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Vegetable raingardens can produce food and reduce stormwater runoff

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ABSTRACT

Raingardens are garden beds designed to capture and filter urban stormwater runoff using a permeable soil substrate and plants tolerant of both drought and inundation. The construction of raingardens is actively promoted in many cities, primarily to protect local waterways from the negative impacts of stormwater such as channel erosion and degradation of water quality. To increase the adoption of raingardens by householders, it might be possible to expand raingarden functionality to simultaneously serve as "vegetable raingardens". Vegetable raingardens would be beneficial in the context of urban agriculture, as they could overcome both space and water scarcity constraints on home vegetable gardening. However, the potential to grow vegetables in raingardens has not been explored and vegetables are significantly different to conventional, hardy raingarden plants. In an 18-month field trial, we assessed vegetable production in purpose-built raingardens. Stormwater was collected from an adjacent rooftop and was applied to the vegetable raingardens through sub-irrigation. One of the vegetable raingardens was lined underneath and the other was unlined, allowing infiltration of excess water to underlying soils. Sub-irrigation was used to limit plant stress and ensure food safety by reducing vegetable contact with potential contaminants present in stormwater. Control gardens were treated with stormwater delivered through overhead spray irrigation, or with potable water delivered by overhead sprays to also examine differences in water source on yield. A range of vegetables were planted including beetroot, onion, spinach, tomato and broad bean. The vegetable raingardens that were tested produced yields generally similar to the control gardens, which represented traditional watering methods for vegetable gardens. The infiltration-type raingarden, sized 7.5% of its catchment area, reduced both the volume and frequency of runoff by >90%. Results indicate that it is possible to both produce adequate yield in raingardens and maintain the function of raingardens in reducing urban runoff, in terms of discharge to waterways.

1. Introduction

In cities, stormwater runs off impervious surfaces at unnaturally high rates and poses a significant threat to the health of urban waterways, with impacts such as channel erosion and degradation of water quality (Paul and Meyer, 2001). In these urban landscapes, Water Sensitive Urban Design (WSUD) and similar concepts such as Low Impact Development (Fletcher et al., 2014) are a way of reducing the quantity of stormwater runoff by increasing infiltration and evapotranspiration (Denman et al., 2006; Lloyd et al., 2002), bringing the flow of runoff in urban landscapes closer to pre-developed, natural levels (Bratieres et al., 2008; Williams and Wise, 2006). These WSUD technologies include raingardens, which are a type of biofiltration or bioretention system (Davis et al., 2009). Raingardens are garden beds that are engineered, using specified permeable substrates (commonly loamy sands) and hardy plants tolerant of both drought and inundation, to retain and treat stormwater that runs off impermeable surfaces such as roads and roofs. The construction of raingardens is being actively promoted in many cities to improve waterway health. For example, in Melbourne, Australia, a programme to install 10,000 raingardens ran from 2008 to 2013. That programme, operated by Melbourne Water, specifically targeted adoption by private householders, highlighting the aesthetic and landscape amenity benefits of such systems. The programme exceeded its 10,000 target, and was effective at raising awareness of stormwater issues (Melbourne Water, 2014). It was adapted from a similar programme in Kansas City (Sustainable Cities Institute, 2013). In Australian and North American cities, particularly those with dry summer climates, there is potential to further increase

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uptake of raingardens among householders by expanding the functionality of these systems. In particular, raingardens have the potential to be used as vegetable gardens, or *vegetable raingardens*.

Using vegetable raingardens as an extension of traditional home vegetable gardening would help to overcome the common negative perception that raingardens offer no tangible benefit to people (Brown et al., 2014). Vegetable raingardens could have the particular benefit of overcoming constraints on vegetable gardening related to water scarcity. Water scarcity is an intermittent problem in many Australian cities, and countless other cities throughout the world, caused by below-average runoff into water catchments (Barker-Reid et al., 2010; Edwards, 2011). A common response has been to implement water restrictions, which require households to avoid or ration some uses of potable water, particularly in relation to gardening (DEPI, 2014). Such restrictions were in place in Melbourne for over ten years, between 2001 and 2012 (Edwards, 2011). Water restrictions are also an important contemporary issue in the USA, particularly in California, Colorado and Texas. A vegetable raingarden would capture stormwater (particularly from roofs) and use it to irrigate vegetables. This is consistent with the increasingly common practice of using stormwater and greywater in home gardening, which is not subject to water restrictions (Barker-Reid et al., 2010; Hatt et al., 2007; Misra et al., 2010).

Exploratory research has indicated that another WSUD technology, green roofs, can be successfully used for vegetable production without negative impacts on stormwater retention or runoff water quality (Whittinghill et al., 2013, 2014). Nonetheless, the feasibility of a vegetable raingarden has not yet been evaluated. A fundamental issue is that vegetables are significantly different to the plants that are conventionally used in a raingarden, which tend to be perennial, native species selected for their ability to survive the extreme wetting-drying regime in a raingarden, and for their capacity to remove pollutants from runoff (Read et al., 2008). In comparison, vegetables are generally much more sensitive to drought and over-watering, both of which can lead to poor growth and yield, and ultimately plant death in severe conditions (Bahadur et al., 2011; Vartapetian and Jackson, 1997). Vegetables also need relatively high levels of nutrients to ensure desired yields (Nonnecke, 1989), which may be in conflict with objectives of reducing concentrations and loads of pollutants in stormwater runoff.

Fluctuation in water availability is a critical issue in sustaining productive yields in a vegetable raingarden, particularly in the summer months when water might be limited. Therefore, it is necessary to optimize the design of a raingarden to reduce potential water limitations. In particular, it might be preferable to invert a vegetable raingarden so that it is irrigated from below, as a sub-irrigated or "wicking" type of garden bed, instead of from the top like conventional raingardens. Sub-irrigation has been found to offer higher water use efficiency than spray and drip irrigation in tomatoes (Ahmed et al., 2000; Goodwin et al., 2003; Incrocci et al., 2006; Santamaria et al., 2003). A key advantage of a sub-irrigated raingarden would be reduced evapotranspiration rates and therefore reduced plant stress, minimizing the need for supplemental irrigation. Ideally, a vegetable raingarden would require no supplemental irrigation, as is typically the case for conventional raingardens, to reduce demand for potable water and maximize storage capacity for stormwater runoff. Sub-irrigation might also be beneficial for food safety, as pollutants could be filtered out of the runoff water as it moves upwards through the raingarden before coming into contact with plants (Tom et al., 2013).

However, modifying or managing a raingarden for vegetable production may reduce its ability to capture stormwater runoff. For optimal capture, a raingarden should only be wet during and immediately after rainfall, so that the soil pore spaces are largely empty within 72–96 h (Davis et al., 2009; Melbourne Water, 2010), allowing the next rainfall event to be captured. Pore spaces will rarely be empty if the raingarden is kept constantly moist through regular irrigation, or through using a sub-irrigated design or waterproof lining. For example, it has been reported that sub-irrigation leads to more runoff from green roofs than overhead irrigation (Rowe et al., 2014). It is also well established that lined raingardens have relatively poor hydrologic performance (Li et al., 2009), although lined raingardens also have important benefits; they can be built close to buildings because the lining prevents water damage to foundations, and they can be used in situations where hazardous runoff is anticipated (Davis, 2008; Davis et al., 2009).

To address these knowledge gaps and inform raingarden design for implementation as a WSUD technology, we built two sub-irrigated vegetable raingardens and two surface-irrigated vegetable gardens (as controls), and assessed their performance over an 18-month period to account for seasonal variation. The following research questions were evaluated:

1. Can a sub-irrigated "vegetable raingarden" produce vegetable yield comparable to a surface-irrigated (control) vegetable garden?
2. Does this raingarden require irrigation to supplement rainfall, to maintain adequate soil moisture (under Melbourne conditions)?
3. Can the runoff management function of a raingarden be retained, if it is used and modified for vegetable production?
4. In relation to the preceding three questions, how does performance vary between a raingarden that is lined and an unlined raingarden in which runoff water is allowed to infiltrate into the underlying soil?

2. Methods

Two purpose-built, 3.3 m^2 raised garden beds (pre-fabricated, corrugated steel beds sourced from Birdies Garden Supplies), with dimensions of 2.2 m (length) × 1.5 m (width) x 0.8 m (height), were installed and plumbed as *vegetable raingardens* at the University of Melbourne's Burnley campus in Melbourne, Australia (37°49′44.22″ S, 145°1′13.40″ E). Both received roof water from an adjacent building with a tile roof of area 133 m^2 (Fig. 1). One of the raingardens was lined with a PVC liner to prevent water from draining into the underlying soil. This raingarden is referred to as

Fig. 1. Field trial raingardens; the Lined in the foreground and the Unlined to the right of the photo, with the two control gardens and the tile roof in the background. Each of the four gardens was constructed using a pre-fabricated modular raised garden bed made of corrugated steel. The four gardens were arranged in a non-random quadrant formation.

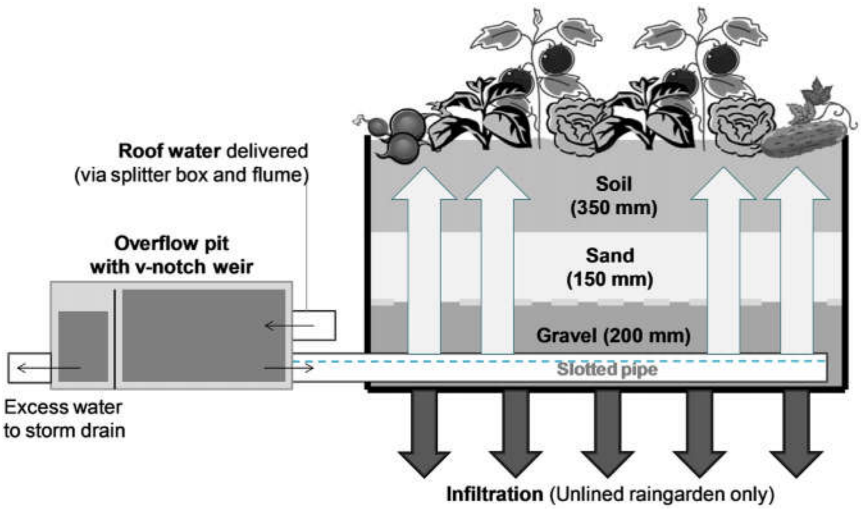

Fig. 2. Cross-section diagram of the raingarden design. Light arrows represent the upward movement of runoff water (delivered via a slotted pipe in the gravel layer) through capillary rise, and dark arrows represent infiltration into the underlying soil. The sand was prevented from settling into the gravel layer by a sheet of geotextile, but there was no barrier between the sand layer and the overlying soil.

the Lined raingarden hereafter. The other raingarden had no lining (the Unlined raingarden) and was therefore designed to promote infiltration, consistent with objectives of restoring a more natural flow regime.

Both raingardens contained three layers; a gravel layer, a filter layer, and growing media (Fig. 2). The bottom layer of 20 mm scoria gravel was overlain by a thin "filter" layer of fine sand, and a 350 mm thick top layer of commercially available vegetable garden soil (a blend of two soils and three manures with water holding capacity of 56.9% and bulk density of 0.64 g cm^{-3}). Following significant rainfall (i.e. anything greater than 1 mm, enough to exceed the "initial loss"; Boyd et al., 1993), roof water was delivered directly into the raingarden via a slotted pipe in the gravel layer. It was intended that the water would then move upwards through the media, driven by capillary action (Fig. 2). Given that the two raingardens each received approximately one third of the total water from the roof (conveyed via a splitter box), each raingarden was approximately 7.5% of the size of its catchment area. This is well above the recommended 2% minimum size for a biofiltration system (Bratieres et al., 2008), but within the likely size range for domestic applications of the vegetable raingarden. In both raingardens, a purpose-built overflow pit (external to the garden bed) regulated the water level to prevent waterlogging.

Even at times of low soil moisture, the Lined raingarden was only sub-irrigated; supplemental irrigation was applied by recharging its overflow pit to capacity. The free-draining Unlined raingarden represented an "infiltration" type of raingarden, which is generally preferable for runoff management (Li et al., 2009). The Unlined raingarden was allocated to a plot with a high infiltration rate (>100 mm h^{-1}), according to single-ring infiltrometer measurements, so that drainage would be relatively unimpeded. Unlike the Lined raingarden, it was anticipated that the Unlined raingarden would require supplemental irrigation regularly during dry weather, and it was therefore fitted with a surface (drip) irrigation system. Roof-water collected in a specially installed 3.44 kL rainwater tank was used for all supplemental irrigation.

Two surface-irrigated vegetable gardens were built adjacent to the two raingardens and acted as controls. They did not receive any water directly from the roof, but they were otherwise identical to the two raingardens, including the same filter/growing media. Both control gardens were fitted with micro-spray irrigation systems to simulate watering methods typically used in domestic vegetable gardens, such as hand watering and sprinklers. The two control gardens differed from each other only in the source of their irrigation water; the Potable control received tap water and the Tank control used roof water collected in the tank. This was primarily for assessment of food safety, which was the subject of a parallel study (Tom et al., 2013).

During dry weather, the control gardens were irrigated using a deficit irrigation strategy, as were the raingardens. A set volume of irrigation water (138 L for the Unlined raingarden and control gardens) was applied when the volumetric soil water content was <10%, which was slightly higher than the permanent wilting point of the soil (6.5%). Soil water content in each raingarden was measured using a Campbell CS616 water content probe (at 3–10 cm depth), which logged at 6-min intervals. The water content probes were calibrated for the vegetable garden soil. Soil water content data was downloaded and checked three times a week, so that irrigation was applied approximately every other day, if needed. The aim of this strategy was to maximize water use efficiency rather than yield. Soil temperature in each garden was measured using an iButton temperature logger (at 5 cm depth), which logged at 120-min intervals.

To assess the capability of the raingardens to reduce runoff, inflow was measured using trapezoidal flumes positioned upstream of the overflow pit for each raingarden. Each of the two flumes recorded water depth with a SITRANS Probe LU ultrasonic depth sensor. Inflow was compared to the outflow from the overflow pit to the storm drain, which was measured by a v-notch weir and an Odyssey capacitance depth logger within the pit. This overflow occurred when the water level in the raingarden reached approximately the top of the sand layer. There was also a depth logger housed in a PVC pipe within each of the two raingardens, to measure the water level (height of saturation). Rainfall at the site was measured using a tipping bucket rainfall recorder; a Davis Rain Collector II with an Odyssey "rain gauge" data logger. All of the monitoring apparatus logged data continuously for 18 months.

Fourteen vegetable species were planted as either seeds or seedlings to test a range of plants commonly grown in home vegetable gardens, including root, leaf, leguminous and fruiting vegetables (Table 1). There were three growing seasons (two summers and one winter) in the 18-month monitoring period. Edible parts of plants were harvested when mature/ripe; generally weekly or fortnightly for the fruiting and leguminous vegetables, but less frequently for the others. Edible parts were oven-dried at 80 °C to a constant mass to obtain yield. Where applicable, the number of

Table 1
Details of the plants evaluated for yield across the three growing seasons; Summer 1 (S1), Winter (W) and Summer 2 (S2).

Type	Species	Common name	Variety	Seedling or seed	Season	Plants per bed
Root and bulb	*Beta vulgaris*	Beetroot	Crimson Globe	Seed	S1	≥8
			Not specified	Seedling	S2	≥8
	Allium cepa	Onion	Brown	Seedling	W	≥8
	Allium porrum	Leek	Not specified	Seedling	W	≥18
Leaf	*Lactuca sativa*	Lettuce	Cos	Seedling	S1	4
	Spinacia oleracea	Spinach	Viking	Seed	W	≥15
Fruit and legume	*Solanum lycopersicum*	Tomato	Mama's Delight (Round)	Seedling	S1	1
			Sweet Bite (Cherry)	Seedling	S1	1
			San Marzano (Plum)	Seedling	S2	2
	Cucumis sativus	Cucumber	Lebanese	Seed	S1	2
	Capsicum annuum	Pepper	Chilli Salsa	Seedling	S2	2
	Vicia faba	Broad bean	Early Long Pod	Seed	W	≥5
	Phaseolus vulgaris	Common bean	Butter (Yellow)	Seedling	S2	5
Herb	*Ocimum basilicum*	Basil	Sweet Basil	Seedling	S1	4
			Greek Basil	Seedling	S2	2
	Petroselinum crispum	Parsley	Afro (Curly-leaved)	Seedling	S1	4
			Italian (Flat-leaved)	Seedling	S2	4

fruits or pods harvested was counted. In the second summer season, the number of harvested tomatoes affected by blossom end rot and cracking/splitting was also recorded. Yield data for each vegetable species were pooled for each garden, rather than treating individual plants within gardens as replicates. Differences in yield between the four gardens were then assessed. Descriptive statistics were used to assess differences in irrigation requirements, water level, soil moisture and inflow and overflow data between the raingardens and, if applicable, between the raingardens and control gardens. The ability of the two raingardens to reduce runoff was evaluated based on both the frequency (days) and volume of flow. Regressions were used to analyze irrigation requirements in relation to rainfall and temperature, and in the analysis of soil moisture in relation to water level (95.0% confidence level). Statistical analysis was conducted using Minitab 16 Statistical Software.

3. Results

3.1. Yield

Differences in yield between the four gardens varied between species/varieties. Overall, the dry weight of vegetables produced by the raingardens was comparable to the control gardens, although the Lined raingarden was generally the least productive (Fig. 3). For example, in the winter growing season, the Lined raingarden produced only 4.3% of the total spinach yield of the four garden beds, and only 6% and 16.1% of total onion and leek yield. The Unlined raingarden tended to be more comparable to the controls, but for some species/varieties both raingardens produced relatively low yield, which is exemplified by tomato. In the first summer, when round and cherry varieties were planted, yield by both dry weight and the number of fruit was generally greater in the two control gardens than the raingardens (Table 2). In the second summer, plum tomato yield (by both weight and number) was greatest in the Tank control, although the Potable control produced even lower yield than the Lined raingarden. The number of plum tomatoes affected by both blossom end rot and cracking was greatest in the Lined raingarden but the Tank control garden was also significantly affected (Table 2).

Table 2
Yield of the three varieties of tomato (round and cherry in the first summer season and plum in the second) by total dry weight and the total number of fruit, for the two control gardens and two raingardens. Also presented are the average weight of individual fruit (total fresh weight/total count) and, for plum tomato in the second summer only, the number of tomatoes affected by blossom end rot (B.E.R.) and cracking.

	Control gardens		Raingardens	
	Potable	Tank	Unlined	Lined
Total dry weight (g)				
Round	604	599	268	152
Cherry	350	290	198	236
Plum	805	1864	1278	896
Total number of fruit				
Round	113	126	61	32
Cherry	1161	507	575	716
Plum	422	951	810	570
Average fresh weight of individual fruit (g)				
Round	93	99	83	78
Cherry	4	8	5	4
Plum	32	35	26	22
Number of fruit affected by B.E.R.				
Plum	55	149	95	188
Number of fruit affected by cracking				
Plum	2	11	4	12

3.2. Irrigation requirements

To maintain adequate soil moisture (>10% volumetric soil water content) in summer, the Unlined raingarden needed frequent supplemental irrigation via the surface drip system at volumes very similar to the micro-spray irrigation of the control gardens. The Unlined raingarden required a total of 3462 L in the first summer (control gardens: 3448 L) and 3523 L in the second summer (control gardens: 3580 L). Although the Unlined raingarden needed no irrigation in winter (control gardens: 1254 L), it is clear that

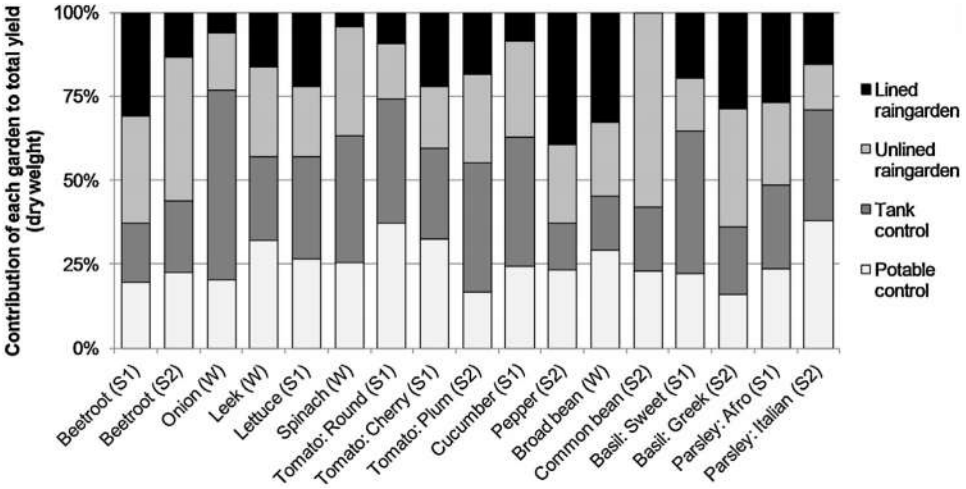

Fig. 3. Percentage contribution of each of the four gardens (two raingardens and two controls) to the total yield (by dry weight) of various species/varieties of vegetables and herbs over three growing seasons; Summer 1 (S1), Winter (W) and Summer 2 (S2). For root and bulb vegetables only (beetroot, onion and leek), which had variable numbers of plants in each garden, total yield is calculated according to the mean weight of individual plants. For beetroot, this does not include the weight of edible leaves; i.e. edible root (tuber) only.

its design was sub-optimal from an irrigation perspective, as it failed to convey large volumes of roof water from the subirrigation system to the vegetable root zone. The total volume of water received by the control gardens, which received no roof water via sub-irrigation, was much less than that received by the two raingardens; only 20–28% for the first two growing seasons, and 36% of the Unlined in the second summer. Yet, overall, the control gardens showed very little or no relative reduction in soil moisture or yield.

As expected, the irrigation requirements of the Unlined raingarden were particularly high when rainfall was low and soil and air temperatures were high, such as in January 2012 and January 2013 (Fig. 4). However, the relationship between rainfall and deficit irrigation volumes over the 18-month monitoring period was not statistically significant ($R^2 = 0.20$, $P = 0.071$), and irrigation requirements were better correlated with soil temperature ($R^2 = 0.52$, $P = 0.003$).

The Lined raingarden had much lower irrigation requirements than the Unlined, with no supplemental irrigation needed in the winter or second summer growing seasons. This was a period spanning 12 months, and the spring-summer period was exceptionally dry; the total amount of rainfall at the site between September and January was 153 mm, which is 51% of the Melbourne average for that period. The Lined raingarden had consistently greater soil moisture than the Unlined and the controls from approximately mid-way through the winter growing season (August 2012) to the end of the monitoring period.

A key factor causing the greater soil moisture in the Lined raingarden during these months was its water level, which was consistently at or near the sand-soil boundary (25–35 cm above ground level). As designed, water in the Lined raingarden could only be lost through evapotranspiration and overflow, so that a large volume was usually retained in the garden bed between rainfall events. In the Unlined raingarden, on the other hand, the water level only reached the sand and soil layers following heavy rainfall and then declined rapidly. In every growing season, the mean water level was below even the gravel-sand boundary. Variations in the water level in the Unlined raingarden did seem to have some influence on soil moisture ($R^2 = 0.78$, $P < 0.001$). This was not the case for the Lined raingarden ($R^2 = 0.02$, $P = 0.641$). This is because the water level in the Lined was much more consistent over the monitoring period, with the exception of the dry second summer growing season, but soil moisture varied considerably.

3.3. Runoff reduction

The inflow hydrographs for the raingardens showed a series of peaks corresponding to rainfall, with no baseflow, which is typical of runoff from impervious surfaces. With the significant loss of water through infiltration into the underlying soil, the Unlined was the better of the two raingardens for runoff reduction. It reduced the volume of runoff by 91% and the frequency by 93%. In most months (11 of 17), there was no overflow at all; overflow occurred on only one day (26th February 2013) between July 2012 and the end of monitoring in March 2013. Furthermore, in the preceding period, the maximum number of days of overflow per month was only two. As such, runoff reduction by the Unlined raingarden did not seem to be affected by the supplemental irrigation it received. In comparison, the Lined raingarden reduced the volume of runoff (total overflow relative to inflow) by 63% and the frequency (number of days of overflow relative to inflow) by 34%. Zero overflow occurred from the Lined raingarden in only one, exceptionally dry month (January 2013) (Fig. 5). The Lined raingarden captured approximately 21 kL of runoff over the 18-month monitoring period, although it was clearly less effective than the Unlined. Its performance was also more variable over time, particularly in response to variation in rainfall and evapotranspiration rates. As expected, it was most effective in reducing runoff from rainfall events that were preceded by dry periods, such as October 2012 and January 2013.

For both raingardens, rates of overflow were less than rates of inflow up to the 99.9th percentile, with the Unlined particularly effective at attenuating peak flow (Table 3). However, for both raingardens, the maximum overflow rate was higher than the maximum inflow rate. This only occurred during high intensity rainfall events in December 2011, and particularly during severe thunderstorms on the 25th. It indicates that, for periods of less than two minutes, the entire inflow to the raingardens was being discharged to the stormwater drain, combined with some rainfall that had fallen directly onto the garden beds.

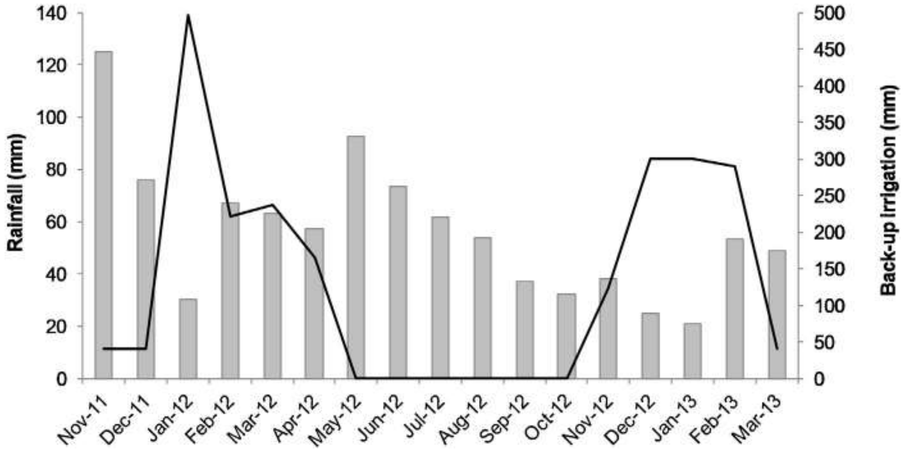

Fig. 4. Irrigation requirements of the Unlined raingarden under the deficit irrigation regime (black line), in relation to monthly rainfall totals (bars).

Table 3
Attenuation of peak flow; percentiles of inflow and overflow rates for the Unlined and Lined raingardens.

		Percentile of flow rates ($L\,m^{-1}$)					
		95.0	97.5	99.0	99.5	99.9	100.0
Unlined	Inflow	0.13	0.26	0.89	1.75	5.33	72.19
	Overflow	0.00	0.00	0.00	0.00	0.00	90.43
Lined	Inflow	0.12	0.20	0.70	1.65	5.14	74.90
	Overflow	0.00	0.00	0.05	0.38	3.95	83.66

4. Discussion

4.1. Yield and irrigation requirements

The aim of this 18-month field trial was to test the yield production, irrigation requirements, and runoff capture performance of vegetable raingardens. The results indicate that it is indeed possible to grow food in vegetable raingardens while sustainably using water resources and achieving stormwater runoff mitigation.

The sub-irrigated raingardens tested in our study, sized 7.5% of their catchment area, produced yield comparable to surface-irrigated vegetable gardens without the need for additional irrigation to supplement rainfall, under the temperate Melbourne climate. The raingarden that was lined required no supplemental irrigation even in a dry and hot spring-summer period with half of the average rainfall, although the Unlined (infiltration-type) raingarden needed regular irrigation in summer. In any case, supplemental irrigation could comply with all but the most severe of Melbourne's water restrictions and it is likely to have little or no negative effect on runoff reduction. Indeed, if the supplemental irrigation water is collected stormwater from a rainwater tank rather than tap water, this could further increase the opportunity for reducing volumes of urban runoff.

The drawback of having no supplemental surface irrigation in the Lined raingarden was that it generally produced the lowest yield. In the case of tomatoes, it was also more susceptible to physiological disorders. The plum tomatoes in the Lined raingarden were the smallest and most affected by both blossom end rot and cracking, with the Potable control the least affected. Blossom end rot is usually attributed to a calcium deficiency, often associated with some type of stress such as water deficit (Obreza et al., 1996; Pires et al., 2011; Saure, 2001; Sun et al., 2013). Similarly, while there are various potential causes of cracking in tomatoes, cracks can develop if ripening fruit expands too rapidly, and a rapid influx of water can contribute to the occurence and severity of cracking (Saltveit, 2005). This might have been a factor in the Lined raingarden, which had the most extreme wetting-drying regime of the four gardens in the second summer season.

Nonetheless, differences in yield between the four gardens cannot be explained by differences in irrigation application alone. Shade is unlikely to be a factor, given that the four garden beds

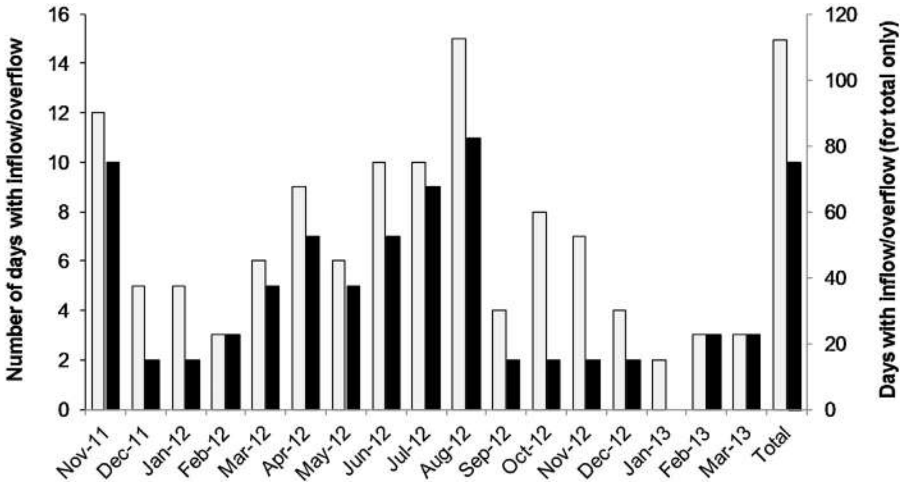

Fig. 5. Number of days per month of inflow (>1 $L\,m^{-1}$) (white bars) to the Lined raingarden compared to the number of days of overflow (black bars).

were positioned to ensure equal exposure to sunlight. One possible cause of the differences in yield, which warrants further research, is the activity of soil fauna. In particular, many earthworms were observed in the gardens by the end of the first summer growing season. It is well known that earthworms increase the fertility of vegetable gardens and they might also affect the flow of water through the media, as in natural soils (Wilkinson et al., 2009). It is possible that conditions in the sub-irrigated raingardens, particularly the Lined, were less favourable for earthworm and other animal activity. Apart from vegetable growth, this might also affect the capability of the system to remove pollutants from runoff (Tomar and Suthar, 2011).

Another important consideration is the availability of nutrients for plant growth, and how it is affected by the source of irrigation water and other variables. For example, Denman et al. (2006) found that nutrients in stormwater can increase the growth of trees relative to irrigation by tap water. Similarly, in our field trial, the Tank control garden produced greater yield than the Potable control for cucumber, onion, plum tomato, and basil. It also produced larger tomato fruit for all three varieties. However, given that the two raingardens were also irrigated with the roof water, and that this was partly delivered through surface irrigation in the Unlined, the benefit of any additional nutrients from this source seems to be limited. Future research could investigate whether vegetable yield is affected by using more polluted runoff, such as runoff from the heavily trafficked road reported on by Trowsdale and Simcock (2011), although food safety would be the foremost concern in that instance.

4.2. Effect of lining on runoff reduction

The use of lining will affect not only irrigation requirements, and to some extent yield, but also the ability of the raingarden to reduce urban runoff. In our study, the Unlined (infiltration-type) raingarden reduced both the volume and frequency of runoff by >90%. Consistent with previous work (Davis, 2008; Davis et al., 2009; Li et al., 2009), the Lined raingarden was less effective, although it still captured approximately two thirds of inflow. The Lined raingarden was most effective for rainfall events that were preceded by dry periods. Therefore, in the instances where lining is necessary, such as where the raingarden is built close (<5 m) to a structure, a lined raingarden would provide satisfactory but not optimal runoff reduction. In the instances where lining is not required, the choice of lined or unlined might depend on the primary objectives of the system; for runoff reduction, unlined systems are most appropriate, while for yield and water conservation, lined systems are likely to perform best. The optimal design for a vegetable raingarden might be “partially lined”, as a compromise between the Lined and Unlined raingardens that were tested.

4.3. Other design recommendations

The simplest way to ensure that runoff reaches the vegetable root zone is to introduce the water within the soil (top) layer, or on the surface, as in a conventional raingarden. This is worth considering given that, contrary to some previous reports (e.g. Ahmed et al., 2000; Goodwin et al., 2003), the sub-irrigated raingarden design offered no clear yield or irrigation requirement benefits. In the field trial, the two raingardens received a large volume of rainwater from the roof during the monitoring period (>33 kL in 18 months), but this water was not effectively conveyed to the vegetable root zone, at least in the Unlined (infiltration-type) raingarden. Consequently, for some vegetables such as tomato and onion, yield was relatively low in at least one of the two raingardens, in comparison to the two controls.

Also critical to the design of vegetable raingardens is the type and arrangement of filter media. Our study followed the separate vegetation and filter layer design recommended by Hsieh and Davis (2005), in which the vegetation layer is optimized for plant survival and the filter layer is optimized for pollutant removal. This was anticipated to limit contamination of vegetables by the upward-moving roof water, and to act as a buffer to minimize leaching of organic matter from the soil layer. It is possible that the sand layer acted as a capillary break, forming a barrier to the upward movement of water. This seems to have been overcome in the Lined raingarden by the second half of the monitoring period, possibly as the boundaries between the media layers became less discrete and/or as the sand became less hydrophobic. However, it was not overcome in the Unlined raingarden. An alternative design is a uniform profile in which the vegetation and filter layers are combined. This is used in many conventional raingardens, but the media must be sandy (e.g. loamy sand) with minimal additional organic matter, as this is optimal for the removal of pollutants from runoff (Bratieres et al., 2008; FAWB, 2009; Henderson et al., 2007). In a vegetable raingarden, a uniform sandy layer by itself is unlikely to be optimal for vegetable growth.

Media depth is another issue. The vegetated soil layer in our raingarden design was approximately 35 cm deep, to support vegetable growth. This is also consistent with a 30 cm-minimum soil depth recommended for biofiltration systems (Davis et al., 2003; Hsieh and Davis, 2005). However, sub-irrigation might be more effective if the growing media is <35 cm. Research testing green roofs for vegetable production demonstrates that vegetables can be grown in shallow growing media, although this does tend to require the use of fertilizers (Ouellette et al., 2012; Whittinghill et al., 2012).

Other recommended amendments to our sub-irrigated raingarden design include installing wicks to promote capillary rise of runoff water from the gravel layer into the soil layer, and designing the overflow system to allow the water level to rise closer to the soil surface following significant rainfall, rather than only to the base of the soil layer (Melbourne Water, 2013).

4.4. Choosing vegetable species

There was variation in yield between the different vegetable species, and also within species; between varieties and between growing seasons. Nonetheless, other than some species being more prone to pest damage, especially broccoli (*Brassica oleracea*) in winter for which yield could not be measured, no species or variety performed particularly poorly. Even the relatively deep-rooted species (e.g. tomato) appeared to have little or no advantage in the sub-irrigated raingardens. As such, it seems that many or all common vegetables have the potential to be produced in vegetable raingardens, with minimal fertilizer inputs and minimal supplemental irrigation. An associated greenhouse experiment (paper in preparation) confirmed that a range of vegetables can be produced effectively without any irrigation to supplement stormwater inputs, given average summer rainfall for Melbourne. Bean, beetroot, leaf parsley and plum tomato were tested and they all performed well, as was also the case in this field trial.

We also recommend a replicated field experiment, to further assess the suitability of different vegetables to raingardens. This will also help to determine influences on plant growth other than water availability, such as the influence of earthworms.

4.5. Green roofs

The results of this study also have implications for vegetable production on green roofs. The Lined raingarden that was tested can be regarded as a green roof system, although only as the intensive type; i.e. it could only be used on a building with structural reinforcement, given the depth and weight of the filter/growing media. Rainwater for irrigation could be collected and conveyed from another part of the building's roof (Whittinghill and Rowe, 2011). Effective runoff management, low irrigation requirements and reasonable yield are likely benefits of a "vegetable green roof" based on the Lined raingarden design. However, relative to the tested raingarden, the system might be more exposed to the weather if it were positioned on a roof, to the extent that yield and irrigation requirements might be altered. An issue that requires future research, for both raingardens and green roofs, is how to meet the nutritional needs of vegetable plants while minimizing negative impacts on runoff quality and the environment.

5. Conclusion

This study has demonstrated that the *vegetable raingarden*, like the *vegetable green roof*, is an opportunity to expand stormwater reuse practices in urban food production, and to incorporate food production into Water Sensitive Urban Design. Provided that it is designed and managed effectively, a subirrigated vegetable raingarden can produce yield similar to a vegetable garden watered using more traditional methods, while also significantly reducing urban runoff.

Some important design issues for consideration include the use of waterproof lining and the arrangement of filter/growing media. The use of waterproof lining in this field trial was a key influence on both runoff reduction and soil moisture. The infiltration-type raingarden, without lining, reduced both the volume and frequency of runoff by >90%, although it needed regular irrigation in summer. On the other hand, the raingarden with lining reduced the volume and frequency of runoff by 63% and 34%, respectively, but it did not need supplemental irrigation even in a dry and hot spring-summer period.

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