Productivity Benefits from Plastic Mulch in Vegetable Production Likely to Limit Adoption of Alternate Practices that Deliver Water Quality Benefits: An On-Farm Case Study

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Communication

Productivity Benefits from Plastic Mulch in Vegetable Production Likely to Limit Adoption of Alternate Practices that Deliver Water Quality Benefits: An On-Farm Case Study

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Abstract: Intensive tillage, high fertiliser inputs, and plastic mulch on the soil surface are widely used by vegetable growers. A field investigation was carried out to quantify the impact of alternate land management and fertiliser practices designed to improve offsite water quality on the productivity of vegetable rotations within a sugarcane farming system in a coastal region of subtropical northeast Australia. Successive crops of capsicum and zucchini were grown in summer 2010–2011 and winter 2011, respectively, using four different management practices. These were 'Conventional'—the current conventional practice using plastic mulch, bare inter-rows, conventional tillage, and commercial fertiliser inputs; 'Improved'—a modified conventional system using plastic mulch in the cropped area, an inter-row vegetative mulch, zonal tillage, and reduced fertiliser rates; 'Trash mulch'—using cane trash or forage sorghum residues instead of plastic mulch, with reduced fertiliser rates and minimum or zero tillage; and 'Vegetative mulch'—using Rhodes grass or forage sorghum residues instead of plastic mulch, with minimum or zero tillage and reduced fertiliser rates. During the second vegetable crop (zucchini), each management practice was split to receive either soil test-based nutrient inputs or a common, luxury rate of nutrient addition. The 'Trash mulch' and 'Vegetative mulch' systems produced up to 43% lower capsicum and zucchini yields than either of the plastic mulch systems. The relative yield difference between trash systems and plastic mulch management systems remained the same for both the soil test-based and high nutrient application strategies, suggesting that factors other than nutrition (e.g., soil temperature) were driving these differences.

Keywords: capsicum; zucchini; yield; mulch; Australia

1. Introduction

The use of plastic mulch on the soil surface is a successful commercial crop production system practiced in several cropping industries [1,2]. Recent studies have reported increased soil organic carbon (SOC) mineralisation under plastic mulch being offset by higher root biomass production [3], providing a neutral effect on soil health while enhancing crop productivity. Enhanced soil health through the incorporation of previous crop stubbles and plastic mulch has also been reported by Huo et al. [4].

Previous studies on vegetable systems in Australia reported an accumulation of large amounts of residual nutrients in the vegetable system as a result of over-application relative to crop nutrient demand [5,6]. This accumulation of excess nutrients in soil has not been restricted to the conventional vegetable system, with Nachimuthu et al. [7] also recording accumulation of phosphorus (P) in organic and integrated (a conventional practice incorporating some organic principles) systems. There is strong evidence that this over application of nutrients in vegetable production systems in Australia has the potential to cause adverse environmental impacts through the loss of dissolved nutrients in the water, either via the leaching of excess nutrients to groundwater or the loss of nutrients in surface water runoff [5,8].

These intensive vegetable systems also have high risks of soil erosion due to excessive tillage, resulting in sediment and particulate nutrient movement into adjacent water bodies [9,10]. The use of plastic mulch on the soil surface, typically in the portion of the field where crops are grown, eliminates erosion risks from that area. However, it typically increases total runoff from the field and channels that runoff through the uncropped interspace, exacerbating the erosion risks from that area [11]. Previous studies in the USA [12,13] and more recently in Australia [11] reported the negative environmental impacts of plastic mulch and the advantages of vegetative mulch in inter-rows in terms of reducing runoff and erosion. However, none of these studies reported the productivity and economic sustainability of systems proposed as alternatives to conventional plastic mulch systems. There is a clear need to develop alternate vegetable systems that will reduce the environmental impact of farming practices without offsetting productivity. In Australia, many growers and state and federal government agencies are collaborating to develop improved farming systems that will deliver such outcomes for a variety of crop industries across Great Barrier Reef (GBR) catchments [10,14]. This study was part of that initiative.

The Burnett Mary region is in the southern part of the GBR catchment and is predominantly known for producing horticulture and sugarcane crops. The value of the horticulture industry in the Burnett Mary region has grown from $27.4 M in 1980 to $467.8 M in 2010 [11], with more than 70% of that gross value derived from intensive vegetable production alone. Most vegetable growers in this district follow either sugarcane—vegetable or a continuous vegetable rotation, with those in the former system growing vegetable crops in a one in five year rotation with sugarcane. The favourable sub-tropical climate allows for vegetables to be grown year round, with at least two seasonal crops grown per year. Nutrients are applied to vegetables as a basal application with additional in-season applications through trickle irrigation. The regular in-season applications occur from planting up to a week before the last harvest of vegetables.

This investigation was designed to study the impact of a range of management practices on productivity in intensive vegetable production systems. It was hypothesised that land management practices designed to improve offsite water quality could be implemented without negatively impacting productivity. The impact of these practice changes on water quality and vegetable yield were detailed in Nachimuthu et al. [11], while this short communication assesses the impact of increased nutrient inputs as a way of overcoming the observed decline in yield and economic returns of those management practices.

2. Materials and Methods

2.1. Site Descriptions

The site was established in the Burnett Mary region of Queensland, Australia, in a well-drained field containing a mixture of Yellow Brown Chromosol or Dermosol soils [15]. The average sand, silt, and clay fractions of the soil were 77%, 16%, and 8%, respectively. The area has a subtropical climate with long term average maximum and minimum temperatures of 17 °C and 27 °C, and the long-term average rainfall of 1019 mm, with >50% of rainfall occurring in the summer months (January–March).

A manual rain gauge was installed at the experimental site and daily rainfall was recorded. Rainfall during the initial capsicum crop monitoring period (October 2010–January 2011) was 884 mm, nearly double the long-term average of 463 mm (1942–2012, Bureau of Meteorology). Rainfall during the fallow period between vegetable crops (February–mid May 2011) was 303 mm, slightly lower than long-term average of 362 mm, but a period of intense rainfall in March 2011 (236 mm) was double the long-term average. Rainfall during the zucchini crop monitoring period (May–late July 2011) was only 60.4 mm, well below the long-term average of 137 mm (1942–2012, Bureau of Meteorology).

Prior to vegetable cultivation, the field supported a commercial sugarcane crop for the preceding five years, 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, with a soil pH (1:5, water) of 6.5 and 1.0% organic carbon (Leco combustion) in the 0–0.1 m soil layer. The field layout is depicted in Figure 1, and was designed to facilitate the monitoring of field scale runoff volumes from the contrasting management systems. The entire field was subdivided into five management units 9 m wide, with four of these units sown to vegetable crops, and these contiguous management units were further split into two blocks draining in opposite directions from the highest elevation near mid field. The smaller 120 m blocks (where runoff flumes and water quality samplers were installed [11]) were treated with the contrasting fertiliser application strategies, as shown in Table 1, throughout the monitoring period, while the 160 m blocks received the same contrasting applications in the initial capsicum crop but a common, high application (HF) rate in the following zucchini crop (see Section 2.2.1). Soil temperature (5 cm depth) was monitored during the capsicum and zucchini crop season using Tinytag plus2 (Gemini data loggers (UK) Ltd, Chichester, West Sussex PO198UJ, England), with data presented in Figures S1 and S2 (supplementary data).

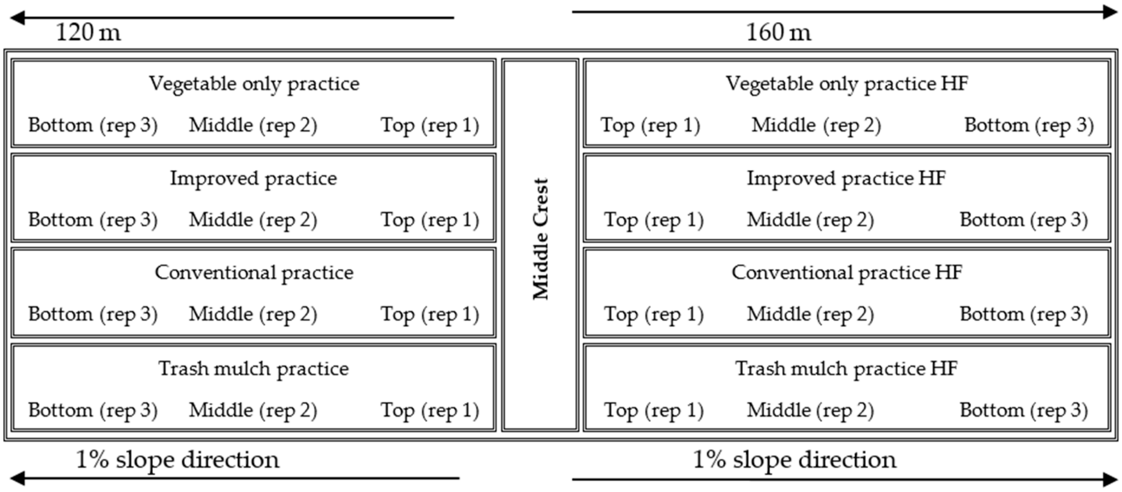

Figure 1. Field lay out of the experimental plot. The field was split into four management units with each unit being 280 m long and 9 m wide (i.e., 5 × 1.83 m cane rows), with contrasting management systems randomly allocated to each strip. The 280 m length was subdivided into two subunits of approximately 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. HF indicates high fertiliser input treatments.

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
First crop (planting date)	Capsicum (13 October 2010)	Capsicum (13 October 2010)	Capsicum (13 October 2010)	Capsicum (13 October 2010)
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

Fertiliser	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
Fallow management (1 February 2011–13 May 2011)	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 residues	Rhodes grass mulch, capsicum residues
Ground cover in inter-row	Capsicum residues	Capsicum residues, Jap millet mulch	Trash mulch, capsicum residues	Rhodes grass mulch, capsicum residues
Second crop (planting date)	Zucchini (13 May 2011)	Zucchini (13 May 2011)	Zucchini (13 May 2011)	Zucchini (13 May 2011)
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
Fertiliser *	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

* Trash mulch system high fertiliser (HF), Improved system HF, Conventional system HF and Vegetable only system HF received a common rate of nutrients to supply 161 kg N/ha, 33 kg P/ha, and 162 kg K /ha; [#] PCTF-Precision Control Traffic Farming; ** The vegetable only system had a fallow phase after the zucchini crop. Again, forage sorghum was planted on 23 October 2011 and 50 kg N/ha was top dressed to establish a good mulch before planting the next crop. Forage sorghum was mulched on 4 January 2012. Pumpkin seedlings (var. Kent Special) were planted on 28 February 2012 using a mechanical planter and auto steer GPS. Commercial fertiliser application (113 N, 26 P, and 163 K) was applied through fertigation. Final harvest was conducted on 25 July 2012. The meaning of PCTF.

2.2. Management Systems

The experiment was conducted in strip plot design, with each strip subdivided into three pseudo-replications for plant sampling and yield estimation (Figure 1). Four management systems were monitored during the capsicum crop, and eight management systems (splitting of the original management systems to include a common high nutrient regime in the 'non-runoff monitoring' part of the field) were monitored during the zucchini crop. Management systems differed in combinations of nutrient inputs, mulch cover, and tillage, with key features outlined in Table 1. All management systems were assessed for yield and gross margins.

Nutrient Inputs

The nutrient inputs for the capsicum crop, as well as for the smaller sub-sections of each management strip in the zucchini crop (120 m long, Figure 1), are outlined in Table 1, with the Conventional systems representing the current industry practice in the region. There were suggestions of nutrient limitations in both management systems without plastic mulch during the capsicum crop, so a common, high nutrient input regime (designated HF in Figure 1) was instigated on the longer sub-block (Figure 1) to test the extent to which nutrient availability may have contributed to the poor productivity of those free-draining systems. This regime was designed to ensure that no nutrient limitations were experienced, with nutrients added into the water supply during trickle irrigation events (fertigation).

2.3. Yield Estimation and Economic Analysis

Three replicate yield assessment areas, each 10 m × 1.83 m, were designated in the top, middle, and lower elevation areas in each subplot of each management system. The capsicum and zucchini were harvested and weighed, with yields reported on a per hectare basis. A gross margin analysis was performed on each system based on the market value of harvested produce and the production input cost (fertiliser, tillage, and plastic mulch).

2.4. Statistical Analysis

The yields generated for each pseudo-replicate (top, middle, and lower elevation areas of the field) in each management unit were used to measure the uniformity of crop performance between the treatments. Results from each management unit are presented as means with an associated standard deviation (Figure 2 and Table 2). The relative differences between management systems were discussed.

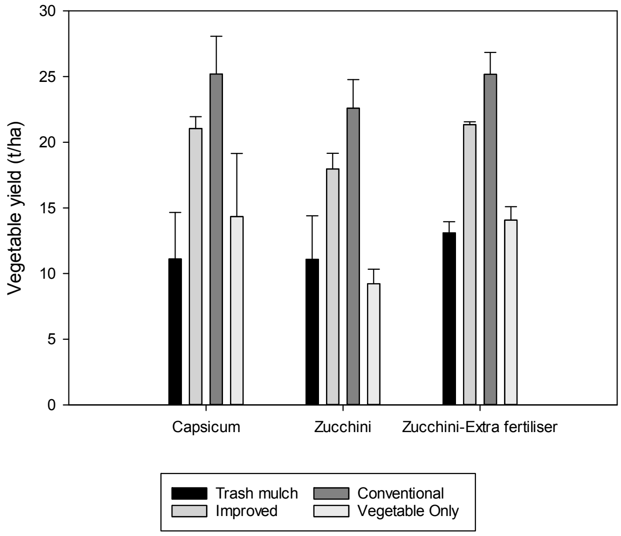

Figure 2. Impact of management systems on vegetable yield (t/ha) (mean with standard deviation).

Table 2. Impact of management practices on vegetable yield (mean ± standard deviation).

Management Practices	Capsicum	Zucchini	Zucchini Extra Fertiliser
Trash mulch	11.10 ± 3.55	11.09 ± 3.31	13.10 ± 0.86
Improved	21.05 ± 0.89	17.97 ± 1.19	21.34 ± 0.22
Conventional	25.20 ± 2.87	22.59 ± 2.18	25.18 ± 1.66
Vegetable only	14.35 ± 4.80	9.22 ± 1.10	14.08 ± 1.02

3. Results and Discussion

Despite similar or greater nutrient input (Table 1) in the 'Trash mulch' and 'Vegetable only' systems, relative to the 'Improved' system, both zucchini and capsicum productivity responded in a similar way to these management systems. Capsicum fruit yields (Figure 2 and Table 2) were highest for the 'Conventional' system, followed by the 'Improved' and 'Trash mulch' systems. Similarly, the zucchini fruit yields (Figure 2 and Table 2) were highest for the 'Conventional' system, followed by the 'Improved' and 'Trash mulch systems' in both the soil test-based nutrient application and the high nutrient input systems. Yields in the 'Improved' system were only about 80% of the yields of the 'Conventional' system, while yields in the 'Trash mulch' and 'Vegetable only' systems were only 43% and 49% of the 'Conventional' system, respectively, for the management systems with soil test-based nutrient applications. A pumpkin crop following the zucchini crop in the 'Vegetable only' system (data not shown) also yielded only 39% of the district average productivity [11]. Gross margin analyses for the zucchini crop suggested that the reductions in grower profitability for the 'Trash mulch' and 'Vegetable only' systems were clearly very large (>AUD$14,000/ha, or 24% of the expected gross margin in a conventional system). Even moving to the 'Improved' system would result in a grower profitability decline, although with lower magnitude (>AUD$6000/ha, or 67% of the expected gross margin in a conventional system).

These consistent observations of lower productivity and profitability systems without plastic mulch for both vegetable crops suggests that such trash mulch systems may not be a viable or sustainable system for the industry to move towards—a concern already prevailing in the GBR catchment farming communities [16]. The observations of crops grown under plastic mulch out-yielding those grown under vegetative mulch have also been reported in other studies [17,18]. The big differences in productivity between conventional and other management systems were unlikely to be due to inadequate nutrient availability resulting from reduced fertiliser rates in zucchini, as unlike the preceding capsicum crop, similar nutrients (based on pre-plant soil tests) were supplied to zucchini in the 'Trash mulch', 'Vegetable only', and 'Conventional systems' (Table 1). An additional indication of the lack of nutrient involvement in the systematic yield differences was obtained by comparing yield results to those obtained from the high nutrient input subplots in each management system. While yields were uniformly higher with extra fertiliser input, responses were generally small (2–5 t/ha) and the management system relativities stayed virtually the same. Under uniformly high nutrient inputs, yields of the 'Trash mulch' and 'Vegetable only' treatments were still only 52–54% of those in the 'Conventional' system, while those in the 'Improved' treatment were 85% of the 'Conventional' system. Unlike the capsicum crop, where very wet conditions depressed yields, the zucchini crops had high yields and net returns more in line with regional commercial expectations.

Additional nutrient inputs tended to reduce yield variability in some of the systems (Table 2), and in the 'Improved' system allowed yields to approach those of the 'Conventional' system under standard management (i.e., 23 t/ha vs. 21 t/ha). However, yields in the 'Trash mulch' and 'Vegetable only' management systems with additional nutrient inputs (13 t/ha and 14 t/ha, respectively) were still <60% of those in the standard 'Conventional' system. Similar trends were also observed in plant dry biomass collected throughout the season (data not presented). This suggests that factors other than in-crop nutrient inputs (e.g., the impacts of ground cover or plastic mulch on soil temperature, surface soil wetting, and drying cycles, etc.) were causing the productivity differences between plastic and trash mulch management systems.

Soils are characteristically warmer under plastic mulch [1,19,20], and data collected during the zucchini crop were consistent with this, showing differences of 2–3 °C in soil temperatures between management systems (supplementary data, Figure S1). However, the extent and potential impact of temperature differences will be affected by seasonal conditions. The initial capsicum crop at this site was grown during spring to early summer under a warmer climate and, at least during the growth period leading up to the heavy rainfall season in late December 2010 to January 2011, there was no evidence of a consistent effect of plastic mulch on elevating soil temperatures (supplementary data, Figure S2). Therefore, while plastic mulch provided relatively higher productivity benefits over the freely draining 'open' mulch systems in both crops (Figure 2 and Table 2), the reasons for those benefits are likely to be quite different.

While the plastic mulch provided few consistent benefits in raising soil temperature during the summer, the very heavy rainfall that occurred from late December to January was likely to result in significant leaching of nutrients in the open systems [11], while the systems covered with plastic mulch would have been much less affected. This was consistent with the observation of poor crop nutrient status in the trash mulch systems, and led to the conclusion that the main difference in crop performance between the management systems was related to the nutrient management inputs. This was the reason for the elevated focus on nutrient availability as a yield-determining factor in the subsequent zucchini crop.

However, in the late autumn-winter zucchini crop growing season, there were two important factors that may have reduced the importance of nutrient constraints as the prime determinant of yield differences between management systems. The first was the complete lack of any substantial in crop rainfall that was likely to result in nutrient leaching in the open systems. There was a total in crop rainfall of only 60 mm during the growing season, thus differences in nutrient losses would be an unlikely explanation for the observed yield differences between open and plastic mulch systems. The second was the cooler temperatures experienced in the autumn-winter zucchini growing season. Soil temperatures in the open systems during the zucchini growing season were ~10 °C lower than those during the capsicum season, and the benefits of plastic mulch in elevating soil temperatures were much more obvious (supplementary data, Figure S1). This had a direct effect on the rates of crop development, with a three day delay of the first zucchini harvest in the 'Trash mulch' and 'Vegetable only' systems compared to the 'Improved' and 'Conventional' systems in the first week of harvest, in addition to lower yields for at least the first four weeks of harvest. These obvious temperature impacts between mulch and non-mulch systems suggest that this was the factor that provided the productivity benefit in the zucchini crop.

It is noteworthy that the yield of the 'Trash mulch' and 'Improved' systems were similar in week 5 of picking, so it was uncertain whether an extended harvesting season in the non-plastic mulch systems could have reduced the cumulative yield gap to some extent. Even if this were the case, an extended commercial harvesting period would be undesirable from both practical and economic perspectives, given the high cost of labor and irrigation on top of an already high proportion of variable costs represented by labor in the 'Conventional' vegetable systems.

The zucchini yield gap between 'Improved' and 'Conventional' systems (both employing plastic mulch) could be a response to residual nutrients left after the capsicum harvest (both the amount and distribution in the bed) as well as the rate of fertiliser applied in the zucchini crop itself, as soil temperatures were similar in both management systems. The residual nutrients left in the soil profile after the capsicum crop in the 'Conventional' system were much higher than in the 'Improved' system [11,21]. The yield gap of 5 t/ha between the 'Improved' and 'Conventional' systems with fertiliser applications based on a pre-planting soil test (e.g., 82 and 105 kg N/ha, respectively) decreased slightly to 4 t/ha when luxury fertiliser rates were applied (e.g., 161 kg N/ha). The gap between the 'Improved' system with the luxury fertiliser application and the 'Conventional' system with the soil test-based application was only 2 t/ha (Figure 2 and Table 2).

Part of the appeal of the vegetative mulch systems to natural resource managers in Great Barrier Reef (GBR) catchments lies in the potential of those systems to reduce runoff and associated soil and nutrient loss compared to plastic mulch systems [13]. However, the apparent improvement in environmental sustainability of those systems may be misleading from a number of perspectives. From a food production standpoint, unless the productivity gap associated with those systems can be overcome (in a way that does not negate those environmental gains, such as leading to an increase rather than a decrease in nutrient inputs), additional area will need to be cultivated to supply a similar volume of fresh produce to market, and the associated environmental impact needs to be taken into account. Similarly, the reduced runoff and associated nutrient loss in these 'open' mulch systems may have negligible water quality impact in the long term if the 'improvements' simply represent a change in the nutrient loss pathway, from runoff to deep drainage. The latter is a major risk in well-drained sandy loam soils in coastal catchments [21].

4. Conclusions

This study has clearly demonstrated the inability of high nutrient inputs to overcome the productivity differential between management systems. This suggests that vegetable yield was dominated by land management (soil tillage and mulch management) rather than nutrient availability. These conclusions are based on the productivity of both the capsicum and zucchini test crops. Further studies are required to maximise the environmental and economic benefits of modified cropping systems in these sensitive coastal environments, with a systems approach needed to reduce the productivity gap between management systems. In particular, better matching of nutrient inputs with the rate of crop demand over time using fertigation, and possibly optimising the distribution of nutrients (bands vs. mixing) to maximise uptake by roots of different crop species, may reduce the productivity penalty for reducing the whole of season nutrient inputs. However, as these results have clearly shown, additional nutrient inputs in vegetative mulch systems will still not offset the yield advantages obtained from plastic mulch systems. Until viable alternatives are developed, growers cannot afford to make radical systems changes.

Supplementary Materials: The following are available online at http://www.mdpi.com/2311-7524/3/3/42/s1, Figure S1: Soil temperature recorded at 5 cm depth during the winter zucchini crop, showing the difference between plastic mulch and trash systems; Figure S2: Soil temperature recorded at 5 cm depth from December 2010 until late January 2011 during the spring/summer capsicum crop, showing the difference between plastic mulch and trash systems.

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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 analysed 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, as well as making editorial suggestions. Neil Halpin supervised this project and contributed towards design and progress of the research by providing scientific input into this project.

Conflicts of Interest: The authors declare no conflict of interest.

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