Agriculture, Ecosystems and Environment 180 (2013) 21–28

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Runoff water quality from dryland cropping on Vertisols in Central Queensland, Australia

T. Murphy[a,*], C. Dougall[a], P. Burger[a], C. Carroll[b]

[a] Resource Assessment and Information Unit, Department of Environment and Resource Management, PO Box 19, Emerald, Qld 4720, Australia
[b] Reef Science, Department of Environment and Resource Management, 209 Bolsover St, Rockhampton, Qld 4700, Australia

ARTICLE INFO

Article history:
Received 19 February 2011
Received in revised form 10 June 2011
Accepted 30 July 2011
Available online 6 October 2011

Keywords:
Great Barrier Reef
Vertisol
Water quality
Metolachlor
Nutrients
Sediment
Cropping

ABSTRACT

The effects of agricultural practices on runoff water quality are a major concern worldwide, particularly where there is the potential to cause harm to aquatic ecosystems receiving the runoff. Cropping land has been identified as a major source of pollutants in the Fitzroy Basin, the largest catchment discharging into the Great Barrier Reef (GBR) lagoon. However, knowledge of pollutant generation rates in runoff from the dryland cropping (grains) industry's best management practices (BMPs) on Vertisol soils is limited, partly due to the scarce distribution of these soils worldwide. During a 9 year study sediment movement in runoff from grains dryland cropping was measured at the outlet of 2 contour bays where the distance between contour banks, referred to as the slope length, was standard (single) (180 m) and triple (450 m) the recommended space. Additionally, nutrient and herbicide movement in runoff was quantified for a sorghum (*Sorghum bicolour*) crop grown with fertiliser and herbicide applied at planting for a single wet season. During this period a double spaced slope length (380 m) was also monitored. All contour bays were farmed under a zero tilled–controlled traffic farming system. Average annual runoff and sediment yield at the standard slope length was 75 mm and 1.2 t ha^{-1} respectively. This was greater than losses from grazing land use (0.1 t ha^{-1} yr^{-1}) observed during the study, but less than losses from conventional tillage practices (4 t ha^{-1} yr^{-1}) previously reported from a long term study in the region. Total nitrogen concentrations (median 8.3 mg L^{-1}) in runoff from the sorghum crop were higher than those reported for other agricultural land uses at similar scales, and high proportions of NO_x–N in relation to total nitrogen were observed (69%). Estimated NO_x–N lost in runoff from the double spaced slope length after fertiliser application was 7-8 kg ha^{-1}. Off farm movement of metolachlor (2-chloro-N-(6-ethyl-o-tolyl)-N-[(1RS)-2-methoxy-1-methylethyl]acetamide) (Strada®) was observed with a maximum event mean concentration of 360 μg L^{-1} detected 19 days after application, equivalent to 4.3% of the applied amount. Current dryland cropping BMPs have reduced sediment losses compared to conventional practices. However, observations from a single wet season indicate that high concentrations of nutrients and herbicides can be transported off farm in runoff where they have the potential to be transported to the GBR. Further monitoring and analysis of delivery ratios of pollutants from paddock to catchment is required in the Fitzroy Basin, as is the continued development and adoption of BMPs that reduce nutrient and herbicide movement off farm.

1. Introduction

The effects of agricultural practices on water quality are a major concern worldwide, particularly where there is competing needs for water resources. The major non point source pollutants associated with agricultural land use are sediment, fertilisers and pesticides. These pollutants have the potential to impact surrounding aquatic ecosystems such as Australia's Great Barrier Reef (GBR) (Haynes et al., 2000; Jones et al., 2003; Smith et al., 2006). The Fitzroy Basin is the largest catchment discharging into the GBR lagoon and has been identified as a major source of pollutants (Cogle et al., 2006). Cropping land largely utilised for grain growing in the Fitzroy Basin has been associated with disproportionate concentrations of sediment, nutrient and pesticides at a basin and sub catchment scale (Packett et al., 2009). Studies indicate that the Fitzroy River is efficient at transporting finer sediment fractions generated from these cropping lands to the estuary (Packett et al., 2009; Douglas et al., 2006a,b). This is despite the greater concentrations of cropping lands, and sediment generation (Joo et al., 2005), being located far from the mouth of the Fitzroy River (>619 km river length). Evidently, improvements to land management practices

* Corresponding author. Tel.: +61 7 49 879 327; fax: +61 7 49 879 333; mobile: +61 0419 773109.
E-mail address: ta.murphy@hotmail.com (T. Murphy).

0167-8809/$ – see front matter.
doi:10.1016/j.agee.2011.07.023

through the cropping (grains) industry's best management practices (BMPs) may reduce the amount of pollutants discharging into the southern GBR.

The development and adoption of BMPs or conservation agriculture for the dryland cropping industry has occurred in many parts of the world. The majority of research quantifying the effects of these practices on surface water quality has been undertaken on loam textured soils, due to their extensive occurrence worldwide (Richardson and King, 1995). In comparison, research conducted on clay textured soils, such as Vertisols, has largely been confined to the Blackland Prairie of central Texas, United States (U.S) and north eastern Australia's cropping lands.

Heavy clay soils, such as Vertisols, are agriculturally important and provide their own unique management issues. When Vertisols are wet they have low permeability and are highly erosive. Understanding regionally specific hydrologic responses of soils to climate and management is paramount to improved management. This was confirmed by Harmel et al. (2006) in a long term study at the Grassland Soil and Water Laboratory in Texas where soil water phases to temporal runoff patterns on clay soils was reported. In north-eastern Australia's grain growing region, when there is both a large soil water deficit and mass of crop stubble almost all rainfall infiltrates. In comparison once the soil becomes saturated, cracks in the soil close, and rainfall infiltration rate, runoff and soil loss is determined by the amount of stubble protecting the soil from rainfall impact and surface runoff (Carroll et al., 1997). The understanding of these management issues has helped shape the dryland cropping industry's BMPs to reduce soil loss in runoff.

At a paddock scale the effectiveness of BMP farming systems such as zero-till, opportunity cropping, controlled traffic farming (CTF) and the use of contour banks in improving runoff water quality from Vertisols has been studied to varying degrees. The effectiveness of opportunity cropping and zero-till in reducing sediment loads in runoff on clay soils is well established (Freebairn and Wockner, 1986; Sallaway et al., 1990; Richardson and King, 1995; King et al., 1996; Carroll et al., 1997; Harmel et al., 2006; Thomas et al., 2007), however there is lack of studies quantifying their effects on nutrient and herbicide losses in Australia. Carroll et al. (1997) found opportunity cropping using zero-till was the most effective cropping system to produce consistent high ground cover, reduced runoff and soil loss in a study at Capella, Central Queensland when farming wheat (*Triticum aestivum*), sorghum (Sorghum bicolour) and sunflower (*Helianthus annuus*). Similar findings were observed from studies undertaken at the Grassland Soil and Water Laboratory in Texas where zero-till compared to conventional tillage, and incorporation of winter cover crops, was shown to reduce sediment as well as nutrient losses (Chichester and Richardson, 1992; Richardson and King, 1995; King et al., 1996; Harmel et al., 2006).Along with tillage, the effect of wheel traffic on reducing soil loss has been reported in Australia (Tullberg et al., 2007). CTF is a system where equipment is restricted to permanent traffic lanes, reducing soil compaction and allowing the management of high levels of cover and cropping (Tullberg et al., 2001). Studies on heavy clay soil used for extensive grain production have shown CTF where combined with zero-till allows high cover and crop growth, reducing runoff resulting in reduced soil loss compared to wheeled soil (Tullberg et al., 2001; Rohde and Yule, 2003). CTF is now widely adopted where extensive grain cropping is undertaken in Australia. Studies in China have shown that CTF when combined with zero-till was effective in improving soil condition but no studies have reported effects on soil loss (Bai et al., 2009; Chen et al., 2008). While large scale adoption is rare in the USA and Europe (Tullberg et al., 2007), an early study in the 1980s in Texas, U.S. reported sediment and nutrient losses from a zero-till CTF system (Richardson and King, 1995). However it is unlikely that the amount of compaction generated from this system would be comparable to today's CTF systems given the change in machinery size, advances in global positioning systems and the associated reduction in wheeling. This suggests that the effectiveness of CTF in reducing nutrient and herbicide in runoff under current systems is yet to be tested in a long term, paddock scale situation on Vertisols, particularly in north eastern Australia.

Compared to CTF, contour banks have long been used in dryland farming, and are the most common practice implemented to reduce erosion since it was recognised as a serious issue across all cropping regions in the 1930s in Queensland, Australia (Cowie et al., 2004; Freebairn et al., 2009). Contour banks, also known as terraces, and graded banks used in dryland cropping are designed to reduce the slope length of a paddock, resulting in reduced sheet and rill erosion from the area between banks (Wischmeier and Smith, 1978). Deposition along the bank itself, referred to as the contour bank channel, has also been shown to account for large proportions of trapped sediment where channels have a low slope (Foster and Highfill, 1983; Freebairn and Wockner, 1986). Contour banks are designed to withstand runoff from specific return periods for rainfall events (eg. 1:10 years) and when they fail can concentrate water to form gullies (Freebairn and Wockner, 1986). No long term paddock scale studies have reported sediment, nutrient and pesticide runoff from zero-till, CTF systems farmed down the slope on varying slope lengths in north eastern Australia.

It is evident that improvements to land management in the cropping (grains) industry may reduce pollutant runoff to the southern GBR. The effectiveness of BMPs such as opportunity cropping, zero-till and standard spaced contour banks in reducing sediment in surface water runoff is well established. Additionally, at sub catchment and basin scale sediment, nutrient and pesticide contributions from cropping land have been reported in the Fitzroy basin. However, few studies have reported the pesticide and nutrient loads and concentrations of runoff from cropping land at a paddock scale. More specifically there is a lack of information reported that quantifies the generation rates of sediment, nutrient and pesticides in surface runoff from zero-till, CTF systems farmed down the slope on varying contour bank slope lengths on Vertisols.

This study aims to characterise paddock scale runoff and sediment yields from a 9 year study of a zero-till, CTF system on Vertisols under single and triple contour bank slope lengths, and quantify nutrient and pesticide yields from the 2009/10 wet season under this farming system. This information will assist in identifying the effectiveness of current dryland cropping BMPs in reducing sediment concentrations and loads from cropping land compared to conventional management practices. Additionally concentrations and loads of nutrients and pesticides moving off farm in runoff will be quantified and allow comparison with sub catchment and basin concentrations in the Fitzroy Basin where they have the potential to be transported to the southern GBR. The study site is located in the Gordonstone creek catchment, situated in a cropping landscape in the Fitzroy Basin, and is currently utilised for the Paddock to Reef Program (Carroll et al., 2012). Rainfall, runoff and water quality have been measured at a paddock scale from October 2000 to March 2010.

2. Methodology

2.1. Study site

The dryland cropping paddock sites at 'Moonggoo' are situated in the upper Gordonstone catchment, 10 km south of Capella, Central Queensland, Australia (Lat. $-23°9'56''$, Long. $148°3'17''$). Moonggoo is a commercial grain farm that has been cultivated continuously for approximately 60 years. Long term average annual rainfall at Moonggoo is 595 mm (Capella PO) with 75% falling

Table 1
Topographic characteristics of the cropping paddock contour bay sites monitored from 2000-2009 and during the 2009/2010 wet season.

Contour bay site	Contour bay			Contour bank channel	
	Slope length (m)	Slope (%)	Area (ha)	Slope (%)	Length (m)
Single spaced slope length	180	0.78	10	0.2	495
Double spaced slope length	380	0.78	43	0.14	1095
Triple spaced slope length	450	0.95	45	0.13	885

during the wet season. Long term average temperature for the area is 29.7 °C, recorded by Bureau of Meteorology weather stations at Emerald (035264) and Clermont (035019), both within 50 km of the study site. During January and February 2010 the average minimum and maximum temperatures were 22 and 32 °C. Maximum temperatures of 38 and 39 °C were also observed during this period. The soil, known worldwide as a Vertisols, is a coarse self-mulching, black, cracking clay overlying basalt. The minimum clay content throughout the soil profile is 55% and surface soil (0–10 cm) organic carbon content is moderately low (<1%). The soil is moderately alkaline throughout with pH ranging from 6.9 to 7.8. A full soil description of the site is reported by Irvine (1998). Vertisols account for approximately 84% of cropped soils in the Fitzroy Basin.

During the study three contour bays (10, 43 & 45 ha respectively) with standard (single), double and triple spaced slope lengths were monitored (Table 1). The single and triple spaced slope lengths were monitored from October 2000 until March 2009 where rainfall, runoff and sediment yields were measured. During the 2009/2010 wet season (6 months starting March) rainfall, runoff and sediment, nutrient and pesticide yields in runoff, were also measured incorporating an additional contour bay with a double spaced slope length.

Slope lengths refer to the distance between contour banks. A standard (single) slope length in the Central Highlands region, in northern Australia is designed for a broad based contour bank to withstand a 1 in 10 year runoff event on a given vertical interval or slope (Bourne and Tuck, 1993). Double and triple spaced slope lengths are simply double and triple the standard slope length for a given slope. The triple spaced slope length in this study is actually about 2.5 times the standard slope length for its slope. From an economic viewpoint longer spaced banks are preferred by farmers where machinery traffic operates 'down the slope' and over the banks as they generate less damage to farm machinery, and require fewer contour banks to initially be constructed and then maintained.

A zero-till, 'down the slope' CTF system was implemented across all treatments. Most machinery is on the same wheel spacing, excluding the header. The contour bay with the double spaced slope length was farmed across the slope without permanent wheel tracks until 2009.

A small 150 ha grazing paddock is instrumented further down the Gordonstone Creek catchment, with soils similar to the cropping paddock site.

2.2. Land management

At the cropping paddock sites 11 crops were grown from October 2000 to March 2009 as shown in Table 2. For the 2009/10 wet season sorghum was planted in wide row spacings on the 12th January 2010. Pre-emergent pesticide Strada® was applied as a 'blanket spray' the same day as planting. Active ingredient (a.i.) metolachlor was applied at ~1.44 kg ha^{-1}, although this application rate was not verified by soil samples, nor does it account for spray drift. N was applied as urea at 37 kg N ha^{-1} at planting, as shown in Fig. 1, largely incorporated into the soil with a single tyne. Ground cover at the grazing land paddock site was very high (>50%) due to good rainfall over several seasons.

Table 2
Crop type, planting and harvest date from 2000 to 2010 at Moonggoo cropping paddock sites.

Planting date	Harvest date	Crop
Jan 2000	May 2000	Sorghum
Dec 2000	Apr 2001	Sorghum
Jun 2002	Oct 2002	Wheat
Apr 2003	Sep 2003	Chickpeas (*Cicer arietinum*)
Jan 2004	Apr 2004	Mung beans (*Vigna radiata*)
May 2005	Oct 2005	Wheat
Nov 2005	Mar 2006	Sorghum
Jun 2006	Oct 2006	Wheat
Feb 2007	Jul 2007	Sorghum
Sep 2007	Feb 2008	Sorghum
Apr 2008	Oct 2008	Chickpeas
Dec 2008	May 2009	Sorghum
Jan 2010	May 2010	Sorghum

2.3. Ground cover

Ground cover was monitored at the cropping paddock sites with photos taken from a height of 4 metres. During the period 2000–2009 ground cover estimation methods based on yield were utilised to infill periods between photos. Yields were calculated based on harvest weight divided by area for each of the contour bay treatments. These yields were then used to estimate stubble cover immediately after harvest and during the period until the next planting, based on the relationships identified by Sallaway et al. (1988) and Renard et al. (1997). During the 2009/2010 wet season cover was measured three times. Cover was calculated from photos using a 'point grid' method as described by Sallaway et al. (1988). Results were cross checked with visual estimates.

2.4. Rainfall & hydrology

During the study period 5 pluviometers (0.1–0.5 mm) were installed at the cropping paddock sites, and 1 at the grazing paddock site. Rainfall was recorded at 1 min resolution. All pluviometers were equipped with volumetric rain-gauges to validate data.

Individual storms were defined as periods of rainfall separated by at least six hours. The erosive potential of storms was quantified

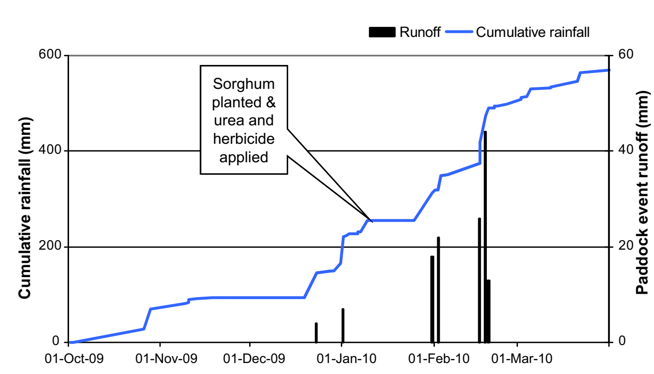

Fig. 1. Timeline of rainfall, runoff and management at the cropping paddock sites during the 2009/2010 wet season.

using an EI_{30} index calculated by multiplying the total kinetic energy of a storm by its peak 30 min rainfall intensity. To quantify annual erosivity, the EI_{30} values of all individual storm events exceeding 12.7 mm were added together. Storms producing less than 12.7 mm were also included in the calculation, if they had a peak 15 min rainfall intensity exceeding 25.4 mm h^{-1} (Sheridan and Rosewell, 2003). The resulting value, known as the erosivity (R) factor, is used in many erosion models (Wischmeier and Smith, 1978).

Flumes installed at the outlet of each contour bay provided a known water height to discharge relationship. Pressure transducers installed at the flumes allowed water height to be logged by data loggers during runoff events. All hydrological and water quality data was stored in a Hydstra (V.10.1.2) database (Kisters, 2009), where editing, quality assurance, data conversion and analysis was undertaken.

2.5. Event sampling and pollutant constituent analysis

Isco automatic samplers collected discrete flow weighted samples at all flume outlets for the cropping paddock sites (Isco, 2011). During the 2009/2010 wet season nutrient and herbicide samples from the paddock trial sites were chilled to 4 °C within 18 h of automated sampling. Nutrient samples were frozen and herbicide samples were kept in darkness at 4 °C until processed. Discrete sediment samples were collected at the grazing paddock site using a Rimik RPS50 sampler (Agridry, 1995).

At the cropping paddock sites an integrated sample of bedload and suspended material moving through the flume was collected. However, total soil movement, defined as the mass soil that moves into or through the contour channel was not measured.

Sediment loads and event mean concentrations (EMCs) were calculated using Hydstra's water quality total maximum daily load (WQTMDL) program in 'single shot mode'. These calculations are based on the United States Environment Protection Agency (USEPA) total maximum daily load process (USEPA, 1999). Specifically, discrete sample concentrations were interpolated linearly, the concentration of the first sample of an event was interpolated back to the start of the event and the last sample was interpolated to a value of zero at cessation of discharge. During the 2009/2010 wet season at least 5 samples distributed across each event were used to calculate loads and EMCs, except for nutrients where a minimum of 3 samples were used due to lack of samples. During the period 2000–2009 not all runoff events were recorded or sampled and in some cases data was corrupted due to contour banks failing or runoff backing up in flumes. In these cases figures were estimated using the most relevant data available, either from a similar site or using the average EMC for the study period.

Calculation of pesticide EMCs was conducted in Excel, where the last sample of the event was not interpolated to zero at cease of discharge. It is important to note that discrete pesticide samples from all three treatments for cropping at the paddock scale were used to calculate a 'bulk' single EMC for each event. At least 7 samples were used in calculation of EMCs for the 4 events that were analysed. No soil samples were taken to confirm application rates, nor were losses from spray drift taken into account.

2.6. Laboratory analysis

To determine the mass per volume of total suspended solids (TSS), the total volume of the sample was measured, and then a small amount of flocculent (alum) added. After settling, excess water was removed and the remainder oven dried to equilibrium at 105 °C in glass beakers. Net weight of dry sediment, divided by the sample volume is concentration (TSS). Water samples collected for detection of metolachlor (2-chloro-*N*-(6-ethyl-o-tolyl)-*N*-[(1RS)-2-methoxy-1-methylethyl]acetamide) were analysed by liquid chromatography mass spectrometry (LCMS) at the Queensland Health and Forensic Scientific Services (QHFSS) Laboratory, accredited by the National Association of Testing Authorities, based on USEPA standard method 8141.

Nutrient analysis was also conducted at the QHFSS laboratory using methodology based on American Public Health Association (APHA) standard methods (APHA, 2005). Ammonia levels were measured from filtered samples (0.45 μm) using the automated phenate method and a continuous flow analytical instrument, where sodium salicylate is used in lieu of phenol (APHA standard method 4500-NH_3 H). Nitrogen oxides (NO_x–N) were detected in samples using the automated cadmium reduction method and a continuous flow analytical instrument based on APHA method 4500-NO3 I. Concentrations of filterable reactive phosphorus (FRP) were measured from filtered samples (0.45 μm) using the automated ascorbic acid reduction method based on APHA method 4500-P G.

Total nitrogen (TN) is a combination of organic nitrogen and ammonia, and were again determined using the automated phenate method following kjeldahl digestion based on APHA method 4500-N_{org} D. Total dissolved nitrogen (TDN) and phosphorus (TDP) were measured from filtered samples (0.45 μm) using the automated phenate method based on APHA method 4500-P J. Total phosphorus (TP) was measured by ascorbic acid reduction of phosphomolybdate for FRP using APHA method 4500-P following kjeldahl digestion. Dissolved organic nitrogen (DON) was estimated by the subtraction of NO_x–N and ammonia from TDN, and similar for phosphorus (DOP) by subtracting FRP from TDP concentrations.

3. Results

3.1. Ground cover

3.1.1. 2000–2009

In general, ground cover was maintained above 30%, except following the harvest of pulse crops when cover deteriorated to less than 10%. These low cover periods were experienced during the 2003 and 2004 wet seasons, and a short period at the start of the 2008 wet season before sorghum was planted.

3.1.2. 2009/2010 wet season

Ground cover was relatively low during the wet season and consisted of the previous season's sorghum stubble combined with sorghum planted in wide row spacings in January 2010. Cover measured from site inspections ranged from 14 to 18%, whereas analysis using the bare ground index (BGI) (Scarth et al., 2006) measured 29%, 24% and 21% respectively for the single, double and triple spaced slope lengths at the start of the wet season. The sorghum crop gradually contributed to a small amount of ground cover over the wet season.

3.2. Hydrology

Average wet season rainfall recorded at the cropping paddock sites from 2000 to 2009 was 426 mm with an average R factor of 3347. The last three wet seasons were the wettest and most intense producing between 516 and 702 mm with R factors ranging from 4247 to 5395. Total rainfall during the 2009/2010 wet season was 574 mm; rainfall and runoff from individual events are shown in Fig. 2. The first 2 runoff events of the season (late Dec/early Jan), prior to planting, accounted for 64% of the wet season's rainfall erosivity (EI_{30}), but produced minimal runoff. These 2 events had peak 30 min rainfall intensities of 69 and 94 mm h^{-1} respectively.

Wet season average annual runoff during the 9 year study was 75 and 56 mm for the single and triple spaced slope lengths, from

Table 3
Annual water year (12 months starting October) rainfall, runoff and soil yields from 2000 to 2008 at Moonggoo cropping paddock sites.

Water year	Rainfall	Single slope length		Triple slope length	
		Runoff (mm)	Soil yield ($t\,ha^{-1}$)	Runoff (mm)	Soil yield ($t\,ha^{-1}$)
2000	572	165	3.5	99	4.0
2001	400	2	0.1	0.4	<0.1
2002	346	0	0.0	0	0.0
2003	473	26	0.7	32	1.5
2004	412	0	0.0	5	0.15
2005	562	24	0.6	7	0.3
2006	510	0	0.0	1	<0.1
2007	829	343	2.8	258	4.9
2008	431	112	3.3	103	4.6
Total		672	11	505	16

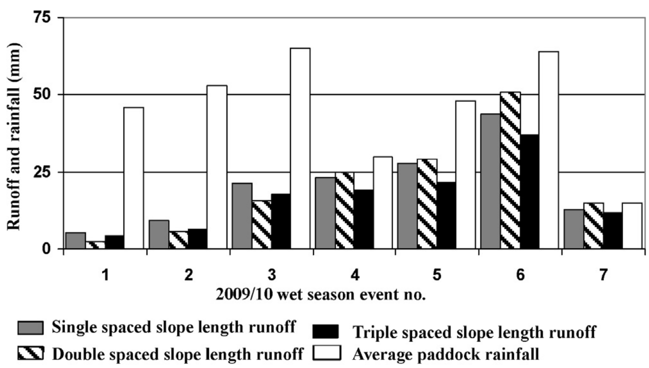

Fig. 2. Cropping paddock runoff and rainfall at single, double and triple spaced slope length during 2009–2010 wet season in the Gordonstone Catchment.

37 and 31 runoff events respectively. During the 2009/2010 wet season 7 runoff events were recorded at the cropping paddock sites with totals of 144, 143, and 118 mm at the single, double and triple spaced slope lengths. Their average event runoff to rainfall ratio was 52, 51 and 39% respectively, generally increasing as the season progressed (Fig. 2).

3.3. Water quality

3.3.1. TSS

During the 9 year study period average annual TSS yields for comparable water years (12 months starting October) at the single and triple spaced slope lengths was approximately 1.2 and 1.7 $t\,ha^{-1}$ respectively. Annual TSS yields from 2000 to 2008 from the single and triple spaced bays are shown in (Table 3). From 2000 to 2008 the triple spaced slope length produced TSS yields 40% greater than the single slope length during years with comparable data. During the 2009/10 wet season the single and double spaced slope lengths produced 2.2 and 3.6 $t\,ha^{-1}$. The triple spaced slope length was not sufficiently sampled for reporting total wet season loads. The double and triple spaced slope lengths produced 67% and 57% higher yields per hectare than the single for comparable events during the 2009/2010 wet season. The grazing paddock had an approximate average annual TSS loss of 0.1 $t\,ha^{-1}$, from 12 runoff events over 8 years. However the majority of these events occurred in the 2007, 2008 and 2009 wet seasons.

Table 4
Metolachlor EMCs, total yields and estimated percent of applied detected at the cropping paddock sites in the Gordonstone Catchment during the 2009–2010 wet season.

Days since spraying and planting	Event mean concentration ($\mu g\,L^{-1}$)	Total yield (g.a.i. ha^{-1})	Estimated % of applied
19	361	62	4.3
21	232	51	3.5
35	34	9	0.6
36	40	17	1.2

During the 9 year study period the cropping paddock single and triple spaced slope lengths had average water year TSS EMCs of 2.6 and 3.9 $g\,L^{-1}$ for years where runoff occurred. Grazing land concentrations were much lower at approximately 0.5 $g\,L^{-1}$. During 2009/2010 total wet season EMCs of 1.5, 2.4 and 2.7 $g\,L^{-1}$ for the single, double and triple spaced slope lengths were observed, however only the first 4 events of the season were sampled at the triple spaced slope length. Concentrations from the first two events ranged from 2.9 to 7 $g\,L^{-1}$, the following events ranged from 0.7 to 3 $g\,L^{-1}$. TSS concentrations at the grazing paddock site ranged from 0.1 to 0.3 $g\,L^{-1}$ from 8 samples in the sole runoff event during the 2009/2010 wet season.

3.3.2. Herbicides during the 2009/2010 wet season

At the cropping paddock sites metolachlor was detected at reportable limits in all samples analysed (19–38 days after application). The highest discreet sample concentration was detected from the first runoff event 19 days after application at 640 $\mu g\,L^{-1}$. Metolachlor EMCs declined from 361 to 40 $\mu g\,L^{-1}$ over 18 days (Table 4). This equated to 17% and 25% respectively, of those at 19 days by 35 days and 36 days, consistent with being ~2.5 runoff half-lives (7.2 days) after the first event. Half-lives were calculated from runoff EMCs, no soil concentrations were recorded. Concentrations were not comparable across treatments due to low number of samples and their position in the hydrograph. From estimated application rates of 1440 $g\,ha^{-1}$, yields of ~62 $g\,ha^{-1}$ (4.3% of applied) were observed 19 days after application.

Table 5
Average concentration ($mg\,L^{-1}$) of nitrogen and phosphorus species from runoff at the cropping paddock sites in the Gordonstone catchment during the 2009/2010 wet season, including total nitrogen (TN), total phosphorus (TP), oxidised nitrogen (NO_x–N), ammonia, particulate nitrogen (PN), dissolved organic nitrogen (DON), particulate phosphorus (PP), dissolved organic phosphorus (DOP) and filterable reactive phosphorus (FRP).

Nitrogen fractions ($mg\,L^{-1}$)				TN ($mg\,L^{-1}$)	Phosphorus fractions ($mg\,L^{-1}$)			TP ($mg\,L^{-1}$)
NO_x–N	Ammonia	PN	DON		PP	DOP	FRP	
5.9	0.2	1.4	1.1	7.3	0.41	0.016	0.017	0.53

3.3.3. Nutrients during the 2009/2010 wet season

At the cropping paddock sites, the TN median sample concentration was 8.3 mg L^{-1} (range 2.4–12.6). NO_x–N accounted for the largest proportion of the nitrogen fraction at 69% with a median concentration of 6.2 and average of 5.9 mg L^{-1} from all samples at the cropping paddock sites (Table 5). PN and DON accounted from 17 and 12% of nitrogen fractions, followed by ammonia at 2%. Estimated NO_x–N lost in runoff from the double spaced slope length after fertiliser application was 7–8 kg ha^{-1}, equal to roughly 20% of the total nitrogen applied at planting, not taking into account losses from leaching, denitrification due to water logging, or gains from soil mineralization. PP accounted for the largest proportion of the phosphorus fraction at 92% with a median concentration of 0.35 mg L^{-1} with small contributions from FRP and DOP at concentrations of 0.02 mg L^{-1}.

4. Discussion

The results from this study quantify the off farm movement of sediment, nutrient species and the herbicide metolachlor from a Vertisol soil as observed in runoff from zero-till, CTF systems farmed down the slope on varying contour bank slope lengths. Specifically, long term average annual runoff and sediment yield at the standard slope length was 75 mm and 1.2 t ha^{-1} respectively, total nitrogen concentrations (8.3 mg L^{-1}) with high proportions of NO_x–N in relation to total nitrogen were observed (69%) from a single wet season from a sorghum crop. Estimated NO_x–N lost in runoff from the double spaced slope length after fertiliser application was 7–8 kg ha^{-1}, equal to roughly 20% of the fertiliser application. Off farm movement of metolachlor (2-chloro-*N*-(6-ethyl-o-tolyl)-*N*-[(1RS)-2-methoxy-1-methylethyl]acetamide) (Strada®) was observed with a maximum event mean concentration of 360 μg L^{-1}, or roughly 4% of the applied amount, detected 19 days after application.

It is likely that a proportion of these pollutants in runoff from cropping at the paddock scale will be transported to the Fitzroy Basin outlet. Delivery ratios of 40% for finer sediment fractions generated from cropping lands have been reported when transported from sub catchment to basin (Packett et al., 2009). Further monitoring and analysis of delivery ratios of pollutants from paddock to sub catchment is required in the Fitzroy Basin. Nutrient concentrations from floodwaters in the Fitzroy basin outlet during a study from 1994 to 2008 had maximum TP and TN concentrations, associated with runoff from cropping land, of 0.63 and 4.1 mg L^{-1} respectively (Packett et al., 2009). These concentrations are significant compared to median TP and TN concentrations of 0.42 and 8.3 observed at the paddock scale during this study and highlight the potential for cropping lands to influence the water quality of the southern GBR.

4.1. TSS

The sediment yields recorded at Moonggoo during the 9 year study (1.2–1.7 t ha^{-1} yr^{-1}) were similar to the long term average reported for the Capella soil erosion study zero-till treatment of 1.4 t ha^{-1} yr^{-1} (1983–1993). However, sediment yields recorded from Moonggoo were much less than the conventional tillage treatment at the Capella study (4 t ha^{-1} yr^{-1}) (Carroll et al., 1997). These results reconfirm that zero-till farming systems have been effective in reducing soil loss on cropping lands in central Queensland (Carroll et al., 1997; Thomas et al., 2007), and are comparable with studies undertaken in Texas, U.S. (Richardson and King, 1995; King et al., 1996; Harmel et al., 2006). Annual sediment losses from grazing land use observed within the study are within an order of magnitude of basaltic soil generation rates in central Queensland (Pillans, 1997). However, sediment losses from zero-till in central Queensland are still well in excess of these generation rates and pose a serious threat to the long term sustainability of dryland farming in the region.

The average total water year TSS EMCs for the cropping paddock sites during the study period (2.6–3.9 g L^{-1}) were much higher than the TSS concentrations at the grazing site (~0.5 g L^{-1}). These concentrations are much less than found on sodic duplex soils in the Fitzroy Basin, where cropping and grazing trials had average EMCs of 6 and 2 g L^{-1} respectively. (Neilsen, pers. comm.; Stevens et al., 2005) However erosion at these sites is likely to be driven by greater slopes (~3–5%) and sodic subsoils compared to Moonggoo. Similarly EMCs from the study are also much lower than reported by Carroll et al. (1997) for zero-till and conventional tillage at the Capella study. In any case these studies concur with reports that land used for cropping in the Fitzroy Basin produced the highest concentrations of suspended sediments compared to grazing (Packett et al., 2009). Additionally the cropping paddock concentrations, and to a lesser extent the grazing paddock, were much higher than those reported for banana and sugarcane farm plots in the Wet Tropics not exceeding 0.05 g L^{-1} from 2002 to 2006 (Faithful et al., 2007). This may be a result of high ground cover associated with the Wet Tropics and less episodic crop fallows.

4.2. Impacts of contour bank spacing on TSS yield

The impacts of contour bank spacing in reducing sediment yields were observed at the paddock scale with the triple spaced slope length generating 40% more unit soil loss for a 9 year period. In the 2009/2010 wet season, under conditions conducive to runoff, the double and triple spaced slope lengths produced 67 and 57% more unit soil loss (t ha^{-1}) than the standard single spaced slope length. These results highlight the risks of combining low cover and long slope lengths. Runoff from the triple spaced slope length was generally less than the single. The increased sediment yield from the single spaced slope length compared to the double and triple was a result of increased sediment concentration. These findings were largely supported by a review of studies in north-western Australia where double spaced slope lengths lost more soil than single spaced slope lengths due to the increased velocity of runoff and its ability to scour and transport sediment (Dilshad et al., 1996).

4.3. Nutrients

Although from a from a very limited data set, the observed nutrient concentrations from runoff at the cropping paddock sites during the 2009/2010 wet season were higher than those reported for other cropping studies and land uses in the GBR catchment. TN median concentrations (8.3 mg L^{-1}) were higher than those reported for cropping (3.6 mg L^{-1}) and grazing (1.56 mg L^{-1}) on sodic duplex soils with a greater slope in the Fitzroy Basin (Neilsen, pers. comm.; Stevens et al., 2005), as well as sugarcane (3.1 mg L^{-1}) and banana (2.6 mg L^{-1}) land uses at similar scales in the Wet Tropics (Faithful and Finlayson, 2005). Similarly, Faithful et al. (2007) reported median concentrations from sugarcane over 4 wet seasons of 5.8 mg L^{-1}. However the nutrient concentrations from the cropping paddock are potentially less significant in terms of impacts on the GBR lagoon than those observed in the Tully-Murray Basin due to the Tully-Murray's greater discharge and it's vicinity to the lagoon. Discharge from the 13.7 ha sugarcane plot reported by Faithful et al. (2007) over 4 years was at least 10 times greater than the discharge from the single spaced slope length (10 ha) over an inclusive 10 year period.

High proportions of NO_x–N (69%) in relation to total nitrogen were observed at the cropping paddock sites during the 2009/2010 wet season. These findings are in contrast to a study by Silburn and Hunter (2009) on an irrigated cotton farm on black Vertisols in the Emerald irrigation area. Their findings indicated that the majority of N was transported with sediments under low cover conditions as opposed to dissolved. However Chichester and Richardson (1992) and Richardson and King (1995) in a 5 year study on Vertisols in Texas, USA indicated dissolved nitrogen losses were much greater than absorbed nitrogen under a zero-till CTF system. Proportions of NO_x–N from the cropping paddock sites were also similar to those characterised by Bainbridge et al. (2009) for sub catchments with sugarcane and banana land uses where high fertiliser inputs are applied. Given that the loss of soluble nitrogen is greatly dependent on the timing of fertiliser in relation to the timing and size of runoff events (Richardson and King, 1995), further monitoring is required to characterise nutrient speciation in runoff under zero-till CTF in extensive dryland grains cropping in central Queensland.

Reviews from both the United States and northern Australia have reported that zero and reduced-tillage generated higher concentrations and losses of dissolved nutrients in runoff than tilled systems (Baker and Laflen, 1983; Dilshad et al., 1996). However findings by Chichester and Richardson (1992) and Richardson and King (1995) in Texas, USA strongly indicate that the loss of both soluble and absorbed nutrients from agricultural lands could be minimized using zero-till on clay soils. Estimated NO_x–N lost in runoff from the double spaced slope length after fertiliser application was 7–8 kg ha^{-1}, roughly 20% of the total nitrogen applied at planting, not taking into account losses from leaching, denitrification due to water logging, or gains from soil mineralization. In comparison, reported losses in runoff from fertiliser application on paddock scale sites ranged from 1 to 5 kg NO_3–N ha^{-1} (1.4–3.2% of applied) in the Burdekin basin, Australia (Thorburn et al., 2011), 3.5 kg N ha^{-1} yr^{-1} (3% of applied) in the Burnett–Mary Catchment, Australia (Hunter and Armour, 2001) and 3.1 kg ha^{-1} yr^{-1} of soluble N (2% of applied) in Texas under zero-till CTF (Richardson and King, 1995).

4.4. Herbicide

Metolachlor has predominantly been used in the grain growing region of northern NSW, Australia with atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-*s*-triazine) generally used for sorghum in north–eastern Australia (Osten et al., 2007). During the 2009/2010 wet season pre-emergent pesticide metolachlor (Strada®) was used where runoff from 4 events 19–36 days after application generated a total yield of 10% of the estimated applied amount (active ingredient). EMCs and yields from events 19 days (360 μg L^{-1}, 4.3%) and 36 days (40 μg L^{-1}, 1.2%) after application were observed at the paddock trials. These results are comparable with those reported for a rainfall simulation study on Vertisols where metolachlor concentrations and losses 2 days (279 μg L^{-1}, 14%) and 34 days (31 μg L^{-1}, 1.9%) after application were reported (Silburn et al., 2013). These results highlight that residual herbicide concentrations in runoff and receiving waters are highly dependent on the timing and characteristics of the first few rainfall events after application (Shipitalo et al., 2008; Wauchope et al., 2002). Metolachlor is primarily moved off field in solution rather than adsorbed to sediment. Where 40% cover or above is maintained zero-till has been shown to be effective in reducing herbicide losses (including metolachlor) due to reduced runoff (Fawcett et al., 1994). Subsequently the low cover conditions experienced over the 2009/2010 wet season produced conditions conducive to high losses.

5. Conclusions

The results from this 9 year study show that zero-till CTF farming systems are effective in reducing soil loss on Vertisols compared to conventional tillage practices. Additionally, standard spaced slope lengths, under the conditions observed during the study period, are still a valuable management tool in dryland cropping zero-till CTF systems for reducing soil loss compared to double and triple spaced slope lengths. Soil loss from cropping land is still very high compared to grazing land use on similar land types and is well in excess of basaltic soil generation rates in the region, posing a serious threat to the long term sustainability of dryland farming.

Under current dryland cropping BMPs high concentrations of nutrients and herbicides can be moved off farm in runoff where they have the potential to be transported to the sub catchment and end of basin in lesser concentrations and or changed form. This highlights the potential for cropping lands to influence the water quality of the southern GBR. Further monitoring and analysis of delivery ratios of pollutants from paddock to sub catchment is required in the Fitzroy Basin, as is the continued development and adoption of BMPs that reduce nutrient and herbicide movement off farm.

Acknowledgements

We would like to thank David and Alan Storey from Moonggoo for their ongoing support throughout the past 10 years. This paper is a contribution to the Paddock to Reef Monitoring, Modelling and Reporting Program. Funding from the Fitzroy Basin Association through the Australian Government's Caring for our Country Program is gratefully acknowledged. Great assistance has been provided by staff from the wider Reef Rescue project team. We would also like to thank Stewart Neilsen and other past staff for their efforts maintaining the Neighbourhood Catchment Project. Thank you also to reviewers of this paper for providing valuable comments and suggestions.

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