JOURNAL
OF LIVING ARCHITECTURE
A GREEN ROOFS FOR HEALTHY CITIES PUBLICATION

Volume 10 Number 1 Pages 13-25 2023

Autumn Production of Romaine Lettuce on an Extensive Green Roof

Stuart A. Walters[1]*, V. Thomas[1], Karen S. Midden[1], and John W. Groninger[1]

[1]School of Forestry and Horticulture, Southern Illinois University, Carbondale IL 62901, U.S.A.
**corresponding author:* awalters@siu.edu

ABSTRACT

Extensive green roofs provide a significant amount of potential available space to expand urban agriculture. Successful crop production in this type of growing system requires growers to overcome temperature extremes, as well as drought conditions and low fertility associated with a shallow and porous rooting substrate. Four cultivars of Romaine lettuce (*Lactuca sativa*) that included 'Outredgeous', 'Parris Island Cos', 'Rouge d'Hiver', and 'Rubens Baby', were grown to maturity in an 8 cm deep expanded lightweight clay substrate on an extensive green roof during the autumn production seasons of 2012 and 2013. Fast and slow release fertilizer regimes popular with growers and a no fertilizer control were provided along with supplemental water via drip irrigation as needed. Chlorophyll content, as measured by a SPAD meter, provided a useful indicator of crop plant vigor and overall plant productivity. Abnormally cold growing conditions during the critical maturation period in autumn 2013 resulted in lower yields compared to 2012. Results indicated that lettuce productivity was improved by the addition of fertilizers, with the fast release providing the greatest growth and productivity. These results demonstrate the feasibility of producing a nutritious and popular autumn crop on an extensive green roof suitable for local urban food systems. However, this research also highlights the vulnerabilities of this system to weather. Utility of green infrastructure for teaching urban agriculture and plant biology is also discussed.

Key words: *Agriculture education, edible landscaping, food insecurity, production horticulture, urban sustainability*

INTRODUCTION

The use of extensive green roofs is expanding within a broader movement toward integrated urban sustainability. Local food consumers in urban centers value produce generated under sustainable production methods, including use of circular nutrient economies, reduced carbon footprints, and freshness and improved nutrient density resulting from reduced farm to table transportation distance (Specht et al., 2014). Urban food production also fosters a sense of place among local consumers and civic pride in neighborhood producers (Viera et al., 2018; Whittinghill and Rowe, 2012). Extensive green roofs are ideal to improve sustainability of urban areas, but inherently shallow, drought-prone, and nutritionally poor growing substrates are necessary to satisfy roof weight load requirements, often resulting in both water and fertility issues for crop plants in this production system (Getter and Rowe 2006; Walters and Midden 2018). Thus, appropriate crops, inputs, and cultural practices must be adapted from traditional agriculture systems to this unique environment in order for green roof agriculture production to contribute meaningfully to sustainable urban food systems.

Although conceptually possible on extensive green roofs, recent research demonstrates the challenge of optimizing crop production to develop truly productive urban foodscapes (Walters and Midden, 2018). Many food plants have been successfully grown on extensive green roofs when sufficient irrigation and supplemental nutrient additions were provided (Papafotiou et al., 2022; Tassoula et al., 2021; Walters et al., 2022). However, cultivars associated with hot, dry climates, particularly herbs, typically perform best in urban green roof environments located in temperate climate zones with vegetables requiring more care to address heat and drought conditions associated with exposed urban landscape placement and shallow substrate. Although expanding the crop species grown on extensive green roofs could enhance the applicability of this system, compensatory practices are required for species that are associated with less stressful growing environments. In particular, autumn or early-spring crops could help expand the production season and total annual yield potential of these urban spaces.

Leafy greens are commonly associated with autumn or early-spring growing conditions in temperate zones, as they tolerate cool conditions and light frosts (Fu et al., 2012; Lobell et al., 2007). Cultivar groups with upright growth and shallow rooting (Agricultural Marketing Research Center 2014), such as Romaine lettuce, appear to be well-suited to the limited space and shallow rooting depth of an extensive green roof environment. Producing these nutritious and popular crops on extensive green roofs could expand the impact of urban food production by providing a fresh source of these crops for urban markets (Boroujerdnia et al., 2014; Martinez-Sanchez et al., 2011). Furthermore, given late-winter or late-summer establishment timings and rapid time to maturation, lettuce production allows for a production season where lower temperatures reduce irrigation water demand. Autumn or spring production also allows growers to avoid poor quality and bitter taste that results from high temperatures when lettuce plants mature in late spring or early summer production seasons (Dufault et al., 2009). However, the ultimate feasibility of growing lettuce on green roofs requires establishing small, vulnerable plants during either the late summer, when excessive heat and drought conditions may decrease plant establishment, or in late winter, when low temperatures may restrict plant growth and development.

Past research on extensive green roofs has demonstrated the need for nutrient inputs to optimize lettuce production (El-Abagy et al., 2012). Fast and slow release fertilizers offer competing benefits and tradeoffs. Fast release fertilizers allow application on an as-needed basis but also require multiple applications per growing season. In contrast, slow release fertilizers are generally incorporated into the substrate at the time of planting and are more costly than fast release types. However, both are readily available and widely used across horticultural applications. Thus, the objective of this research was to determine the suitability of four Romaine lettuce varieties for food production on an extensive green roof. Furthermore, fertilizer management (utilizing a fast release and slow-release fertilizer, and an untreated control) for lettuce was evaluated across two growing seasons to determine the viability of popular fertilizer regimes.

MATERIALS AND METHODS

Description of Green Roof Environment

A study was conducted on the Southern Illinois University Carbondale (SIUC) Green Roof over the 2012 and 2013 autumn growing seasons to evaluate the growth of four Romaine lettuce (*Lactuca sativa*) varieties using three fertilizer management regimes. The SIUC campus green roof (37.712993ºN Latitude, 89.22227ºW Longitude) is located within a humid subtropical climate (Beck et al., 2018) and represented the state-of-the-industry extensive green roof standards at the time of its construction in 2010. This green roof consists of several component layers; a waterproof membrane, protective fabric layer, root permeable layer, drainage layer, filter fabric layer, and substrate constrained by an edging system (Ouellette et al., 2013). The drainage layer is a plastic egg-crate type tray system that collects rainwater and allows excess water to drain from the roof.

The extensive green roof substrate was obtained from Midwest Trading Company (Virgil, Illinois, USA) and is predominantly a mineral-based expanded lightweight clay aggregate having ~ 4 to 5% organic matter at establishment. During installation in 2010, the green roof substrate also included 0.91 kg/m^3 slow-release nitrogen fertilizer and 3.63 kg/m^3 of iron sulfate. However, significant amounts of fertility and organic matter (vermicompost) have been added and extracted via research use on the SIUC green roof over the years. From 2010 through 2012 summer growing seasons, the area utilized for this study was cropped with tomatoes (Ouellette et al., 2013). Immediately following tomato harvest and prior to establishment of the current study, soil analyses indicated the substrate pH to be 7 to 7.5, organic matter content of 3.9 to 4.8%, and C/N ratio of 14.8 to 16.7 (Vogt, 2016). This green roof can support 11 kg/m, which limits the soilless substrate depth to approximately 8 cm.

Plant Material and Experimental Treatments

The study utilized a 4 x 3 randomized complete block design with 4 Romaine lettuce cultivars and 3 fertility treatments constituting main effects. Each block consisted of plots with each of the three fertility treatments randomly assigned to a plot within a block with a total of three blocks per year.

The Romaine lettuce cultivars evaluated were ‘Outredgeous’, 'Parris Island Cos', 'Rouge d'Hiver', and 'Rubens Baby'. ‘Outredgeous’ is a ruffled, sweet, attractive, bright red baby leaf Romaine lettuce. ‘Parris Island Cos’ has dark green foliage, a vigorous growth habit, with a crisp texture and sweet flavor, mosaic virus tolerance, and heat and cold tolerance (Botanical Interests. Inc., 2023a). ‘Rouge d'Hiver’ is a French heirloom with compact growth, having a rich, smooth texture and leaves that appear brown to red in color (Botanical Interests. Inc., 2023b). ‘Rubens Baby’ has crunchy leaves with an outer burgundy-color. Both 'Parris Island Cos' and ‘Rouge d'Hiver’ seeds were from Botanical Interests® (Broomfield, Colorado), while ‘Outredgeous’ and ‘Rubens Baby’ were obtained from John Scheepers Kitchen Garden Seeds (Bantam, Connecticut). These cultivars were selected for this study based on their wide availability, diverse visual foliage traits, and popularity with consumers.

Seeds of the Romaine lettuce cultivars were planted in plug trays filled with a sterilized soil-less mix of peat, perlite, vermiculite (1:1:1) in the SIUC Agriculture teaching greenhouse on 26 and 27 August for 2012 and 2013, respectively. At the cotyledon stage, lettuce seedlings were thinned to one per plug and a 50 mg/L N solution of Peter's 20-20-20 (N-P-K) fertilizer was applied. Seedlings were grown to the 4-5 leaf stage and then acclimated to outdoor conditions for one week before transplanting onto the green roof on 3 and 2 October for 2012 and 2013, respectively.

Twenty plants of each lettuce cultivar were grown in each experimental plot. Lettuce plant spacing within a plot was 15.2 cm within a row and between row spacing of 30.5 cm. Drip tape irrigation was used 2 to 3 times weekly to provide moisture to plants as needed since the green roof substrate dries quickly. A fabric row cover supported by a PVC framework was placed over the entire experimental area when temperatures dropped below 1.7°C at night (Figure 1). All lettuce plants appeared to be free of diseases or insect pests throughout both years the experiment was conducted.

The fertilizer treatments evaluated were chosen to compare the effectiveness of two popular commercial fertilizer treatments using standard application rates: 1) Miracle Gro™ fertilizer (MG; Scotts Miracle-Gro Products Inc., Maryville, Ohio, 16,100 mg/kg N); 2) Osmocote™ fertilizer (O; Scott Miracle-Gro Products Inc.; Maryville, Ohio, 190,000 mg/kg N); and 3) no fertilizer (0 mg/kg N). Miracle Gro™ (24N-8P-16K) is a water-soluble all-purpose fast-release fertilizer that may be absorbed by the plant via the leaves or through the soil into the roots; this material provides a rapid plant response but at the expense of low persistence in the substrate. Recommendations are to apply every 7 to 14 days to the soil adjacent to plant roots (Miracle- Gro Plant Food & Care, 2014).

Osmocote™ (19N-6P-12K) is a slow-release fertilizer that releases nutrients over time from various capsule sizes placed on the soil surface or in the soil close to plants; nutrients can be provided up to and over a period of 4-months before needing to be reapplied. For outdoor use, the recommendation is to sprinkle Osmocote™ evenly over the area adjacent to the plant and work into the top 3 to 8 cm of the soil (Scotts Miracle Grow, 2014). Fertilizer applications for Miracle Gro™ consisted of ~2L solution per plot applied weekly, where Osmocote™ was applied prior to lettuce transplanting with 45 g applied into a 1 m^2 area and mixed into the 8 cm of substrate. Soils were recycled and analyses were not conducted between the two study years because our previous research indicated that virtually all added nutrients were expended during the growing season.

Figure 1. Extensive green roof Romaine lettuce fertilizer experiment soon after planting in 2013.

Data Collection and Analysis

The height, width, and chlorophyll content of each lettuce plant was collected in early, mid, and late November (early-, mid-, and late-growing season, respectively). Plant height was determined by measuring from the base of the plant to the tip of the uppermost leaf. Plant width was measured across the top of the plant from one side to the other. Chlorophyll content was obtained from a leaf at the center-most area of each plant using a Konica Minolta SPAD-502 chlorophyll meter (Special Products Analysis Division, Konica Minolta Sensing, Inc., Osaka, Japan; Figure 2). On 30 November each year, the lettuce plants in all experimental units were harvested, fresh weight determined, placed in labeled small paper bags and placed in a laboratory bench oven with adjustable dial temperature control

(Humboldt Mfg. Co., Norridge, Illinois) at 70°C for 3 days. After this time, lettuce dry weight was determined.

Figure 2. Final leaf chlorophyll content being collected with SPAD meter in late-November 2013.

Lettuce plant height, plant width, leaf chlorophyll content, and fresh and dry weight were subjected to analysis of variance procedures appropriate for a factorial experimental design using the GLM procedure of SAS (SAS Inst., Cary, North Carolina). Normality was determined and data were also analyzed to determine if year by treatment interactions were present. Fisher's protected least significant difference (LSD) test was used to separate fertilizer and lettuce cultivar treatment differences at $P \leq 0.05$. Despite large growth differences between 2012 and 2013, presumably due to early cold conditions in 2013, no year x variety or variety x fertilizer interactions were detected. Therefore, these terms were removed from the model and pooled into the error term for further analysis.

RESULTS

Both fertilizer treatments resulted in greater growth and higher yielding plants than the unfertilized control during each growing season (Table 1). Differences between the fast- and slow-release fertilizer treatments became readily apparent by mid-season during the 2012 season; the fast-release fertilizer resulted in taller plants that eventually produced more plant biomass (Table 2). In contrast, the two fertilizer treatments did not differ ($P > 0.05$) from each other for yield biomass in 2013. Plant height growth proceeded steadily through the

2012 growing season, while little growth occurred in 2013 particularly with little height gain occurring between the mid- and late-season growing periods. For both fertilizer treatments, lettuce plant diameter generally mirrored height growth, and both dimensions were consistent with marketable Romaine lettuce plants in 2012, but not 2013.

Table 1. Romaine lettuce plant height as influenced by 3 fertilizer treatments in a green roof environment during early, mid, and late season 2012 and 2013.

	Plant Height (cm)					
	Early Season		Mid-Season		Late Season	
Fertility Treatments	2012	2013	2012	2013	2012	2013
No Fertilizer	7.8a	5.6a	15.5b	7.5b	20.2c	8.2b
Fast Release Fertilizer	7.6a	5.7a	22.1a	8.9a	35.4a	9.9a
Slow Release Fertilizer	7.5a	5.7a	17.8b	8.8a	28.1b	9.7a

Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant differences (LSD) test ($P \leq 0.05$). Data collected in early, mid, and late-November correspond to early, mid, and late growing season, respectively.

Table 2. End of season plant width, fresh weight, and dry weight of Romaine lettuce plants at harvest as influenced by 3 fertilizer treatments grown on a green roof during 2012 and 2013.

	Plant Width (cm)		Fresh Weight (g)		Dry Weight (g)	
Fertility Treatments	2012	2013	2012	2013	2012	2013
No Fertilizer	32.5b	10.4b	101.5c	38.1b	53.4b	16.1b
Fast Release Fertilizer	52.2a	14.2ab	457.0a	77.7a	220.5a	23.2a
Slow Release Fertilizer	48.7a	18.4a	297.5b	55.9b	151.6a	18.8b

Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant differences (LSD) test ($P \leq 0.05$).

Lettuce leaf chlorophyll content generally reflected significant plant size differences in response to fertilizer treatments and foretold overall yield. SPAD values more than 30 were associated with the largest, fastest growing, and highest yielding plants from the middle of the growing season onward (Table 3). Chlorophyll content for healthy plants (as estimated by SPAD values) was approximately 24 across all fertility treatments in 2012 with the highest yielding treatments exceeding 30 by the end of the growing season (Tables 2 and 3). The low yields at the end of the 2013 growing season were accompanied by low chlorophyll contents that were only slightly higher than those of highest yielding fertilizer treatments at the early part of the 2012 growing season.

Differences were observed among lettuce cultivars for plant height, and fresh and dry weight. Small but significant differences ($P \leq 0.05$) were detected among cultivars for plant height (Table 4), with ‘Outredgeous’ and ‘Rouge d'Hiver’ generally providing the greatest heights.

No differences (P > 0.05) were observed among lettuce cultivars for plant diameter. Additionally, ‘Parris Island Cos’ and ‘Rouge d’Hiver’ had greater yields than ‘Rubens Baby’ and ‘Outredgeous’ (Table 5). Fresh weights for ‘Parris Island Cos’ and ‘Rouge d’Hiver’ were about 27 and 28% greater, respectively, compared to ‘Outredgeous’, and 142 and 144% greater, respectively, than ‘Rubens Baby’. Chlorophyll content indicated small but significant (P ≤ 0.05) differences between lettuce cultivars that were eventually reflected in height and yield differences (Table 6).

Table 3. Romaine lettuce plant leaf chlorophyll content (as measured by SPAD values) at early, mid, and late season during 2012 and 2013 as influenced by 3 fertilizer treatments on a green roof.

	Leaf Chlorophyll Content					
	Early Season		Mid-Season		Late Season	
Fertility Treatments	2012	2013	2012	2013	2012	2013
No Fertilizer	24.5a	14.5a	26.2b	23.1c	26.6c	25.0b
Fast Release Fertilizer	24.4a	14.3a	35.3a	27.1a	37.7a	28.7a
Slow Release Fertilizer	24.3a	14.5a	33.1a	25.7b	32.0b	26.7ab

Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant differences (LSD) test (P ≤ 0.05). Data collected in early, mid, and late-November correspond to early, mid, and late growing season, respectively.

.

Table 4. Plant height of Romaine lettuce cultivars grown on a green roof at early, mid, and late season.

	Plant Height (cm)		
Cultivar	Early Season	Mid-season	Late Season
Outredgeous	7.1b	14.7a	21.2a
Parris Island Cos	6.0c	12.0b	18.2ab
Rouge d'Hiver	7.5a	14.6a	20.3a
Rubens Baby	6.1c	13.2ab	15.7b

Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant differences (LSD) test (P ≤ 0.05). Data collected in early, mid, and late-November correspond to early, mid, and late growing season, respectively.

DISCUSSION

This study demonstrates the autumn production on an extensive green roof of several popular Romaine lettuce varieties in quantities and at maturity times comparable to commercial operations and under popular fertilizer regimes. However, differences between the 2 years highlight the importance of growing season weather in determining final yield. During 2012, temperatures generally remained within the optimal production range for lettuce (between 10°C and 25°C) throughout the growing season. However, in 2013, temperatures remained consistently colder, oftentimes less than 5°C, and were particularly low during the 2 weeks before harvest, a time particularly influential to crop yield. Accordingly, overall lettuce plant growth ceased at this time in 2013. Although the autumn growing season allows producers to avoid high temperatures and the associated high water demands of late summer, these results also highlight the challenges of producing crops where growth can be suppressed by the onset of early winter weather conditions.

Table 5. End of season plant width, fresh weight, and dry weight of Romaine lettuce cultivars grown on a green roof.

Cultivar	Plant Diameter (cm)	Fresh Weight (g)	Dry Weight (g)
Outredgeous	29.7a	168.6ab	70.1ab
Parris Island Cos	28.7a	215.0a	105.3a
Rouge d'Hiver	33.8a	217.8a	103.2a
Rubens Baby	27.7a	89.1b	48.6b

Means within a column-followed by the same letter do not differ significantly according to Fisher's protected least significant differences (LSD) test (P 0.05).

Table 6. Leaf chlorophyll content (as measured by SPAD) at early, mid, and late season for Romaine lettuce cultivars grown on a green roof.

	Leaf Chlorophyll Content		
Cultivar	Early Season	Mid-Season	Late Season
Outredgeous	18.2b	28.1b	29.6ab
Parris Island Cos	18.5b	27.9b	29.1b
Rouge d'Hiver	21.1a	30.4a	31.5a
Rubens Baby	21.0a	28.5ab	28.6b

Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant differences (LSD) test ($P \leq 0.05$). Data collected in early, mid, and late-November correspond to early, mid, and late growing season, respectively.

Romaine lettuce chlorophyll content revealed differences in plant nitrogen status among fertilizer treatments, and foretold growth and yield differences between these same treatments; and also disclosed the differences in lettuce plant growth and yields observed between the 2012 and 2013 autumn growing seasons (Mendoza-Tafolla et al., 2019). In our experience, SPAD readings of 30 or greater are associated with productive crop growth. Chlorophyll meters are particularly useful tools for producers to determine vegetative crop yield potential working in small-scale alternative agriculture ventures, such as green roofs or other atypical production environments where fertilizer input standards have not been established.

This study provided clear evidence of the value of this tool on green roofs by demonstrating the interrelationship between plant growth parameters, plant nutrition, and chlorophyll content through time under autumn weather conditions on an extensive green roof. Although somewhat costly (~$2,500 to $3,000 USD), Chlorophyll meters are highly portable (only slightly larger than a smartphone), easy to operate, acquire data rapidly, and produce instant results allowing for their use at many locations through the course of a growing season. However, it is important to note that healthy plants may not generate high yields if other factors, such as temperature, are not favorable as was the case in our study during 2013.

While both fertilizer treatments produced adequate nutrition for Romaine lettuce crop production at recommended rates, the fast release fertilizer product produced a higher yield under the conditions of this study. Moreover, the high porosity and low cation exchange capacity of the green roof substrate and a high nutrient-demanding crop (such as lettuce) may be particularly well suited to the use of a fast release fertilizer. In our study, the delivery of essential nutrients at regular intervals via a fast release fertilizer most likely resulted in improved yield for this nutrient demanding crop (Resh, 2022). The slower release fertilizer appears to lag in performance under the conditions of our green roof substrate. However, in time, if organic matter content and microbial diversity increases in the substrate (Hoch et al., 2019; Molineux et al., 2014), the slow release fertilizer may eventually provide more favorable results (Goyal et al., 1999).

Our results suggest that Romaine lettuce is well-adapted to our green roof environment. Lettuce is a crop that has performed well in other extensive and intensive green roof environments used for local urban food production (S.A. Walters, personal observations, 2023). We focused on autumn production to avoid lettuce plants reaching maturity during the extreme summer heat in our region that would result in reduced product quality, and the large irrigation investment that would be needed to produce a crop at that time. The low stature of lettuce plants is also an asset to minimize damage that often occurs due to wind exposure typical of urban rooftops. Additionally, as an education institution operating on a late August to early May academic calendar, an autumn production season allows a green roof used for food production to demonstrate urban agriculture practices and knowledge to students. Urban educators may also consider using green roof production systems as a teaching tool to introduce principles and practices of urban agriculture, plant genetic diversity, and plant-environment interactions.

Widely diverse plant and crop species have been effectively grown on the SIUC green roof since the completion of this study, including pepper, basil, perennial herbs, and various flowering plants. Future research plans for the SIUC green roof include screening additional native and food crop species, and production technologies for green roof production systems. We also plan to evaluate whether differences in the green roof growing environment relative to conventional production systems have implications for food quality and palatability that remain unaddressed. Furthermore, as the green roof ages, new opportunities and challenges are likely to emerge regarding a rooting substrate that is becoming more biologically and physically complex (with various organic matter additions), which may be analogous to natural soil formation (Riviere et al., 2022).

All Romaine lettuce cultivars selected for inclusion in this study generally proved to be well adapted to production on the SIUC green roof. The color and textural differences of the four varieties provides a diverse and pleasant visual impact, further contributing to the conventional value of lettuce production on multi-use roofscapes. This study showed significant yield differences among the cultivars evaluated. Thus, lettuce cultivar selection should take growing environment into consideration. Producers should conduct small, roof specific suitability trials before undertaking large local green roof production initiatives.

Total yields in our study were roughly half those expected in convention production environments. However, the willingness of urban consumers to pay a premium for locally produced food (Printezis and Grebitus, 2020) and reduced transportation and storage costs may at least partially compensate for lower yields from the extensive green roof. A further cost savings associated with our production system included no maintenance needs beyond water and fertilizer application. That is, no weeding or disease control measures were needed and no wind damage was observed.

Screening of newer lettuce cultivars and evaluation of additional production techniques is planned for future studies. Further areas of interest regarding lettuce production should address product quality challenges and changes in nutrient/antioxidant content associated with the harsh green roof environment relative to soil-based conventional urban agriculture production systems. Furthermore, the porous nature of the rooting substrate challenges conventional moisture sensors to provide accurate readings required to activate automated drip irrigation systems. Thus, further work is needed to develop sensors to accurately measure and provide the appropriate responses to these challenging environments (Walters et al., 2022).

Romaine lettuce demands considerable nutrient inputs to produce a marketable crop on an extensive green roof and any excess nutrients leaching through the substrate may contribute to urban water pollution unless measures are adopted to capture runoff (Berndtsson et al., 2006; Emilsson et al., 2007). While the use of a slow-release fertilizer potentially reduces excess nutrient runoff, this benefit may be negated by providing lower yields in a small, highly valuable green roof growing space. Additionally, the design of our green roof prevents capture or monitoring of nutrient content or runoff. Future research to match nutrient supply and demand would require a soil-water solution sampling lysimeter-type monitoring system to be installed in a green roof substrate to help align resource supply and utilization so that broader sustainability goals can be achieved.

CONCLUSION

Extensive green roofs offer an opportunity to contribute to local urban agriculture. This study demonstrates the feasibility of producing Romaine lettuce during autumn growing seasons in the low nutrient absorption characteristics of an extensive green roof and substrate by employing fertilizer treatments that provide plant available nutrients. Frequent applications of the quick-release formulation produced larger plants and higher yields, yet the slow release-type followed closely in productivity. Our research also demonstrated that chlorophyll meters are a powerful tool to help guide green roof crop production managers to maintain adequate fertility for vegetative plant productivity and yield, although at considerable expense. These results also highlight the sensitivity of autumn Romaine lettuce production systems to weather conditions. Further research is needed to develop improved sustainability of water and nutrient management, as well as to identify new cultivars and production techniques adapted to expand the applicability of autumn crop production for extensive green roof environments.

ACKNOWLEDGEMENTS

We would like to express our gratitude to Tom Cooper, Mike Curry, and the late Grace Koehler. These three green roof professionals generously shared their expertise, time, and guidance in the design and installation of our green roof. An acknowledgement long overdue. Funding support for this research was provided by Southern Illinois University Carbondale.

LITERATURE CITED

Agricultural Marketing Resource Center. 2014. https://www.agmrc.org/commodities-products/vegetables/lettuce. Accessed March 8, 2023.

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A. and Wood, E. 2018. "Present and future Köppen-Geiger climate classification maps at 1-km resolution." *Scientific Data,* 5: 180214.

Berndtsson, J.C., Emilsson, T. and Bengtsson, L. 2006. "The influence of extensive vegetated roofs on runoff water quality." *Science of The Total Environment,* 355: 1(3): 48-63.

Boroujerdnia, M., Ansari, N. and Dehcordie, F. 2014. "Effect of cultivars, harvesting time and level of nitrogen fertilizer on nitrate and nitrite content, yield in Romaine lettuce." *Asian Journal of Plant Sciences,* 6: 550-553.

Botanical Interests, Inc. 2023a. Lettuce Romaine Parris Island Cos. Botanical Interests, Inc. https://www.botanicalinterests.com/product/Parris-Island-Cos-Romaine-Lettuce-Seeds?gclid=Cj0KCQiApKagBhC1ARIsAFc7Mc5sxme8C0OwZ_A5pTXRq_LbfY_b2jy9iAJ40TxlkMK4baCUyna4xZAaAqKfEALw_wcB. Accessed March 8, 2023.

Botanical Interests, Inc. 2023b. Lettuce Romaine Rouge D'Hiver. Botanical Interests, Inc. https://www.botanicalinterests.com/product/Rouge-D-Hiver-Romaine-Lettuce-Seeds?gclid=Cj0KCQiApKagBhC1ARIsAFc7Mc5Pz6RDR294VNcMFm9y2KcRYm_ohd6Xw0cj2eY8CCEH_8aVMmHA_XYaAsAhEALw_wcB. Accessed March 8, 2023

Dufault, R.J., Ward, B. and Hassell, R.L. 2009. "Dynamic relationships between field temperature s and Romaine lettuce yield and head quality." *Scientia Horticulturae,* 120: 452-459.

El-Abagy, H.M., Helmy, Y.l., and Omar, N.M., El-Greadly, N.H.M. and El-Tohamy, W.A. 2012. "Comparative study on the effect of some nutritional fertilizers on growth and yield of lettuce plants." *Journal of Applied Sciences Research,* 8(2): 896-900.

Emilsson, T., Berndtsson, J.C., Mattsson, J.E. and Rolf, K. 2007. "Effect of using conventional and controlled release fertiliser on nutrient runoff from various vegetated roof systems." *Ecological Engineering,* 29(3): 260-271.

Fu, W., Li, P. and Wu, Y. 2012. "Effects of different light intensities on chlorophyll fluorescence characteristics and yield in lettuce." *Scientia Horticulturae,* 135: 45-51.

Getter, K. and Rowe, B. 2006. "The role of extensive green roofs in sustainable development." *HortScience,* 41: 1276-1285.

Goyal, S., Chander, K., Mundra, M.C. and Kapoor, K.K. 1999. “Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions.” *Biology and Fertility of Soils,* 29: 196-200

Hoch, J.M.K., Rhodes, M.E., Shek, K.L., Dinwiddie, D., Hiebert, T.C., Gill, A.S., Estrada, A.E.S., Griffin, K.L., Palmer, M.I. and McGuire, K.L. 2019. “Soil microbial assemblages are linked to plant community composition and contribute to ecosystem services on urban green roofs.” *Frontiers in Ecology and Evolution,* 7: 198.

Lobell, D.B, Cahill, K.N. and Field, C.B. 2007. “Historical effects of temperature and precipitation on California crop yields.” *Climatic Change,* 81: 187-203.

Martinez-Sanchez, A., Tudela, J.A., Luna, C., Allende, A. and Gil, M.l. 2011. “Low oxygen levels and light exposure affect quality of fresh-cut Romaine lettuce.” *Postharvest Biology and Technology,* 59(1): 34-42.

Mendoza-Tafolla, R.O., Juarez-Lopez, P., Ontiveros-Capurata, R.E., Sandoval-Villa, M., Alia-Tejacal, I. and Alejo-Santiago, G. 2019. “Estimating nitrogen and chlorophyll status of Romaine lettuce using SPAD and LEAF readings.” *Notulae Botanicae Horti Agrobotanici Cluj-Napoca,* 47(3): 751-756.

Molineux, C.J., Connop, S.P. and Gange, A.C. 2014. “Manipulating plant microbial communities in extensive green roof substrates*.” Science of the Total Environment,,* 493: 632-638.

Ouellette, N.A, Walters, S.A. and Midden, K.S. 2013. “Fertility management for tomato production on an extensive green roof.” *Journal of Living Architecture,* 1: 1-14.

Papafotiou, M., Matini, A.N., Tassoula, L., Stylias, E.G., Elefthverios, G., Kalantzis, A. and Dariotis, E. 2022. “Acclimation of Mediterranean native sages (*Salvia* spp.) and interspecific hybrids in an urban green roof under regular and reduced irrigation.” *Sustainability,* 14: 4978.

Printezis, I. and Grebitus, C. 2020. “College-age millennials’ preferences for food supplied by urban agriculture.” *Frontiers in Sustainable Food Systems,* 4: 48.

Resh, H.M. 2022. *Hydroponic Food Production*. 8th Edition. Boca Raton, Florida: CRC Press. 603 p.

Riviere, L., Delruelle, A. Reimers, J., Boisson, S. and Mahy, G. 2022. “Disentangling dynamics of green roof vegetation analogue to dry grassland over 3 years: Plant and substrate response to microenvironmental variations.” *Journal of Living Architecture,* 9(2): 1-17.

Specht, K., Siebert, R., Hartmann, 1., Freisinger, U. B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H. and Dierich, A. 2014. “Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings.” *Agriculture and Human Values* 31: 33-51.

Tassoula, L., Papafoiou, M., Liakopolous, G. and Kargas, G. 2021. “Water use efficiency, growth and anatomic physiological parameters of Mediterranean xerophytes as affected by substrate and irrigation on a green roof.” *Notulae Botanicae Horti Agrobotanici Cluj-Napoca,* 49: 12283.

Vogt, V. 2016. “The study of three fertility treatments on four Romaine lettuce cultivars grown on an extensive green roof.” Unpublished M.S. Thesis, Southern Illinois University, Carbondale, Illinois, 36 p.

Walters, S.A. and Midden, K.S. 2018. “Sustainability of urban agriculture: vegetable production on green roofs.” *Agriculture,* 8: 168.

Walters, S.A., Gajewski, C., Sadeghpour, A. and Groninger, J.W. 2022. “Mitigation of climate change in urban agriculture: Water management of culinary herbs in an extensive green roof environment.” *Climate,* 10: 180.

Viera, L.C., Serrao-Neumann, S., Howes, M. and Mackey, B. 2018. “Unpacking components of sustainable and resilient urban food systems.” *Journal of Cleaner Production,* 200: 318-330.

Whittinghill, L.J. and Rowe, D.B. 2012. “The role of green roof technology in urban agriculture.” *Renewable Agriculture and Food Systems,* 27(4): 314-322.