effectively reduced runoff loads for all species of P, especially for day one. Losses of P were also observed prior to the application of fertilisers suggesting soils were elevated in P reserves from prior mill mud applications.

Rainfall one day after the broadcast applications of ametryn, atrazine, diuron and hexazinone on CP treatments produced the highest herbicide event mean concentrations and loads. The highest risk to herbicide loss in runoff was within a few weeks after application with percentage losses for all herbicides >2% in runoff one day after application. Avoiding application within at least three weeks of heavy rainfall will reduce the risk of herbicide loss in runoff by an order magnitude for ametryn and atrazine, and by approximately half for diuron and hexazinone.

Event mean concentrations from all herbicides applied by broadcast were more than double those for banded applications in runoff one day after rainfall. Further reductions were made in runoff loads from applications on CTF treatments compared with CP treatments. "Runoff-available-herbicide" half-lives calculated from event mean concentrations were 6-9 days for ametryn and atrazine and 8-11 days for diuron and hexazinone. Herbicides were detected in runoff at the paddock scale up to 123 days after application.

There were strong relationships between herbicide load on the trash and event mean concentration in runoff, for all four herbicides. This, and the strong relationships between event mean concentration and time after application, suggests that relatively simple models for herbicide runoff could be derived for cane trash blanket systems.

In summary, the recommended best practice for management of water quality in cane farming is no-till green harvested controlled traffic farming, with fertilisers and herbicides applied as early as possible before the onset of the wet season. Residual herbicides should be banded on centres of beds only and fertilisers applied sub-surface.

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6 GLOSSARY

Ammonia	The term 'ammonia' commonly refers to two chemical species of ammonia that are in equilibrium in water: the un-ionised ammonia (NH_3) and the ammonium ion (NH_4^+). Commonly expressed as total ammonia (the sum of NH_3 and NH_4^+)
DIN	Dissolved inorganic nitrogen is the sum of nitrate + nitrite + total ammonia. It is completely bioavailable form for phytoplankton uptake.
DON	Dissolved organic nitrogen refers to the organic nitrogen fraction that can pass through a 0.45µm filter.
EMC	Event mean concentration is the flow weighted mean concentration (total load/total flow) recorded during runoff event.
FRP	Filterable reactive phosphorus is commonly measured by passing through a 0.45 µm filter and colorimetry. It is used as an indication of bioavailable P.
Load	Total mass carried in runoff or stream flow.
Nitrate	A form of bioavailable nitrogen, namely NO_3^-.
Nitrite	A form of bioavailable nitrogen, namely NO_2^-.
NO_x	Oxidised nitrogen equating to total of nitrate + nitrite.
PN	Particulate nitrogen commonly refers to N that does not pass through a 0.45 µm filter. PN is composed of both organic matter and inorganic material. The organic PN is bioavailable in the long term. In contrast, DIN in the environment is quickly assimilated to organic N under favourable conditions.
DOP	Dissolved organic phosphorus refers to the organic phosphorus fraction that can pass through a 0.45µm filter.
PP	Particulate phosphorus commonly refers to P that does not pass through a 0.45 µm filter. PP is composed of both organic matter and inorganic material. The organic PP is bioavailable in the long term.
TSS	Total suspended sediment is unconsolidated particulate material in the water column.
TN	Total nitrogen refers to the sum of all forms of N, particulate and dissolved.
TP	Total phosphorus refers to the sum all forms of P, particulate and dissolved.

7 APPENDICES

7.1 Trial site (lines represent CP and CTF boundaries, dashed lines mark irrigation paths)

7.2 Selected soil properties averaged across the site (4 profiles)

Depth (cm)	pH (H_20 1:5)	CEC[A] (meq/100g)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)
0 - 10	6.0	6.5	14	51	18	17
20 - 30	6.0	6.2	13	50	21	18
30 - 40	6.1	11.9	12	36	16	38
50 - 60	6.6	15.7	10	36	15	41
80 - 90	7.2	14.8	7	42	17	35
110 - 120	7.3	17.3	9	49	15	30
140 - 150	7.6	n.a.	n.a.	n.a.	n.a.	n.a.

Depth (cm)	Ammonia (mg/kg), NH_4-N (KCl)	Nitrate (mg/kg), NO_3-N (KCl)	Phosphorus (mg/kg), P bicarb Colwell	Cl^- (mg/kg)	EC (dS/m)
0 - 10	8	7	45	75	0.10
20 - 30	1	5	14	47	0.05
30 - 40	<1	6	4	183	0.11
50 - 60	<1	4	2	243	0.20
80 - 90	<1	4	2	247	0.25
110 - 120	<1	5	2	233	0.20
140 - 150	<1	4	1	232	0.20

n.a. = not available
[A] CEC values estimated from sum of cations
[B] P bicarb is an approximation of bio-available P

7.3 Fertiliser Applications

CP (granular) **CTF (granular)**

"Split stool" sub-surface application of granular Nitra King S. Note the inconsistency on cover. This is not a product of CP or CTF treatment, rather it is from blockages of trash in the disk, which can create drag and expose the top of the bed. All simulations were conducted on areas that had approximately 90-100% cover (i.e. undisturbed by operations)

CP (granular) **CTF (granular)**

CP (granular) **CTF (granular)**

CP (dunder) **CTF (dunder)**

Surface application of "Liquid one-shot" Dunder. Note, unlike granular treatments, only one 'strip' of dunder is applied to the CTF treatments (2 m) however the rate/ha is the same as the CP treatment (1.5 m).

7.4 Herbicide Applications

CTF **CTF**

7.5 MAPS weed control fact sheet

WEED CONTROL OPTIONS WHEN TIME IS LIMITED

	Pre plant	Post Plant Pre sugarcane emergence	Spiking Plantcane	Plant to 3-4 leaf	Stooling	Cane Establishment	Pre Out-of-hand
Key Crop Growth Stages							
cost of NOT spraying	increased seed bank, loss of soil moisture		weed competition prior to this losses of up to $600/ha		further $350/ha losses if no control		further $800/ha losses at this stage
Cultivation		← Cultivation difficult & time consuming - not recommended to rely on cultivation alone for weed control →					
Herbicide Strategy	Knockdown	Pre-Emergent + Knockdown Knockdown for nutgrass					Pre-Emergent + Knockdown
Timing of Herbicide	Weed flush prior to plant	Apply pre-emergent as soon as practical			Monitor Cane Growth, Check Weed Control		Time application to maximise length of vine control
Target Weeds	Nut Grass, Annual and perennial Grasses & Broadleaf						Vines, grasses & broadleaf weeds
Herbicide Application	Broadcast spray	Boom spray			Directed spray		
Product Options Application Window	Paraquat, Sprayseed or Glyphosate	Flame + paraquat - UV stable, check soil types Gesapax combi - Apply to moist soil, directed spray after spike stage ← Balance + paraquat - UV stable, check soil types → ← Stomp + Atrazine + paraquat - Incorporate within 7 days → ← Trifluralin + Atrazine + paraquat - Rapid incorporation required → ← Dual Gold + paraquat - Apply to moist soil, requires irrigation or rainfall within 24hrs → ← Paraquat → Sempra, Actril DS, Baton (Nut Grass control/suppression)(consider 2,4-D sensitive varieties)			**The length of these bars indicates the registered application window, not the length of preemergent control given**		Velpar K4 Comanche Atrazine & Diuron Balance & Diuron

SALVAGE OPTIONS ARE UNECONOMICAL AND SHOULD BE AVOIDED

Ratoon herbicide options

	Ratoon immediate post harvest	Ratoon post emergence	Ratoon out-of-hand
Herbicide Strategy	pre-emergent	knockdown and/or pre-emergent	knockdown and/or pre-emergent
Target Weeds	grass and broadleaf	grass and broadleaf and vines	grass and broadleaf and vines
Herbicide Application	boom spray	directed spray	directed spray
Product Options Application Window	Velpar K4 Comanche Balance & mixtures Flame & mixtures	Velpar K4 Comanche Balance & mixtures Flame & mixtures paraquat 24-D gesapax combi atrazine/diurion	

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