AMERICAN UNIVERSITY OF BEIRUT

ROOF TOP GARDENS TO CONSERVE ENERGY AND USE CONDENSATE FROM AIR CONDITIONERS PRODUCTIVELY

by
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AN ABSTRACT OF THE THESIS OF

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It is no secret to anyone living in Beirut in the summer that the city has become a concrete forest and an urban heat island. Old stone houses and gardens have been replaced by concrete towers and parking lots, in the name of development. The result is searing summer nights, a drastic loss of insect and avian biodiversity, and a large increase in energy usage for interior climate control. These problems are not restricted to Beirut but have rather been experienced in rapidly developing urban centers worldwide. Roof gardens can have a non-proportional effect on energy flux, especially if buildings are high and closely packed. The addition of plants and water retaining substrates to roof surfaces can lessen negative effects of buildings on local ecosystems and can reduce energy use. Rooftop gardens can also serve as social green space and urban gardens, as habitat for wildlife, help in local air-quality improvement, and reduce city heat-island effect. Moreover, if roof gardens are irrigated with non-traditional water sources such as air conditioner condensate, then they can be quite sustainable and environmentally friendly. In the present work I assessed the feasibility of building a roof garden on a bare flat roof in Beirut. The possibility of using recycled material as garden substrate was studied; the effect of roof gardens on temperature variations below the roof was evaluated; and finally I assessed whether enough water can be collected from air conditioner condensate to support a roof garden and whether the water is suitable for agriculture. Results suggest that rooftop gardens would be a great addition to the buildings of Beirut.

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CHAPTER I

INTRODUCTION

The world is experiencing reductions in greenery partially caused by an increase in construction and urban sprawl. Natural landscapes are destroyed to make room for buildings and roads. The increase in construction and development results in an urban heat island effect mainly because of a decrease in evapotranspiration (Takebayashi & Moriyama, 2007; Imhoff, Zhang, & Bounouaet, 2010) and a decrease in sunlight reflection because plants reflect more sunlight than buildings and roads (Akbari & Konopacki, 2005). This urban heat island effect is compounded by thermal properties of construction materials (Montavez et al., 2000) and urban canyons (Landsberg, 1981). Many constructions are built from concrete which tends to absorb heat (Goward, 1981), unlike plants which have reflective and cooling properties. Plants tend to cool an area by reflecting some of the incident energy, trapping another portion as chemical energy and releasing some through evapotranspiration. Urban canyons, streets that are surrounded by densely packed buildings on both sides (especially skyscrapers), retain more heat than rural areas, further contributing to the heat island effect (Arnfield, 2003). Additionally, urban sprawl contributes to the heat island effect by increasing impervious surfaces such as concrete and black top.

As populations grow, people migrate to cities, dense construction increases and concomitantly the heat island effect. More people, buildings and roads result in warmer ambient temperatures (Bacci & Maugeri, 1992). During the summer, buildings surrounded by urban infrastructure stay warmer than buildings that are surrounded by vegetation (Susca, Gaffin, and Dell'Osso, 2011). Ultimately development increases the need for cooling energy, thus releasing more heat into the environment.

Impervious surfaces do not allow water to percolate into the ground, thus increasing storm water runoff and decreasing the quality of the water (Getter & Rowe, 2006). In cities, about 25% of rainfall is absorbed into the ground whilst in forests, about 95% is able to percolate the ground (Scholz-Barth, 2001). Water that does not percolate the ground becomes runoff often flowing into sewage systems. Many sewage systems cannot handle this combination of sewage and storm water and the system ultimately overflows, polluting streams and rivers and causing negative environmental and health effects (Rowe, 2011; Getter & Rowe, 2006).

Similar to many cities, Beirut is growing by adding concrete at the expense of cooling greenery. Because of intense summer heat, residents are now using energy-hungry air conditioner (A/C) units more frequently. These units cool the inside of buildings but emit warmer air to the outside, thus compounding the problem. Many residents in Beirut use split type residential A/C units that emit air that is about 10°C warmer than ambient air (Han & Deng, p. 1473, 2003).

Families in Lebanon consume an average 6907 kW of energy per year (Houri & Ibrahim-Korfali, 2005). These levels are similar to the energy use of people living in Western Europe. Most of Lebanon's energy used to be imported from Syria but these imports are not sufficient to meet the needs of the people. Parts of Lebanon face 13 hours of power cuts daily and residents rely on generators to supply their energy needs during power outages (Dagher & Yacoubian, 2012). These generators tend to be very polluting but the heat in cities makes them indispensable.

A proposed partial solution to increased urban heat would be to introduce green roofs. Green roofs are vegetated areas on the tops of buildings. There are two main types of green roofs: extensive and intensive. Intensive roofs are ones that require a lot of labor and water, and generally have deep substrate depths (Oberndorfer et al., 2007). Extensive green roofs require minimal labor, could be rain dependent, have native plants growing, and have shallow substrate depths (Dunnett & Kingsbury, 2004). Many green roofs fall between the intensive and extensive categories in that they may require some intervention after planting to maintain the roof. Depending on geographical location and climate as well as personal plant preferences and roof garden purpose, some green roofs have plant mixtures that do not require irrigation whilst some have very delicate plant varieties that require intensive tending and irrigation.

Green roofs are able to reduce energy demands. Compared to conventional roofs, white reflective roofs reduce the amount of heat absorbed. However, painting a roof white is still not as effective at reflecting light as green roofs. Installing a green roof versus painting it white would result in energy savings of 40-110% (Susc et al., 2011). Green roofs also extend roof membrane life (Rowe, 2011; Porsche & Köhler, 2013) and cool buildings below through passive cooling (Theodosiou, 2003). Additionally, green roofs increase evapotranspiration, roof albedo (reflectivity of radiation by a surface), and thermal mass (Liu & Baskaran, 2003). Some roof gardens with dense foliage can decrease roof surface temperature significantly when compared to a bare concrete roof surface, thus decreasing energy demands for summer cooling (Del Barrio, 1998; Theodosiou, 2003; Wong, Chen, Ong, & Sia, 2003).

During summer, a green roof on an eight-story building in Madrid decreased cooling energy requirement by 6% (Saiz, Kennedy, Bas, & Pressnail, 2006). In Ottawa, Canada, a roof membrane with a green roof above had a median temperature fluctuation of about 6°C. The reference roof membrane, made of a modified bituminous roofing assembly, had a temperature fluctuation of 45°C over the course of a year (Liu & Baskaran, 2003). The modified bituminous reference roof membrane absorbed solar energy and reached 70°C while a green roof membrane remained around 25°C in July (Liu & Baskaran, 2003). In addition to cooling individual buildings, green roofs could reduce ambient daytime city temperature. A simulation where 50% of Toronto's roofs were covered with green gardens and the buildings containing the roofs were evenly distributed around the city resulted in an ambient air temperature reduction of up to 2°C in some areas (Bass, Krayenhoff, Martilli, Stull, & Auld, 2003). The U.S. Green Building Council (2008) found that buildings use 39% of total municipal energy and 71% of electricity. If more green roofs were installed, they could have a significant impact on reducing energy demands as well as pollution (Rowe, 2010). Thus, green roofs have the potential to work as insulators throughout the year and reduce cooling energy needs.

Green roofs can also increase wildlife habitats and biodiversity in urban settings. However, Brenneisen (2006) found that increasing natural substrate depths in green roofs leads to an increase in biodiversity. Depending on the intended use of the roof garden, an increase in insect biodiversity could be seen as beneficial to the environment or unwanted by building residents. In the past, it was believed that only a limited number of common species could exist on green roofs (Klausnitzer, 1988) but this is no longer what scientists agree upon. Green roofs provide space for many species of beetles, spiders and other organisms, with variety among locations, substrate type and vegetation. Some suggest that the most effective way to promote biodiversity is to use natural material as a green roof substrate (Brenneisen, 2006). However, Schrader & Böning (2006) found that older green roofs contain more organic carbon in the growing medium than more recently built green roofs but insect and arachnid biodiversity remained similar irrespective of garden age.

In addition to reducing energy demands, green roofs would increase pervious surfaces. In large urban areas, the majority of rainfall that does not percolate the ground turns into storm water runoff. The intensity of storm runoff can be mitigated by storing part of the precipitation volume in green roof substrates and releasing it slowly. Green roofs in Michigan, USA, sloped at 2 % with a 4 cm substrate depth had mean rainwater retention of 87% during light (1.27 mm), medium (4.06 mm), and heavy (10.08 mm) 5 minute interval rainfall events (VanWoert, Rowe, Andresen, Rugh, Fernandez, & Xiao, 2005). Studies also show that green roofs are able to reduce noise pollution in buildings. One study using extensive green roofs with substrate depths between 3 and 18 cm found that they have excellent noise reduction properties (Van Renterghem, & Botteldooren, 2011). Additionally, flat roofs that contain green roofs on top were found to be better at reducing traffic noise than angled roofs or roofs without gardens (Van Renterghem, & Botteldooren, 2009).

A/C units produce large quantities of condensate depending on humidity, temperature, and dewpoint. Condensate could be collected and used productively in many areas in the world (Baasiri & Ryan, 1986). One area, San Antonio, Texas, collected 946 L of condensate per day from a shopping mall (Guz, 2005). If condensate were collected and properly managed, it could be used for irrigation (Hastback, Dieckmann, & Brodrick, 2012) and reduce municipal water demands for roof gardens.

In view of the discussion above, rooftop gardens could be constructed to productively use space, provide wildlife habitat, reduce surface water runoff, reduce noise pollution, and moderate summer-month temperatures in buildings. We hypothesize that introducing green roofs in Beirut would decrease energy demands. Moreover, if these rooftop gardens are irrigated with A/C condensate, they would save domestic municipal water for other household usage. The present study was performed to assess the effectiveness of using recycled material as a growing substrate in a rooftop garden. Additionally, the possibility of cultivating plants with A/C condensate as irrigation water was evaluated. Furthermore, cooling properties of rooftop gardens was explored and, lastly, the amount of A/C water that could be collected during the summer months was investigated.

CHAPTER 2

MATERIALS AND METHODS

The present study was performed during 2015 on the roof of the biology department building at the American University of Beirut (AUB), Beirut, Lebanon. The roof is flat, covered with a dark gray, tar shingle-waterproofing layer. The building is three stories high, faces north south and is not shaded by any neighboring tall trees or buildings.

A. Experiment Setup

Six wood boxes each measuring 1.2 m x 1.0 m x 0.2 m (L x W x D), were constructed of one inch marine plywood (purchased locally) and placed on wooden tables which stood 90 cm above the roof surface. The boxes and tables were placed at the southeast corner of the roof above office 315. A fiberglass coating was applied to the boxes to eliminate leaking from joints. Each box had a false bottom installed to separate the substrate from the bottom and allow for drainage of irrigation water. The false bottom sat on PVC pipe sections and was made from perforated clear 0.5 mm Plexi glass sheets and plastic netting with 2 mm mesh size to allow water-drainage. The boxes had a 3% slope relative to the horizontal in order to allow water to drain in one direction. A hole was drilled in the middle of the lower end and a drainage nozzle inserted and a 10 L bucket placed below. Three of the boxes were filled with a substrate consisting of one-third mulch, one-third compost, and one-third soil (treatment A) and three with substrate made of one-third mulch, one-third compost, and one-third pressurized cardboard pellets (treatment B)

(Table 1). The mulch consisted of wood chips whilst compost was from recycled butchery offal, and cardboard pellets were made from recycled paper products (*Cedar Environmental*, Lebanon). The only non-recycled product used in the substrate materials was the soil. All ingredients were mixed by hand and then placed in the experimental garden boxes to a depth of 15 cm.

B. Experiment 1: Estimation of water holding capacity of substrates.

Six 600 mL plastic containers with perforated bottoms were used for the present experiment. These containers were weighed, filled with each of the air-dried substrates, and weighed again. Six hundred mL of water were then slowly poured into each container and allowed to drain from the bottom perforations for 10 minutes. Then the plastic containers with wet substrate were weighed again. The difference between the weight of the wet and dry substrate was calculated to determine water retention. This experiment was repeated after plants were grown and harvested in the various substrate treatments to investigate whether use and weathering made a difference in water retention.

C. Experiment 2: Romaine lettuce seedling cultivation.

Each garden box was planted with 30 romaine lettuce seedlings purchased from a local nursery. Seedlings were spaced eight centimeters from the edges and 20 cm apart. Seedlings were planted in five rows of six plants per garden box on April 1, 2015 and harvested on May 20, 2015 (Figure 1). During the first week and a half of the experiment the plants were watered every day with 10 L of a combination of effluent water collected from the previous irrigation event and tap water. At 10 days post planting, the watering

Table 1: Composition of growing media evaluated in rooftop gardens at the American University of Beirut. Quantities are by volume relative to total volume.

	Quantity	Quantity	Quantity
Treatment A	1/3 Mulch	1/3 Compost	1/3 Soil
Treatment B	1/3 Mulch	1/3 Compost	1/3 Cardboard pellets

schedule was switched to every other day, but the same quantities of water were always used on each garden box. However, if it rained, the plants were not irrigated on that day.

At harvest, rootless plant weight and length were measured using a toploader balance and a 50 cm length ruler, respectively. Scissors were used to separate the lettuce roots from the plants and then the plants were measured by pushing them down so that the leaves would fully extend on top of the ruler and the length of the longest leaf on the lettuce plant could be measured. Each lettuce plant was then weighed separately in a plastic container on the zeroed balance.

Parameters (leaf length and leaf weight) were analyzed using Statistical Analysis System: SAS for windows (V 9.2, SAS Institute Inc., Cary, North Carolina, USA) and $\alpha = 0.05$. ANOVA was used to assess if there were differences between plant weights and plant lengths in treatment A and treatment B; between plants in the edge and middle locations of the garden boxes (Fig. 2); and between plants in the top and bottom locations (Fig. 3).

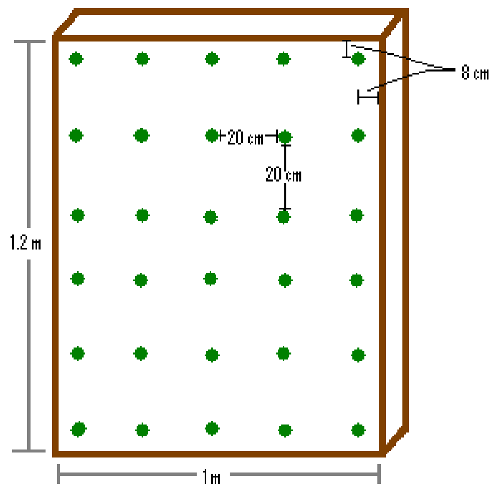

Figure 1: Schematic layout of the planting of lettuce seedlings in treatment A and B in the garden boxes set on the roof of the Biology department at the American University of Beirut, Lebanon.

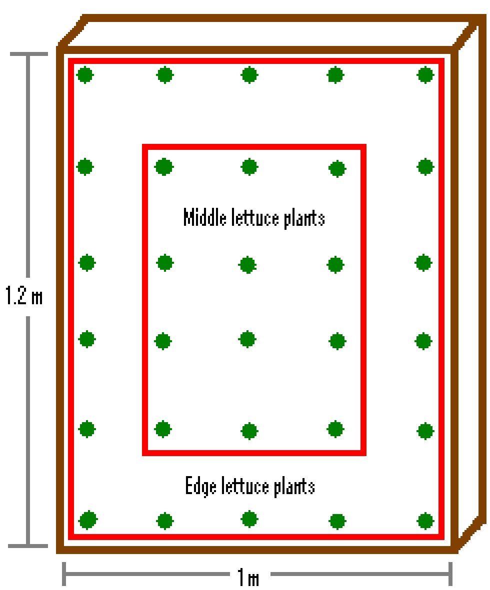

Figure 2: Schematic layout of edge and middle lettuce plants groupings for comparing differences in weight and length planted in the rooftop garden boxes set on the roof of the Biology department at the American University of Beirut, Lebanon.

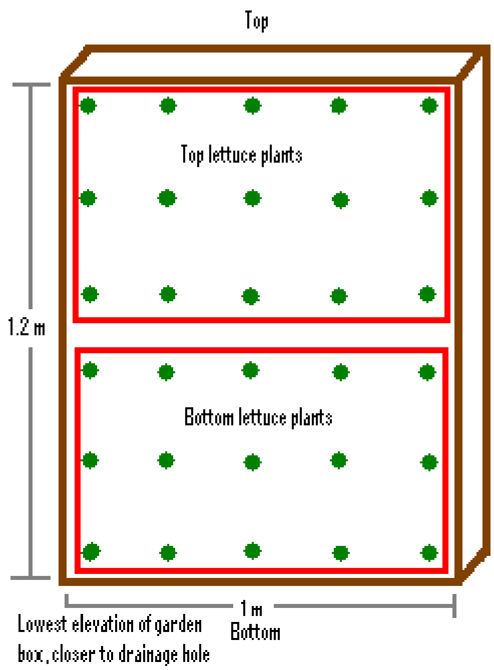

Figure 3: Schematic layout of top and bottom lettuce plants groupings for comparing differences in weight and length planted in the rooftop garden boxes set on the roof of the Biology department at the American University of Beirut, Lebanon.

D. Experiment 3: Radish cultivation.

Farmer radish seeds were purchased from a local garden supply store and 105 seeds were planted in each of the boxes on June 23, 2015. In each garden box, the seeds were planted in five rows, 21 plants per row, spaced 5 cm apart. Edge seeds were planted 8 cm away from the side of the garden box (Fig. 4). Each garden box was irrigated with 10 L of tap water immediately after planting. Subsequently, plants were irrigated with 10 L of tap water for each box every other day between 5:00pm and 8:00pm.

All germinated seeds per garden box were counted weekly. Fourty five days after planting, number of plants per garden box was recorded and all plants were harvested. The number of leaves per plant, total leaf weight per plant, longest leaf length per plant, and root weight and length per plant were assessed for every individual plant. Total leaf and root biomass for each garden box was calculated as the sum of leaf weight or root weight of all plants in the garden box.

Twice during the experiment, tap water used for irrigation and effluent water from the garden boxes were collected in 200 mL beakers. Electrical conductivity (EC), pH, and total salinity of the samples were analyzed in the agricultural soil lab using a conductivity – salinity – temperature recorder (Eutech Instrument, CyberScanCon 11) and pH meter (Oakton, pH 6+).

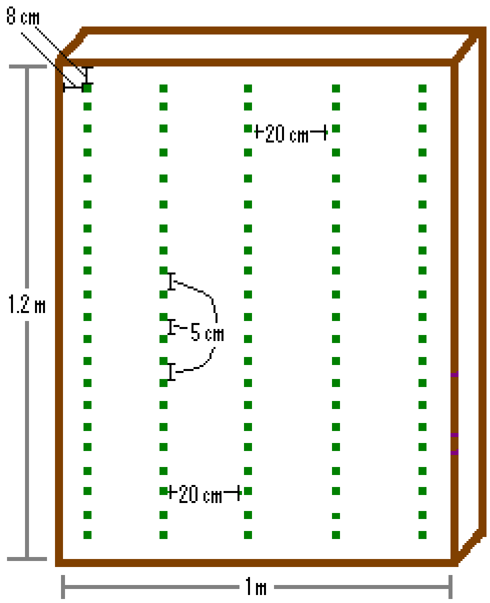

Figure 4: Schematic layout of radish seed spacing in each rooftop garden box set on the roof of the Biology department at the American University of Beirut, Lebanon.

E. Experiment 4: Estimation of daily condensate volumes.

A 12,000 BTU Split System A/C unit was retrofitted with flexible plastic tubing (1.5 cm diameter) so condensate could be redirected back into the room from whence it came and collected in 20 L plastic containers. The A/C temperature setting was programmed to be at 22°C and condensate was collected for 53 days during the summer months of 2015. Collected condensate from June 24, 2015-July 17, 2015 and from August 26, 2015-October 1, 2015 was stored on the roof in a 300 L plastic Nalgene container.

A weather station on the roof of the biology department was used to record outside temperature, outside humidity, dewpoint temperature, wind speed, wind direction, wind chill, heat index, temperature-humidity-wind index, barometric pressure, and precipitation every 30 minutes. Average daily temperature, air moisture and dewpoint temperature were plotted against condensate production rate to evaluate which parameter could best be used to estimate A/C condensate production.

F. Experiment 5: Evaluation of garden cooling effect.

Nine HOBO remote temperature sensors were configured using a base station, coupler, and HOBO ware® software to record average temperature every 30 minutes starting 6:00 pm on June 23, 2015 and ending at 2:00 pm on August 7, 2015. Loggers were activated using the same base station and programmed to have a delayed start so loggers would record simultaneously. The remote sensors were placed in plastic containers and attached to the bottom center of each garden box. Three loggers were positioned under an empty garden box containing no substrate to act as a control treatment replicating a wood roof. Data collected at 6:00 am, 12:00 pm, 6:00 pm, and 12:00 am were used for analysis and comparison among treatments.

G. Experiment 6: Demonstration of feasibility of irrigating with A/C condensate.

Two garden boxes (one treatment A, one treatment B) were planted with 105 radish seeds each on August 25, 2015. Each of these two garden boxes had seeds planted in five rows, 21 seeds per row, and spaced 5 cm apart. Radish seeds were equally watered with the A/C condensate from the A/C unit in room 311. Ten days after planting the radish seeds, (September 4, 2015), lettuce and basil seedlings were planted in the same manner as the lettuce seedlings during experiment 2. Two garden boxes were planted with basil seedlings (one treatment A, one treatment B) and the remaining two garden boxes were planted with romaine lettuce seedlings (one treatment A, one treatment B). Garden boxes were watered every other day with condensate from room 311's A/C unit between 5:00pm and 8:00pm and each box was given the same quantity. Ten days after seedlings were planted, 20 g of fertilizer (NPK 20-20-20) was added to 10L irrigation water of each garden box. Apart from this one fertilizer-water application, no other additives were given to the plants.

Germination in radish garden boxes that could be identified was counted three times: week three (September 15, 2015), week four (September 21, 2015), and on harvest day (October 2, 2015), just past week five. Photos were taken prior and post-harvest. All plants were harvested in October and distributed to graduate students to taste. No data was collected from the lettuce and basil treatments other than visual observation of growth differences.

CHAPTER 3

RESULTS

A. Experiment 1: Estimate water holding capacity of substrates.

Before use, substrate B retained an average of 211.5 ml of water in a 600 ml container (39.89 g). Treatment A retained 235.8 ml water (Fig. 5). After 7 weeks of use during experiment 2, treatment B retained an average of 54.07 ml water while treatment A retained 73.84 ml water.

B. Experiment 2: Romaine lettuce seedling cultivation.

Before planting the lettuce seedling, the average root length per plant was 7.9 ± 1.6 cm (mean ± SD) while the average leaf length was 9.28 ± 1.2 cm. The average leaf weight per plant was 2.12 ± 0.7 g. During the first four weeks, lettuce plants in treatment A grew better than those in treatment B. However, after the fifth week, plants in treatment B started growing faster than those in treatment A.

At harvest (50 days after planting), the average weight of treatment B plants (excluding roots) was 132.7 ± 52.8 g, significantly greater than the average weight of treatment A plants (95.4 ± 42.1 g) ($P<0.0001$) (Table 2a). The average length of the lettuce plants (excluding roots) in treatment B was 22.8 ± 3.2 cm, whereas the average length of treatment A lettuce plants was 17.6 ± 3.4 cm, again significantly different from each other ($P<0.0001$) (Table 2a).

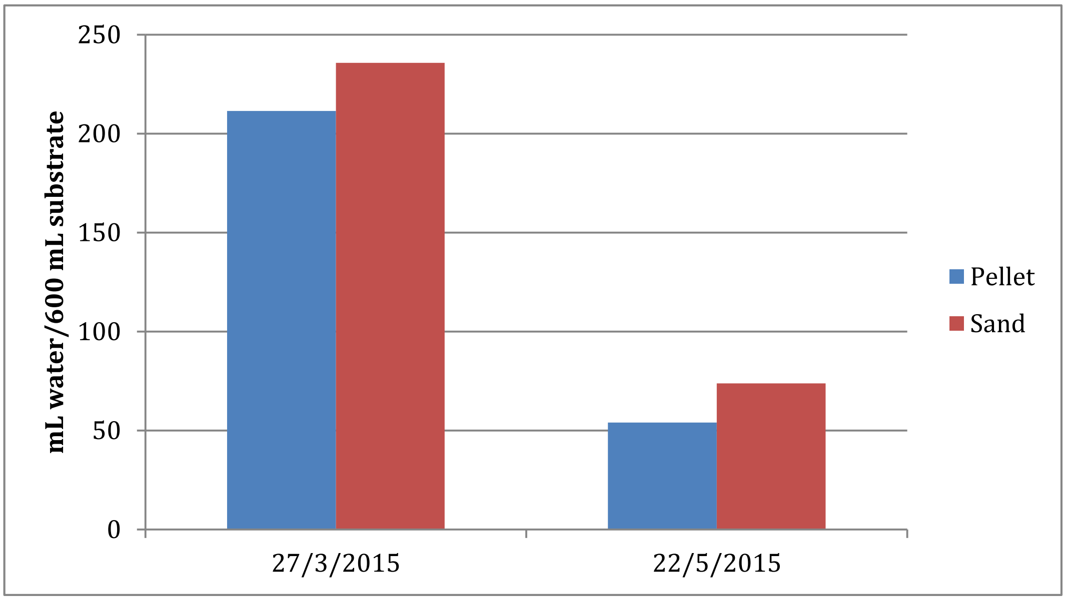

Figure 5: Water retained in treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) and treatment A (1/3 compost, 1/3 mulch and 1/3 soil) before planting any plants in the treatments (March 27, 2015) and after harvesting plants in the treatments (May 22, 2015).

The average weight of plants grown beside the edge of the boxes was 106.3 ± 52.3 g ($P<0.0001$) significantly less than the average weight of plants grown in the middle of the garden boxes (124.7 ± 47.7 g) ($P<0.0001$) (Table 2b). In addition, the average length of the edge plants was 19.5 ± 4.2 cm, significantly less than the average length of the middle plants (21.1 ± 4.0 cm) ($P<0.0001$) (Table 2b).

The mean weight for the back plants was 64.2 ± 19.5 g while the mean weight for front plants was 154.3 ± 59.0 g (Table 2c). The mean length of back plants was 16.4 ± 2.4 cm whereas the average length of the front plants was 22.9 ± 4.2 cm. Again, the differences were significant ($P<0.0001$).

Table 2:

a- Comparison (means ± SD) of weight and length of lettuce plants from a rooftop garden at AUB. Lettuce seedlings planted in two growth media: treatment A = 1/3 compost, 1/3 mulch and 1/3 soil, and treatment B = 1/3 compost, 1/3 mulch and 1/3 cardboard pellets.

Variable	Treatment B	Treatment A	P value
Weight (g)	132.7 ± 52.8	95.4 ± 42.1	<.0001
Length (cm)	22.8 ± 3.2	17.6 ± 3.4	<.0001

b- Comparison of size of plants grown in the edges of growth garden boxes to plants grown in the center of garden boxes. Data from treatment A and B were pooled.

	Edge	Middle	P value
Weight (g)	106.3 ± 52.3	124.7 ± 47.7	0.02
Length (cm)	19.5 ± 4.2	21.1 ± 4	0.01

c- Comparison of size of plants grown in the lower side of the garden boxes to plants grown in the higher side of garden boxes. Data from treatment A and B were pooled.

	High	Low	P value
Weight (g)	64.2 ± 19.5	154.2 ± 59.0	<.0001
Length (cm)	16.4 ± 2.4	22.9 ± 4.2	<.0001

C. **Experiment 3: Radish cultivation.**

At harvest, significantly more seeds had germinated per garden box in treatment A (81 ± 7.2) than in treatment B seeds (46.7 ± 9.3; mean ± SD) (Table 3). Two weeks post planting, an average of 23 plants per garden box had germinated in treatment A and 12 plants per garden box had germinated in treatment B. Overall, 77.1% of planted seeds germinated in treatment A whereas 44.4% germinated in treatment B.

Leaf length and number of leafs per plant as well as, root length and root weight per plant were similar between treatments. Conversely, leaf weight per plant was significantly heavier in treatment B than in treatment A (Table 4). However, because of greater germination rates in treatment A, compared to treatment B, total leaf biomass in treatment A was greater than in treatment B and total root biomass in treatment A was greater than total root biomass in treatment B (Table 5).

Total salinity and EC in samples of effluents from both treatments were greater than total salinity and EC in the water used for irrigation. Roof tap water had an EC of 1.5 mS/cm EC. Early in the radish planting season, effluent conductivity was 4.7 mS/cm in treatment B effluent and 5.4 mS/cm in treatment A effluent (Table 6a). Two weeks later, EC of the effluent water from treatment B was 4.8 mS/cm, and EC of treatment A effluent was 3.2 mS/cm (Table 6b). The pH of the irrigation and effluent samples ranged between 8.0 and 8.5 and changed insignificantly between irrigation water and effluent.

Table 3: Average radish germination rates per garden box at harvest treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) and treatment A (1/3 compost, 1/3 mulch and 1/3 soil) (± SD).

	Seeds per box	Germination 2 weeks	Germination after 2 weeks	Average germination	% total germination
Treatment B	105	39 ± 7.2	7.7 ± 2.1	46.7 ± 9.3	44.4
Treatment A	105	77 ± 5.6	4 ± 1.7	81 ± 7.2	77.1

Table 4: Average leaf weight and length, root weight and length, and number of leafs per radish plant (± SD) in treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) and treatment A (1/3 compost, 1/3 mulch and 1/3 soil) in rooftop garden boxes at the American University of Beirut.

	Treatment B mean	Treatment A mean	P value
Leaf weight (g)	14.4 ± 6.2	13.6 ± 7.5	0.463
Leaf length (cm)	15.4 ± 2.4	14.5 ± 3.2	0.0348
Root weight (g)	37.0 ± 16.5	29.2 ±14.8	0.0015
Root length (cm)	13.1 ± 2.3	12.4 ± 2.2	0.0475
Number leafs	8.7 ± 1.7	8.1 ± 1.6	0.0096

Table 5: Total leaf weight, total root weight, and total plant weight (± SD) of radish planted in treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) and treatment A (1/3 compost, 1/3 mulch and 1/3 soil) based media in roof gardens at the American University of Beirut.

	Total leaf weight (g)	Total root weight (g)	Total weight (g)
Treatment B	578.6 ± 139.9	1398.3 ± 303.9	1976.9 ± 440.1
Treatment A	1069.3 ± 88.0	2512.0 ± 108.6	3581.3 ± 188.2
P value	0.0068	0.0039	0.0044

Table 6

a- Water pH, total salinity, and electrical conductivity of tap water and effluent from treatment B and treatment A before planting with radish in a rooftop garden at the American University of Beirut.

	pH	Total Salinity	Electrical Conductivity
Roof tap	8.1	656.3 ppm @ 25°C	1.5 m S/cm
Treatment B discharge	8.3	2201.7 ppm @ 25°C	4.7 m S/cm
Treatment A discharge	8.3	2563.2 ppm @ 25°C	5.34m S/cm

b- Water pH, total salinity, and electrical conductivity of tap water and effluent from treatment B (cardboard pellet based substrate) and treatment A (soil based substrate) planted with radish in a rooftop garden at the American University of Beirut.

	pH	Total Salinity	Electrical Conductivity
Roof tap	8.0	708.7 ppm @ 25°C	1.7 m S/cm
Treatment B discharge	8.5	2091.6 ppm @ 25°C	4.8 m S/cm
Treatment A discharge	8.1	1488.8 ppm @ 25°C	3.2 m S/cm

D. Experiment 4: Estimation of daily condensate volumes.

The average rate of condensate production during the entire collection period was 0.82 L/hr (Fig. 6). The average rate of A/C condensate collection during July was 0.71 L/hr while the average rate of collection in August was 0.73 L/hr. During the month of September, condensate was collected at an average rate of 1.07 L/hr (Fig. 6). Condensate formation was directly proportional to dewpoint temperature. A plot of condensate volume per hour versus dewpoint temperature yielded the model $y = 0.159\,x – 2.777$ with a regression coefficient $R^2 = 0.71$ (Fig. 7). No correlation was found between rate of A/C condensate formation and air humidity or ambient air temperature.

During the collection period in June, average dewpoint temperature was 19.74°C, and the average rate of condensate production was 0.39 L/hr. Average dewpoint temperature during July condensate collection period was 21.92°C and the average rate of condensate production was 0.71 L/hr. During the collection period in August, the average rate of condensate production was 0.73 L/hr and the average dewpoint temperature was 22.38°C. During September, the average collection rate was 1.07 L/hr and average dewpoint temperature was 23.99°C.

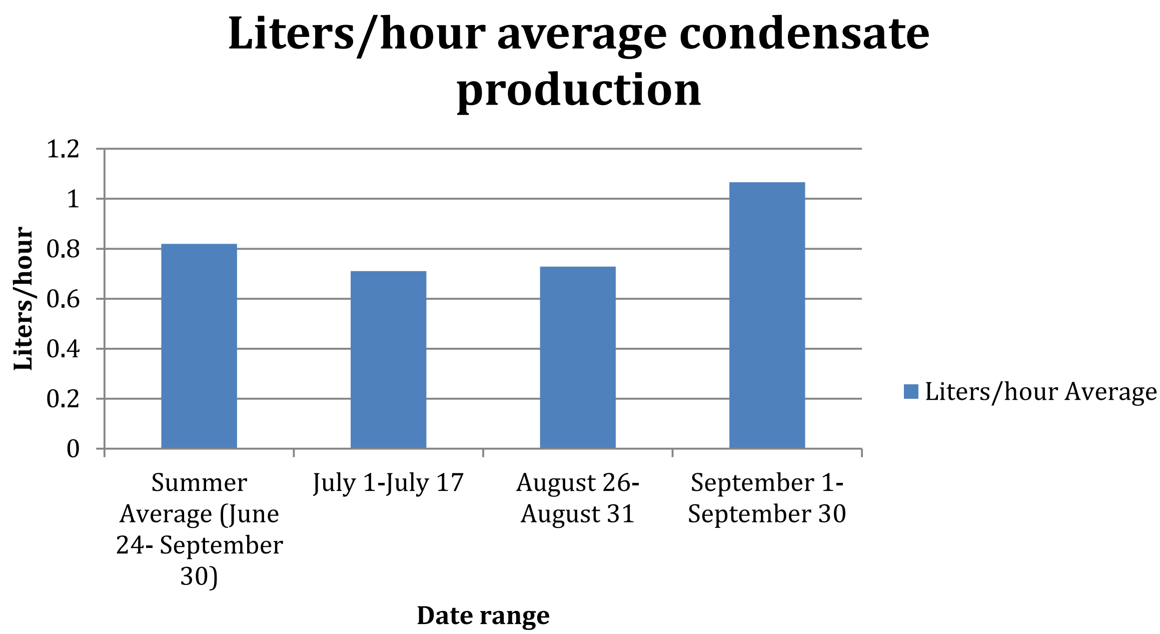

Figure 6: Condensate production rate for 24 hours a day from a 12,000 BTU split system A/C unit during summer months at the American University of Beirut, 2015.

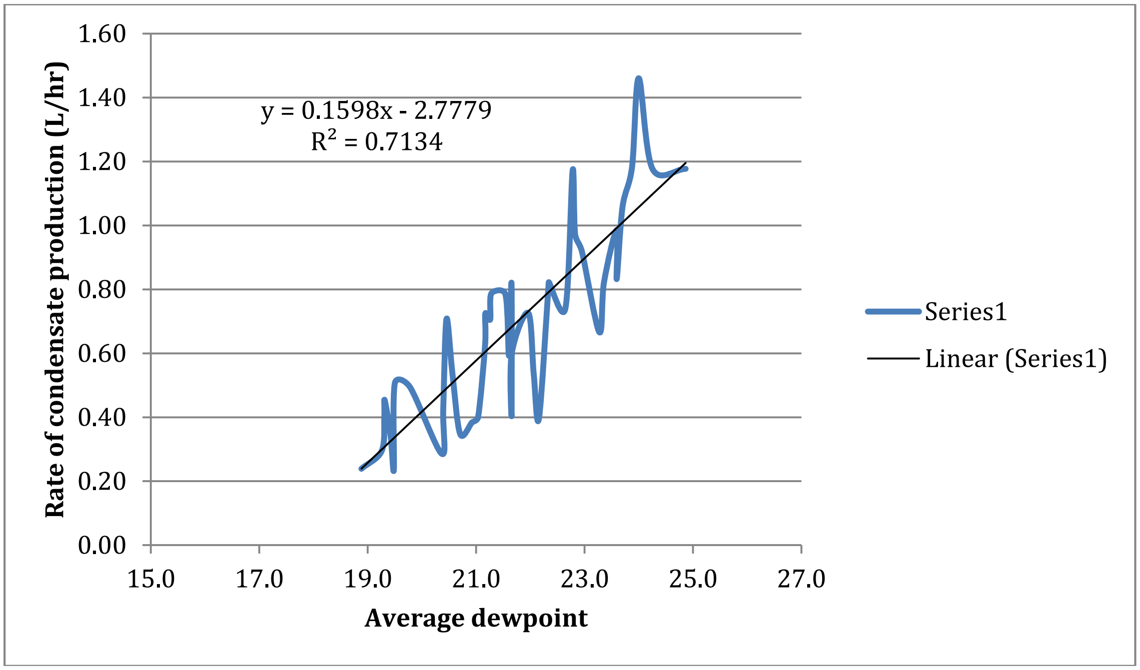

Figure 7: Condensate collection rate from a 12,000 BTU split system A/C unit *vs*. average dewpoint temperature obtained from the weather station on the roof of AUB (2015).

E. **Experiment 5: Evaluation of garden cooling effect.**

Growing media and plant cover in the rooftop gardens did modulate daily temperature variations. At mid-day, the warmest temperature recorded (37.8°C) was under the garden box with no media (Fig. 8). On the same day, the coolest mid-day temperature (35.8°C) was under the garden boxes containing treatment A. The temperature under treatment B was 37.1 °C.

The warmest temperature at 12:00 am (midnight) was 31.0°C under treatment A (Fig. 9) and 30.2 °C under the garden box with no media. The temperature under treatment B was again between the two numbers. Temperature fluctuations of each treatment throughout the day were analyzed by looking at the temperature changes on three days: June 24, July 15, and August 5, 2015. Temperatures fluctuated most under the empty treatment and fluctuated least under treatment A. On June 24, the warmest temperature (33.5°C) was recorded at 1:00 pm under the empty garden box (Fig. 10) while the coolest temperature (23.2°C) was recorded at 5:00 am under the same treatment. On July 15, 2015, the warmest temperature (36.2°C) was recorded at 4:00 pm under the empty treatment (Fig. 11) while the coolest temperature (25.9°C) under the same treatment. The warmest (37.2°C) and coolest (27.9°C) temperatures on August 5, 2015 were recorded under the empty treatment and occurred at 4:00 pm and 6:00 am respectively (Fig. 12).

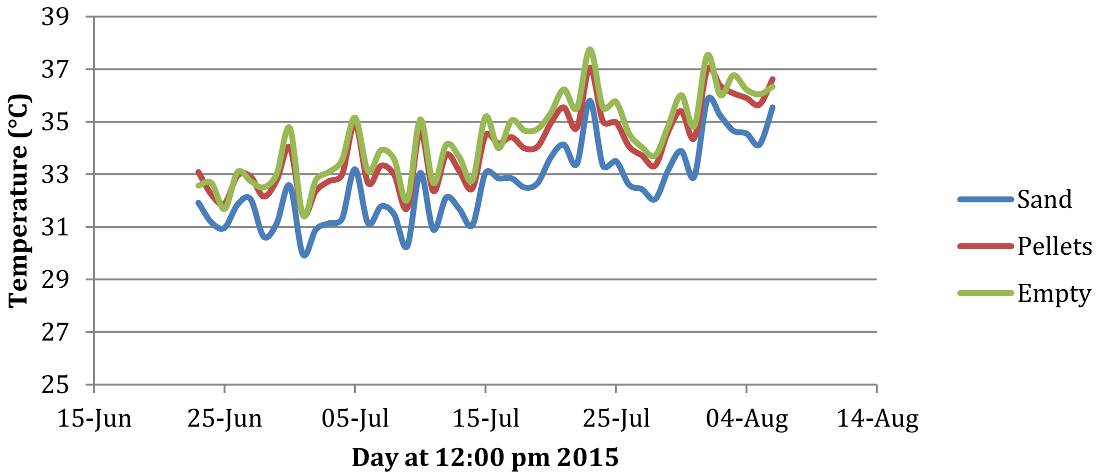

Figure 8: Ambient air average temperature recorded by 3 sensors below garden boxes with treatment A (1/3 compost, 1/3 mulch and 1/3 soil) above, 3 sensors below garden boxes with treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) above and 3 sensors below garden boxes with no ("empty") treatment above at 12:00 pm (noon) for 45 days during summer months at AUB.

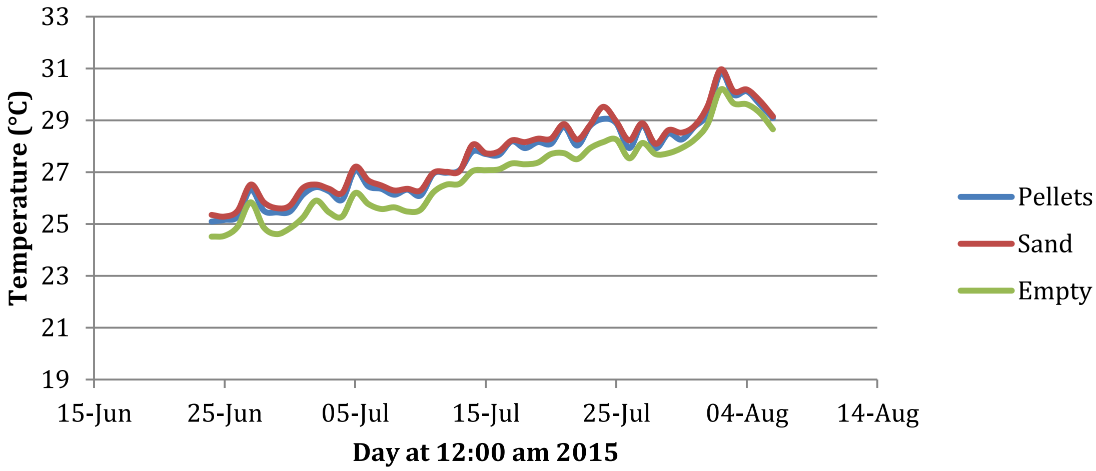

Figure 9: Ambient air average temperature recorded by 3 sensors below garden boxes with treatment A (1/3 compost, 1/3 mulch and 1/3 soil) above, 3 sensors below garden boxes with treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) above and 3 sensors below garden boxes with no ("empty") treatment above at 12:00 am (midnight) for 45 days during summer months at AUB.

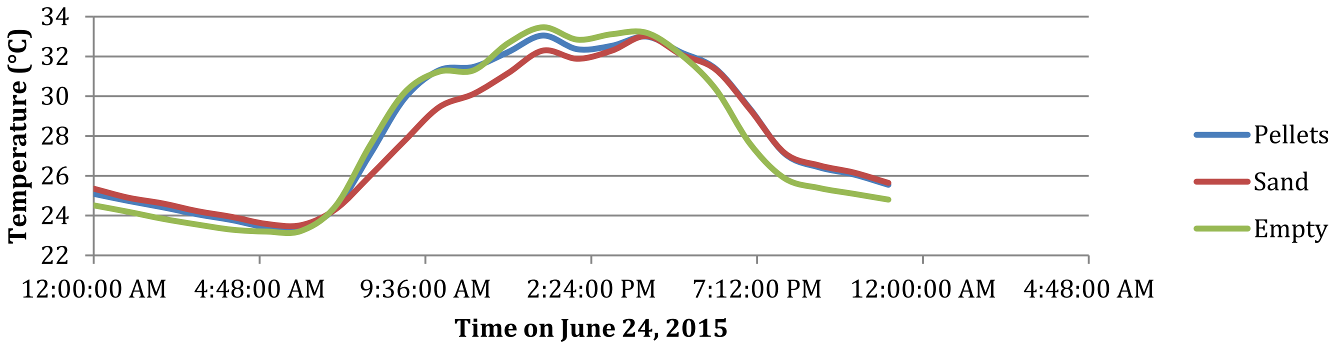

Figure 10: Temperature change throughout the day on June 24, 2015 recorded by 3 sensors below garden boxes with treatment A (1/3 compost, 1/3 mulch and 1/3 soil) above, 3 sensors below garden boxes with treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) above and 3 sensors below garden boxes with no ("empty") treatment above at AUB.

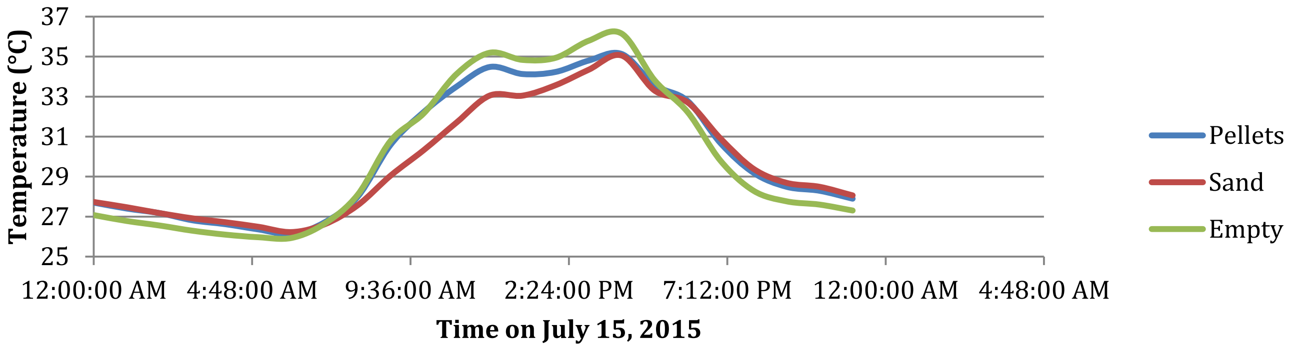

Figure 11: Temperature change throughout the day on July 15, 2015 recorded by 3 sensors below garden boxes with treatment A (1/3 compost, 1/3 mulch and 1/3 soil) above, 3 sensors below garden boxes with treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) above and 3 sensors below garden boxes with no ("empty") treatment above at AUB.

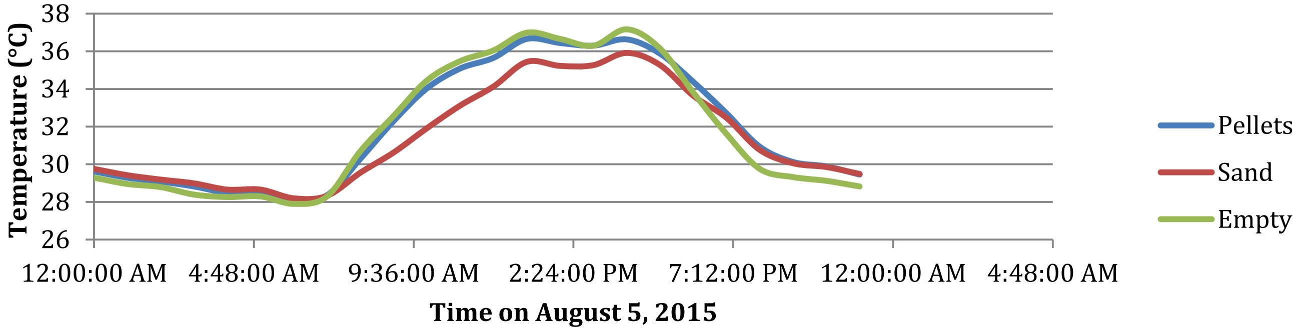

Figure 12: Temperature change throughout the day on August 5, 2015 recorded by 3 sensors below garden boxes with treatment A (1/3 compost, 1/3 mulch and 1/3 soil) above, 3 sensors below garden boxes with treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) above and 3 sensors below garden boxes with no ("empty") treatment above at AUB.

F. Experiment 6: Demonstration of feasibility of irrigating with A/C condensate.

All three species of plants tested grew well when irrigated with A/C condensate. Similarly, the kind of growth substrate used did not appear to have an effect when A/C condensate was used for irrigation. As in previous experiments, plants cultivated in the substrate B grew larger than those in substrate A (see photos below). Growth of radish plants (leaves and roots) in substrate B appeared to be greater than those of plants in substrate A but germination of radish seeds was greater in substrate A than in substrate B. Similarly, size of lettuce and basil plants in substrate B appeared larger than similar plants in substrate A.

Figure 13: Radish plants harvested from treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) (“C” top) and treatment A (1/3 compost, 1/3 mulch and 1/3 soil) (“D” bottom) on October 2, 2015 that had been watered with only A/C condensate (at the conclusion of experiment).

Figure 14: Basil plants that were irrigated with only A/C condensate on day of harvest (October 2, 2015) from treatment B (1/3 compost, 1/3 mulch and 1/3 cardboard pellets) (front) and treatment A (1/3 compost, 1/3 mulch and 1/3 soil) (back).

Figure 15a: Lettuce plants solely irrigated with A/C condensate on day of harvest (October 2, 2015) in treatment b (1/3 compost, 1/3 mulch and 1/3 cardboard pellets).

Figure 15b: Lettuce plants solely irrigated with A/C condensate on day of harvest (October 2, 2015) in treatment A (1/3 compost, 1/3 mulch and 1/3 soil).

CHAPTER 4

DISCUSSION

Results of the present study suggest that rooftop gardens are suitable for the production of vegetables in urban areas. Results also indicate that rooftop gardens modulate daily temperature variation on the roof. The work also shows that recycled materials can be used as planting substrates successfully. Finally, air conditioner condensate was shown to be a suitable source of irrigation water for rooftop gardens.

A. Experiment 1: Estimate water holding capacity of substrates.

An important issue to consider when building rooftop gardens is the extra weight that will be imposed on buildings (Oberndorfer et al., 2007; VanWoert, Rowe, Andresen, Rugh, & Xiao, 2005). The weight of the garden is the sum of the structure or casing, the substrate itself, water retained in the substrate and the plants. Generally no large trees are planted on roofs so we assume that weight of plants is negligible. The casing of the rooftop garden was also a constant so we did not take its weight into account in the present work. Accordingly, the important variables were the weight of the substrate and the weight of the water retained in it. The weight of substrate A was greater than that of substrate B and it retained more water. Accordingly, rooftop farmers should prefer to use the cardboard substrate if plant growth in it were comparable or better than in the soil substrate. However, because substrate A had greater water retention, it would better help reduce precipitation runoff, an important attribute of rooftop gardens (Mentens, Raes, & Hermy, 2006). If rooftop gardens are built to mitigate storm water runoff and insulate buildings, then more planning and structural improvements have to be done on the roof before installing the garden (Oberndorfer et al., 2007; VanWoert, et al., 2005).

Water retention of both substrates decreased after the substrates had been used for growing lettuce. I believe that the reason was that much of the organic matter in the compost portion of both substrates leached out with effluents following irrigation, reducing water binding surfaces as well as reducing water retaining pore space, and thus water retention capacity decreased. The leachate was noticed from the color of the effluent which started out as dark brown and became lighter in color during subsequent irrigation events. A similar effect was described by Friedrich (2005) when selecting growing media for a green roof. When excessive amounts of organic matter are used in a substrate, much of it leaches out of the medium as effluent during irrigation and that reduces water retention (Oberndorfer et al., 2007; Moran, Hunt, & Smith, 2005; Beattie & Berghage, 2004; Dunnett, & Kingsbury, 2004).

B. Experiment 2: Romaine lettuce seedling cultivation.

Both substrate A and B proved effective for plant growth. Early in the growth phase, plants in treatment A grew better than in treatment B possibly because substrate A had more surface area per unit volume of material (more matric potential) and thus more water was available to the plant roots. However, after four weeks, roots of plants in treatment B probably surrounded and attached to the individual pellets and thus had access to water stored in the pellets which probably was stored longer than water in substrate A.

Plants around the edges of the garden boxes grew slower than plants in the middle in all treatments. All plants were planted at a distance from the edge so I do not believe water access to the roots was a factor. Possibly, when a plant was surrounded by other plants, its reaction was to grow faster, reaching for sunlight. Plants on the edges were less surrounded and thus did not have to compete for light and grew smaller. I was not able to find similar reports in the literature concerning rooftop gardens.

The garden boxes used in the present work were slanted in order to facilitate drainage. However, results suggest that plants on the lower side of the garden box grew faster than those on the higher side. Although the garden boxes had a false bottom through which irrigation water drained, it is possible that some of the water flowed down the gradient within the media and thus afforded lower plants better access to water than higher placed plants. Again, I was not able to find similar work reported in the literature so I have little to which I can compare present results.

C. Experiment 3: Radish cultivation.

Radish seeds in treatment A germinated earlier than in treatment B. Moreover, a greater proportion of the seeds germinated in treatment A than in treatment B. A possible explanation is that more water is retained in pores in treatment A, thus allowing all seeds access to water (see Price & Meitzner, 1998), whilst most of the water in treatment B drained down through the false bottom because of weak matric potential in substrate B. However, once seeds had germinated and roots had gotten established, the roots of plants in substrate B had access to water in the pellets whilst the roots in substrate A had less water storage space. Accordingly, by harvest time the plants that germinated in treatment B had grown larger than those in treatment A (Table 4). These results strongly corroborate results of experiment 2 with lettuce growth. Accordingly, and in order to get better growth, seeds could be first germinated indoors in a soil medium and then transferred to rooftop gardens with pellet growing media once established, as suggested by MacIvor, Ranalli, & Lundholm (2011).

When individual plant growth is compared between the two treatments, plants in treatment B were larger and more productive than in treatment A. However, because germination was much greater in treatment A than in treatment B, total harvested biomass was greater in treatment A. Again, individual plants in treatment B probably grew better because they had more access to water stored in the pellets and more water translates to better growth. A similar effect was observed by Durhman, Rowe, & Rugh (2007) who observed better plant growth when they increased the thickness of substrates used and thus increased water storage and availability to the roots. Accordingly, it would make economic sense to use substrate A as a growing medium for radish since it yields a greater harvest biomass. Alternatively, as mentioned in the previous paragraph, seeds could be germinated in a soil substrate and transplanted to a pellet substrate after root development.

Electrical conductivity (EC) was greater in the effluents than in the irrigation water. Probably, a substantial amount of organic matter leached out with the effluent. This could be observed in the color of the leachate. However, with time and continued irrigation, leachate amounts decreased. This would indicate the need to replace some of the growing media after a few cycles of planting and harvesting. Also, it would suggest the need for fertilization. The pH of the water did not change before and after irrigation. This is probably because of the high bicarbonate alkalinity of the water and possibly of the substrates which maintains pH at *circa* 8.2. In a country like Lebanon where ground water tends to be calcareous, we do not worry about pH of the water or the growing medium being irrigated. However, if we were to depend only on rainwater for irrigation or on air conditioner condensate as will be described below, then substrate pH would have to be managed by adding agriculture lime or some other buffer.

D. Experiment 4: Estimation of daily condensate volumes.

The present study suggests that amount of condensate is directly proportional to ambient dewpoint. Loveless, Farooq, & Ghaffour (2013) found that condensate formation was proportional to specific humidity of the air. Since dewpoint and specific humidity are interdependent variables, these results are not contradictory. Beirut is a hot coastal city and in summer months has dewpoint temperatures close to ambient air temperatures and high specific humidity.

Present results indicate that a 12,000 BTU Split A/C unit system could produce about 1 L of condensate per hour. The American University of Beirut has 1338 split A/C units on campus as well as 898 fan coil units. All of the units are used for cooling and heating (K. Bechara, AUB physical -plant, personal communication, October 30, 2015). A simple calculation would suggest that split system A/C units on campus alone could produce over 1,300 L of condensate per hour or 31,200 L of condensate per day during summer months AUB. Most people in Lebanon do not reuse A/C condensate (unpublished data). Present results suggest that this is a wasted resource that could be used very productively with little investment necessary.

E. Experiment 5: Evaluation of garden cooling effect.

It is not surprising that noon temperatures were cooler under garden boxes than elsewhere on the roof. Liu & Minor (2005) found that green roofs in Toronto reduce heat gain of building roofs by 70-90% in the summer. Models of green roof energy dynamics by Del Barrio (1998) and Theodosiou, (2003) suggest similar results. In the present work, dry soil would normally increase in temperature and have less insulating capacity than cardboard. However, when the gardens were irrigated, substrate A probably held more water than substrate B and thus had more heat capacity. Accordingly, daily temperature variation under treatment A was less than under treatment B. Evapotranspiration also plays a role in cooling the area below a rooftop garden. However, evapotranspiration is a function of leaf cover, type of plant, soil structure and water potential as well as amount of water in the soil. These parameters were not evaluated in the present work and cannot be discussed. Finally, our garden boxes were constructed of wood which is a good insulator and would absorb less heat than concrete. Typical roofs in Beirut are concrete, often with black tar shingle coverings, and thus daily temperature variations would be greater than those observed in the present work. In summary, water holding capacity would improve germination and growth of plants and reduce daily temperature fluctuations, but would reduce the cooling of the roof during night hours. Evapotranspiration would have a cooling effect both during day and night. In all cases, green roofs would add insulation to the roof below.

F. Experiment 6: Demonstration of feasibility of irrigating with A/C condensate.

Plant growth in the present work suggests that A/C condensate can be used for irrigation. Logically, A/C condensate is very similar to rainwater and should be suitable for irrigation. Jaber & Qiblawey (2011) found that A/C condensate can be used for irrigation after minimal pretreatment and thus could be suitable for irrigation of rooftop gardens. They do not mention what pretreatment methods were necessary and I cannot think of any other than possibly adding agricultural lime if using recycled organic substrates or adding fertilizer periodically as the plants require.

Similar to experiment 3, germination rates in experiment 6 were more numerous in treatment A than in treatment B. However, there were more plants that germinated three weeks after planting in substrate B than in substrate A. As previously stated, the probable cause is water holding capacity of the media used. Harvest size of all plants was greater in treatment B than in treatment A and that too has been discussed above. Suffice it to say that irrigation with A/C condensate was just as productive as irrigation with municipal tap water. Substrate pH would probably have to be managed in the medium without soil and fertilizer would have to be added in both treatments after a few planting cycles.

CHAPTER 5

CONCLUSION

The present work demonstrates the suitability of having rooftop gardens in urban settings. They allow for use of collected A/C condensate productively. The gardens also produce food locally, reduce temperature variation in the roofs below them, allow for the productive use of recycle waste and potentially increase insect, reptile and avian biodiversity in cities. I would add that it also helps increase mammalian diversity. An increase in green roof area in Beirut would doubtlessly improve environmental conditions and reduce summer heat island effect. What's more, the vegetables were delicious. Future studies need to include assessments of water retention of substrates used. Additionally, effluent water quality and A/C condensate quality should be evaluated.

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