Urban Food Systems Symposium

Yields of relay cropped greens grown in green roof production systems

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Abstract

As interest in urban food production increases, urban farmers are looking for solutions to the challenge of space availability. One solution is to move production to building rooftops, a space that is often underutilized. The use of green roof technology is one method of achieving food production on rooftops; however, there are some additional challenges associated with this practice as a result of the fast-draining, low-nutrient media used. This is particularly challenging for vegetable crops, which typically require more nutrients than the ornamental plants traditionally grown in green roof media. Some rooftop farmers are adding additional organic matter in the form of compost to their beds as an alternative to chemical fertilizers. Currently, there is little research on how rooftop production systems affect crops. Green roof platforms were established at the Harold R. Benson Research and Demonstration Farm in Frankfort, Kentucky, to examine crop yield in green roof systems supplemented with compost. Treatments were a topsoil no compost control, a green roof media no compost control and 3 green roof media treatments: the addition of 0.33, 0.66, or 1 kg m^{-2} of compost. Organic fertilizers were used to supply additional nutrients to vegetable plants. The crops selected were lettuce, arugula, mizuna, mustard, Swiss chard, kale, and spinach. These were relay cropped in succession during two growing seasons (2018 and 2019). At each harvest, the amount of time harvesting required (in seconds), total yield, and marketable yield (determined by visual examination) were measured for each platform. Yield results were analyzed in R. Analysis of variance was performed on all variables for each crop; compost treatment and year were fixed effects. Significant differences between treatment means were analyzed using Tukey HSD (alpha of 0.05). Results for kale show differences between 2018 and 2019 for harvest time and total yield in the topsoil control, but no differences for marketable yield. These differences are likely due to weather conditions. Kale harvest time, total yield in 2019 but not 2018, and marketable yield were highest in the topsoil control. Harvest time of the topsoil control was not significantly higher than the 1 kg m^{-2} of compost in green roof media. The marketable yield of the topsoil control was not significantly higher than 0.66 or 1 kg m^{-2} compost treatments in green roof media. Results for additional crops will also be presented.

Keywords

urban agriculture, soilless media, compost, lettuce, spinach, kale

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INTRODUCTION

Green roofs have been the focus of research on sustainable development practices and green infrastructure alternatives to grey infrastructure. The earliest research into the many benefits of modern green roofs is now several decades old. One of the benefits that has received much of the research and policy attention is stormwater management, both the reduction in stormwater quantity and changes to the stormwater quality (Czemiel Berndtsson, 2010; Rowe, 2011). Much of the focus of the stormwater quality research has been to understand if and how green roofs improve the quality of stormwater runoff. How green roofs affect stormwater depends heavily on management practices, including irrigation and the use of fertilizers, the composition of the green roof media, and media age and depth (Buffam and Mitchell, 2015; Buffam et al., 2016; Clark and Zheng, 2013; Czemiel Berndtsson, 2010; Hathaway et al., 2008; Mitchell et al., 2017; Rowe, 2011). Other benefits to green roofs that are well established include reductions in roof surface temperatures, reduction in urban heat islands, reductions to energy use within the building for cooling or heating (depending on the climate where the roof is located) (Alsup et al., 2013; Fassman-Beck et al., 2013; Gong et al., 2019; Jadaa et al., 2019; Karczmarczyk et al., 2020; Rowe, 2011; Saadatian et al., 2013; Susca et al., 2011), reductions in noise pollution, improvements to air quality, and increased biodiversity and habitat (Dimitijević et al., 2018; Francis and Lorimer, 2011; Van Renterghem and Botteldooren, 2011).

More recently, green roofs have been considered as a tool to increase urban food production. Although this benefit has been in practice in the United States since at least 2009 (Greenroofs.com, 2020), peer review research on the use of green roofs has lagged behind research into other benefits. One focus of that research has focused on the effects that food production on green roofs could have on the other established benefits of green roofs, stormwater management in particular (Kong et al., 2015; Matlock and Rowe, 2017; Whittinghill et al., 2015, 2016a) . A typical extensive (less than 15 cm green roof media) covered with a mix of *Sedum* spp. only requires about 7.03 g nitrogen m^{-2} (FLL, 2002). In contrast, nitrogen application recommendations for crop plants in Kentucky range from 2.24 to 16.81 g m^{-2} (Rudolph et al., 2019), as much as double the recommendation for sedums. This additional use of fertilizers often leads to higher nutrient concentrations in runoff water (Whittinghill et al., 2015; Whittinghill et al., 2016). Some rooftop farmers use a combination of fertilizers and compost to achieve appropriate levels of nutrients (Whittinghill et al., 2016). Increases in initial green roof organic matter content, usually through the addition of compost to the media, can also increase nutrient concentrations in stormwater runoff (Czemiel Berndtsson, 2010; Eksi et al., 2015; Matlock and Rowe, 2017; Mitchell et al., 2017). Little of the research has focused on the yield potential of food production on rooftops, and little of that has gone beyond demonstrating that certain crops can be grown in relatively shallow media.

Research into the yield potential of food production has often found that production in these relatively shallow media depths is possible. Mixed vegetable production was examined in one set of studies performed at Michigan State University; these included tomato (*Solanum lycopersicum),* green beans (*Phaseolus vulgaris*), cucumbers (*Cucumis sativus*), sweet peppers (*Capsicum annuum*), basil (*Ocimum basilicum*) and chives (*Allium schoenoprasum*) in plantings (Whittinghill et al., 2013, 2016b). The comparison with ground level plots had mixed results, with some crops doing better on the green roof due to warmer temperatures and others not doing as well on the green roof (Whittinghill et al., 2013). The use of mulches to control water loss did not increase total yield over that of the no mulch control, but increasing the amount of fertilizer supplied did increase total yields (Whittinghill et al., 2016). A later study at Michigan State University looking at cucumber and pepper growth in media with differing amounts of compost found that total and marketable weights were often higher in the media mixes than in the ground, but did not find a clear dose response to the compost (Eksi et al., 2015). An additional study at that institution included two herbs, including basil, in their plant selection, and found that growth was affected by nutrient source, but the focus of that experiment was how that growth would affect plant survival in the green roof environment, rather than yield (Matlock and Rowe, 2017). A greenhouse experiment performed at Barnard College, Columbia University examined nitrogen cycling in green roof media with different nutrient sources, including composts and synthetic fertilizer (Kong et al., 2015). Their study plant was Swiss chard, and while they did see increases in yield with the addition of nutrients to the green roof media and synthetic fertilizers usually outperformed no nutrient input control, there were not clear differences between that treatment and the compost treatments, or between the compost treatments and the control with no nutrient input. Other studies including vegetable crops (Chen et al., 2018) or herb plants (Kokkinou et al., 2016) examined plant performance, but did not measure any yield metrics. Another study using multiple vegetable crops in Italy looked at growing on rooftops, but used hydroponic techniques and a commercial soil rather than green roof media (Sanyé-Mengual et al., 2015).

This line of research is important to pursue for several reasons. First, understanding at what media depths food production is possible will help determine how widely green roof agriculture could be implemented. Deeper green roof media requires a stronger underlying roof structure, or higher load capacity. When a building is being considered for retrofit from a conventional roof to a green roof, the building is examined by a structural engineer in order to determine the limitations of the building roof, which will dictate the maximum depth of the roof, and therefore the optimal plant community on that green roof. It is believed that most existing rooftops could only support as little as 7.6 cm of media, or a load capacity of 146 kg m^{-2} (Kortright, 2001). Retrofitting existing buildings to increase their roof load capacity would incur considerable costs (Whittinghill and Rowe, 2012) and is often not considered feasible. Second, understanding how food production on green roofs compares to more traditional ground level agriculture will help us understand the impact that it could have on the local food system and food security. One of the primary reasons people become involved in urban agriculture is to increase food security, either for themselves or for their community (Ghose and Pettygrove, 2014; Koscica, 2014). This usually focuses on providing fresh fruits and vegetables in food deserts, or areas without grocery stores or farmers markets where fresh fruits and vegetables can be purchased (Dutko et al., 2012). The impact that a given urban agricultural pursuit has on food security will depend on the amount of produce it is able to add to the local community and the nutritional value of that produce. Third, a balance may need to be struck between increasing yields of crops through management practices, specifically the addition of nutrients to the roof through the use of compost or fertilizers, and the environmental impacts of those practices.

With these factors in mind, this research was designed to explore the production of greens on green roofs. Greens are considered ideal crops for small-scale urban agriculture because they are highly nutritious and are considered a high-value crop. Greens, especially those considered dark green leafy vegetables such as kale, spinach, and mustard, are good sources of several vitamins, including A, C, E, K and many B vitamins (Yan, 2016). They also contain mineral nutrients, including magnesium, potassium, calcium, and iron, and are good sources of fiber and antioxidants (Yan, 2016). High-value crops, or crops that have a high market price, are often considered ideal because they increase the profit margin of the farmer (Bartholomew, 2013; Satzewich and Christensen, 2011). In the case of rooftop farmers, they could help to offset the cost of rooftop construction faster than other crops. Greens also have a relatively short growing period, about 26-30 days from planting to the "baby" stage (Johnny's Selected Seeds, 2020), which, in combination with relay cropping, can maximize the number of harvests during the growing season (Satzewich and Christensen, 2011; Stone, 2016).

MATERIALS AND METHODS

Research was conducted at the Harold R. Benson Research and Demonstration Farm in Frankfort, Kentucky. Green roof platforms were constructed in May 2018. The platforms consisted of a 1.22 x 1.22 m deck constructed from 5.08 x 10.16 cm pressure treated lumber, including 2 joists, topped with severe weather common square southern yellow pine plywood sheeting. This deck was elevated 0.6 m above the ground with 10.16 x 10.16 cm pressure treated lumber legs. This was topped with a raised bed made from 5.08 x 10.16 cm and 5.08 x 15.24 cm pressure treated lumber. All lumber was pressure-treated with Ecolife™ (Viance LLC, Charlotte, North Carolina). The 5.08 cm gap left by the 5.08 x 10.16 cm lumber was covered with Phifer Super Solar Charcoal Fiberglass Replacement Screen to allow for water flow but retain the media. All platforms were then lined with black Smartpond Nylon Mesh Pond Liner to act as a waterproof barrier and filled with 5.08 cm of Rooflite® Drain media, topped with Rooflite® Separation Fabric, and finally filled with 20.32 cm of Rooflite® Intensive green roof media. Additional platforms were constructed according to this design but were filled with 20.32 cm of local topsoil.

A randomized complete block design was used with four replicates each of four nutrient management treatments. Green roof media was amended with one of four compost treatments at the beginning of the growing season in 2018 and 2019 (Table 1). The compost treatments consisted of 0, 0.33, 0.66, and 1 kg m^{-2} of compost Garden Magic® Compost and Manure (0.1-0.1-0.1) (Michigan Peat Company, Houston, TX). The remaining plant nutrients were supplied using three organic fertilizers— Tomato Tone (3-4-6), Bone Meal (4-12-0) and Blood Meal (12-0-0) (The Espoma Company, Milleville, NJ)— applied at each planting to meet the College of Agricultural and Environmental Sciences at the University of Georgia nutrient recommendations for greens of 19.61 g Nm^{-2}, 16 g P_2O_5 m^{-2}, and 16 K_2O m^{-2}. Four topsoil containing platforms were treated with the same organic fertilizer treatment as the 0 compost green roof media platforms and were treated as a control.

Table 1. Nutrient management, planting, and harvesting timeline for the 2018 and 2019 growing seasons.

Activity	**2018**	**2019**
Compost added	May 16	April 4
Fertilizer added and lettuce planted	--	April 11-12
Lettuce harvest	--	May 23-24
Fertilizer spread and arugula planted	June 4	May 28
Arugula harvest	July 11	June 19-21
Fertilizer spread and mizuna planted	July 11	June 21
Mizuna harvest	August 6	July 11
Fertilizer spread and mustard planted	August 6	July 11-12
Mustard harvest	August 30	August 5
Fertilizer spread and Swiss chard planted	--	August 6
Swiss chard harvest	--	September 12-13
Fertilizer spread and kale planted	August 30	September 13
Kale harvest	September 26	October 16-17
Fertilizer spread and spinach planted	September 26	--
Spinach harvest	October 22	--

All green roof platforms were then planted with a succession of seven types of greens using a relay cropping technic. Greens planted included *Lactuca sativa* (Encore lettuce mix), *Eruca sativa* (Astro arugula), *Brassica rapa* (Mizuna Asian greens), *Brassica juncea* (Red giant mustard greens), *Beta vulgaris* (Fordhook giant swiss chard), *Brassica napus* (Red Russian kale), *Spinacia oleracea*

(Covair spinach). Due to a late start after plot construction in 2018 and drought conditions in 2019, not all greens were planted during both growing seasons. *B. vulgaris* was introduced in 2019 during the warmest part of the growing season because of its higher heat tolerance than other green species included in the study. The planting and fertilizer application schedule can be seen in Table 1.

Greens were harvested at the baby stage. At each harvest, data were collected on the amount of time it took to harvest each plot (referred to as harvest time) and the total and marketable yield of the crop. Marketable yield was determined by visual examination. If there were obvious signs of insect damage or discoloration, leaves were deemed unmarketable. During the 2018 growing season, data were also collected on the number of plants and total number of leaves per plot.

Statistical analysis was performed in R (Version 1.2.5001, The R Project for Statistical Computing, Vienna, Austria). Data were normalized by plot area to account for the difference in area of the two growing systems. Data that did not conform to a normal distribution were transformed using square root (mizuna, kale, and spinach harvest times; mustard, kale, and spinach total yields; and arugula, mizuna, mustard, and spinach marketable yields) and base ten logarithmic (arugula harvest time and mizuna total yield) transformations. Analysis of variance (ANOVA) models were run with compost treatment and year as factors. Post-hoc testing was performed using Tukey's Honestly Significant Difference (HSD), with alpha level of 0.05. Means presented in tables or graphs are untransformed mean values.

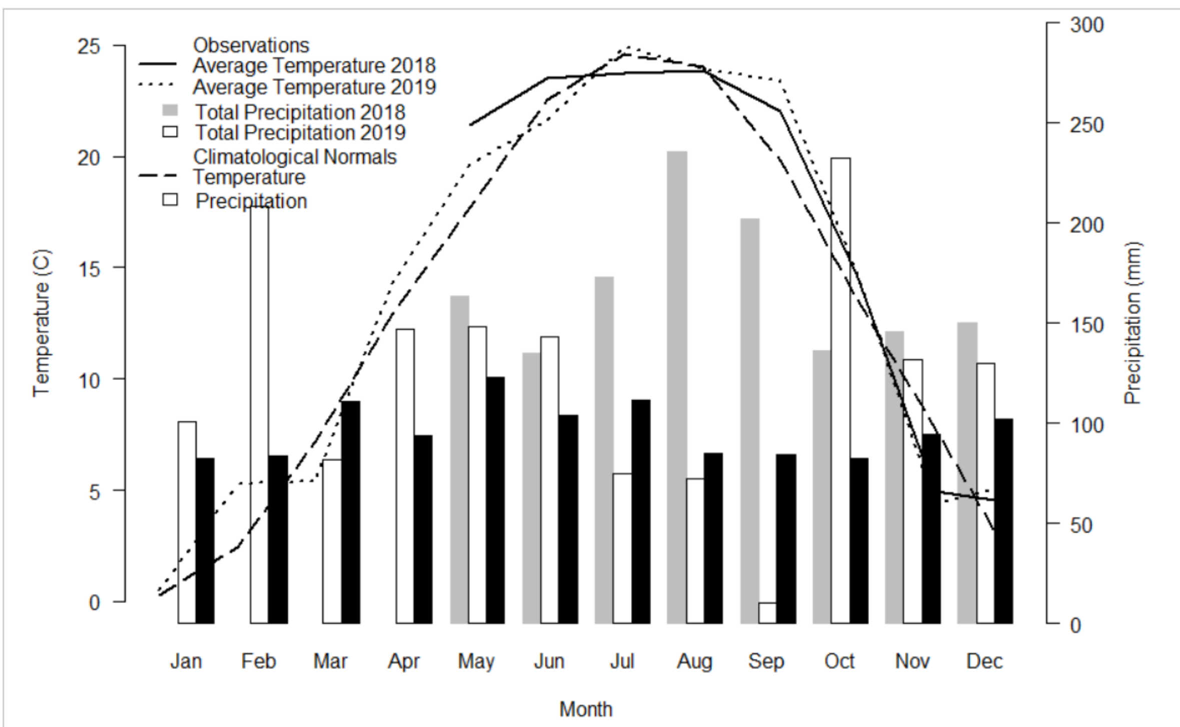

Figure 1. Average air temperature and total precipitation by month for both years of the study, 2018 and 2019, and Climatological normal for the region for temperature and precipitation.

RESULTS

Weather

Air temperatures in May and early June were slightly higher in 2018 than in 2019, but higher after that until September in 2019 (Figure 1). Total precipitation in 2018 was 1828 mm, slightly higher than that of 2019, at 1483 mm. This may have been due to the drought in 2019. Both July and August 2019 received lower than average amounts of rainfall, 75 and 72 mm compared to 111 and 85 mm for the climatic norms, respectively (Figure 1). September 2019 was the height of the drought and had a total of 10 mm of rainfall, compared to 202 mm and a climatic norm of 84 mm (Figure 1). During the drought, there was also a seven-day period of time from September 27 to October 3 for which maximum temperatures exceeded 32° C. This was the longest stretch of time in either summer where temperatures were that high. In 2018, the highest rainfall was 236 mm and occurred in August. This was about the same as the highest rainfall in 2019, 232 mm, which took place in October (Figure 1).

Table 2. Mean harvest time in seconds of crops grown in the no compost topsoil control and four green roof media compost treatments. Where indicated, means are for individual growing seasons. Values in parentheses represent the standard error. Means represent 4 observations per growing season. Lower case letters denote difference among compost treatments within each crop, or within a growing season for that crop.

		Topsoil Control	**Green Roof Media Treatments**			
Crop	**Harvest Year**	**0 kg m^{-2} Compost (s)**	**0 kg m^{-2} Compost (s)**	**0.33 kg m^{-2} Compost (s)**	**0.66 kg m^{-2} Compost (s)**	**1 kg m^{-2} Compost (s)**
Lettuce	2019	1115 (327)	976 (264)	1237 (235)	672 (173)	747 (81)
Arugula	2019	1113 (110) ab	640 (85) b	1777 (561)[1] a	1443 (315) ab	641 (83) b
Mizuna	2018	128 (53)	158 (49)	151 (51)	143 (41)	173 (55)
Mizuna	2019	57 (49) b	412 (46) a	365 (78) a	225 (62) ab	445 (83) a
Mustard	Both	144 (16)	78 (18)	89 (24)	92 (13)	87 (16)
Swiss chard	2019	951 (502)	315 (132)	425 (28)	416 (51)	676 (152)
Kale	Both	181 (44) a	52 (16) b	52 (16) b	52 (16) b	89 (24) ab
Spinach	2018	205 (43) a	27 (8) bc	6 (3) c	53 (17) b	258 (7) bc

1. This mean represents 3 observations due to missing data.

Harvest time

The two-way interaction between compost treatment and year had no significant effect on harvest time of mustard (F=0.973, p=0.437) or kale (F=0.217, p=0.927). Compost treatments had no significant effect on the harvest time of lettuce (F=1.605, p=0.408), mustard (F=2.351, p=0.0738), or Swiss chard (F=1.398, p=0.282) (Table 2). There were no significant differences between the harvest times of the topsoil control and any of the green roof media compost treatments for arugula or the 2018 mizuna harvest. In contrast, the topsoil control had significantly higher harvest times than any green roof compost treatment for spinach and any except the 1 kg m^{-2} treatment for kale, and a significantly lower harvest time for mizuna than any green roof compost treatment except the 0.66 kg m^{-2} treatment in 2019. There were no significant differences among the harvest times of green roof compost treatments for mizuna in 2019 or kale. Differences among the green roof compost treatments were not consistent for the remaining crops. The 0.33 kg/m^2 treatment had a significantly higher arugula harvest time than either the 0 or 1 kg/m^2 treatments but was significantly lower than the 0.66 kg m^{-2} treatment for the spinach harvest. Harvest year had no significant effect on the harvest time of mustard (F=3.352, p=0.0759) (Table 3). There were no significant differences in harvest time of mizuna between the 2018 and 2019 growing seasons for any compost treatment (Table 2). Kale harvest time in 2019 was significantly higher than that of 2018 (Table 3).

Table 3. Mean harvest time in seconds of crops grown in the 2018 and 2019 growing seasons. Values in parentheses represent the standard error. Means represent 20 observations. Lower case letters denote difference between growing seasons for each crop.

Crop	**2018 (s)**	**2019 (s)**
Mustard	112 (12) a	84 (12) b
Kale	51 (11) b	117 (22) a

Table 4. Mean total yield (g) of crops from the no compost topsoil control and four green roof media compost treatments. Where indicated, means are for individual growing seasons. Values in parentheses represent the standard error. Means represent 4 observations per growing season. Lower case letters denote difference among compost treatments within each crop, or within a growing season for that crop. Capital letters demote differences between growing seasons with a compost treatment for a crop.

		Topsoil Control	**Green Roof Media Treatments**			
Crop	**Harvest Year**	**0 kg m^{-2} Compost (g)**	**0 kg m^{-2} Compost (g)**	**0.33 kg m^{-2} Compost (g)**	**0.66 kg m^{-2} Compost (g)**	**1 kg m^{-2} Compost (g)**
Lettuce	2019	1543.67 (255.93) b	2644.22 (129.10) a	2796.05 (158.32) a	2768.30 (229.63) a	2531.25 (199.07) a
Arugula	Both	1126.92 (160.50)[1]	846.94 (236.97)	1109.71 (334.08)	925.46 (271.11)	795.94 (203.19)
Mizuna	2018	124.31 (101.29)	90.00 (31.16)	118.69 (58.63)	83.11 (42.28)	95.66 (41.27)
Mizuna	2019	13.94 (12.03) b	365.69 (109.28) a	330.44 (188.04) a	154.54 (77.39) a	449.05 (106.90) a
Mustard	2018	132.66 (22.92)	36.32 (14.63)	35.97 (15.53)	40.09 (28.11) B	31.76 (10.46)
Mustard	2019	155.10 (47.07) ab	28.60 (14.60) b	57.80 (40.81) b	290.05 (64.50) Aa	22.83 (9.82) b
Swiss chard	2019	378.15 (74.61)	286.10 (130.81)	435.15 (97.69)	399.57 (84.12)	503.85 (114.57)
Kale	Both	204.60 (55.76) a	31.76 (15.31) b	34.22 (5.08) b	36.44 (7.63) b	58.94 (15.01) b
Spinach	2018	44.11 (15.88) a	2.97 (1.27) b	1.17 (0.72) b	9.16 (4.54) b	4.55 (1.72) b

1. This mean represents 7 observations due to missing data.

Total yield

The two-way interaction between compost treatment and harvest year had no significant effect on total yield of arugula (F=1.985, p=0.123) or kale (F=0.224, p=0.922). Compost treatment had no significant effect on the total yield of arugula (F=1.099, p= 0.373), mustard (F=2.351, p=0.0738), or Swiss chard (F=0.607, p=0.664) (Table 4). There were also no significant differences in total yields of mizuna and mustard in 2018 among any compost treatment. The topsoil control had significantly lower total yields of lettuce and mizuna in 2019, but significantly higher yields of kale and spinach. There was no difference between the total yields of the topsoil control and any green roof compost treatment for mustard in 2019. There were no significant differences among green roof compost treatments for total yields of lettuce, the 2019 mizuna harvest, kale or spinach. The total yield of mustard was significantly higher in the 0.66 kg m^{-2} treatment than any of the other green roof compost treatments, which were not significantly different from each other. Harvest year had no significant effect on the total yield of kale (F=1.559, p=0.220) (Table 5) or in mizuna total yield between years within any compost treatment (Table 4). Total yield of arugula was significantly higher in 2019 than in 2018 (Table 5). There were no significant differences in mustard total yield between years within any compost treatment except the 0.66 kg m^{-2} compost treatment, where 2019 was significantly higher than 2018 (Table 4).

Table 5. Mean total yield in grams of crops grown in the 2018 and 2019 growing seasons. Values in parentheses represent the standard error. Means represent 20 observations. Lower case letters denote differences between growing seasons for each crop.

Crop	2018 (g)	2019 (g)
Arugula	392.58 (50.96)[1] b	1492.70 (113.84) a
Kale	54.53 (14.53)	91.85 (27.47)

[1.] This mean represents 19 observations due to missing data.

Marketable yield

The two-way interaction between compost treatment and year had no significant effect on marketable yield of arugula (F-1.089, p=0.380), mizuna (F=0.255, p= 0.904), or kale (F=0.721, p=0.585). Compost treatment had no significant effect on the marketable yield of arugula (F=0.307, p=0.871), mizuna (F=0.255, p=0.904), or Swiss chard (F=1.047, p=0.418) (Table 6). There were no significant differences in marketable yields of mustard among the compost treatments in 2019. Marketable yield of lettuce from the no compost topsoil control was significantly lower than that of the 0.33 kg m^{-2} and 0.66 kg m^{-2} green roof compost treatments. The marketable yield of the no compost control treatment was significantly higher than all the green roof compost treatments for the mustard harvest in 2018 and for the kale except the 1 kg/m^2 treatment. For spinach, the marketable yield of the no compost topsoil control was only significantly higher than the 0 kg m^{-2} treatment. There were no significant differences among the marketable yields of green roof compost treatments for lettuce, the 2018 mustard harvest, kale, or spinach. Harvest year had no significant effect on the marketable yield of kale (F=1.786, p=0.190) (Table 7). There were no significant differences in marketable yield of mustard for any compost treatment except the no compost topsoil control, which was higher in 2018 than 2019 (Table 6). Marketable yield of arugula was significantly higher in 2019 than in 2018 (Table 7). Marketable yield of mizuna was significantly lower in 2019 than in 2018 (Table 7). None of the mizuna or mustard harvests in 2019 were considered marketable due to insect damage.

Table 6. Mean marketable yield in grams of crops grown in the no compost topsoil control and four green roof media compost treatments. Where indicated, means are for individual growing seasons. Values in parentheses represent the standard error. Means represent 4 observations per growing season. Lower case letters denote difference among compost treatments within each crop, or within a growing season for that crop.

		Topsoil Control	**Green Roof Media Treatments**			
Crop	**Harvest Year**	**0 kg m^{-2} Compost (g)**	**0 kg m^{-2} Compost (g)**	**0.33 kg m^{-2} Compost (g)**	**0.66 kg m^{-2} Compost (g)**	**1 kg m^{-2} Compost (g)**
Lettuce	2019	1253.05 (210.57) b	1915.72 (158.44) ab	2441.05 (166.30) a	2157.30 (202.37) a	1906.77 (122.93) ab
Arugula	Both	636.46 (81.31)[1]	608.88 (152.13)	608.88 (152.13)	551.59 (154.04)	481.91 (67.56)
Mizuna	Both	55.44 (47.42)	36.33 (19.28)	54.41 (32.65)	29.12 (16.59)	36.67 (19.78)
Mustard	2018	120.12 (22.76) Aa	25.42 (11.57) b	28.32 (13.17) b	36.41 (27.57) b	26.26 (11.11) b
Mustard	2019	0.00 (0.00) B	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Swiss chard	2019	50.13 (17.04)[1]	139.47 (76.73)	220.55 (66.26)	188.52 (86.55)	266.95 (91.40)
Kale	Both	86.55 (27.46) a	13.85 (3.94) b	18.65 (4.72) b	24.85 (5.20) b	45.01 (13.32) ab
Spinach	2018	10.59 (6.28) a	0.25 (0.25) b	0.47 (0.28) ab	2.12 (1.53) ab	1.52 (0.54) ab

[1.] These means represent 7 observations for arugula and 3 observations for Swiss chard due to missing data.

Table 7. Mean marketable yield in grams of crops grown in the 2018 and 2019 growing seasons. Values in parentheses represent the standard error. Means represent 20 observations. Lower case letters denote differences between growing seasons for each crop.

Crop	**2018 (g)**	**2019 (g)**
Arugula	329.47 (39.29)[1] b	831.34 (82.40) a
Mizuna	29.44 (7.02) a	0.00 (0.00) b
Kale	46.13 (12.83)	29.44 (7.02)

[1.] This mean represents 19 observations due to missing data.

DISCUSSION

Harvest time was measured as the total time it took to harvest a plot and, as such, is correlated with the total yield of that plot. However, significant differences in one metric did not always correspond to significant differences in the other metric. Lettuce, for example, exhibited no significant difference in harvest time across any treatment (Table 2), but did show a significant difference between the total yields of the topsoil control treatment and all green roof media treatments (Table 4). Several factors may have contributed to the difference in total yield but lack of difference in harvest time. First, this was the first crop of the growing season and some harvesters were new to the project. Observation has shown that as harvesters gain experience with the harvesting methods, harvest times decrease. Changes to research methods in the future should enable confirmation of this observation. Second, this was by far the most abundant crop, with total yields at least an order of magnitude greater than the other crops included in the study. The large volume of crop to be harvested may have obscured differences in harvest times. Other crops that did not have significant differences in harvest times among treatments— mizuna in 2018, mustard, and Swiss chard (Table 2)— also exhibited no significant difference in total yield, with the exception of mustard in 2019 (Table 4). All other crops had similar patterns in differences among treatments in harvest time (Table 2) and total yield (Table 4), except arugula. The difference in the arugula results is likely due to the loss of harvest time data in 2018. The lack of difference in harvest times for many of the green roof media treatments suggests that the management practice selected will not have an effect on farm labor costs.

There were almost no significant differences among green roof media treatments for total yield or marketable yield. The only exception was the total yield of mustard greens in 2019, which was significantly higher in the 0.66 kg m^{-2} compost treatment than any other compost treatment (Table 4). This result is not easily explained by an increase in compost or an increase in organic fertilizer over the other treatments. One possible explanation for the lack of difference is the low nutrient content of the compost used in the experiment. The nutrient analysis of the compost was 0.1-0.1-0.1, which meant that the majority of the nutrients was coming from the organic fertilizers used in all treatments. In following studies, compost with a higher nutrient analysis will be used to test the validity of this assumption. Another possible explanation is that the volume of compost was too low in the treatments to show a clear pattern of difference. Research performed at Michigan State University using mixes of green roof media and compost from 0% compost to 100% compost did, however, show a similar lack of clear dose response to the compost (Eksi et al., 2015). This suggests that there are other factors that are likely to affect the yields in the different compost and media mixes.

There were significant differences between the total yield and marketable yield of the topsoil control and some or all of the green roof media treatments for several of the examined crops, although not for all of them. Both arugula and Swiss chard showed no difference between the topsoil control and the green roof media treatments. This suggests that these crops are as suited to rooftop production as they are ground level production. The crop that did have significant differences between the topsoil control and one or more green roof media treatments seem to fall into two categories, early season and late season crops. The lettuce and mizuna are early season and show higher total (Table 4) or marketable yield (Table 6) in one or more green roof media treatment than the topsoil control. Mustard, kale and spinach are late season crops and show lower total yield or marketable yield in one or more green roof media treatment than the topsoil control. It is likely that weather and differences in surface and soil temperatures may cause this effect. Lettuce was the first crop planted in the early spring, and if the green roof media was slightly warmer at that time, it would be advantageous to the lettuce, but later in the year when temperatures are high, this would impede germination for mustard, kale and spinach. Swiss chard was a late season crop but is more heat tolerant that the other crops selected, and therefore less likely to be as affected by soil and surface temperature. Although plot surface temperatures were not measured in this experiment, they are being measured in follow-up experiments, which may provide support for this theory.

In several crops, the impact of weather and insect pest pressure may have obscured treatment effects. Plot construction took place relatively late in the 2018 growing season. For this reason, the first crop, lettuce, was skipped that year. It did, however, also cause later planting times for the mid-season crops (Table 1), which resulted in higher temperatures at planting and during growth (Figure 1). This likely caused the differences between the 2018 and 2019 growing seasons for arugula total yield and marketable yield and total yield of mustard in the 0.66 kg m^{-2} treatment.

Arugula harvests were slightly lower than but close to yields reported by one for-profit urban farmer, which would be an equivalent of 1159 g per research plot (Stone, 2016). Caterpillar pests were seen throughout the growing season and caused some damage to all crops. The main crop pests were flea beetles. These affected arugula to a certain extent, but dramatically affected both mizuna and mustard, especially in the 2019 growing season. Marketable yields for both crops in that growing season was 0 g (Tables 6 and 7). Some steps were taken to control the flea beetle population, but they proved ineffective. Future research studies with greens will incorporate greater pest control measures. Heat in 2018 and insect pests in 2019 led to much lower mustard and mizuna yields than the about 697 grams per research plot reported by an urban grower (Stone, 2016).

Swiss chard, kale and spinach also have much lower yields than might be expected. Swiss chard yields could be expected to be as high as 1559 g (Stone, 2016). Although Swiss chard is more heat tolerant than the other greens planted, its planting and growth coincided with a drought in Kentucky (September in Figure 1). Irrigation was supplied to the plots during this time, but it is likely that not enough was supplied. Green roof media is designed to be very well draining. That water loss, combined with evaporative losses through the surface of the media, may have still resulted in water stress. Both kale and spinach also had lower yields than might have been expected: 967 g and 1015 g, respectively, from an urban farm (Stone, 2016) and 1636 g spinach based on rural agricultural production in the U.S. in 2019 (USDA NASS, 2020). Both were final crops— spinach in 2018 and kale in 2019. In 2019, temperatures were still quite warm when spinach was planted. This was followed by a brief cool period during which the spinach started to grow but was not long enough before the first frost for much spinach to reach the appropriate harvest size. In 2019, kale was subjected to a similar situation.

Lettuce may have been the only crop to experience yields in the expected range: 1159 grams based on yields from the urban farm (Stone, 2016) and 2439 based on rural agricultural production (USDA NASS, 2020). As this crop was only planted during one growing season, further experimentation may be needed to confirm these results. Further experimentation should also be performed to determine if this success was due to the crops' placement in the planting schedule—first in the early spring, when conditions for growing greens were most ideal in 2019.

CONCLUSION

Although this research did experience some setbacks, and yields of some crops were lower than anticipated, important lessons were learned. A lack of difference between the topsoil organic fertilizer treatment and many of the green roof media treatments suggests that these greens could be as productive in a well-managed green roof setting as they are in ground level agriculture. There are, however, still many questions that need to be answered, most having to do with differences between the green roof media and roof environment and in ground production at grade. Further exploration of the effects of nutrient sources on yield is needed. This should be combined with exploration of the effect of those nutrient sources on runoff water quality. If high yield production on green roofs results in water quality degradation downstream, alternative production methods may be needed to improve urban food security. Differences in how green roof media and soil behave in terms of water and cation exchange capacity are somewhat understood, but how surface temperature differences affect germination and plant growth need to be further explored. This may lead to best management practices for plant timing, green roof media recommendations, or new green roof media formulations. Lettuce was by far the most productive crop grown during this experiment and shows promise for high yield green roof production that could contribute significantly to urban food security, especially if dark, highly nutritious varieties are incorporated into the planting mix.

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