Paddock Scale Water Quality Monitoring of Vegetable-Sugarcane and Legume-Sugarcane Farming Systems

Summary report
2010-2013
Burnett Mary Region

Gunasekhar Nachimuthu[1], Neil Halpin[1] and Mike Bell[2]
[1]Department of Agriculture, Fisheries and Forestry &
[2]Queensland Alliance for Agriculture and Food Innovation (QAAFI), University of Queensland

1. Key findings

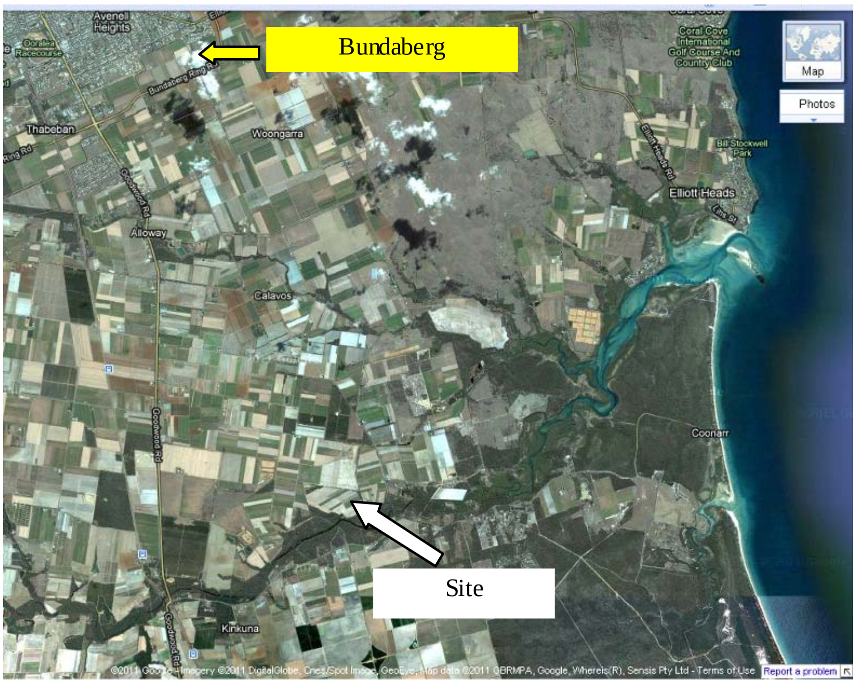
The project has delivered a number of key findings from what were years in which summer rainfall was 50-100% greater than the long term average. These were as follows –

- Sediment and nutrient losses during grain legume or vegetable rotations with sugarcane were dominated by losses occurring during the sugarcane crop.
- The most sensitive period for soil and nutrient loss occurred during the transition period between crops in the rotation, and during the early stages of crop establishment.
- Soil disturbance, the presence of groundcover (crop residues/trash/living mulch) and soil compaction were the major factors affecting runoff volumes and loads of sediment and total nitrogen (N) and phosphorus (P). The most effective management systems that ameliorated soil compaction, minimised soil disturbance and maintained ground cover reduced sediment and nutrient loads by 50-60%.
- Legume residues or legume companion crops were effective at providing groundcover and at reducing soil loss, but also tended to increase losses of the biologically active fractions of N (Dissolved Inorganic N) and P (Filterable Reactive P).
- Runoff losses of DIN were relatively small in all systems tested (0.7- 2.7 kg DIN/ha), but leaching losses of nitrate-N were estimated in excess of 140 kg N/ha from the current commercial practice intensive vegetable systems. This leached N was lost before being able to be recovered by the subsequent sugarcane crop and represents a risk to groundwater quality.
- The risk of offsite losses from herbicides with long half-lives in the field was illustrated by high concentrations of Diuron recorded in runoff that occurred more than 2.5 months after herbicide application. There was also concern about increased losses of Metribuzin when applied in systems with reduced tillage and surface residues/trash.
- Similarly effective weed control during the plant cane crop could be achieved by reduced application rates of residual herbicides and/or the replacement of residual herbicides with less persistent knockdown products. However, excluding Diuron in the ratoon crop resulted in poor weed control and the need for additional herbicide applications.
- The most substantial improvements in runoff (if not drainage) water quality were achieved at the expense of cropping system productivity – especially in the systems with intensive vegetables. The management strategies showing most promise involve strategic/zonal tillage, reduced nutrient inputs and reduced rates of residual herbicide use. These promising systems will need research attention to fine tune management so as to limit constraints to productivity and profitability.

2. The project

The Burnett-Mary region is the catchment for rivers flowing into southern part of GBR. It has extensive areas of sugarcane and horticultural production and increasing production of summer grain legumes in sugarcane fallows. Horticultural production comprises both plantation crops (avocadoes, macadamias) and intensive vegetable production (capsicums, tomatoes, cucurbits, chillies and sweet potatoes). While these intensive operations may be run as solely horticultural ventures, they are also often grown on sugarcane farms during extended fallow periods between sugarcane crop cycles. The land is typically leased by horticultural producers but after 12-18 months of production, is returned and replanted to sugarcane. This type of management represents roughly half of the land in fallow from sugarcane production, with the remainder sown to summer grain legume crops (peanuts, soybeans).

Sediments, pesticides and nutrients that are found in runoff water from cropping areas in the Burnett-Mary region are likely to affect river water quality and downstream ecosystems in the southern GBR (Mitchell et al., 2005). An initial investigation carried out in Burnett Mary Region (Stork et al., 2008) identified the presence of nutrients and herbicides in runoff water from vegetable, macadamia and sugarcane production systems. This preliminary work suggested a focus on improving management practices to reduce the environmental impact of these key cropping systems.



The project was designed to investigate the impact of a range of management practices in vegetable-sugarcane farming systems on runoff water quality and compare those data with that from either continuous vegetable production systems or a sugarcane farming system utilizing fallow soybean cropping, with reduced tillage and controlled traffic management. The monitoring period covered the transition from sugarcane into a soybean or vegetable fallow period of 12 months, after which all except the continuous vegetable production system transitioned back to sugarcane for a plant and most of a 1st ratoon crop. The findings of this project will help to determine the water quality benefits from different farming systems and management practices, as well as allowing growers and industry to assess the impact of such changes on productivity and profitability. The scientific understanding generated by the study highlights the knowledge gaps and investment opportunities, as well as being a source of information for future extension activities. The project involved collaboration between the University of Queensland (QAAFI), DAFFQ, the Burnett Mary Regional Group (BMRG), DNRM, DEHP, DSITIA and CSIRO. The experiment was conducted on a commercial property in the Alloway district near Bundaberg (see below).

1 Methodology

A three year field investigation was conducted to quantify the impact of changing management practices on offsite water quality generated during the fallow (vegetable or grain legume) and sugarcane production phases of regionally significant intensive cropping systems. The grain legume and intensive vegetable systems were assessed during a 1 year rotation break (during which crops of soybean; or capsicum and zucchini, were grown) before the land was returned to plant and subsequent 1st ratoon sugarcane crops. Management practices were assessed for their impact on productivity and profitability, as well as for their capacity to reduce sediment, nutrient and pesticide movement from fields to streams or groundwater.

The site was established on well drained Chromosol or Dermosol soils with 1% slope. The focus during soybean or vegetable phase was on nutrients and sediments in runoff water, as well as leaching losses with potential impacts on groundwater. During the sugarcane phase equal focus has been given to sediments, nutrients and herbicides. There were five contrasting management systems that were established in randomly allocated strips in a commercial cane field.

Sugarcane-Intensive vegetable cropping systems

1. **Current commercial practices (Treatment C)** - Cane trash removed via burning, conventional tillage, plastic mulch, standard fertilizer recommendations and bare inter-rows. Capsicums were grown from Oct 2010 to Jan 2011, there was a short fallow from Feb to May 2011, zucchini was

grown from May to July 2011 and sugarcane from Aug 2011 - Sept 2012 (plant crop) and from Sept 2012 to current (1st ratoon).

2. **Improved practices (Treatment B)** - Cane trash burnt, tillage and plastic mulch, reduced fertilizer application with an in-season, inter-row vegetative mulch. The same crop sequence was grown as in Treatment C, although vegetative mulches (millet and forage sorghum) were grown in interspaces during the capsicum crop and again in the subsequent fallow before zucchini.
3. **Aspirational but untested practices (Treatment A)** - Last cane ratoon sprayed out after green cane harvesting leaving a trash mulch, reduced fertilizer application and vegetable seedlings transplanted into cane beds after minimum tillage. The same crop sequence was grown as in Treatments C and B, although trash cover was reinstituted between the capsicum and zucchini phases by growing and subsequently mulching forage sorghum in the row and inter-row areas.

Continuous vegetable and sugarcane-grain legume cropping systems

4. **A continuous vegetable production system with aspirational practices (Treatment H)** - Last cane ratoon removed by tillage and formed beds sown to Rhodes grass to generate a surface mulch that was sprayed out before capsicum planting. Beds were maintained permanently with similar management to Treatment A. The crop sequence was similar to Treatments A, B and C during 2011, after which a forage sorghum green manure was established from Aug 2011 to Jan 2012, followed by a short fallow until Feb 2012. Pumpkin was then grown from Feb to Aug 2012, with another fallow over the 2012/13 summer.
5. **A sugarcane-grain legume system with trash retention, minimum tillage and controlled traffic, referred to as the New Farming System (NFS)** - Cane sprayed out and fallow from Sep 2010 to Dec 2010, soybean (harvested for grain) from Dec 2011 to May 2011, a short fallow from May 2011 to July 2011 and then sugarcane from August 2011 as for Treatments A, B and C. This treatment provides a useful reference to other regions and sugar cropping systems monitored in the program.

Additional treatments during Zucchini and Sugarcane crops

The block was initially divided into two subsections that drained in opposite directions from the crest of slope. Runoff was monitored in one subsection, while the other end was used to determine whether the 'optimised' nutrient application strategies adopted in the various management systems where runoff was being monitored actually limited crop productivity. These plots therefore received a higher (and standardised) rate of fertilizer application (161N, 33P, 162K kg/ha) in the zucchini crop, each crop on yield potentials in the various management systems. The details of fertiliser application for zucchini are given at the end of Table 1. All the treatments received higher rate in other end had difference in soil nutrient levels before this application.

Table 1. A comparative summary of treatment characteristics

	NFS	"C"	"B"	"A"	"H"
Previous management	Cane – 1.8m PCTF	Cane – 1.8m PCTF	Cane – 1.8m PCTF	Cane – 1.8m PCTF	Rhodes Grass
First Crop	**Soybean**	**Capsicum**	**Capsicum**	**Capsicum**	**Capsicum**
Trash Management	Retained	Removed	Removed	Retained	Retained
Cultivation	Strip	Full Tillage	Full Tillage	Strip	None
Ground cover in Bed	Trash blanket	Plastic mulch	Plastic mulch	Trash blanket	Rhodes grass
Ground cover in inter-row	Trash blanket	None	Jap millet growing	Trash blanket	Rhodes grass
Fertilizer N, P, K	Traditional 0N, 0P, 50K	Traditional 315N, 130P, 306K	Improved 147N, 35P, 175K	Improved 200N, 24P, 200K	Improved 200N, 24P, 200K
Fallow management	Soybean growing	Knockdown herbicide	Forage sorghum grown and slashed before planting zucchini	Forage sorghum grown and slashed before planting zucchini	Forage sorghum grown and slashed before planting zucchini
Ground cover in Bed	Trash blanket	Plastic mulch	Plastic mulch	Trash mulch, capsicum mulch	Rhodes grass mulch, capsicum mulch
Ground cover in inter-row	Trash blanket	Capsicum mulch	Capsicum mulch, Jap millet mulch	Trash mulch, capsicum mulch	Rhodes grass mulch, capsicum mulch
Second crop	**Fallow**	**Zucchini**	**Zucchini**	**Zucchini**	**Zucchini**
Cultivation	No tillage	No tillage	No tillage	No tillage	No tillage
Ground cover in Bed	Trash blanket and soybean trash	Plastic mulch	Plastic mulch	Forage sorghum mulch	Forage sorghum mulch
Ground cover in inter-row	Trash blanket and soybean trash	None	Forage sorghum mulch	Forage sorghum mulch	Forage sorghum mulch
Fertilizer* N, P, K	N/A 0N, 0P, 0K	Soil test based 105N, 8P, 111K	Improved 82N, 13P, 76K	Soil test based 104N, 19P, 86K	Soil test based 104N, 19P, 86K
Third crop	**Cane Plant crop**	**Cane Plant crop**	**Cane Plant crop**	**Cane Plant crop**	**Pumpkin**
Cultivation	No tillage/ minimum disturbance	Full tillage in beds and inter-rows	Tillage only in beds	No tillage/ minimum disturbance	No tillage/ minimum disturbance
Ground cover	Soybean/ cane trash residues	Nil	Forage sorghum/zucchini residues	Forage sorghum/ zucchini residues	Forage sorghum residues
Fertilizer in Cane/ pumpkin N, P, K	6ES 60N, 3.5P, 100K	Traditional 146N, 3.5P, 100K	6ES 146N, 3.5P, 100K	6ES 146N, 3.5P, 100K	113N, 26P, 163K
Herbicide (refer table 2)	Knock-down and low rate residual	Residual – traditional rate	Knock- down and low rate residual	Knock-down	Knock-down
Fourth crop	**Cane 1st Ratoon**	**Cane 1st Ratoon**	**Cane 1st Ratoon**	**Cane 1st Ratoon**	**Fallow**
Cultivation	Nil	Nil	Nil	Nil	Nil
Groundcover	GCBT	GCBT	GCBT	GCBT	
Herbicide (refer table 2)	Knock-down and low rate residual	Residual – traditional rate	Knock- down and low rate residual	Knock-down	Knock-down
Fertiliser N, K	95N (banded), 120K	160N (broadcast), 120K	140N (banded), 120K	50N (banded), 120K	

*** Conventional fertiliser rate of 161 N, 33 P, and 162 K kg/ha was applied to other end of the trial in all treatment**

Table 2. Summary of herbicide applied to different treatments in the sugarcane plant and 1st ratoon crops

Crop stage	Date	Treatment	Active ingredient (and rate, g/ha)
Plant crop	19/09/2011 (Applications at planting)	Treatment A	Glyphosate (810g), 2,4-D (937.5g)
		Treatment B	Paraquat/Diquat (324/276g), Metolachlor (1248g), Atrazine (1350g)
	Filling in on 22/12/2011	Treatment C	Atrazine (1980g), Pendamethalin (1001g), Paraquat/Diquat (324/276g)
		Treatment NFS	Paraquat/Diquat (324/276g), Metolachlor (1248g), Atrazine (1350g)
	11-12/1/2012 (2nd herbicide applications)	Treatment A*	
		Treatment B	Paraquat/Diquat (324/276g), Metribuzin (1350g)
		Treatment C	Paraquat/Diquat (324/276g), Metribuzin (1350g)
		Treatment NFS	Paraquat/Diquat (324/276g), Metribuzin (1350g)
1st ratoon	8/11/2012	Treatment A	Paraquat (400g), Fluroxypyr (260g), 2,4-D (625g)
		Treatment B	Paraquat (400g), Metribuzin (750g), 2,4-D (625g)
		Treatment C	Paraquat (400g), Diuron (1620g), 2,4-D (625g)
		Treatment NFS	Paraquat (400g), Fluroxypyr (260g), 2,4-D (625g)

*Treatment A was companion-planted with soybeans after fill-in and was not sprayed with any herbicide

2 Results and discussion

2.1 Rainfall, Runoff and Total soil and nutrient losses

The monitoring period was characterised by above average rainfall at times in each of the 2010/11 (capsicum), 2011/12 (sugarcane plant crop) and 2012/13 (sugarcane 1st ratoon) summer seasons (Fig. 1), with these high rainfall periods resulting in intense (and some cases overwhelming) runoff events in the capsicum/soybean/fallow phases of the break period, and in the sugarcane plant and 1st ratoon crops. Conversely, there was not enough rainfall to generate any runoff during the zucchini/forage sorghum crops.

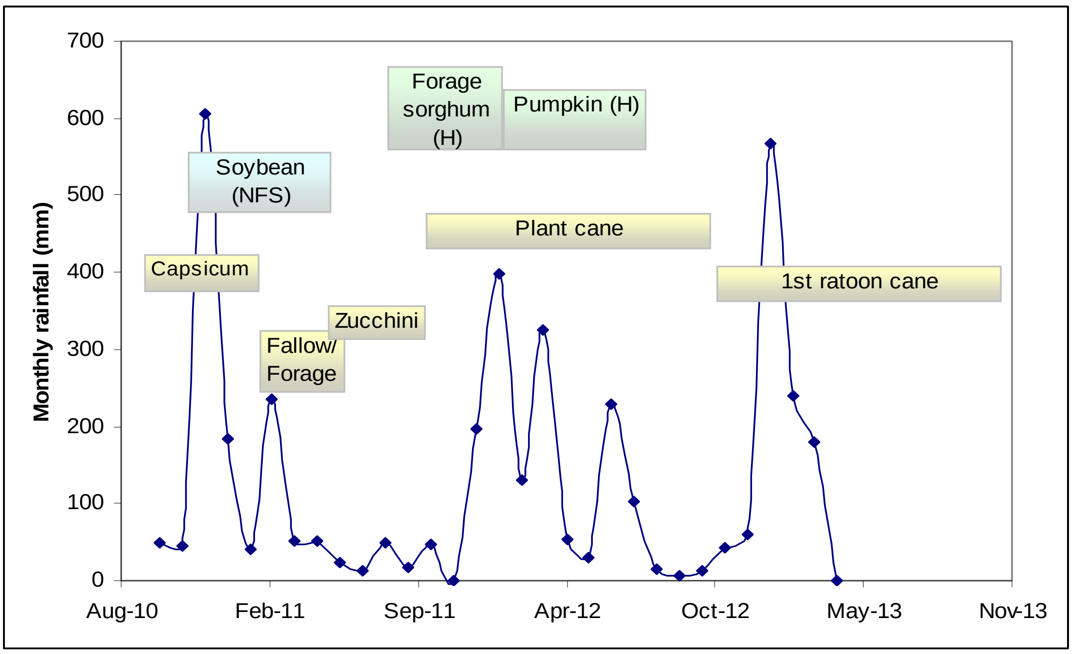


Figure 1. Monthly rainfall totals relative to crop establishment periods at the Bundaberg monitoring site.

There were different treatment effects on runoff volumes during the vegetable/sugarcane fallow phase and the subsequent sugarcane cropping phase (Fig. 2). During the former from Oct 2010-Aug 2011, measured runoff volumes followed a trend of Treatment C> Treatment B> Treatment A> Treatment H> NFS, with runoff in the soybean/fallow sequence in NFS less than 20% of that in Treatment C. Monitoring was not possible on some occasions of severe flooding. While the effects of plastic mulch on runoff were expected (Treatments C and B versus Treatments A and H), the reduction in runoff volumes arising from the inter-row mulch (Treatment B) in a plastic mulch system were noteworthy. Similar trends are evident for measured soil loss (Fig. 3). In the vegetable systems, moving from management system C to B to A reduced sediment loss by 50 and 65%, but the most successful system (NFS) generated only 15% of the sediment of Treatment C. These data clearly illustrate the beneficial role of surface cover in reducing runoff and soil loss. It is also worth noting that the reduction in runoff was accompanied by a sharp increase in deep drainage in the 'open' systems (Treatments A, H and NFS), with implications for leaching of mobile nutrients like nitrate-N (discussed later).

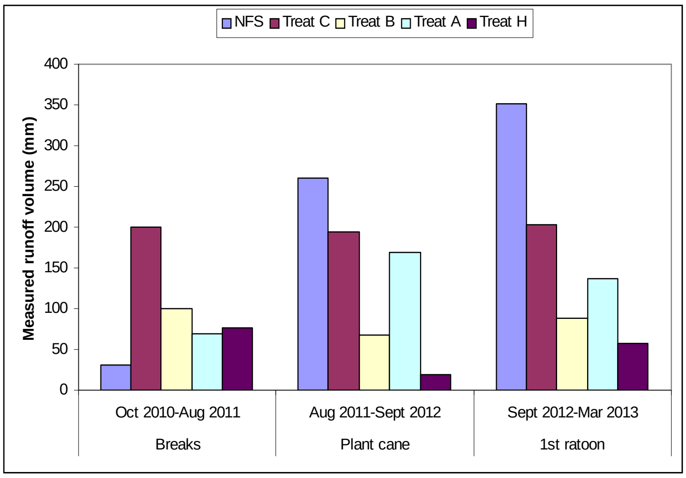


Figure 2. Cumulative runoff for different management systems during the vegetable/soybean and sugarcane phases.

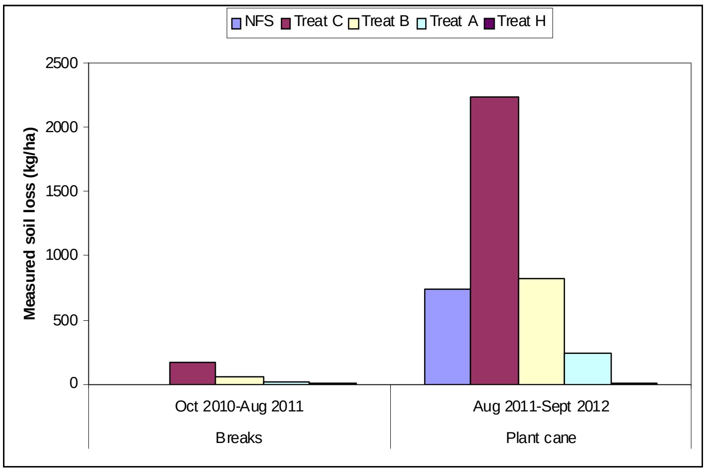


Figure 3. Cumulative sediment loads for different management systems during the vegetable/soybean and sugarcane phases.

The trend of results for measured runoff volume changed during the sugarcane plant crop, with effects seemingly related to the effects of tillage on drainage capability. The measured runoff volume (Fig 2) was approximately double in the zero tilled treatments (Treatment A and NFS) compared to treatments that had tillage (Treatment B and C). However, these large differences in runoff volumes did not translate into differences in loss of sediment (Fig. 3), which was a function of not only runoff volume but also the amount of soil disturbance from tillage operations (including filling in), with the losses in order of Treatment C>> Treatment B and NFS> Treatment A. There was at least a 50% reduction in measured soil loss for the treatments that had strategic tillage in the bed (Treatment B) or for the treatments with minimum tillage (Treatment A and NFS) compared to the full tillage treatment (Treatment C). The reduction in soil loss in Treatment A relative to NFS was at least partly due to the establishment of a companion planting of soybean in the inter-row areas at the time of filling in. While seemingly attractive, this practice could impact negatively on cane growth if soybean effectively acted as weed, competing with the cane crop for water or nutrients.

Soil loss during the plant crop was dominated by runoff events that occurred after filling in (NFS – 71% of yearly total) or after both planting and filling in (70-90% of yearly totals in Treatments B and C), when soil freshly loosened by tillage was present (Fig. 4). Relative losses were much smaller around planting in Treatments A and NFS, due to the minimal disturbance in those systems, but the soil disturbance from filling in was much more damaging.

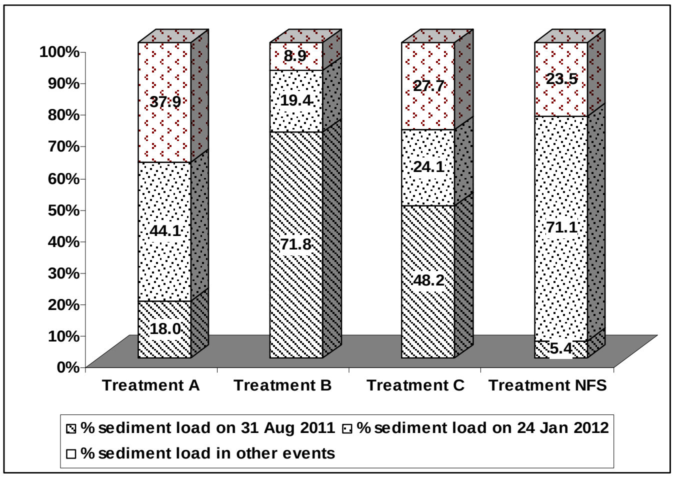


Figure 4. Percentage sediment loads in different events during sugarcane plant crop in 2011-12.

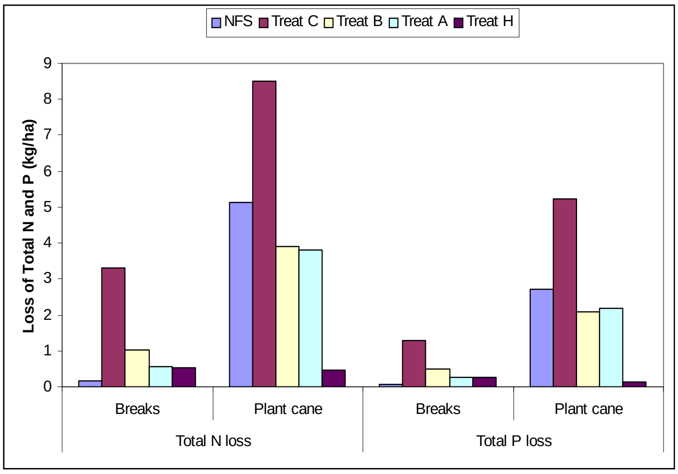


Figure 5. Losses of total N and P in runoff during the vegetable/soybean and sugarcane plant crop phases.

While the first ratoon crop was not fully monitored for runoff and water quality, the trend of results from the few runoff events in early 2013 were similar to that of plant cane crop (Fig. 2). The treatments that had tillage (Treatment B + Treatment C - total of 291 mm) had lower measured runoff volumes than treatments that had no tillage in the previous season (Treatment A + NFS - total of 489 mm).

Relatively small losses of Total N and P were consistent with runoff and sediment movement during the vegetable/soybean phase, with differences between management systems consistent with differences in fertiliser inputs. However in the sugarcane plant crop, the markedly greater losses seemed to be related more to the nutrient input from crop residues (Fig. 5). While the full tillage and greater nutrient inputs in Treatment C resulted in the highest losses (8.5 kg N/ha and 5.2 kg P/ha), the losses from the NFS (5.1 kg N/ha and 2.7 kg P/ha) were higher than that from both Treatments A and B, although all were much higher than recorded in the vegetable/soybean phase. We suspect that surface decomposition of the larger and relatively N and P-rich soybean residue, combined with greater runoff volumes, contributed to the relatively higher losses in NFS.

Across the monitoring period Total N losses were low (4.4 to 11.8 kg N/ha) and followed the same trends as soil loss, with at least a 50% reduction in Total N loss for the treatments that had reduced tillage compared to full tillage. Cumulative Total P loss was similarly low (2.5 to 6.5 kg P/ha) and showed similar trends to Total N.

2.2 Dissolved Inorganic N, Filterable reactive P and leached Nitrate-N

Losses of both Dissolved Inorganic N (DIN) and Filterable Reactive P (FRP), the biologically active fractions of total N and P losses, were also much greater during the sugarcane plant crop than during the vegetable or soybean phases (Fig. 6). Higher losses in Treatment A, and to a lesser extent NFS, were related to residual N and P fertiliser not utilized by a poor zucchini crop (Treatment A) or the surface-managed residues from the grain (NFS) or intercropped (Treatment A) soybeans. The proportion of Total N lost as DIN was highest for these treatments with legumes (56.3% and 22.5% in Treatment A and NFS, respectively). Similar trends were evident for the proportion of Total P lost as FRP, with Treatments A (59%) and NFS (39%) recording greater proportional losses of Total P as FRP than Treatments B and C (6-7%).

The relatively small runoff losses of N (either Total or DIN) were at least partly due to the fact this site was established on a relatively well drained sandy loam soil, where deep drainage of water (from rainfall and irrigation) and soluble nutrients were regularly recorded. An example of the profile nitrate-N concentrations after harvest of the zucchini and soybean crops (Fig. 7) clearly shows accumulation of nitrate-N in the soil profile when fertiliser application rates exceeded crop demand, and leaching of that nitrate-N well below the crop root zone where there was sufficient time and water flux (ie. during the capsicum crop and subsequent fallow in Treatment C).

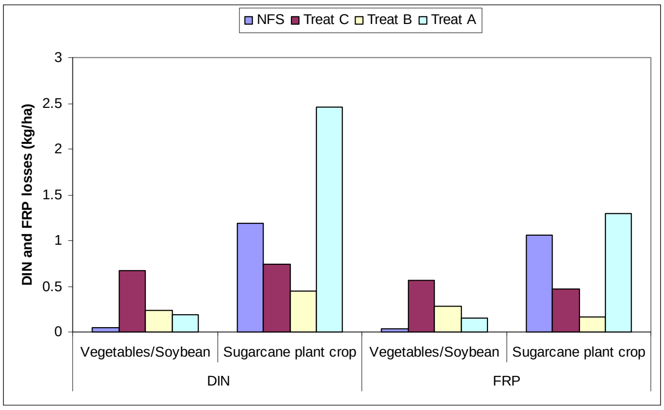


Figure 6. Losses of Dissolved Inorganic N (DIN) and Filterable Reactive P (FRP) in runoff during the vegetable/soybean and sugarcane plant crop phases.

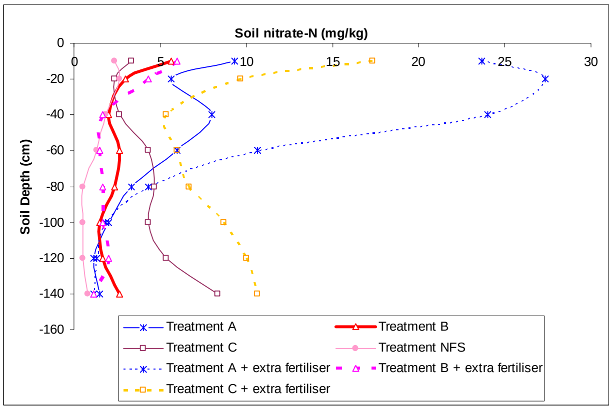


Figure 7. Soil nitrate-N (mg/kg) concentrations at different depths after zucchini harvest

The deeper profile layers immediately after capsicum harvest in Treatment C contained 27 and 22 mg/kg of NO_3-N at 110-130cm and 130-150cm depths, respectively, while those same layers after harvest of the zucchini crop, grown using nutrient recommendations based on preplant soil tests, only showed concentrations of 5 to 8 mg/kg NO_3-N. This reduction in deep NO_3-N concentrations represents leaching losses of 100-110kg N/ha which, given minimal in-crop rainfall, was mainly due to water from irrigation. Soil moisture monitoring showed irrigation water was regularly wetting below 40cm depth, ensuring adequate water penetration into deeper soil layers to facilitate leaching losses of NO_3-N.

These losses exceed the cumulative Total N losses in runoff during the vegetable and plant cane periods combined by an order of magnitude (see Fig. 5), and provide a very different assessment of the offsite inorganic N losses from these vegetable farming systems than indicated by the low DIN losses in Fig. 6 – especially if this leached NO_3-N reaches deep water tables, and ultimately moves laterally into streams. Leaching of NO_3-N was also clearly evident where additional fertiliser was applied in the high input subplots (Fig. 6), with that N applied via trickle irrigation enriching most profile layers to the depth of sampling (150cm).

There was little evidence of residual leached NO_3-N in deep soil layers after the sugarcane plant crop. However, given that after zucchini harvest there was 40-50 kg NO_3-N/ha from 110-150cm, the free draining nature of these soils and the heavy rainfall recorded in Dec and Jan 2012 (the early stages of the plant crop when N demand was low), it is highly likely that at least this N was also lost deeper in the soil profile or into the local water table.

2.3 Herbicide losses in runoff and dissipation in soil (Sugarcane phase)

The time between the herbicide application and rainfall or irrigation significantly influenced the herbicide concentrations measured in runoff water. Herbicide dissipation in soil and trash was monitored, as well as concentrations and loads in runoff water during the sugarcane plant crop and the early stages of the 1st ratoon. All herbicides recorded relatively short half-lives of 5-25 days with the exception of Diuron (81 days) and Paraquat (260 days), so runoff risks after herbicide application differed greatly with herbicide choice.

Herbicide concentrations in runoff water in the plant crop were generally consistent with application rates (Table 2). For example, Atrazine loads and Event Mean Concentrations (EMC) were higher in Treatment C compared to Treatment NFS (Table 3). A notable exception was where Metribuzin loads and concentrations were higher in Treatment NFS than Treatment C, despite similar application rates. This was due to the presence of surface trash in Treatment NFS, which intercepted the applied Metribuzin, rather than allowing it to contact soil as in Treatment C. Metribuzin residues were subsequently leached from trash during rainfall and runoff events.

Table 3. Summary of herbicide loads (g/ha) and event mean concentrations (EMC, µg/L) in different treatments during the sugarcane plant cane crop in 2011-12

Treatment	No of sampled events	Sampled Runoff	**Atrazine**	Desethyl Atrazine	Desisopropyl Atrazine	Metolachlor	Pendi-methalin	**Simazine**$	**Metribuzin***
Loads		mm	g/ha	g/ha	g/ha	g/ha	g/ha	g/ha	g/ha
Trt NFS	4	55.5	19.22	1.161	0.458	8.108	0.000	0.132	7.044
Trt C	4	56.1	24.081	2.090	1.059	0.227	14.826	0.103	1.504
Trt B	3	31.7	9.272	1.276	0.613	6.239	0.000	0.100	0.531
EMC		mm	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
Trt NFS	4	55.5	34.6	2.091	0.825	14.605	0.000	0.237	14.263
Trt C	4	56.1	42.9	3.726	1.889	0.406	26.433	0.185	3.608
Trt B	3	31.7	29.3	4.031	1.935	19.702	0.000	0.317	1.677

* Only two sampled events due to later application times (see Table 2);

$ - residues from applications in previous cane crops several years ago

During plant cane, reduced herbicide application rates in Treatment B and NFS resulted in similar weed control compared to the higher rates in Treatment C, suggesting current application rates could be reduced. When 30% less Atrazine was applied in NFS than Treatment C, Atrazine losses were reduced by 20% despite similar runoff volumes while in Treatment B, 40% less runoff was accompanied by a 62% reduction in Atrazine loss (Figure 2 & Table 3). Furthermore, knock down herbicides combined with inter-row soybean mulch in Treatment A were effective in controlling weeds and producing a reasonable cane crop without use of residual herbicides. However, the resulting elimination of residual herbicides in runoff was accompanied by a 12% decline in yield (Fig. 8) - possibly due to soybeans acting as weed.

During the ratoon crop, there were no runoff-generating rainfall events for *ca*. 2.5 months after herbicide application, resulting in substantial dissipation of applied herbicides and low concentrations in events when runoff was finally recorded (late Jan 2013). For example, concentrations of 2,4-D (<0.4 µg/L), Atrazine (0.01 µg/L) and Metribuzin (0.4 µg/L) were recorded in runoff on the 25th - 28th Jan 2013 in the respective treatments. However, Diuron concentrations in runoff from the event on 28th Jan 2013 in Treatment C were much higher at 14 µg/L, indicating the continued persistence of Diuron in soil several months after application. Unlike during the plant crop, replacing residual herbicides like Diuron with alternative knockdown herbicides in Treatments A and NFS resulted in poor weed control and additional herbicide applications were necessary later in the crop.

2.4 Impacts of management on vegetable and sugarcane yields

Changed management systems significantly reduced the offsite movement of sediment, nutrients and herbicides in this these cropping systems, but benefits were achieved at the expense of crop productivity – especially in the vegetable crops (Fig. 8). Capsicum yields in Treatments B and C were only *ca*. 80% and 45% of those achieved in Treatment C (standard industry practice), with gross returns showing a similar pattern and the profitability of those crops eroded substantially (Treatment B) or eliminated entirely (Treatment A). Zucchini yields followed a similar pattern despite nutrient inputs being guided by preplant soil testing, with yields in Treatment B *ca.* 80% and those in Treatment A and H only *ca.* 45-50% of Treatment C, respectively. Trends were similar even when a very high fertiliser rate was applied as a standard to all the treatments, with yields of Treatments B, A and H still 85%, 52% and 56% of Treatment C, respectively. The similar relative treatment rankings despite very different seasonal conditions, and in the case of zucchini, nutrient inputs, suggest that management practices with the most improved runoff water quality may negatively impact productivity and profitability in vegetable production system. Trends continued in the continuous horticulture system (Treatment H), where improved water quality again was associated with poor productivity. The pumpkin yields were only 39% of those obtained in commercial crops under the same seasonal conditions.

While similar productivity rankings were observed between treatments in the sugarcane plant crop, the magnitude of differences in sugar yields was much lower than in vegetables. Yields of sugar from Treatments A, B and NFS were 88%, 92% and 86% of Treatment C, respectively, suggesting there may be more scope to maintain sugar yields while improving the water quality.

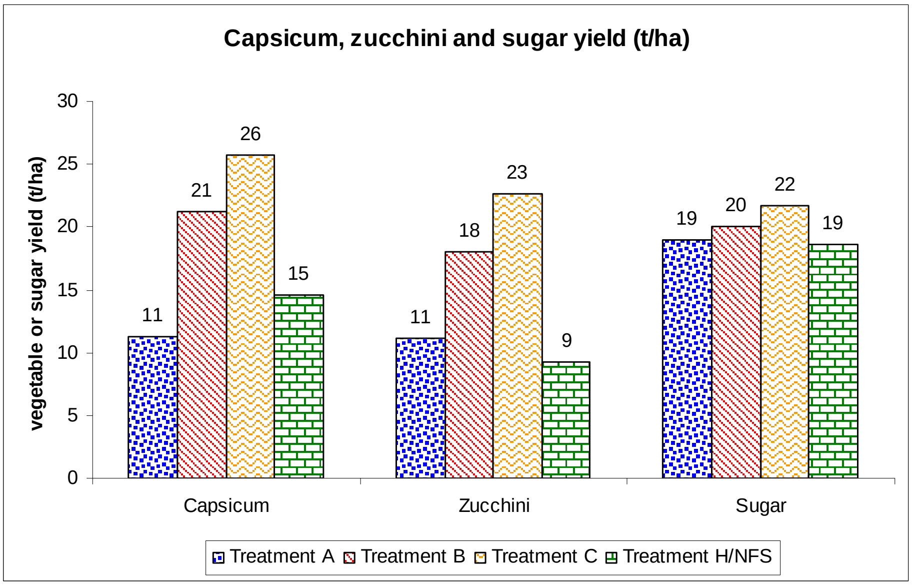


Figure 8 Vegetable and plant crop sugar yield for different managements during 2010-2013

3 Conclusion

Results indicate that sediment and nutrient losses during grain legume or vegetable rotations with sugarcane are dominated by losses occurring during the sugarcane crop. The highest risk periods for sediment and nutrient loss were clearly during the transition period between crop systems (either from cane to vegetable/legume or from vegetable/legume back into cane) especially for those management practices where soil cover is low and aggressive tillage is used. However, a further risk period was during the early stages of the sugarcane plant crop, where soil disturbance associated with filling in after cane planting lead to significant loss of soil, nutrients and herbicides. While sediment and nutrient loads during the 1st ratoon crop (with trash cover and no soil disturbance) were not fully monitored, results from monitoring during the Jan 2013 flood event indicated that runoff water quality was much better than during the plant cane crop.

While total soil loss was low in all management systems, due to combination of low slopes and well drained soils, significant improvements could still be made by reducing tillage and improving ground cover. The impact of these improvements could be increased if soil compaction from the preceding sugarcane crop cycle could be avoided through adoption of precision controlled traffic systems. In this study unameliorated soil compaction in reduced or zero tillage systems lead to greater runoff and hence an increased risk of offsite losses.

An area of concern for the sugarcane-grain legume cropping system is the relatively high DIN loads in runoff that seemed to result from surface decomposition of legume residues. While absolute losses were small compared to other central and north Queensland sites (1.2 kg DIN/ha with old residues in NFS and *ca*. 2.5 kg N/ha with fresh legume companion crop residues in Treatment A), they were markedly higher than from tilled management systems without legumes but with markedly higher N fertiliser inputs. Options to manage legume residues to minimize DIN losses and maximize crop N recovery are needed.

While soil and nutrient losses in runoff were relatively low during the vegetable phase of vegetable-cane rotations, this result severely underestimates the potential impact of excessive nutrient loads on water quality in receiving waters. Substantial nutrient leaching losses (especially of NO_3-N) were recorded down the profile during the vegetable crops, and while sugarcane was able to extract nutrients from deeper in the soil profile than vegetables, large losses had occurred from the cane root zone before the crop was able to access these leached nutrients.

Herbicide losses during the sugarcane crop were related to the rate of application, the rate of dissipation on soil and trash and the timing of application relative to runoff events. The risk of herbicide runoff loss appeared to be higher when products were applied onto trash (cane or soybean), rather than to bare soil. Replacing residual herbicide such as Diuron with less persistent knockdown herbicides resulted in poor weed control and additional herbicide applications at the later stages of the crop, suggesting alternative chemicals or application strategies will be needed to maximize water quality benefits without compromising management outcomes.

The decline in productivity associated with management strategies that delivered improvements in runoff water quality, especially in vegetable production, will need to be addressed before commercial adoption of these strategies is likely. While productivity loss was smaller in the sugarcane phase, there would appear to be easy gains (2 t sugar/ha in these studies) from optimising the N fertiliser rate following a grain legume fallow crop in reduced tillage systems.

Future research needs

1. The most sensitive period for soil and nutrient loss occurs during the transition period between crops in the rotation, so research into the timing (spring v autumn) and method of transition (Direct Drill, Zonal Tillage or Full Tillage) and their impact on sediment and nutrient loads is warranted.
2. The small sugar yield difference between full tillage and reduced tillage treatments suggests a system with reduced tillage in permanent beds, combined with trash mulch in the inter-rows and improved fertiliser strategies could be used to address the yield gap. Options could include use of a break crop after vegetables to produce enough biomass to form a useful inter-row mulch, combined with minimum tillage cane planting, or alternately planting a mulch crop in the final vegetable crop inter-rows a couple of weeks before final harvest.
3. Closing the vegetable yield gap between Treatments B and C to allow improved water quality while maintaining productivity and profitability. Nutrient availability was the main factor influencing the yield gap between Treatment B and C during the vegetable phase, so further studies involving nutrient placement options (band frequency, position, composition) and more effective deployment of split nutrient applications without increasing total nutrient input should be explored. The interactions of these strategies with inter row mulches also needs further testing.
4. Given the unusually wet weather during the summer growing seasons in this study, our results likely represent a worst-case scenario. Some of these systems need testing under drier ('normal') rainfall conditions, which clearly suggest a longer term study to explore the performance of these cane-intensive horticulture rotations that are very important in this region.
5. Future studies on herbicide monitoring are warranted with rainfall simulators as the most sensitive period for runoff of most products is the first few weeks after application.

The current study has shown that variations around Treatment B (modified nutrient application strategies under plastic mulch, but with an inter-space mulch to minimize runoff and sediment loss) may be the most practical solution to improve water quality and maintain productivity. However more work is required to optimize this approach and reduce the size of any potential productivity gap. Better matching of nutrient inputs by fertigation with the rate of crop demand and possibly the optimal distribution of nutrients (bands v mixing) to allow uptake by roots of different crop species may reduce the productivity penalty for reducing total nutrient inputs.

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