

Article

# Impact of Practice Change on Runoff Water Quality and Vegetable Yield—An On-Farm Case Study

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**Abstract:** Intensive agricultural practices in farming systems in eastern Australia have been identified as a contributor to the poor runoff water quality entering the Great Barrier Reef (GBR). A field investigation was carried out to measure the off-farm water quality and productivity in a coastal farming system in northeastern Australia. Two vegetable crops (capsicum and zucchini) were grown in summer 2010–2011 and winter 2011 respectively using four different management practices (Conventional—plastic mulch, bare inter-row conventional tillage and commercial fertilizer inputs; Improved—improved practice with plastic mulch, inter-row vegetative mulch, zonal tillage and reduced fertilizer rates; Trash mulch—improved practice with cane-trash or forage-sorghum mulch with reduced fertilizer rates, minimum or zero tillage; and Vegetable only—improved practice with Rhodes grass or forage-sorghum mulch, minimum or zero tillage, reduced fertilizer rates). Results suggest improved and trash mulch systems reduced sediment and nutrient loads by at least 50% compared to conventional systems. The residual nitrate nitrogen in soil accumulated at the end-of-break crop cycle was lost by deep drainage before the subsequent sugarcane crop could utilize it. These results suggest that future research into establishing the linkages between deep drainage, groundwater quality and lateral movement into adjacent streams is needed. The improvement in runoff water quality was accompanied by yield reductions of up to 55% in capsicum and 57% in zucchini under trash mulch systems, suggesting a commercially unacceptable trade-off between water quality and productivity for a practice change. The current study has shown that variations around improved practice (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 thus reduce the size of any potential productivity and profitability gap that would necessitate an expensive policy intervention to implement.

**Keywords:** capsicum; zucchini; runoff; nutrients; sediments; GBR

## 1. Introduction

Agricultural intensification to feed the rapidly rising global population [1] has led to large scale environmental problems, especially degradation of soil and water resources [2–4]. In northeastern Australia, sugarcane and grazing lands have been a major focus for export of nutrients and herbicides into the Great Barrier Reef (GBR) lagoon [5–9]. Studies of vegetable cropping systems and their impact on offsite movement of nutrients to the GBR lagoon are limited compared to sugarcane and grazing

systems. An initial investigation carried out in this region [10] identified the presence of nutrients (nitrogen and phosphorus) and herbicides (e.g., diuron and atrazine) in runoff water from vegetable, macadamia and sugarcane production systems.

The Burnett Mary region is the catchment for rivers flowing into the southern part of the GBR. The region is known for producing sugarcane and horticultural produce, with the value of the horticulture industry in the region growing from AU\$27.4 M in 1980 to \$467.8 M in 2010 [11]. More than 70% of that gross value is derived from intensive vegetable production, with the majority of that grown in rotation with sugarcane—often as a one (year vegetable) in five year rotation. The favourable sub-tropical climate allows vegetables to be grown year round, with at least two vegetable crops grown during the vegetable break year.

The amount of fertilizer utilized in intensive vegetable production is of great concern in Australia [12]. There is strong evidence that conventional vegetable production systems in Australia have the potential to cause adverse environmental impacts through leaching of accumulated nutrients to groundwater or via runoff into surface water receiving bodies [12–14]. The sediments and nutrients in runoff water are likely to affect river water quality and downstream ecosystems such as the GBR [6]. These concerns have necessitated a focus on improving the vegetable management practices to reduce the environmental impact of farming practices.

In the Burnett Mary region, nutrients are applied to vegetables as a soil-applied basal application with subsequent topdressings through trickle irrigation. These in-season applications are scheduled to occur regularly from planting to a week before the last harvest of vegetables, although occasionally a scheduled fertilizer application is missed if plant tissue testing indicates nutrient sufficiency. Productivity and product quality are the primary drivers of nutrient application strategies, rather than nutrient use efficiency.

The Australian Government allocated \$200 million through the Reef Rescue program to help growers and managers improve farming practices [15] in an attempt to reduce the amount of nutrient and sediment leaving farms and subsequently improving the quality of runoff water entering the GBR lagoon. This five year investment (2008–2013) was initiated to provide sound data quantifying the reduction in pollutant loads arising from the adoption of improved farming practices. Currently, there is a distinct lack of scientific data to support such linkages in Great Barrier Reef catchments, and the magnitude and timeline associated with the improved outcomes are not clear.

In addition to the shortage of seasonal or annual monitoring of farm scale nutrient losses from vegetable cropping systems in GBR catchments, there are also few field programs comparing grower standard practices with other management approaches. Given the general scarcity of field scale data on nutrient loss from intensive vegetable cropping systems, the ability to reliably predict the impact of changed management practices on water quality in GBR catchments is seriously limited.

Our study is one of the first of its kind for the vegetable industry and is aimed at addressing this current knowledge gap. The central hypothesis was that improved land management practices will improve the quality of runoff water leaving vegetable farms, and was based in the Bundaberg area of the Burnett Mary. The project focused on the measurement of nutrient (nitrogen and phosphorus) concentrations and calculated runoff loads leaving adjacent management strips in a vegetable cropping field. The soil concentrations of these key nutrients and potassium (which is also applied in significant quantities in fertilizer programs but is not linked to water quality outcomes) were also monitored to assess nutrient accumulation. In the case of nitrogen, and to a lesser extent phosphorus, any accumulation in soil below 1 m deep could be linked to a risk of off-farm impacts by deep drainage.

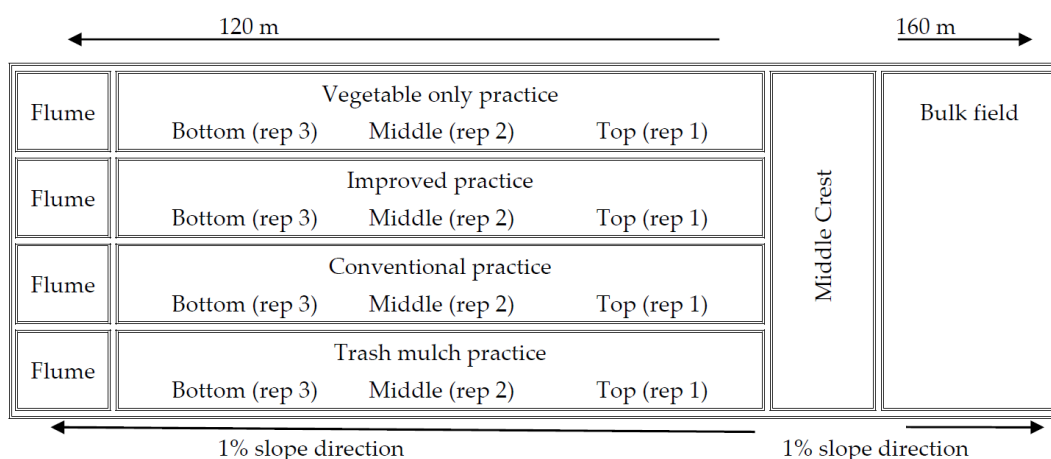
## 2. Materials and Methods

### 2.1. Site Description

The site was established in the Burnett Mary region of Queensland, Australia (supplementary material), in a well-drained field containing a mixture of Yellow Brown Chromosol or Dermosol

(sandy) soils [16] depending on the location. The average sand, silt and clay fractions of the soil were 77%, 16% and 8%, respectively. Soil pH and organic carbon (Dumas combustion) were 6.5% and 1%, respectively. Bulk density (determined using soil coring [17]) was similar in all treatments below the cultivated layer (i.e., 20–25 cm), averaging 1.65–1.79 Mg/m<sup>3</sup>. In the cultivated layer, bulk density was lower in the Conventional practice with tillage (1.18 and 1.35 Mg/m<sup>3</sup> in the 0–10 cm and 10–20 cm layers, respectively), compared to 1.3 and 1.43 Mg/m<sup>3</sup> in the equivalent layers in the Trash mulch and Vegetable only systems with strip or zero tillage. The area has a subtropical climate where long-term average mean maximum and minimum temperatures were 17 and 27 °C. The long-term average rainfall is 1019 mm, with >50% of that rain falling in the summer months (January–March).

The site was a commercial cane field where the sugarcane crop had been grown using trash retention (green cane trash blanket) and controlled traffic technologies. The site was very uniform in the top 70 cm of the soil profile. The field was split into four management units with each unit being 280 m long and 9 m wide (i.e., 5 m × 1.83 m cane rows), with contrasting management systems randomly allocated to each strip. The 280 m length was subdivided into two subunits of approximately 120 m and 160 m based on a highpoint in the middle of the field, with drainage in either direction in response to a 1% slope. Runoff flumes were installed to quantify the runoff, sediment and nutrient movement from the smaller 120 m × 9 m blocks (Figures 1 and 2), with details provided in Section 2.7.1. This paper covers two crops (capsicum and zucchini) separated by a managed fallow phase during a one year break from sugarcane culture (Table 1 and Section 2.4).



**Figure 1.** Field layout of the experimental plot.

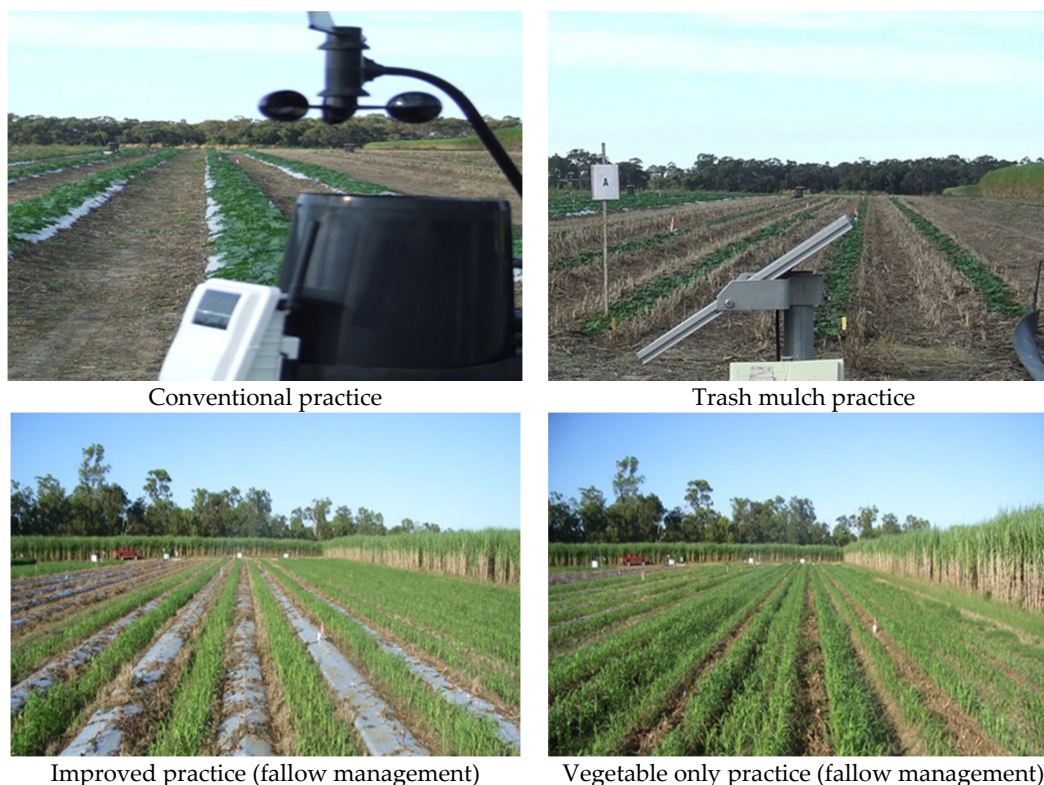
## 2.2. Management Practices

The experiment was conducted in a strip plot design with three pseudo-replications in each strip for soil and plant sampling. Four treatments were investigated in this on-farm case study. The difference between treatments was based on combinations of nutrient management, mulch cover, and tillage management strategies. All treatments were monitored for runoff water quality and leaching losses from deep drainage, as well as crop performance and profitability. A comparative summary of the key features of each treatment is listed in Table 1, with a more detailed description provided below.

**Table 1.** A comparative summary of treatment characteristics.

Treatment	Conventional Practice	Improved Practice	Trash Mulch Practice	Vegetable Only Practice
Previous management	Cane—1.8 m PCTF #	Cane—1.8 m PCTF #	Cane—1.8 m PCTF #	Rhodes grass
<b>First Crop</b>	Capsicum	Capsicum	Capsicum	Capsicum
Trash Management	Removed	Removed	Retained	Retained
Cultivation	Full Tillage	Full Tillage	Strip	None
Ground cover in Bed	Plastic mulch	Plastic mulch	Trash blanket	Rhodes grass
Ground cover-inter-row	None	Jap millet growing	Trash blanket	Rhodes grass
Fertilizer	Traditional	Improved	Improved	Improved
N (kg/ha)	315	147	200	200
P (kg/ha)	130	35	24	24
K (kg/ha)	306	175	200	200
<b>Fallow management</b>	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	Plastic mulch	Plastic mulch	Trash mulch, capsicum mulch	Rhodes grass mulch (RGM), capsicum mulch
Ground cover in inter-row	Capsicum mulch	Capsicum mulch, Jap millet mulch	Trash mulch, capsicum mulch	RGM, capsicum mulch
<b>Second crop</b>	Zucchini	Zucchini	Zucchini	Zucchini
Cultivation	No tillage	No tillage	No tillage	No tillage
Ground cover in Bed	Plastic mulch	Plastic mulch	Forage sorghum mulch	Forage sorghum mulch
Ground cover in inter-row	None	Forage sorghum mulch	Forage sorghum mulch	Forage sorghum mulch
Fertilizer	Soil test based	Improved	Soil test based	Soil test based
N (kg/ha)	105	82	104	104
P (kg/ha)	8	13	19	19
K (kg/ha)	111	76	86	86

# PCTF—Precision control traffic farming.

**Figure 2.** Field photos under different management practices investigated in this case study.

### 2.2.1. Conventional Practice

Conventional practice reflects the current sugarcane-vegetables production systems which are characterized by burning the sugarcane crop residue (trash) and full conventional tillage after cane

harvest. A surface cover of plastic mulch is deployed on the beds prior to establishment of the vegetable crops (plasticulture), bare inter-rows are maintained between vegetable beds and industry standard fertilizer application strategies (both pre-planting and via trickle irrigation in crop, and detailed in Table 1) were followed in both the spring–summer capsicum crop and the autumn–winter zucchinis. The plastic mulch was maintained over the beds for the whole vegetable phase.

#### 2.2.2. Improved Practice

Improved practice differed from conventional practice in that nutrient application rates were reduced for vegetable crops (to rates nominally based on actual crop nutrient accumulation—Table 1) and inter-rows were sown to a cover crop (millet) which was managed as a living mulch to reduce sediment movement. A forage sorghum crop was planted in the inter-row areas post capsicum harvest and mulched before planting zucchini.

#### 2.2.3. Trash Mulch Practice

Trash mulch practice utilized the existing sugarcane trash blanket rather than deploying plastic mulch or using inter-row mulch crops in the vegetable phase. A single pass of a ripper tine in the centre of the permanent cane bed was the only tillage event between the sugarcane and vegetable phases. This tillage event was performed under RTK-GPS auto steer guidance. The vegetables received a reduced rate of fertilizer compared to industry standards (Table 1). Weeds were controlled in the vegetable phase with a combination of knock down herbicides and hand chip-hoes.

#### 2.2.4. Vegetable Only Practice

The continuous horticulture system (Vegetable only practice) was established in April 2010 with permanent beds formed and Rhodes grass (*Chloris gayana* cv. Katambora) established as a mulch crop to provide ground cover prior to capsicum planting. The mulch was subsequently sprayed out before planting, but this organic mulch was re-established between vegetable crops to retain ground cover and enhance soil organic matter. Nutrient inputs were minimized (similar levels to the Trash mulch practice initially—Table 1), with guidance from soil and tissue sampling and nutrient removal assessments.

### 2.3. Capsicum Establishment and Fertilization

Capsicum seedlings (*var. Gospel*) were planted on 13 October 2010 using a mechanical planter and auto steer GPS technology. A uniform spacing of 30 cm was maintained between the plants. Irrigation was applied using subsurface trickle irrigation (*Netafim*<sup>®</sup> Streamline 80 with emitters 20 cm apart, Netafirm Design office, Laverton North, VIC, Australia), with the lines situated approximately 2 cm below the soil surface. Pre-plant fertilizer application was done using a mechanical fertilizer spreader. Fertilizer was applied in a single band 5 cm below the plant line for Trash mulch and Vegetable only practices, whereas in other practices the fertilizer was applied in three bands distributed across the bed but later incorporated into the bed during the bed formation and plastic mulch application.

In-crop fertilizer was applied through the trickle every week using power injector pumps connected to fertilizer mixing tanks and lateral lines for each treatment during irrigation (fertigation). Weekly commercial sap tests were used to guide trickle inputs from week 7 using existing industry benchmarks. The total amounts of major nutrients applied in the different management practices are listed in Table 1.

### 2.4. Fallow Phase

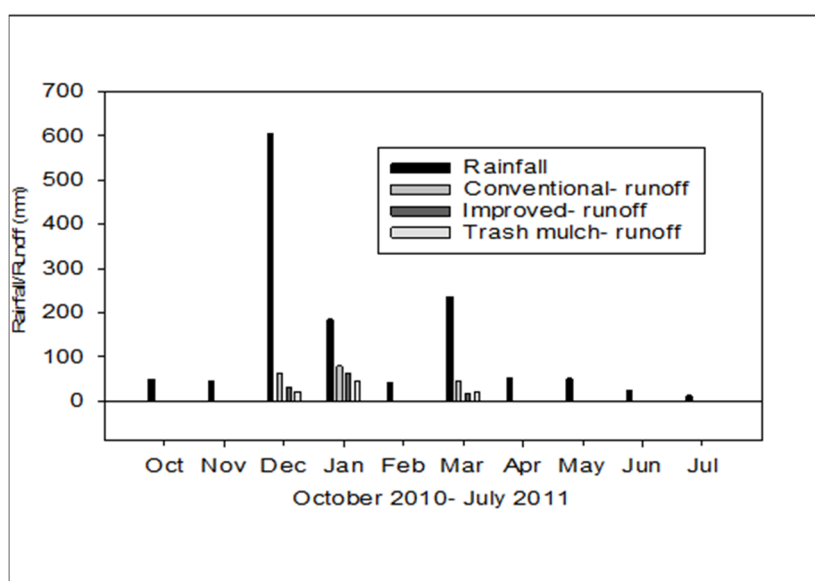
Forage sorghum (*Jumbo*) was planted on 16 February 2011 in inter-rows of Improved, Trash mulch and Vegetable only practices and beds of Trash mulch and Vegetable only practices. They were flail mowed on 15 April 2011 to form the mulch before zucchini planting in May 2011.

### 2.5. Zucchini Establishment and Fertilization

Zucchini seedlings (*var. Regal Black*) were planted on 13 May 2011 using a mechanical planter and auto steer GPS technology. A uniform spacing of 50 cm was maintained between the plants. Irrigation and fertilizer application methods were similar to capsicum, except that the basal fertilizer application was supplied through the trickle, given the presence of plastic mulch in some systems. Total amounts of fertilizer applied are listed in Table 1.

### 2.6. Rainfall

An automatic tipping bucket rain gauge was installed on-site to measure rainfall, recorded at 1 min intervals. A stand-alone rain gauge was also installed at each site to back-up the automatic systems, with rainfall data read manually after each event. A summary of monthly rainfall data is presented in Figure 3.



**Figure 3.** Cumulative monthly runoff and rainfall (mm) from October 2010 to July 2011 during the vegetable production period at the experimental site.

### 2.7. Sampling Description and Analysis

Sampling schedules were devised to assess nutrient and water balances, as well as to quantify off-site losses in both runoff and deep drainage. Profile soil water dynamics were monitored using capacitance probes (in a series of Enviroscan<sup>®</sup> systems, Sentek Technologies, Stepney SA 5069, Australia). Runoff, soil and plant sampling and analysis are described below.

#### 2.7.1. Runoff Sampling and Analysis

San Dimas flumes (200 mm) [18] were used to measure the runoff volume from each treatment. The galvanized steel flumes were manufactured as per standard specifications outlined by Walkowiak [19]. The flumes were installed approximately 5 m away from the end of the vegetable rows (Figure 1), outside the actual cropping area. Steel and rubber belting were used as a barrier to collect runoff from four inter-rows and direct the runoff water into the flume for flow measurement and sample collection. The standard flow calibration equation for converting flow height into flow discharge for a 200 mm San Dimas flume is:

$$Q \text{ (L/s)} = 0.053 \times \text{depth (mm)}^{1.34}$$

The flow height was measured using a Teledyne ISCO 730 (Teledyne ISCO, Lincoln NE 68504, USA) bubbler module connected to a Teledyne ISCO 6712 standard portable water sampler which logs the flow height and rainfall in minute intervals. The module uses a differential pressure transducer and a flow of bubbles to measure liquid levels to determine flow height.

Runoff volumes, generated in response to either rainfall or irrigation, were aggregated over a 24 h period (9 a.m. to 9 a.m.) that was defined as a runoff event. A uniform time interval was used to determine sample intervals during runoff events in early summer 2010–2011, so that runoff water characteristics were captured for the entire hydrograph. As the 2010 summer season was extremely wet, after a number of runoff events the samplers were re-programmed to flow volume-based sampling, rather than the initial time-based procedure. The flow weighted composite sampling was adopted to reduce the analytical cost and is reportedly more accurate because the discharge volume is constant for each representative sample [20,21]. After each runoff event, samples were collected and frozen immediately prior to transporting for analysis. Samples generated from each event were analyzed for total suspended solids (TSS), and dissolved and total nutrients using standard procedures at the Chemistry Centre, Department of Science, Information Technology, Innovation and Arts, EcoSciences Precinct, 41 Boggo Road, Dutton Park using American Public Health Association method [22] (Table 2).

**Table 2.** Summary of analytical methods for soil, plant and runoff water used in the experiment.

Sample	Analyte	Name	PQL *	Unit	Method Description
Water	NH <sub>4</sub> -N	Ammonium nitrogen as N	0.002	mg/L	Water: Nutrients (NH <sub>4</sub> NO <sub>x</sub> PO <sub>4</sub> ) dissolved segmented flow analysis
Water	NO <sub>x</sub> -N	Oxidised nitrogen as N	0.001	mg/L	Water: Nutrients (NH <sub>4</sub> NO <sub>x</sub> PO <sub>4</sub> ) dissolved segmented flow analysis
Water	PO <sub>4</sub> -P	Phosphate phosphorus as P	0.001	mg/L	Water: Nutrients (NH <sub>4</sub> NO <sub>x</sub> PO <sub>4</sub> ) dissolved segmented flow analysis
Water	DKN	Dissolved Kjeldahl nitrogen as N	0.04	mg/L	Water: Nutrients (DKN DKP) dissolved AA
Water	DKP	Dissolved Kjeldahl phosphorus as P	0.02	mg/L	Water: Nutrients (DKN DKP) dissolved AA
Water	TKN	Total Kjeldahl nitrogen as N	0.04	mg/L	Water: Nutrients (TKN TKP) low level AA
Water	TKP	Total Kjeldahl phosphorus as P	0.02	mg/L	Water: Nutrients (TKN TKP) low level AA
Water	EC	Conductivity at 25 °C	5	µS/cm	Water: pH + EC + Alkalinity
Water	pH	pH at 25 °C	0		Water: pH + EC + Alkalinity
Water	TSS	Total suspended solids	1	mg/L	Water: Solids total suspended gravimetric
Soil	NH <sub>4</sub> -N	Ammonium Nitrogen	1	mg/kg	Soil: NO <sub>3</sub> -N NH <sub>4</sub> -N extractable 1 M KCl; AA
Soil	NO <sub>3</sub> -N	Nitrate nitrogen	1	mg/kg	Soil: NO <sub>3</sub> -N NH <sub>4</sub> -N extractable 1 M KCl; AA
Soil	KCl-P	Phosphorus	50	µg/kg	Soil: P extractable 1 M KCl; AA
Soil	Colwell-P	Phosphorus	2	mg/kg	Soil: P extractable 0.5 M NaHCO <sub>3</sub> ; AA

\* PQL—practical quantification limit.

### 2.7.2. Calculation of Nutrient and Sediment Loads

Nutrient and sediment loads per rainfall event were calculated by multiplying volumes of runoff water (L/ha) by the flow-weighted concentration of nutrient or sediment (mg/L), while nutrient or sediment losses for each event are presented as event mean concentrations (EMC-nutrient/sediment load in an event/flow volume in same event), total sediment/nutrient loads (kg/ha) and nutrient loads expressed as a percentage of the fertilizer applied. For those events where time-based sampling was done, the event load was calculated using the methodology described by US EPA [20,21]. The results are presented as cumulative totals for the events monitored, similar to the farm scale water quality results presented by Hollinger et al. [23].

### 2.7.3. Soil Sampling and Analysis for Nutrients

Soil samples were collected from three pseudo-replicate areas (designated by transects across the top, middle, bottom slope areas in each management system) before capsicum planting, after capsicum harvest and post zucchini harvest. Soil was aggregated from regular depth increments (0–10, 10–30, 30–50, 50–70, 70–90, 90–110, 110–130 and 130–150 cm) down the soil profile and stored in a cool room (4 °C) prior to analysis. Soluble N and P were determined from KCl-extracts of field-moist soil, while

a complete analysis of key nutrient pools was also undertaken on dried and ground samples for a standard analytical suite [24].

### 2.8. Yield Estimation

Three pseudo-replicate areas, each 10 m × 1.83 m, were marked in each treatment. The capsicum and zucchini crops were harvested as with standard commercial practice (a series of sequential harvests), weighed and the cumulative yield was reported on a per hectare basis.

### 2.9. Statistical Analysis

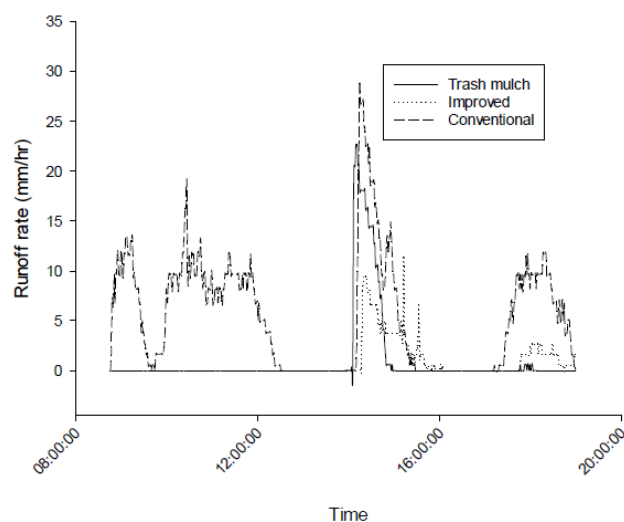
The field (each management unit) was divided into three pseudo-replicates along the slope (top, middle and bottom), with data presented as treatment means with an associated standard error [25]. The nutrient and sediment loads in runoff from different management practices were compared using relative differences between management practices.

## 3. Results

### 3.1. Rainfall and Runoff

Rainfall during the October 2010–July 2011 vegetable rotation period was extremely variable, although the total rainfall received exceeded the annual average. Rainfall during the capsicum crop monitoring period was nearly double (190%, or 884 mm) the long-term average for the region (463 mm). Rainfall during the fallow period between vegetable crops totaled 303 mm (16% lower than long-term average of 362 mm), despite the rain in March 2011 being double the long-term average for that month. Rainfall during the zucchini crop monitoring period was only 60.4 mm (44% of the long-term average of 137 mm), with no runoff events occurring during the zucchini crop monitoring period.

An example of the treatment impact on runoff dynamics during an event on 12 December 2012 (in which 47.5 mm of rain fell) is provided in Figure 4. This shows reductions in runoff volume and increased time to initial runoff in the Trash mulch and Improved practices, compared to Conventional practice.



**Figure 4.** Runoff rates recorded for trash mulch, improved and conventional practices during a capsicum crop that experienced a 47.5 mm rainfall event on 12 December 2010. This event was typical of summer storms in this coastal Queensland region.

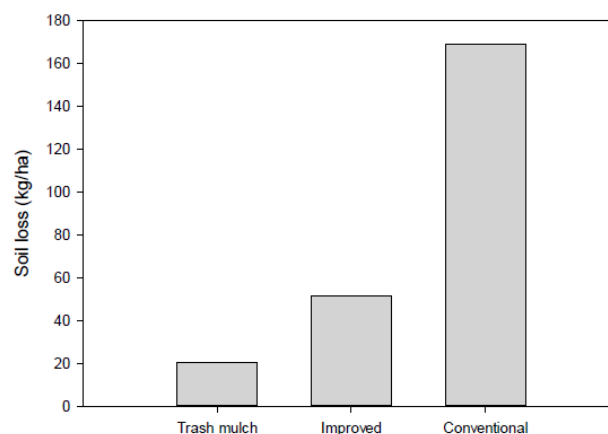


The runoff volume during the capsicum crop and fallow monitoring period revealed significant differences in runoff volumes as a result of management practices. The monthly rainfall and runoff volumes are presented in Figure 3. Conventional practice consistently produced greater runoff volumes than other treatments. The living organic mulch growing in the inter-rows of Improved practice significantly reduced runoff compared to Conventional practice, despite both systems employing plastic mulch over the bed areas. The open system with trash mulch (Trash mulch practice) recorded even less runoff.

### 3.2. Soil Loss, Total N, Dissolved inorganic nitrogen (DIN), Dissolved organic nitrogen (DON), Total P and Filterable reactive P (FRP) Losses

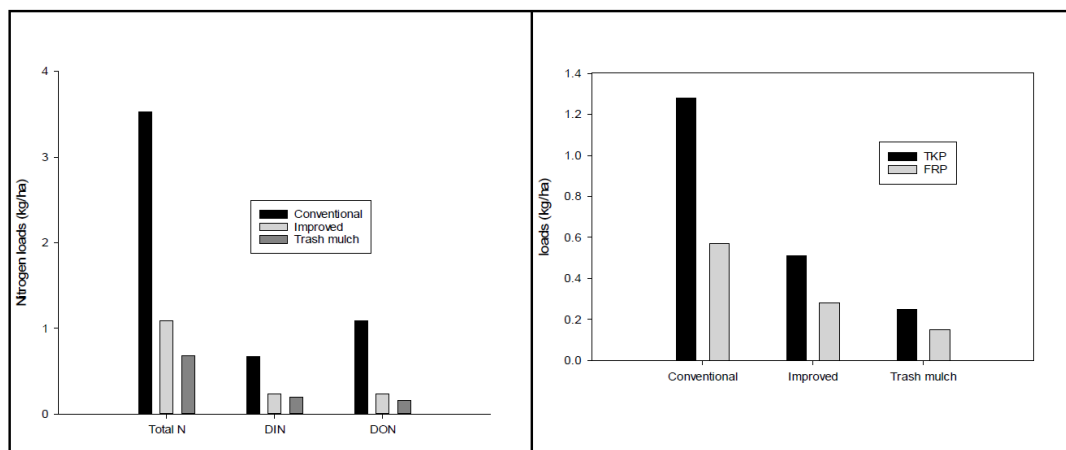
The land management practices had a large impact on soil loss. During the capsicum monitoring period, Conventional practice had the highest soil loss of at least 143 kg/ha (some data were lost during the large rain events during the last week of December 2010 and early 2011), while Improved practice lost only 30 kg/ha soil.

Trash mulch and Vegetable only practices had losses less than 10 kg/ha during the same period. Similarly, in the fallow period, soil losses of 26, 21.8 and 13.2 kg/ha were measured for Conventional, Improved and Trash mulch practices respectively. There was no runoff or soil loss during the zucchini crop production period. In total, Conventional practice had a cumulative soil loss three times higher than Improved practice and eight times higher than Trash mulch practice (Figure 5).



**Figure 5.** Cumulative soil loss from Trash mulch, Improved and Conventional management practices during the vegetable phase.

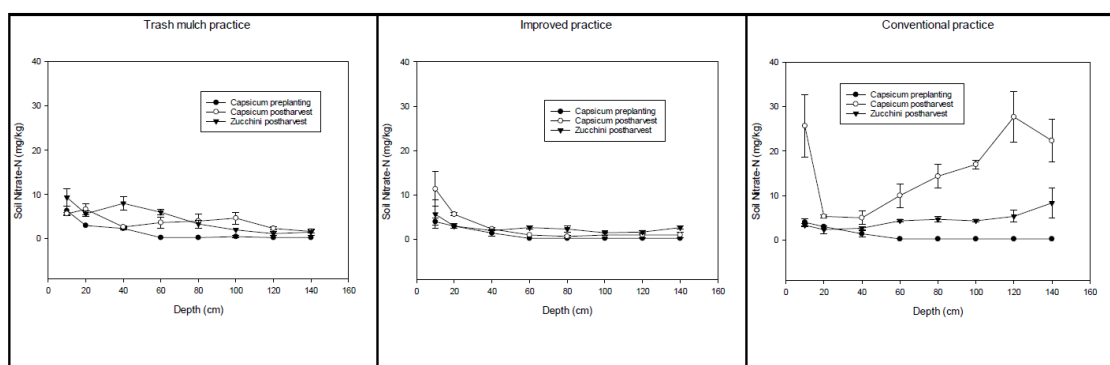
The higher runoff volumes and the bare interspaces in Conventional practice resulted in the highest off-farm movement of total nitrogen (TN), dissolved inorganic nitrogen (DIN), and dissolved organic nitrogen (DON), total phosphorus (TKP) and filterable reactive phosphorus (FRP) in runoff water (Figure 6). The nutrient and sediment loads presented are underestimated, particularly for the extreme weather events that occurred during December 2010. The losses in all the treatments are likely to increase if modelling is used to estimate the additional loads during those extreme events, but treatment relativities are likely to remain the same and not alter the conclusions of these findings.



**Figure 6.** Total nitrogen (TN), dissolved inorganic N (DIN), dissolved organic N (DON), total P (TKP) and filterable reactive P (FRP) losses from Trash mulch, Improved and Conventional practices during the vegetable phase.

### 3.3. Soil Nitrate-N

Soil nitrate-N concentrations were monitored for three treatments (Trash mulch, Improved and Conventional), with results suggesting that there was net nitrate-N accumulation in the soil profile in all treatments after the two vegetable crops (Figure 7). The highest net nitrate-N accumulation was observed in Conventional practice compared to Trash mulch and Improved practices, which was consistent with fertilizer application rates (Table 1). Further, the highest concentrations of nitrate-N in deeper profile layers (27.6 mg/kg at 120 cm and 22.3 mg/kg at 140 cm depth) occurred in Conventional practice at the end of the capsicum crop (Figure 7). The nitrate-N concentrations at the same depths (120 cm and 140 cm) for this treatment after the zucchini crop were only 5.3 and 8.3 mg/kg (Figure 7). With no heavy rainfall during the zucchini crop and root activity, based on soil moisture extraction patterns (data not presented), only observed to a depth of 40 cm, it was unlikely that crop uptake of nitrate-N by zucchini was responsible for the depleted deep nitrate-N concentrations. However, the heavy rainfall in March, (during the fallow period prior to the zucchini planting), combined with irrigation water inputs during the zucchini crop season, provided ample opportunities for leaching losses of nitrate-N.

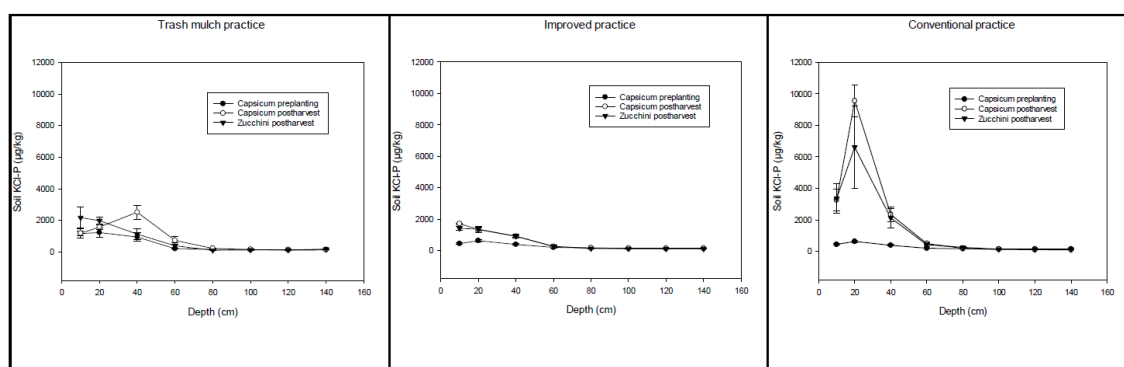


**Figure 7.** Soil nitrate-N dynamics in trash mulch, improved and conventional practices before and after vegetable crops.

The net nitrate-N accumulation at the end-of-break crop cycle in the Improved practice was lower than other practices (Figure 7), suggesting the rational approach used to match the crop uptake with fertilizer N inputs has been able minimize the risk of off-farm environmental impacts.

### 3.4. Soil Phosphorus Status

Soil phosphorus concentrations were monitored by analyzing KCl-extractable P during each crop cycle, and Colwell P at the beginning and end of the vegetable crop phase (i.e., pre capsicum planting and post zucchini harvest). Soil KCl-P concentrations followed a similar pattern to that of nitrate-N (Conventional practice > Improved practice > Trash mulch practice), although treatment differences were only observed in the top 40–60 cm of the soil profile. Highest concentrations (>3000  $\mu\text{g}/\text{kg}$ ) of KCl-P were found in top 40 cm of the soil in the Conventional practice (Figure 8).



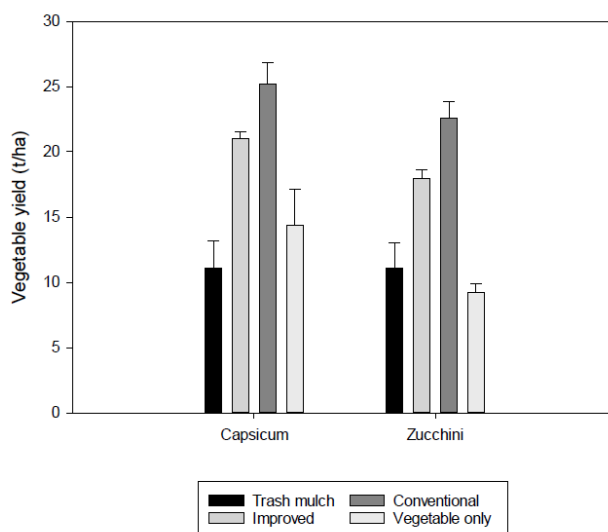
**Figure 8.** Soil KCl extractable-P dynamics in trash mulch, improved and conventional practices before and after vegetable crops.

Soil Colwell P concentrations before and after vegetable cropping suggest an accumulation of phosphorus in top soil of the Conventional practice (data not presented). However, below 10 cm depth, the average concentrations at the end of the zucchini crop were slightly higher than Colwell P concentrations before planting capsicum in Improved and Conventional practice, although differences were not statistically significant. There were no differences between Colwell P concentrations in Trash mulch practice between the beginning and end of the break crop period.

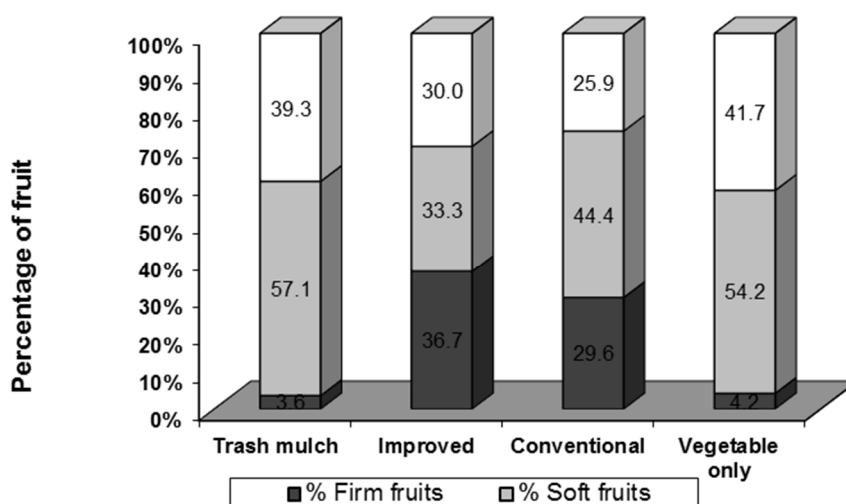
### 3.5. Capsicum and Zucchini Yield

#### 3.5.1. Capsicum Yield

The capsicum fruit yield (Figure 9) was highest for Conventional practice, followed by Improved and Trash mulch practices. Yields in Improved practice were only about 80% of the yield of Conventional practice, while yields in Trash mulch practice were only 45% of Conventional practice. A shelf life study of harvested capsicum fruits also showed major treatment effects on fruit quality. Fruit from Improved and Conventional practices had much higher percentages of firm fruit two weeks after harvest than Trash mulch and Vegetable only practices (viz, 37% and 30%, versus 4% and 4%, respectively—Figure 10). Conversely, the proportion of rotten fruit at the same stage showed Conventional (26%) < Improved (30%) < Trash mulch (39%) and Vegetable only (42%) practices. While the reductions in gross margins for Trash mulch practice were clearly very large and unsustainable (>\$17,000/ha), even the losses in moving to Improved practice management resulted in reductions in gross margins of ~\$4400/ha.



**Figure 9.** Impact of management systems on vegetable yield (t/ha). Vertical bars indicate standard errors of treatment means.



**Figure 10.** Impact of management systems on capsicum fruit quality after two weeks of storage.

### 3.5.2. Zucchini Yield

The zucchini fruit yield (Figure 9) was highest for Conventional practice, followed by Improved and Trash mulch practice. Yields in Improved practice were only about 80% of the yield of Conventional practice, while yields in Trash mulch and Vegetable only practices were only 43% and 49% of Conventional practice, respectively. Unlike the capsicum crop, where yields were influenced by very wet conditions, the zucchini crops had high yields and net returns more in line with regional expectations. While the reductions in gross margins for Trash mulch and Vegetable only practices were clearly very large and unsustainable (>\$15,000/ha), even the losses in moving to Improved practice management resulted in reductions in gross margins of \$5000–\$6000/ha. Though at least part of these losses may have been due to reduced nutrient availability in the non-plastic mulch systems, the relative yield difference between trash systems and plastic mulch management systems remained the same for both the soil test based (Table 1) and high nutrient application strategies (with 161 kg N/ha, 33 kg P/ha and 162 kg K/ha) in zucchini, suggesting that factors other than nutrition were driving these differences [26].

## 4. Discussion

This study explored the following hypotheses; (1) that the nutrient loads in runoff water can be reduced by implementing improved management practices; and (2) that these water quality improvements can be achieved whilst maintaining productivity at a level equivalent to the conventional management practices. Our results clearly suggest that the first hypothesis is true but that the second cannot be supported.

### 4.1. Impact of Vegetable Crop Management Practices on Runoff and Water Quality

Land use and management practices play a vital role in soil loss from agricultural fields. Soil erosion includes different stages such as detachment, transport and sedimentation [27,28]. With respect to water erosion, water applied through irrigation often exceeds the crop evapotranspiration demand [29]. A similar process occurs during periods of heavy rainfall and flooding. The most important factors are those that influence the partitioning of incident water (rainfall or irrigation) between crop use and off-site movement (either via runoff or drainage), with important factors shown to be differences in ground cover [23,30–32] and the soil moisture before the rainfall event. However, the amount of sediment generated for a given amount of runoff will also be influenced by the speed of the runoff and the ability of the runoff to detach and entrain soil particles. For example, the use of cultivation to produce fine soil tilth ensures soil particles are more easily detached or entrained because they are not consolidated [33]. The management practices adopted in this trial (Figure 2) provided various combinations of factors that would affect the runoff fraction of incident rainfall, the speed of that runoff and the propensity of that runoff to entrain sediments (and nutrients). The imposed plastic and trash mulch practices in combination with tillage and inter-row groundcover clearly had a significant impact on the various components of the water balance during the 2010–2011 summer seasons, with these changes expected to have a significant impact on off-site water quality [34]. Other studies have shown that plastic mulch substantially accelerates runoff generation and soil erosion due to the re-direction of incident water from the impervious plastic mulch in the row to the inter-row area [35,36], and this was consistent with observations during both capsicum crop growth and the fallow period between capsicum and zucchini production. Conventional, improved and trash mulch practices recorded 22, 19 and 15 runoff events in total during both capsicum and fallow phase. For each runoff event, Conventional practice consistently produced the greatest runoff (Figures 3 and 4) and the highest sediment concentrations and soil loss rates (Figure 5). The highest TSS concentration for Conventional practice was found at the peak of flow and decreased on the receding edge of the hydrograph, consistent with findings in other studies [37].

In addition to the greater runoff volumes with plastic mulch, a major contributor to sediment generation in Conventional practice was the lack of either trash mulch or live mulch in the inter-row (in contrast to the Trash mulch, Vegetable only and Improved practices, respectively). The presence of a living groundcover (millet during the capsicum crop and forage sorghum during the subsequent fallow period) in the inter-row in Improved practice would have both retarded the speed with which runoff from plastic-covered beds travelled along the inter-rows (allowing greater time for infiltration), as well as reducing the soil water content of the inter-row (lower antecedent water content), thus slowing the initiation of runoff and resulting in lower runoff volumes compared to Conventional practice. Earlier findings have reported that 85% of ground cover is adequate to prevent runoff and erosion [38] with a recent study reporting a ground cover straw mulching rate of 75 g/m<sup>2</sup> as beneficial in reducing soil and water loss [39]. However, in some of the events during the post capsicum fallow (from March 2011), the disturbance of soil to plant the forage sorghum actually resulted in higher sediment event mean concentrations and an increase in soil loss in Improved practice, even though there was less total runoff volume (Figure 3). The difference in soil loss between Improved practice and Conventional practices during the fallow was much smaller (22 kg/ha *cf* 26 kg/ha) than during the capsicum crop (29 kg/ha *cf* 143 kg/ha). Between these two plastic mulch treatments, the higher soil loss in Conventional practice was attributed to a greater number of runoff events and runoff

volumes compared to Improved practice. Rice and Horgan [40] reported that the offsite movement of nutrients was related more to runoff volume than to concentration of nutrients. The highest risk periods for sediment and nutrient loss are the transition period between crop systems (from sugarcane to vegetable), especially for those management practices with plastic mulch where soil surface cover is low and aggressive tillage has been used before the plastic mulch was laid.

The elimination of plastic mulch (Trash mulch and Vegetable only treatments) in the vegetable phase allowed greater rainfall infiltration, thus reducing the volumes of runoff and soil loss to 50% or less than that recorded in systems with plastic (Conventional and Improved), which was consistent with other findings [41]. However, these improvements came at a significant cost to productivity (Figure 9) of both the capsicum crop in summer 2010–2011 and the zucchini crop during winter 2011. Despite similar or greater nutrient input in Trash mulch and Vegetable only practices, relative to Improved practice, both capsicum and zucchini productivity responded in a similar way to these management systems (Figure 9). A following pumpkin crop in Vegetable only practice [42] also only yielded 39% of district average productivity [11]. These consistent observations of better water quality outcomes but lower productivity and profitability in the open (non-plastic mulch) treatments for a range of vegetable crops suggest that this trash mulch system may not be sustainable in the long term—a concern already prevailing in the GBR catchment farming communities [43]. An alternative system that is environmentally and economically sustainable needs to be explored. Runoff monitoring was continued during the following sugarcane plant cane crop [42], although the plastic mulch was removed from the Conventional and Improved systems. Results revealed that the Conventional practice recorded maximum runoff and soil loss, similar to the vegetable phase.

Loss of total N and total P in runoff is often strongly correlated to the loss of sediment (i.e., TSS) [23,35,44]. However, dissolved inorganic fractions are often considered critical for marine water quality. The higher concentrations of soluble N and filterable reactive P measured in runoff in the Conventional practice (Table S4, Supplementary material) contributed to the high nutrient loads (Figure 6), and were consistent with the higher rates of N and P application during the capsicum crop in those treatments (Table 1). Similar observations of increasing nutrient concentrations with increasing rates of fertilizer application have been reported in other studies [3,45]. The higher post-harvest soil nutrient status of Conventional practice (Figures 7 and 8) could be correlated with higher nutrient concentrations in runoff during the fallow period after capsicum harvest, a finding similar to that reported by Hollinger et al. [23]. However, the physical separation between the zones of nutrient enrichment (the planted bed) and the area of runoff and sediment generation (in the bare inter-row area) in this study suggest this association may only be circumstantial, or be driven by decomposing capsicum residues. The fact that DON concentrations were similar (Improved and Trash mulch practices) or higher (Conventional practice) than DIN in Figure 6 is consistent with the latter hypothesis, and suggests considerable nutrient runoff losses arising from decomposing residues. Further study of this phenomenon using  $^{15}\text{N}$  tracers is warranted.

Despite the reduction in fertilizer N input in Improved practice cf. Conventional practice,  $\text{NO}_x$  event mean concentrations (which were summed up with  $\text{NH}_4\text{-N}$  and presented as DIN in this paper in Table S4, Supplementary material) were well above the ANZECC [46] guidelines of 10  $\mu\text{g/L}$   $\text{NO}_x\text{-N}$  and 60  $\mu\text{g/L}$   $\text{NO}_x\text{-N}$  for fresh water lakes and lowland rivers of Queensland, respectively. Similarly, despite the lower loads of dissolved reactive P in runoff from Trash mulch practice (Figure 6), individual event mean concentrations (Table S4, Supplementary material) were still well above the ANZECC [46] guideline value of 10  $\mu\text{g/L}$  total P and 50  $\mu\text{g/L}$  total P for fresh water lakes and lowland rivers, respectively. However, these guidelines are for catchment scale assessment, not field scale assessment, and this difference in scales is significant. The concentrations of nutrients in runoff reported here are those that actually left the cropping field. Concentrations may increase or decrease before reaching the fresh water receiving bodies, with drains likely to alter the soluble P concentrations [47] and nitrate-N concentrations likely to be altered by drains or riparian vegetation uptake and/or denitrification. Previous studies in this region recorded similar DON (0.47 mg/L)

and DOP (0.06–0.08 mg/L) concentrations in streams as in farm runoff, but much lower stream DIN (0.03 mg/L) and FRP (0.005 mg/L) concentrations compared to that measured in farm runoff of DIN (0.64 mg/L) and FRP (2.01 mg/L) [48,49].

Regardless, this trial has demonstrated that changes to management can significantly reduce nutrient concentrations in runoff. The levels of FRP in Trash mulch practice were 0.1 to 1.3 mg/L lower than that recorded for the current accepted systems represented in Conventional practice—a significant reduction in terms of water quality standards [46]. However, this work has also shown that these reductions were only achieved through significant reductions in productivity and profitability that would greatly challenge the sustainability of these farming systems. Cultivating additional areas to supply a similar volume of fresh produce to market would potentially increase the overall environmental impact, so the challenge remains to make these improved systems more productive and profitable.

In addition, although the quantum of deep drainage could not be determined from these studies, there was clear evidence of leaching losses which were proportionately much more significant in systems where the greatest reductions in runoff were recorded. The exceptionally wet summer in 2010–2011 provided an extremely challenging set of conditions to conduct this research. Although it was useful to have a number of runoff events during the growing season, conditions were such that runoff in the later period of December and early January may have been driven more by the extent to which soil profiles were saturated [50] rather than any differences in soil management.

#### 4.2. Yield and Shelf Life

Treatment differences for both capsicum and zucchini fruit yield followed similar trends, with Vegetable only < Trash mulch < Improved < Conventional practices (Figure 9). The observations of crops grown under plastic mulch out-yielding those grown under vegetative mulch have also been reported in other studies [51,52]. Whilst the reduced productivity may have been linked to different application rates and greater nutrient leaching losses in the non-plastic systems in capsicum, this was unlikely to be the case in zucchini when large rainfall events did not occur and similar nutrient application rates were used in the Trash mulch, Vegetable only and Conventional practices based on pre-plant soil tests (Table 1). Soils are characteristically warmer under plastic mulch [53,54] and data collected during this study were consistent with this, with maximum temperatures 2–3 °C cooler under the non-plastic mulch treatments (Figure S2, supplementary material). These differences in soil temperatures increased in July 2011 compared to June 2011, which could be expected to have a significant effect on fruit maturation. We observed this in our study, with a three-day delay of the first harvest in Trash mulch and Vegetable only practices in the first week compared to Improved and Conventional practices, in addition to lower yields for at least the first four picking weeks. The yield of Trash mulch and Improved practices were similar in week 5, so it was uncertain whether an extended picking season in the non-plastic mulch systems could have reduced the yield gap to some extent. This would have been unpractical and uneconomical from a commercial perspective, given the high cost of labour, irrigation and the already high proportion of variable costs represented by labour in conventional vegetable systems.

While Improved and Vegetable only systems were subject to regular leaching due to extended periods of heavy rainfall during the capsicum phase, there was no rainfall during the entire zucchini phase and the trend of results showing plastic mulch systems out yielding the trash mulch systems was repeatable. Pumpkin yields in Vegetable only practice during the following 2012 winter season were only 39% of the average commercial yield [42] under conventional practices, confirming the lower productivity of the trash mulch systems. Results from the three vegetable crops grown over two years suggest that trash mulch systems will be a real risk to commercial horticulture growers, as they will suffer considerable economic loss by adopting these practices.

Interestingly the yield gap between Improved and Conventional practice for zucchini could be a factor of residual soil fertility from the capsicum crop (both amount and distribution in the bed) as

well as fertilizer rate, as soil temperatures were similar for both the treatments. The residual nutrient concentrations in the soil profile from the capsicum phase in Conventional practice were much higher than in the Improved practice (Figures 7 and 8).

While the shelf life study in capsicum revealed better quality of fruit from Improved practice, we observed uniform cracking of fruit from high nutrient applications in zucchini (especially in the Conventional practice). Fruit quality has been shown to be affected by higher N fertilizer rates [55,56] with several studies concluding that N fertilization in fruit and vegetable production should be reduced to a minimum level without affecting yield [56]. The rational use of fertilizer in the soil test based fertilizer treatments may therefore have helped to achieve both better fruit quality and an improved environmental outcome, although the gap in yield between treatments clearly warrants further attention.

These results demonstrate the difficulty in simultaneously maintaining productivity and improving environmental outcomes in short duration, nutrient-intense horticultural crops. Although trash mulch and improved practices were effective in reducing total nutrient losses in the fallow period when compared to the Conventional practice, all of the improved management practices resulted in decreased yield and economic returns in both capsicum and zucchini. This result again suggests that adopting improved management practices may lead to economic loss to growers [57], and that compensation measures may be required to overcome the financial disincentive to adopt new management systems. The current study has shown that variations around improved practice (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 thus reduce the size of any potential productivity gap. In particular, better matching of nutrient inputs by fertigation with the rate of crop demand over time, and possibly the optimal distribution of nutrients (bands vs. mixing) to allow uptake by roots of different crop species, may reduce the productivity penalty for reducing the nutrient inputs of the whole season.

#### 4.3. Nutrient Accumulation and Leaching Losses

Tracing the nutrients in farming systems is a complex process which is often influenced by a range of factors such as current management, soil characteristics, seasonal variability and management history of the farm [58]. We used the end-of-season soil sampling to measure the depth to which leaching had occurred and to monitor the dynamics of nutrient leaching in relation to rainfall and irrigation events. These data allowed us to quantify losses from the horticultural root zone to some extent.

##### 4.3.1. Nitrogen and Phosphorus Leaching

The leaching of applied nutrients in a sandy soil with low anionic sorption capacity and a high hydraulic conductivity was not unexpected [59,60], especially when combined with uncontrolled wetting through a permeable trash mulch in trash mulch and vegetable practices. However, while leaching of nutrients during the zucchini crop did not take place to a similar extent as during the capsicum crop, the data from post-harvest soil samples after the zucchini crop suggested that some of the  $\text{NO}_3\text{-N}$  that was deep in the soil profile after capsicum had been lost during the fallow or the zucchini phase (Figure 7). The apparent leaching below the depths of soil sampling (150 cm) means that the extent of these losses cannot be properly quantified.

During the capsicum crop, the quantum of leaching of both N and P was consistent with application rates. For example, concentrations of  $\text{NO}_3\text{-N}$  were 10 times higher in Conventional practice than in Improved and Trash mulch practices below 100 cm in the soil profile at the end of capsicum, highlighting that Conventional practice could significantly rationalize the use of N fertilizer. Similarly, the post capsicum harvest KCl-P concentrations in Conventional practice were seven to eight times higher than in Trash mulch and Improved practices in the 10–30 cm layer, while both



Trash mulch and Conventional practices were more than three times as high as Improved practice in the 30–60 cm layer (Figure 8). The greater leaching volumes in Trash mulch practice had clearly influenced the extent of P leaching, with the highest P concentrations occurring some 30 cm deeper in the soil profile (Figure 8) than with even higher P application rates (Table 1) under the plastic mulch in Improved practice.

During the zucchini crop, the relative extent of leaching of both N and P was consistent with application rates (soil test based rate) and baseline fertility. For example, concentrations of  $\text{NO}_3\text{-N}$  were three to six times higher in Conventional practice than Improved and Trash mulch practices below 100 cm in the soil profile, highlighting that significant rationalization of the use of N fertilizer should be possible in Conventional systems. There are also other N loss pathways reported in plastic mulch systems which could further decrease the N use efficiency, especially in summer [61], although we were unable to quantify these here. The fact that soil  $\text{NO}_3\text{-N}$  concentrations in Improved practice were lower than any other treatments indicates a better balanced supply of N to meet the crop demand.

The difference in soil  $\text{NO}_3\text{-N}$  concentrations at the end of capsicum crop and at the end of zucchini crop in Conventional practice suggests a loss of at least 159 kg N/ha (estimated using soil nitrate concentrations (Figure 7) and bulk density) through deep drainage.

#### 4.3.2. Phosphorus and Nitrogen Accumulation

The post-zucchini harvest KCl-P concentrations in Conventional practice were three to six times higher than in Trash mulch and Improved practices in the 10–30 cm layer (Figures 7 and 8). Interestingly, the soil Colwell P in the 0–10 cm layer in Conventional practice prior to zucchini planting was 130 mg/kg. Despite Conventional practice only receiving 8 kg P/ha for the zucchini crop where total plant uptake was 20 kg P/ha, the soil Colwell P concentration (0–10 cm) measured post zucchini harvest was effectively unchanged (140 mg/kg). This suggests that the crop has utilized subsoil P and was able to access residual nutrients from the previous capsicum crop. The Enviroscan data clearly showed roots of the zucchini crop extracting water from up to 40 cm depth. The results confirm previous findings that intensive vegetable production systems in Australia tend to apply excessive amounts of nutrient that are not utilized by the crop [12,13,62]. While other crops in a farming system/crop rotation may be able to access these residual nutrients, they have to be retained long enough in the soil profile, and in places accessible to plant roots, for this nutrient recovery to occur. Given the leaching processes observed in this study, having large amounts of residual nutrient in the soil profile represents a potentially significant off-farm environmental risk. Hardie et al. [63] suggested that the tendency of vegetable growers to maintain soil at high moisture contents may exacerbate the risks of deep drainage and leaching of mobile nutrients such as  $\text{NO}_3\text{-N}$ .

The positional availability of any residual nutrients is also an issue. After the final crop harvest of zucchini, the inter-row areas in Conventional practice contained 1–2 mg  $\text{NO}_3\text{-N}$ /kg in the top 30 cm of the soil profile. Prior to this,  $\text{NO}_3\text{-N}$  concentrations in the inter-row during late June 2011 (7 weeks after zucchini planting) for the Vegetable only, Improved and Conventional treatments had been 3, 3 and 9 mg/kg in 0–10 cm and 3, 2 and 6 mg/kg in 10–30 cm depth, with these elevated  $\text{NO}_3\text{-N}$  concentrations arising from decomposition of capsicum crop residues. In Conventional practice, the return of 151 kg N/ha in capsicum residues was entirely vulnerable to loss in runoff or to deep leaching, given the complete lack of root activity in the inter-row areas. However, in Improved practice, the inter-row forage sorghum may have been able to utilize at least some of the 107 kg N/ha returned in capsicum residues in that system, while also physically restricting possible loss in runoff. This again suggests that management options such as those employed in Improved practice offer practical solutions for improved nutrient recycling, although perhaps the most effective strategy to reduce losses and improve nutrient use efficiency is still decreased fertilizer rates [64] if the productivity losses observed in this study can be avoided.

The soil test based or improved fertilizer application rates in zucchini clearly reduced the excess nutrient in the soil profile and hence the risk of leaching (Figures 7 and 8), compared to what had

occurred in the capsicum crop. The reduced application rates were also reflected in the higher apparent efficiency of fertilizer recovery in crop biomass (data not presented). However, these benefits were lost in trash mulch systems, where crop nutrient recovery was reduced even under soil test based fertilizer application. Although Trash mulch practice had received similar nutrient inputs as that of Conventional practice, greater leaching was evident in Trash mulch practice (especially at 40 cm depth in Figures 7 and 8), where soil NO<sub>3</sub>-N concentrations were well above those of Conventional practice. While at least part of this difference was due to the poorer growth and the resulting reduced nutrient demand in Trash mulch practice than Conventional practice, these data clearly demonstrate that introducing management changes that alter the water balance of a system to reduce runoff and sediment generation do not necessarily reduce off-site movement of nutrients [34]. The Improved management practices reduced the runoff losses, while increasing the risk of deep drainage.

## 5. Conclusions

This study compared Conventional practices with a range of other practices in measuring offsite nutrient losses in a vegetable cropping system and established clear evidence to support the hypothesis that improved management practices resulted in better runoff water quality than current Conventional systems. However, the findings did not support the hypothesis that improved management practices can at least maintain crop productivity compared to current Conventional practices. The impact of yield reductions associated with delivering water quality benefits suggests that the trash mulch systems may not be financially sustainable, even in the short term. The results suggest that at least some of the residual nutrients at the end of a break crop cycle may be lost before the subsequent sugarcane crop can utilize them, however this needs to be tested in a wider range of seasonal conditions. Our results suggest that future research into establishing the linkages between deep drainage and water quality in adjacent streams and underground water tables is needed. Future research is also needed to close the vegetable yield gap between Improved and Conventional practices to allow improved water quality while maintaining productivity and profitability. The current loss of profitability recorded in the Improved system was still substantial (>\$10,000/ha across the vegetable rotation year), could not be borne by producers, and would only be possible with appropriate policy settings and a willingness for substantial public financial investment in order to deliver a desired water quality outcome.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2077-0472/7/3/30/s1>, Figure S1: Map of site location and its proximity to GBR, Figure S2: Soil temperature recorded during zucchini crop showing the difference between plastic mulch and trash systems, Table S1: Daily rainfall recorded during vegetable monitoring period, Table S2: Runoff percentage of different treatments at various rainfall events during capsicum crop, Table S3: Time at which runoff initiated during different rainfall events in summer 2010–2011, Table S4: Event mean concentrations (mg/L) during the vegetable phase for different management practices.

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**Author Contributions:** Gunasekhar Nachimuthu is the project scientist and main researcher of this work. Gunasekhar Nachimuthu executed the project, collected and analyzed the data and prepared this manuscript. Michael Bell and Neil Halpin proposed this project. Michael Bell provided project leadership and contributed towards the design and progress of the research by providing scientific input into this project. Neil Halpin supervised this project and contributed towards design and progress of the research by providing scientific input into this project.

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