Stormwater performance of a full scale rooftop farm: Runoff water quality

Leigh J. Whittinghill

Corresponding Author

Former Post-Doctoral Scholar

The Earth Institute at Columbia University

Urban Design Lab

Interchurch Center

475 Riverside Dr. Suite 239

New York, NY 10115, USA

E-mail: leigh.whittinghill.grr@gmail.com

Diana Hsueh

Staff Associate

Geochemistry Department, Lamont-Doherty Earth Observatory, Columbia University

58 Geochemistry

61 Route 9W - PO Box 1000

Palisades, NY 10964-8000, USA

E-mail: dhsueh@ldeo.columbia.edu

Patricia Culligan

Co-Director, Urban Design Lab, The Earth Institute at Columbia University

Professor, Department of Civil Engineering and Engineering Mechanics, Columbia University,

610 S W Mudd

500 W 120 St

New York, NY 10025, USA

E-mail: pjc2104@columbia.edu

Richard Plunz

Co-Director, Urban Design Lab, The Earth Institute at Columbia University

Professor, Graduate School of Architecture, Planning, and Preservation, Columbia University

400 Avery Hall

New York, NY 10025, USA

E-mail: rap9@columbia.edu

Abstract

A number of benefits have been attributed to green roofs including food production. However, little research has been done to quantify the effects of rooftop farming practices on green roof benefits. The impact of rooftop farming on stormwater runoff is especially important, considering the different nutrient management practices on ornamental and agricultural green roofs. In order to advance knowledge on this potential impact, runoff water quality from a full-scale rooftop farm in Long Island City, Queens, New York, was monitored and compared to runoff water quality from a suite of extensive, sedum green roofs, also located in New York City. Samples of runoff water and rain were collected and analyzed for pH, electrical conductivity, turbidity, apparent color, suspended solids, nitrate-N, ammonium-N, phosphorus, potassium, calcium, magnesium, sodium, boron, iron, manganese, copper, zinc, nickel, aluminum, arsenic,

barium, cadmium, chromium, and lead. Results indicate that runoff from all green roofs is higher than the average pH of incoming acid rain water, although the pH of runoff from the rooftop farm was slightly lower than that of the extensive green roofs. The conductivity, apparent color, and suspended solids concentrations of runoff from the rooftop farm were higher than those of the extensive green roofs, but not higher than values reported in the literature on agricultural runoff. The concentrations of nitrate-N, phosphorus, potassium, calcium, and magnesium in runoff from the rooftop farm were also higher than those of runoff from the extensive green roofs. Measured values of nitrate-N, calcium, and magnesium were not higher than concentrations reported elsewhere in the green roof literature or in agricultural literature; nor where they higher than EPA guidelines for water quality. Measured values of phosphorus and potassium were found to be higher than EPA guidelines. However, changes in nutrient management practices would help reduce these values.

Keywords: Green roof, urban agriculture, stormwater management, nutrient leaching

Stormwater performance of a full scale rooftop farm: Runoff water quality

Abstract

A number of benefits have been attributed to green roofs including food production. However, little research has been done to quantify the effects of rooftop farming practices on green roof benefits. The impact of rooftop farming on stormwater runoff is especially important, considering the different nutrient management practices on ornamental and agricultural green roofs. In order to advance knowledge on this potential impact, runoff water quality from a full-scale rooftop farm in Long Island City, Queens, New York, was monitored and compared to runoff water quality from a suite of extensive, sedum green roofs, also located in New York City. Samples of runoff water and rain were collected and analyzed for pH, electrical conductivity, turbidity, apparent color, suspended solids, nitrate-N, ammonium-N, phosphorus, potassium, calcium, magnesium, sodium, boron, iron, manganese, copper, zinc, nickel, aluminum, arsenic, barium, cadmium, chromium, and lead. Results indicate that runoff from all green roofs is higher than the average pH of incoming acid rain water, although the pH of runoff from the rooftop farm was slightly lower than that of the extensive green roofs. The conductivity, apparent color, and suspended solids concentrations of runoff from the rooftop farm were higher than those of the extensive green roofs, but not higher than values reported in the literature on agricultural runoff. The concentrations of nitrate-N, phosphorus, potassium, calcium, and magnesium in runoff from the rooftop farm were also higher than those of runoff from the extensive green roofs. Measured values of nitrate-N, calcium, and magnesium were not higher than concentrations reported elsewhere in the green roof literature or in agricultural literature; nor were they higher than EPA guidelines for water quality. Measured values of phosphorus and potassium were found to be higher than EPA guidelines. However, changes in nutrient management practices would help reduce these values.

1. Introduction

Green roofs have been shown to have a wide number of benefits including reduced air and noise pollution, increased habitat and biodiversity, increased roof lifespan, stormwater retention, energy savings, and mitigation of the urban heat island effect (Alexandri and Jones, 2008; Barrio, 1998; Carter and Jackson, 2007; Getter and Rowe, 2006; Getter et al., 2007; Loder and Peck, 2004; Rowe, 2011; Saiz et al., 2006; VanWoert et al., 2005; Wong et al., 2003). Thanks to an increasing number of rooftop farms and gardens (Greenroofs.com, 2014), food production can be added to this list of benefits. Although rooftop agriculture may solve some of the problems inherent in ground level urban agriculture, such as limited space availability, it presents its own set of challenges (Whittinghill and Rowe, 2012). One of these challenges is a greater requirement for inputs, such as irrigation water and fertilizers, than in-ground urban agriculture, which could impact the stormwater performance of the green roofs (Whittinghill and Rowe, 2012). The ability to retain stormwater and improve stormwater quality is one of the major environmental benefits of green roofs (e.g. Berghage et al., 2009; Emilsson et al., 2007; Rowe, 2011). To date, little research has been done on the impact of farming practices on the ability of a green roof to mitigate stormwater management issues. This is especially important when considering the differences in nutrient management practices between ornamental green roofs, and those used in agricultural production.

Conventional green roofs can improve on the quality of runoff water compared with non-vegetated roofs (eg. Czemieli Berndtsson, 2010). There are many factors which affect the runoff quality of a green roof. These include environmental factors, such as the size of rain events (Czemieli Berndtsson et al., 2006; Teemusk and Mander, 2007), the amount of atmospheric deposition taking place (Alsup et al., 2011), and the presence of acid rain (Berghage et al., 2009;

Bliss et al., 2009). Green roof characteristics also impact runoff water quality. Construction of the roof and drain pipes (Alsup et al., 2011; Czemieli Berndtsson et al., 2006) and the substrate used are particularly important. Substrate composition (Alsup et al., 2010; Czemieli Berndtsson, 2010), compost content (Hathaway et al., 2008), and depth (Czemieli Berndtsson, 2010) all affect runoff quality. The presence of plants (Alsup et al., 2010), plant type (Czemieli Berndtsson, 2010; Dunnett et al., 2008; Monterusso et al., 2004), rooftop maintenance practices such as fertilizer use (Czemieli Berndtsson, 2010; Emilsson et al., 2007), and age of the green roof (Czemieli Berndtsson, 2010; Czemieli Berndtsson et al., 2006; Hathaway et al., 2008; Köhler et al., 2002; Teemusk and Mander, 2007; Van Seters et al., 2009) also affect runoff water quality. Combined, these factors determine if a particular green roof acts as a source or a sink for nutrients and heavy metals. Green roofs are generally considered to reduce runoff heavy metal concentrations compared with other urban surfaces (Czemieli Berndtsson, 2010; Czemieli Berndtsson et al., 2006; Rowe, 2011), but results for nutrients, such as nitrogen and phosphorus are mixed (eg. Czemieli Berndtsson et al., 2006; Hathaway et al., 2008).

Substrate composition, compost content, and depth, and fertilizer use are likely to differ when comparing conventional green roofs to agricultural green roofs. Agricultural rooftops are likely to use substrates with higher organic matter or compost content than conventional green roofs, to help supply nutrients to the crop plants. They are also likely to use deeper substrates to retain water and support the crop plants. The application of fertilizers to green roofs, even at the $5 \text{ g N} \cdot \text{m}^{-2}$ rate recommended for typical extensive green roofs (FLL, 2002), can have a negative impact on runoff water quality, especially if soluble fertilizers are used (Czemieli Berndtsson et al., 2006; Emilsson et al., 2007; Rowe, 2011; Rowe et al., 2006). It is expected that this impact would be increased if fertilizers were applied at the much higher rates of up to $22.3 \text{ g N} \cdot \text{m}^{-2}$

recommended for vegetable crops grown in soil (Warncke et al., 2004). Vegetables grown in green roof media, with low organic matter content and cation exchange capacity (Emilsson et al., 2007), might require rates of fertilizer application that are higher still. This implies that agricultural green roofs are liable to be a much higher source of nutrients than their ornamental counterparts, which could have negative environmental consequences.

Nutrients, especially nitrogen and phosphorus, in runoff water can lead to issues downstream from their source. The addition of nitrogen and phosphorus to surface water bodies can lead to eutrophication, which can lead to increase algae production and hypoxia due to larger amounts of organic matter decomposing, reducing the quality of water body for fish habitat, recreational activities, and drinking water (USEPA, 2003). This has historically been a problem in areas with large amounts of agricultural production that has led to the implementation of many best management practices to reduce nutrient losses from agricultural land in runoff (Osteen et al., 2012; USEPA, 2003). These practices touch on nutrient application rates, such as matching nutrient supply to crop needs through nutrient budgeting based on soil test results (Osteen et al., 2012; USEPA, 2003; Warncke et al., 2004), nutrient application methods, such as incorporation vs topdressing of nutrients, and nutrient application timing (USEPA, 2003). They also include practices to catch nutrients leaving agricultural areas before they enter surface water, such as the use of retention ponds, buffers, bioswales, and constructed wetlands (USEPA, 2003). The former group of practices could most easily be adapted to use on agricultural green roofs, but research has not yet been to determine what adaptations would be necessary to make them effective under the different conditions presented by rooftop agriculture.

There are other methods which could be adapted from both in ground agriculture and conventional green roofs to manage the tradeoff between plant nutrient requirements and runoff

quality. Practices designed to limit irrigation needs would likely increase the green roofs water holding capacity, reducing runoff, and therefore the amount of nutrients being removed from agricultural rooftops during storms. The use of substrate moisture management practices such as mulch (e.g. Gruda, 2008; Monks et al., 1997) have been effective at limiting irrigation needs in in-ground agriculture and could easily be adapted to a rooftop setting. The collection and recycling of runoff for irrigation is another option. Reducing soil disturbance, by reducing tillage and the use of cover crops, reduce the amount of erosion that takes place, and therefore nutrient losses during runoff (eg. Franklin et al., 2012; Tiessen et al., 2003; USEPA, 2003). These practices are also suited to use in rooftop agriculture. The effectiveness or practicality of many of these measures have not, however, been fully explored in agricultural rooftop settings. One prior study performed on test plots indicated that the effect of fertilizing a vegetable green roof would depend heavily on the amount of fertilizer applied and plant nutrient requirements (Whittinghill et al., 2015), but to date little research has been done on full scale green roof farms.

This study was designed to advance knowledge about the effects of rooftop agriculture on stormwater management issues by monitoring the runoff water quality from a full-scale, working roof top farm in Long Island City, Queens, New York. The main objective of this study was to compare the runoff water quality of a full scale agricultural rooftop to that of conventional, extensive sedum green roofs. To that end, runoff water quality results from the rooftop farm were compared to those of a previous study of non-agricultural green roofs around New York City (Culligan et al., 2014), enabling examination of the impact farming has on runoff quality. It was expected that agricultural roofs and conventional green roofs would perform differently, because the rooftop farm has a higher substrate organic content and applies fertilizers at higher rates and with more frequency than is typical for conventional green roofs.

2. Methods

2.1. Site description

The rooftop monitoring took place at the Long Island City Brooklyn Grange (BKG) rooftop farm located at 37-18 Northern Boulevard in Queens, New York. The rooftop farm was installed in 2007 and uses Rooflite[®] green roof media (Skyland USA LLC, Landenberg, PA) mounded into rows with a depth of 20-25 cm (8-10 in) and 2.5-5 cm (1-2 in) between row depth. The farm covers almost all of the 3,995 m² (43,000 ft²) rooftop. Non-vegetated areas of the roof include stairwells, the central roof walkway made of gravel, and walkways between crop rows (Figure 1a). The green roof is planted with vegetables, herbs and some flowers for cutting, including sunflowers. Irrigation is supplied to the plants through a drip irrigation line 3 times daily for 30-40 min, depending on weather conditions. Monitoring for water quality runoff at the farm began in January 2013 and ended in December 2013.

2.2. Ambient Weather Conditions

An Onset[®] (Onset[®] Computer Corporation, Bourne, MA) weather station was installed on the roof on March 21, 2013, to monitor ambient weather conditions (Figure 1b). The weather station was equipped with two tipping bucket rain gauge smart sensors, wind speed and wind direction smart sensors, an air temperature and relative humidity (RH) smart sensor inside a solar radiation shield. All weather station instruments were connected to the HOBO[®] U30 data logger. The HOBO[®] U30 data logger was configured to take readings every second and record 5 min averages.

2.3. Runoff Water Quality

In a drainage basin on the northwest corner of the roof, 250 mL of runoff water was sampled from water entering a drain. This was done once a month between January and April, twice a month between May and October, and once a month after that, weather permitting. More frequent sample collection during the growing season was performed in an attempt to capture the effects of farming practices such as the application of fertilizers. After collection, samples were taken back to the Heffner Laboratory in the School of Engineering and Applied Science at Columbia University and analyzed for pH and electrical conductivity with an AccumetTM excel XL50 dual channel pH/ion/conductivity meter (Fisher Scientific, Hampton, NH), turbidity with a 2020we turbidity meter (LaMotte, Chestertown, MD), and color and true color with a DR/890 colorimeter (Hach, Loveland, CO). Water samples over the limit for color (500 PtCo) were diluted to within the limit, either a 50 or 75 % dilution, and color was then calculated for the full concentration.

A portion of the sample was filtered with a 0.22 μ M filter, stored in a freezer, and sent to Auburn University Soil Testing Laboratory (Auburn University, AL) for analysis for routine elements by ICAP, suspended solids (SS), and ammonium-N (NH_4^+). The routine element by ICAP includes analysis for calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), boron (B), aluminum (Al), arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), lead (Pb), sodium (Na), nickel (Ni), pH, soluble salts, and nitrate-N (NO_3^-).

2.4 Estimated Annual Nutrient Loading

Annual mass loadings for the entire Brooklyn Grange roof were estimated based on average nutrient concentrations and the estimated annual runoff water volume. Annual runoff volume was estimated by multiplying the size of the roof (3,994.83 m²) by the average annual precipitation in New York City (1118 mm, (NOAA, 2014a)), and the average measured portion of precipitation that becomes runoff (60 % (UDL, 2014)). This method of estimation is possible because of New York City's relatively even distribution of rain throughout the year.

2.5. Data Analysis

Results were compared to those of Culligan et al. (2014), which examined runoff water quality from five full-scale extensive sedum green roofs and five traditional non-vegetated roofs installed on buildings in New York City. Data analysis was therefore handled in a manner similar to this prior study. Statistical analyses were performed using R (The R Foundation for Statistical Computing, Vienna, Austria). Data for all water quality metrics that did not conform to a normal distribution were transformed for analysis using either a logarithmic transformation (NH₄⁺, P, and K) or a square root transformation (conductivity, turbidity, apparent color, NO₃⁻, Ca, Mg, and Na). All water quality metrics were analyzed using ANOVA with type of roof as a fixed effect. The significance of treatment interactions was determined using F tests and those interactions that did not have an effect were removed from the analytical model. Significant differences among treatments were separated using multiple comparisons by Tukey HSD with an alpha of 0.05.

3. Results

3.1. Ambient Weather Conditions

Average temperatures were highest between weeks 5 and 9 (May 23, to July 24, 2013) (Figure 2) of the study with sporadic high daily average temperatures in weeks 10 to 16 (August and September) (data not shown). Temperatures begin to decrease in week 20 (early October), with the coldest average temperatures recorded during weeks 29 and 32 (December 7-13, 2013 and December 28, 2013 to January 2, 2014) (Figure 2). Total precipitation for the study period was 529.8 mm. One quarter of this precipitation fell during week 3 (June 7-13, 2013) (Figure 2). The second largest amount of precipitation was recorded during week 27 (November 23-29, 2013). The period between weeks 18 and 23 (September 23 to October 30, 2013) had almost no rain except for one moderate storm during week 20 (on October 7, 2013). Wind on the Brooklyn Grange comes predominantly from the west to northwest, followed by winds from the north, northwest (data not shown). Daily average wind speeds ranged from 0.2 to 22.6 kph, with a maximum wind speed of 40.8 kph on May 25, 2013 (data not shown). Maximum three second gust speeds were higher than 100 kph on three days, September 22, November 26, and December 12, 2013, reaching 163.2, 155.0, and 163.2 kph, respectively (data not shown).

3.2. Physical Characteristics

The average pH of runoff from the Brooklyn Grange was higher than that of rain taken from the previous study, but not than that of the non-vegetated roofs. It was also lower than that of runoff from the extensive sedum green roofs (Figure 3). The conductivity (Figure 3), apparent color (Figure 3), true color (data not shown), and suspended solids (SS) (Figure 4) of runoff from the Brooklyn Grange were much higher than those of samples from all other water sources. The average turbidity of runoff from the Brooklyn Grange was not significantly different from that of samples taken from any other water source (Figure 3).

3.3. Macronutrients

Average concentrations of NO_3^- , P, and K in runoff from the Brooklyn Grange were higher than those from all other water sources (Figure 5). Average NH_4^+ concentration in runoff from the Brooklyn Grange was, however, lower than those of water samples from all other sources (Figure 5). Concentrations of Ca and Mg in runoff from the Brooklyn Grange were also higher than those from all other water sources, followed by runoff from extensive sedum green roofs (Figure 5).

3.4. Micronutrients and Heavy Metals

Average Na concentration of runoff from the Brooklyn Grange was higher than that from any other water source (Figure 6). Concentrations of all other tested micronutrients (nutrients required by plants in small amounts) (B, Fe, Mn, Cu, Zn, and Ni) and all tested heavy metals (Al, As, Ba, Cd, Cr, and Pb) were below the detection limit of 0.1 mg/L in all samples from all water sources (data not shown).

3.5 Estimated Annual Mass Loading

Annual mass loading of SS from the Brooklyn Grange was 1513.99 kg/ha. Macronutrient annual mass loads from the Brooklyn Grange were 33.20, 0.40, 9.26, 131.68, 275.16, and 34.08 kg/ha, for NO_3^- , NH_4^+ , P, K, Ca, and Mg, respectively. Annual mass load for Na from the Brooklyn Grange was 126.64 kg/ha.

4. Discussion

4.1. Physical Characteristics

The average pH of runoff from the Brooklyn Grange (6.79) is on the lower side of values reported in the literature for other green roofs (Table 1). It is, however, on par with results reported in the literature on agricultural runoff (Table 2) and within the range of acceptable pH for both fresh water (6.5 to 9) and drinking water (5 to 9) according to United States Environmental Protection Agency (EPA) guidelines (USEPA, 1986). When compared with the average pH of rain collected during the previous study, the Brooklyn Grange does have a significant neutralizing effect on runoff pH, if not to the same extent as the conventional extensive sedum green roofs in New York City (Figure 3). Altogether this suggests that rooftop farming practices may reduce the neutralizing effect that green roofs have on runoff pH, but not to an unacceptable level.

Few studies have examined conductivity, apparent color, SS, or turbidity in green roof runoff, and these metrics, except for SS, are not frequently included in studies of agricultural runoff. The Brooklyn Grange runoff water does not, however, test higher than some of what can be found in the literature. The average conductivity of runoff from the Brooklyn Grange (326.37 $\mu\text{S}/\text{cm}$) is higher than both extensive sedum green roofs in New York City (Figure 3) and the range reported by the literature on extensive green roofs (Table 1), but lower than some of the values reported for runoff from agricultural lands (Table 2). This is likely caused by the application fertilizer to support crop growth at larger rates than would be necessary to support sedums on an extensive green roof, but lower than that used in some agricultural settings.

The average apparent color and average SS concentration of runoff from the Brooklyn Grange (425.24 PtCo and 225.7 mg/L, respectively) are moderate when compared to values from the green roof literature (Table 1). The difference in apparent color of the runoff samples from

the Brooklyn Grange and the previously studied New York City extensive sedum green roofs (Figure 3) could, in part, be caused by the higher organic matter content of the green roof substrate. This link between organic matter content and apparent color of runoff water was also noted by Berghage et al. (2009). Organic matter content may also be influencing the SS concentrations in green roof runoff, which are well over the EPA's 100 mg/L recommendation for stormwater pollution prevention (USEPA, 2009). These concentrations are, however, small when compared to those reported in runoff from agricultural lands (Table 2), which also do not meet this criterion. A similar pattern is seen when comparing the annual mass load of SS from the Brooklyn Grange to those from other green roofs and agricultural lands (Table 3). The annual mass load from the Brooklyn Grange is likely higher than that from other green roofs because of differences in the amount of runoff water coming from the roofs. Average turbidity from both the Brooklyn Grange (1.57 NTU) and the extensive green roofs in New York City (1.72 NTU) are lower than the values reported in the green roof literature (Table 1), suggesting little effect of rooftop farming on this runoff water quality metric.

The comparison of the physical characteristics of runoff water from the Brooklyn Grange to those of runoff from other green roofs and agricultural lands highlights the need for water quality bench marks to be set for runoff from agricultural green roofs. In particular, which system is it most important to compare them to, ornamental green roofs or agricultural lands? This is most evident when looking at the conductivity of runoff from the Brooklyn Grange. If compared only to green roofs, it would appear that the Brooklyn Grange has a negative impact on water quality, but the conductivity of runoff from the Brooklyn Grange is not as high as the conductivity of runoff from agricultural land. Choosing appropriate benchmarks for runoff water quality from agricultural green roofs will not only set the standard to be met, but will also

influence best management practices. If standards similar to ornamental green roof runoff water quality are chosen, steps will need to be taken to limit the impact of nutrient management practices on some of the runoff quality metrics, such as conductivity.

4.2. Macronutrients

High concentrations of macronutrients (nutrients required by plants in large amounts) were expected, given the Brooklyn Grange's use of compost and fertilizers, which have been shown to impact green roof runoff water quality (Czemiel Berndtsson et al., 2006; Emilsson et al., 2007; Hathaway et al., 2008; Monterusso et al., 2004; Teemusk and Mander, 2007). Some of the results of this study were therefore surprising, when compared to the green roof literature as a whole. The average concentrations of NO_3^- (4.95 mg/L) and P (1.38 mg/L) in runoff from the Brooklyn Grange are higher than those of extensive sedum green roofs in New York City (Figure 5), but are within the low end of the ranges of concentrations reported in the literature for typical extensive green roofs (Table 1). They were also higher than those observed in runoff from experimental green roof platforms on which vegetables were grown (Whittinghill et al., 2015), but that study used lower fertilization rates than those use on the Brooklyn Grange. Nitrate concentrations are also below the USEPA's 10 mg/L guideline for safe drinking water (USEPA, 1986). The average P concentration is, however, above EPA guidelines for lakes, rivers and streams (USEPA, 2001, 2000). The average concentration of NH_4^+ (0.06 mg/L) is also moderate when compared the green roof literature (Table 1) and below EPA guideline concentrations for both acute and chronic toxicity in fresh water (USEPA, 2013). Czemiel Berndtsson et al., (2009) reported that the green roofs they examined acted as sinks for NH_4^+ . The previous study of extensive sedum roofs in New York City showed no difference in NH_4^+ concentrations in runoff,

it did however conclude that annual nutrient loading of NH_4^+ would be lower than that of non-vegetated roofs (Culligan et al., 2014). According to the results of this study, rooftop farming practices alter a green roofs ability to act as a skink for NH_4^+ . In contrast, the Brooklyn Grange appears to be a source of K, with average runoff concentrations (19.63 mg/L) considerably higher than those reported from other green roofs (Table 1). Annual mass loadings for these nutrients were also within the range of those found in the literature on green roofs (Table 3).

It is standard practice at the Brooklyn Grange to add compost to the substrate at the beginning of the growing season, and at times throughout the growing season to specific rows before new crops are planted (Personal Communications, Ben Flanner, 3/20/2014). Prior to the first compost addition of 2013, the growing substrate contained 10.15 % organic matter (Table 5). This is relatively high for typical green roofs, which tend to have between 4 and 12 % organic matter, as stated in the Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) guidelines for green roofs (FLL, 2002). In 2013, 2,540 kg (5600 lb) of compost was added to the rooftop and mixed into the existing substrate (Personal Communications, Bradley Fleming, 4/19/2013), This contributed an estimated additional 635 to 1,905 kg of organic matter to the roof, but would not have increased the percentage of organic matter by much, given that the total weight of the substrate on the roof is between 396,345 and 484,422 kg (Personal Communications, Ben Flanner, 3/20/2014). This addition of compost also contributed a substantial amount of nutrients to the roof. In some cases, the amount of nutrients in green roof runoff may decrease as the roof ages and reaches equilibrium (Czemiel Berndtsson, 2010; Czemiel Berndtsson et al., 2006; Hathaway et al., 2008; Köhler et al., 2002; Rowe, 2011; Teemusk and Mander, 2007; Van Seters et al., 2009), but this is unlikely to be the case on the Brooklyn Grange, if compost is added to the substrate on an annual basis.

Nitrogen and phosphorus are nutrients of particular concern because they contribute to eutrophication in natural water bodies (USEPA, 2003). The EPA has made recommendations for their Multi-Sector General Permit program for preventing pollution in stormwater (USEPA, 2009) and Brooklyn Grange runoff water exceeds these recommendations from nitrate (0.68 mg/L for both Nitrate- and Nitrite-Nitrogen). This suggests that measures should be taken to reduce nutrient loss from the roof via runoff. These nutrient runoff concentrations should not, however, be evaluated only in the context of urban runoff, but in an agricultural and horticultural context as well. When compared to values found in the literature on agricultural runoff, concentrations of NO_3^- , NH_4^+ , P and K are all low (Table 2). Annual mass loadings for all of these nutrients, except K which was higher, were also low or moderate when compared to those from agricultural lands (Table 3). This comparison again raises the question of what standard do rooftop farmers wish to achieve in terms of water quality. At present, with no outside regulation, it is still up to the rooftop farmers themselves, but this lack of oversight by government agencies is unlikely to continue.

If one uses the runoff water quality from the extensive sedum green roofs in New York City as the standard to achieve, the concentrations of NO_3^- , P and K in the rooftop farm runoff should be reduced. This leads to questions of how the specific nutrient management practices on a given rooftop farm might be affecting these concentrations. One starting place is a comparison between the amount of nutrients applied to the roof in all fertilizers and amendments including the compost and the recommended nutrient applications for typical green roofs and market gardens at ground level (Table 6). More P and K were applied to the Brooklyn Grange than recommended, but less N, suggesting that the amount of nutrient applied is not the only factor at play. High amounts of K were intentionally added to some parts of the rooftop farm in an

attempt to build up the soil test levels of K, which have been decreasing since the roofs
instillation (Ben Flanner, Personal Communication, 3/20/2013). This is a fairly common
practice in in-ground agriculture, but applications of K to tomatoes and peppers on the Brooklyn
Grange were even higher than build-up recommendations (Table 6). Higher than recommended
rates of K application could account for higher annual mass loads of this element than expected
based on annual mass loads from agricultural lands (Table 3). As of the 2014 growing season,
the Brooklyn Grange has stopped attempting to build up soil test levels of K, because the higher
rates of application did not appear to be effective in doing so (Ben Flanner, Personal
Communication, 7/24/2014). More in-depth examination of how the release rate of nutrient
sources used and timing of nutrient application affects would be necessary to make
recommendations on what changes to nutrient management practices might reduce the amount of
these nutrients being lost from the roof. This could not only reduce the environmental impacts of
such farms, but cut costs for the farmers, by increasing input use efficiency.

Fewer studies of green roof and agricultural runoff water quality have examined
concentrations of Ca or Mg than the other macronutrients. A study of intensive green roofs by
Czemiel Berndtsson et al. (2009) reported Ca concentrations of 25-32.5 mg/L from intensive
green roofs in Fukuoka, Japan. Berghage et al. (2009) found similar results at Pennsylvania
State University, with runoff Ca concentrations from extensive green roof platforms ranging
from 6.1-25.6 mg/L. Another study by Teemusk and Mander (2007) examined Ca-Mg salt
concentrations in runoff from extensive green roofs and found them to range from 0.07 to 2.83
mg/L. The Berghage et al. (2009) study found higher Mg concentrations in runoff between 2.8
and 12.1 mg/L. The results of these studies are similar to those of Culligan et al. (2014)(Figure

371 3). Van Seters et al. (2009) also examined Ca and Mg in green roof runoff and found
372 concentrations of 18.07-23.32 and 3.3-5.2 mg/L, respectively.

373 Average runoff Ca concentrations (41.02 mg/L) from the Brooklyn Grange were higher
374 than those found in any of these previous studies and higher than those reported in the
375 agricultural literature (Table 2). Average runoff Mg concentrations (5.08 mg/L) were moderate
376 compared to those measured in previous studies by Berghage et al. (2009) and Van Seters et al.
377 (2009) and those reported in the agricultural literature (Table 2), but higher than the EPA has
378 made recommendation (0.064 mg/L) for their Multi-Sector General Permit program for
379 preventing pollution in stormwater (USEPA, 2009a). High calcium concentrations in the runoff
380 from the Brooklyn Grange can be explained by both a high soil test value (Table 5) and the
381 presence of seashells containing calcium in one of the fertilizers used on the farm. This is also a
382 likely contributor to both the high soil pH (Table 5) and the pH of the runoff (Figure 3) and
383 explains the observation of higher annual mass loads than from either other green roofs or
384 agricultural lands (Table 3).

385 *Micronutrients and Heavy Metals.* Average Na concentrations (18.76 mg/L) in runoff
386 from the Brooklyn Grange were not only higher than that from other extensive sedum green
387 roofs in New York City (Figure 6), but much higher than those (0.51-6.7 mg/L) reported by the
388 two other studies that examined this micronutrient in green roof runoff (Berghage et al., 2009;
389 Van Seters et al., 2009). A similar pattern is observed when comparing annual mean loading of
390 sodium from the Brooklyn Grange and other green roofs (Table 3). Sodium concentrations in
391 runoff from the Brooklyn Grange were, however, low when compared to those from the few
392 studies on agricultural runoff that reported sodium concentrations (Table 2). The presence of Na
393 in runoff from the Brooklyn Grange was most likely caused by the presence of NaCl in kelp

meal used as a fertilizer in the past (Table 6). Use of this fertilizer has already been discontinued (Personal Communication, Ben Flanner, 3/20/2013).

No other micronutrients (nutrients required by plants in small amounts) and heavy metals were detected in runoff from the Brooklyn Grange. This suggests that the green roof substrate used on the Brooklyn Grange is able to hold on to the micronutrients (B, Fe, Mn, Cu, and Zn) and heavy metals (Al) that it contains (Table 5). Few studies have examined these micronutrients and heavy metals in green roof runoff (Table 1) or agricultural runoff (Table 2). The detection limit of the analyses performed for this study (0.1 mg/L) was, however, relatively high compared to the concentrations of heavy metals found in green roof runoff in other studies (Table 1). Concentrations of both Cd and Cr reported in the literature are lower than the detection limit, so it is possible that very low concentrations of these metals were present in the runoff. EPA drinking water regulations for all of these heavy metals except Cr are also below the 0.1 mg/L detection limit used in analyses (Table 4). Concentrations of Pb in green roof runoff have been reported as high as 0.27 mg/L (Table 1) and the concentration of Cr in runoff from the Brooklyn Grange was less than the EPA regulation for drinking water. This suggests that even if concentrations below 0.1 mg/L of these heavy metals are present in runoff from the Brooklyn Grange, it is unlikely to be a source of those metals. Further study, with more sensitive tests, would be required to get a more accurate picture of the fate of heavy metals on agricultural green roofs.

Conclusions

The current lack of regulation of runoff water quality from agricultural rooftop presents an opportunity for farmers to self-regulate. In order to do this though, they must first have an

understanding of the quality of water running off their roofs, and how it compares to similar systems, such as conventional green roofs and agricultural lands. Although this study presents the runoff water quality results from one agricultural green roof, it does provide some initial insight into the nature of runoff from such rooftops as it compares those similar systems. Overall, agriculture production on a green roof seems to have little negative impact on the physical characteristics of runoff water. The Brooklyn Grange still exhibits a neutralizing effect on the pH of incoming rain water, if slightly lower than that of other extensive green roofs in New York City. The conductivity, apparent color and SS concentration of runoff from the Brooklyn Grange may be higher than those of other extensive green roofs in New York City, but they compare favorably to values reported in the literature on agricultural runoff. Further study could also help elaborate their connection to differences in substrate organic matter content and fertilization rates.

The concentrations of most macronutrients in runoff from the Brooklyn Grange were higher than those of runoff from other extensive green roofs in New York City, as expected. However, most of these micronutrient concentrations did not exceed concentrations reported in both the green roof and agricultural literature. Those that did not, and those that were over EPA guidelines, could be explained through high soil test values and higher than recommended application rates. This suggests that macronutrient concentrations in runoff water could be reduced through changes in nutrient management practices. The annual addition of compost to the Brooklyn Grange does, however, suggest that unlike on conventional green roofs, nutrient concentrations in runoff are unlikely to decrease with roof age. Unlike macronutrients, the Brooklyn Grange does not appear to be a source of micronutrients with the exception of Na. Further examination of the fate of heavy metals, which have very low (less than 0.1 mg/L) EPA

guidelines, is warranted, although the Brooklyn Grange is unlikely to be a source of heavy metals in runoff.

The quality of runoff water from the Brooklyn Grange is also likely to change moving forward, as farming practices are ever evolving. In addition to discontinuing the use of the fertilizer containing NaCl, farmers at the Brooklyn Grange are trying out a number of other practices on both the Long Island City roof where this study was performed and their Brooklyn Navy Yard rooftop farm, one of their goals is to reduce nutrient losses from the roof (Ben Flanner, Personal Communication, 3/20/2013). They have begun to use cover crops in the walkways between raised rows on both roofs and small bioswales around the drains on the Brooklyn Navy Yard rooftop farm. These bioswales consist of areas around the roof drains that have been turned into raised rows for planting, in an effort to catch more of the runoff and nutrients before they are lost from the roof. Further partnerships between scientists and rooftop farmers will enable these and other practices both novel and borrowed from agriculture to be evaluated for their effectiveness. Such collaborative efforts will ensure and support the sustainability of this type of urban farming.

Acknowledgments

The authors gratefully acknowledge support for this work from the National Science Foundation (NSF) grant CMMI-0928604, the Environmental Protection Agency grant AE-83481601-1, and the Doris Duke Charitable Foundation. Leigh Whittinghill also gratefully acknowledges support from an Earth Institute Post-Doctoral Scholarship. The authors wish to thank Brooklyn Grange Farm for their cooperation with the monitoring work. Any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of any supporting agency.

Resources

- Adeli, A., Shankle, M.W., Tewolde, H., Brooks, J.P., Sistani, K.R., McLaughlin, M.R., Rowe, D.E., 2011. Effect of surface incorporation of broiler litter applied to no-till cotton on runoff quality. *J. Environ. Qual.* 40, 566. doi:10.2134/jeq2010.0175
- Alexandri, E., Jones, P., 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Build. Environ.* 43, 480–493. doi:10.1016/j.buildenv.2006.10.055
- Alsup, S., Ebbs, S., Battaglia, L., Retzlaff, W., 2013. Green Roof Systems as Sources or Sinks Influencing Heavy Metal Concentrations in Runoff. *J. Environmental Eng.* 139, 502–508. doi:10.1061/(ASCE)EE.1943-7870
- Alsup, S., Ebbs, S., Retzlaff, W., 2010. The exchangeability and leachability of metals from select green roof growth substrates. *Urban Ecosyst.* 13, 91–111. doi:10.1007/s11252-009-0106-y
- Alsup, S.E., Ebbs, S.D., Battaglia, L.L., Retzlaff, W. a., 2011. Heavy metals in leachate from simulated green roof systems. *Ecol. Eng.* 37, 1709–1717. doi:10.1016/j.ecoleng.2011.06.045
- Banas, D., Marin, B., Skrabber, S., Chopin, E.I.B., Zanella, a, 2010. Copper mobilization affected by weather conditions in a stormwater detention system receiving runoff waters from vineyard soils (Champagne, France). *Environ. Pollut.* 158, 476–82. doi:10.1016/j.envpol.2009.08.034
- Barrio, E.P. Del, 1998. Analysis of the green roofs cooling potential in buildings. *Energy Build.* 27, 179–193. doi:10.1016/S0378-7788(97)00029-7
- Beck, D. a, Johnson, G.R., Spolek, G. a, 2011. Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environ. Pollut.* 159, 2111–8. doi:10.1016/j.envpol.2011.01.022
- Berg, W.A., Smith, S.J., Coleman, G.A., 1988. Management effects on runoff, soil, and nutrient losses from highly erodible soils in the southern plains. *J. Soil Water Conserv.* 43, 407–410.
- Berghage, R.D., Beattie, D., R., J.A., Thuring, C., Razaei, F., O'Connor, T., 2009. Green roofs for stormwater runoff control EPA-600-R-09-026. United States Environmental Protection Agency Office of Research and Development. Washington, DC.
- Bertol, I., Engel, F.L., Mafra, a. L., Bertol, O.J., Ritter, S.R., 2007. Phosphorus, potassium and organic carbon concentrations in runoff water and sediments under different soil tillage systems during soybean growth. *Soil Tillage Res.* 94, 142–150. doi:10.1016/j.still.2006.07.008

499 Beutel, M.W., Newton, C.D., Brouillard, E.S., Watts, R.J., 2009. Nitrate removal in surface-flow
500 constructed wetlands treating dilute agricultural runoff in the lower Yakima Basin,
501 Washington. *Ecol. Eng.* 35, 1538–1546. doi:10.1016/j.ecoleng.2009.07.005

502 Bliss, D.J., Neufeld, R.D., Ries, R.J., 2009. Storm water runoff mitigation using a green roof.
503 *Environ. Eng. Sci.* 26, 407–418. doi:10.1089/ees.2007.0186

504 Borin, M., Tocchetto, D., 2007. Five year water and nitrogen balance for a constructed surface
505 flow wetland treating agricultural drainage waters. *Sci. Total Environ.* 380, 38–47.
506 doi:10.1016/j.scitotenv.2006.12.039

507 Braskerud, B., 2002a. Factors affecting phosphorus retention in small constructed wetlands
508 treating agricultural non-point source pollution. *Ecol. Eng.* 19, 41–61. doi:10.1016/S0925-
509 8574(02)00014-9

510 Braskerud, B., 2002b. Factors affecting nitrogen retention in small constructed wetlands treating
511 agricultural non-point source pollution. *Ecol. Eng.* 18, 351–370. doi:10.1016/S0925-
512 8574(01)00099-4

513 Braskerud, B.C., 2001. The influence of vegetation on sedimentation and resuspension of
514 soilparticles in small constructed wetlands. *J. Environ. Qual.* 30, 1447–1457.

515 Bravo-Espinosa, M., Mendoza, M.E., Medina-Orozco, L., Prat, C., Garcia-Oliva, F., Lopez-
516 Granados, E., 2009. Copper mobilization affected by weather conditions in a stormwater
517 detention system receiving runoff waters from vineyard soils (Champagne, France). *L.*
518 *Degr. Dev.* 20, 640–653. doi:10.1002/ldr

519 Buccola, N., Spolek, G., Johnson, G.R., 2008. A Laboratory Comparison of Green-Roof Runoff
520 Water Quality, in: *Low Impact Development for Urban Ecosystem and Habitat Protection.*
521 American Society of Civil Engineers, Reston, VA, pp. 1–10. doi:10.1061/41009(333)7

522 Carpenter, D.D., Kaluvakolanu, P., 2011. Effect of roof surface type on storm-water runoff from
523 full-scale roofs in a temperate climate. *J. Irrig. Drain. Eng.* 137, 161–170.
524 doi:10.1061/(ASCE)IR.1943-4774.0000185.

525 Carter, T., Jackson, C.R., 2007. Vegetated roofs for stormwater management at multiple spatial
526 scales. *Landsc. Urban Plan.* 80, 84–94. doi:10.1016/j.landurbplan.2006.06.005

527 Chan, K.Y., Wells, T., Fahey, D., Eldridge, S.M., Dorahy, C.G., 2010. Assessing P fertiliser use
528 in vegetable production: agronomic and environmental implications. *Aust. J. Soil Res.* 48,
529 674. doi:10.1071/SR10056

530 Culligan, P., Carson, T., Gaffin, S., Gibbison, R., Hakimdavar, R., Hsueh, D., Hunter, N.,
531 Marasco, D., McGillis, W., 2014. Evaluation of Green Roof Water Quality and Quantity
532 Performance in an Urban Climate. Office of Research and Development, Environmental
533 Protection Agency, EPA/600/R-14/180.

534 Czemieli Berndtsson, J., 2010. Green roof performance towards management of runoff water
535 quantity and quality: A review. *Ecol. Eng.* 36, 351–360. doi:10.1016/j.ecoleng.2009.12.014

536 Czemieli Berndtsson, J., Bengtsson, L., Jinno, K., 2008. First flush effect from vegetated roofs
537 during simulated rain events. *Hydrol. Res.* 39, 171. doi:10.2166/nh.2008.044

538 Czemieli Berndtsson, J., Bengtsson, L., Jinno, K., 2009. Runoff water quality from intensive and
539 extensive vegetated roofs. *Ecol. Eng.* 35, 369–380. doi:10.1016/j.ecoleng.2008.09.020

540 Czemieli Berndtsson, J., Emilsson, T., Bengtsson, L., 2006. The influence of extensive vegetated
541 roofs on runoff water quality. *Sci. Total Environ.* 355, 48–63.
542 doi:10.1016/j.scitotenv.2005.02.035

543 De Cuyper, K., Dinne, K., Van De Vel, L., 2005. Rainwater discharge from green roofs. *Plumb.*
544 *Syst. Des.* Nov/Dec, 10–16.

545 Dunnett, N., Nagase, A., Booth, R., Grime, P., 2008. Influence of vegetation composition on
546 runoff in two simulated green roof experiments. *Urban Ecosyst.* 11, 385–398.
547 doi:10.1007/s11252-008-0064-9

548 DuPont, T., 2011. Determining nutrient applications for organic vegetables – basic calculations.
549 Pennsylvania State University Cooperative Extension, Northampton and Lehigh Counties.

550 Edwards, A.C., Watson, H. a, Cook, Y.E.M., 2012. Source strengths, transport pathways and
551 delivery mechanisms of nutrients, suspended solids and coliforms within a small
552 agricultural headwater catchment. *Sci. Total Environ.* 434, 123–9.
553 doi:10.1016/j.scitotenv.2011.10.055

554 Emilsson, T., Czemieli Berndtsson, J., Mattsson, J.E., Rolf, K., 2007. Effect of using
555 conventional and controlled release fertiliser on nutrient runoff from various vegetated roof
556 systems. *Ecol. Eng.* 29, 260–271. doi:10.1016/j.ecoleng.2006.01.001

557 Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M., Haering, K., 2008. Soil and water
558 environmental effects of fertilizer-, manure-, and compost-based fertility practices in an
559 organic vegetable cropping system. *Agric. Ecosyst. Environ.* 127, 50–58.
560 doi:10.1016/j.agee.2008.02.014

561 FLL, (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau)., 2002. Guidelines for
562 the Planning , Execution and Upkeep of Green-roof sites. Forschungsgesellschaft
563 Landschaftsentwicklung Landschaftsbau, Bonn, Germany.

564 Franklin, D.H., Truman, C.C., Potter, T.L., Bosch, D.D., Strickland, T.C., Jenkins, M.B., Nuti,
565 R.C., 2012. Nutrient losses in runoff from conventional and no-till pearl millet on pre-
566 wetted Ultisols fertilized with broiler litter. *Agric. Water Manag.* 113, 38–44.
567 doi:10.1016/j.agwat.2012.06.013

568 Getter, K.L., Rowe, D.B., 2006. The role of extensive green roofs in sustainable development.
569 HortScience 41, 1276–1285.

570 Getter, K.L., Rowe, D.B., Andresen, J. a., 2007. Quantifying the effect of slope on extensive
571 green roof stormwater retention. Ecol. Eng. 31, 225–231.
572 doi:10.1016/j.ecoleng.2007.06.004

573 Giordano, J.C.P., Brush, M.J., Anderson, I.C., 2010. Quantifying Annual Nitrogen Loads to
574 Virginia's Coastal Lagoons: Sources and Water Quality Response. Estuaries and Coasts 34,
575 297–309. doi:10.1007/s12237-010-9345-7

576 Göbel, P., Dierkes, C., Coldewey, W.G., 2007. Storm water runoff concentration matrix for
577 urban areas. J. Contam. Hydrol. 91, 26–42. doi:10.1016/j.jconhyd.2006.08.008

578 Greenroofs.com, (GRC), 2014. The green roof and wall project database [WWW Document].
579 URL <http://www.greenroofs.com/projects>

580 Gregoire, B.G., Clausen, J.C., 2011. Effect of a modular extensive green roof on stormwater
581 runoff and water quality. Ecol. Eng. 37, 963–969. doi:10.1016/j.ecoleng.2011.02.004

582 Gruda, N., 2008. The effect of wood fiber mulch on water retention , soil temperature and
583 growth of vegetable plants. J. Sustain. Agric. 32, 629–643.

584 Hama, T., Aoki, T., Osuga, K., Sugiyama, S., Iwasaki, D., 2012. Nitrogen and phosphorus
585 effluent loads from a paddy-field district adopting collective crop rotation. Water Sci.
586 Technol. 66, 1074–80. doi:10.2166/wst.2012.292

587 Harmel, D., Potter, S., Casebolt, P., Reckhow, K., Green, C., Haney, R., 2006. COMPILATION
588 OF MEASURED NUTRIENT LOAD DATA FOR AGRICULTURAL LAND USES IN
589 THE UNITED STATES. J. Am. Water Resour. Assoc. 42, 1163–1178.

590 Hathaway, A.M., Hunt, W.F., Jennings, G.D., 2008. A field study of green roof hydrologic and
591 water quality performace. Trans. ASABE 51, 37–44.

592 Hill, D.D., Owens, W.E., Tchoounwou, P.B., 2005. Impact of animal waste application on runoff
593 water quality in field experimental plots. Int. J. Environ. Res. Public Health 2, 314–21.

594 Hollinger, E., Cornish, P., Baginska, B., Mann, R., Kuczera, G., 2001. Farm-scale stormwater
595 losses of sediment and nutrients from a market garden near Sydney, Australia. Agric. Water
596 Manag. 47, 227–241. doi:10.1016/S0378-3774(00)00107-4

597 Jordan, T.E., Whigham, D.F., Hofmockel, K.H., Pittek, M. a, 2003. Nutrient and sediment
598 removal by a restored wetland receiving agricultural runoff. J. Environ. Qual. 32, 1534–47.

599 Kirkkala, T., Ventelä, A.-M., Tarvainen, M., 2011. Long-term field-scale experiment on using
600 lime filters in an agricultural catchment. *J. Environ. Qual.* 41, 410–9.
601 doi:10.2134/jeq2010.0429

602 Köhler, M., Schmidt, M., Grimme, F.W., Laar, M., Piava, V.L. de A., Tavares, S., 2002. Green
603 roofs in temperate climates and in the hot-humid tropics – far beyond the aesthetics.
604 *Environ. Manag. Heal.* 13, 382–391. doi:10.1108/09566160210439297

605 Kovacic, D. a., Twait, R.M., Wallace, M.P., Bowling, J.M., 2006. Use of created wetlands to
606 improve water quality in the Midwest—Lake Bloomington case study. *Ecol. Eng.* 28, 258–
607 270. doi:10.1016/j.ecoleng.2006.08.002

608 Kovacic, D.A., David, M.B., Gentry, L.E., Starks, K.M., Cooke, R.A., 2000. Effectiveness of
609 constructed wetlands in reducing nitrogen and phosphorus export from agricultural tile
610 drainage. *J. Environ. Qual.* 29, 1262–1274.

611 Kurz, I., Tunney, H., Coxon, C.E., 2005. The impact of agricultural management practices on
612 nutrient losses to water: data on the effects of soil drainage characteristics. *Water Sci.*
613 *Technol.* 51, 73–81.

614 Langdale, G.W., Leonard, R.A., Thomas, A.W., 1985. Conservation practice effects on
615 phosphorus losses from southern piedmont watersheds. *J. Soil Water Conserv.* 40, 157–161.

616 Liang, X.Q., Chen, Y.X., Nie, Z.Y., Ye, Y.S., Liu, J., Tian, G.M., Wang, G.H., Tuong, T.P.,
617 2013. Mitigation of nutrient losses via surface runoff from rice cropping systems with
618 alternate wetting and drying irrigation and site-specific nutrient management practices.
619 *Environ. Sci. Pollut. Res. Int.* 20, 6980–91. doi:10.1007/s11356-012-1391-1

620 Loder, A., Peck, S.W., 2004. Green roofs’ contribution to smart growth implementation, in:
621 *Proc. of 2nd North American Green Roof Conference: Greening Rooftops for Sustainable*
622 *Communities.* The Cardinal Group, Toronto, Portland, OR. 2-4 June 2004, pp. 8–24.

623 Lowrance, R., Sheridan, J.M., Williams, R.G., Bosh, D.D., Sullivan, D.J., Blanchett, D.R.,
624 Hargett, L.M., Clegg, C.M., 2007. Water quality and hydrology in farm-scale coastal plain
625 watersheds : Effects of agriculture, impoundments, and riparian zones. *J. Soil Water*
626 *Conserv.* 62, 65–76.

627 Mangiafico, S.S., Gan, J., Wu, L., Lu, J., Newman, J.P., Faber, B., Merhaut, D.J., Evans, R.,
628 2008. Detention and recycling basins for managing nutrient and pesticide runoff from
629 nurseries. *HortScience* 43, 393–398.

630 Mishra, A., Benham, B.L., Mostaghimi, S., 2006. Sediment and nutrient losses from field-scale
631 cropland plots treated with animal manure and inorganic fertilizer. *Water. Air. Soil Pollut.*
632 175, 61–76. doi:10.1007/s11270-006-9111-4

633 Monks, C.D., Monks, D.W., Basden, T., Selders, A., Poland, S., Rayburn, E., 1997. Soil
634 temperature, soil moisture , weed control , and tomato (*Lycopersicon esculentum*) response
635 to mulching. *Weed Technol.* 11, 561–566.

636 Monterusso, M.A., Rowe, D.B., Rugh, C.L., Russell, D.K., 2004. Runoff water quantity and
637 quality from green roof systems. *Acta Hortic.* 639, 369–376.

638 Moreno-Mateos, D., Pedrocchi, C., Comín, F. a., 2010. Effects of wetland construction on water
639 quality in a semi-arid catchment degraded by intensive agricultural use. *Ecol. Eng.* 36, 631–
640 639. doi:10.1016/j.ecoleng.2009.02.003

641 Morgan, S., Alyaseri, I., Retzlaff, W., 2011. Suspended solids in and turbidity of runoff from
642 green roofs. *Int. J. Phytoremediation* 13, 179–193. doi:10.1080/15226514.2011.568547

643 Mustafa, A., Scholz, M., Harrington, R., Carroll, P., 2009. Long-term performance of a
644 representative integrated constructed wetland treating farmyard runoff. *Ecol. Eng.* 35, 779–
645 790. doi:10.1016/j.ecoleng.2008.12.008

646 National Oceanic and Atmospheric Administration National Climate Data Center, (NOAA),
647 2014a. Normals annual/seasonal station details New York LaGuardia Airport, NY US
648 [WWW Document]. URL <http://www.ncdc.noaa.gov/cdo-web/datasets>.

649 National Oceanic and Atmospheric Administration National Climate Data Center, (NOAA),
650 2014b. Normals daily station details New York LaGuardia Airport, NY US [WWW
651 Document]. URL <http://www.ncdc.noaa.gov/cdo-web/datasets>.

652 O’Green, A.T., Budd, R., Gan, J., Maynard, J., Parikh, S.J., Dahlgren, R.A., 2010. Mitigating
653 nonpoint source pollution in agriculture with constructed and restored wetlands, in:
654 *Advances in Agronomy*. Elsevier Inc., pp. 1–76. doi:10.1016/S0065-2113(10)08001-6

655 Osteen, C., Gottlieb, J., Vasavada, U., 2012. Agricultural resources and environmental indicators
656 , 2012 Edition. Economic Information Bulletin Number 98. Economic Research Service,
657 United States Department of Agriculture.

658 Otero, J.D., Figueroa, A., Muñoz, F.A., Peña, M.R., 2011. Loss of soil and nutrients by surface
659 runoff in two agro-ecosystems within an Andean paramo area. *Ecol. Eng.* 37, 2035–2043.
660 doi:10.1016/j.ecoleng.2011.08.001

661 Pierson, S.T., Cabrera, M.L., Evanylo, G.K., Kuykendall, H. a, Hoveland, C.S., McCann, M. a,
662 West, L.T., 2001. Phosphorus and ammonium concentrations in surface runoff from
663 grasslands fertilized with broiler litter. *J. Environ. Qual.* 30, 1784–9.

664 Rowe, D.B., 2011. Green roofs as a means of pollution abatement. *Environ. Pollut.* 159, 2100–
665 10. doi:10.1016/j.envpol.2010.10.029

666 Rowe, D.B., Monterusso, M.A., Rugh, C.L., 2006. Assessment of heat-expanded slate and
667 fertility requirements in green roof substrates. *Horttechnology* 16, 471–477.

668 Saiz, S., Kennedy, C., Bass, B., Pressnail, K., 2006. Comparative life cycle assessment of
669 standard and green roofs. *Environ. Sci. Technol.* 40, 4312–6.

670 Sauer, T.J., Baniel, T.C., Moore, P.A., Coffey, K.P., Nichols, D.J., West, C.P., 1999. Poultry
671 litter and grazing animal waste effects on runoff water quality. *J. Environmenal Qual.* 28,
672 860–865.

673 Stowe, D.C., Lamhamedi, M.S., Carles, S., Fecteau, B., Margolis, H. a., Renaud, M., Bernier,
674 P.Y., 2010. Managing irrigation to reduce nutrient leaching in containerized white spruce
675 seedling production. *New For.* 40, 185–204. doi:10.1007/s11056-010-9193-0

676 Tanner, C.C., Nguyen, M.L., Sukias, J.P.S., 2005. Nutrient removal by a constructed wetland
677 treating subsurface drainage from grazed dairy pasture. *Agric. Ecosyst. Environ.* 105, 145–
678 162. doi:10.1016/j.agee.2004.05.008

679 Teemusk, A., Mander, Ü., 2007. Rainwater runoff quantity and quality performance from a
680 greenroof: The effects of short-term events. *Ecol. Eng.* 30, 271–277.
681 doi:10.1016/j.ecoleng.2007.01.009

682 Tiessen, K.H.D., Elliott, J. a, Yarotski, J., Lobb, D. a, Flaten, D.N., Glozier, N.E., 2003.
683 Conventional and conservation tillage: influence on seasonal runoff, sediment, and nutrient
684 losses in the Canadian Prairies. *J. Environ. Qual.* 39, 964–80. doi:10.2134/jeq2009.0219

685 Tiwari, K.R., Sitaula, B.K., Bajracharya, R.M., Børresen, T., 2009. Effects of soil and crop
686 management practices on yields, income and nutrients losses from upland farming systems
687 in the Middle Mountains region of Nepal. *Nutr. Cycl. Agroecosystems* 86, 241–253.
688 doi:10.1007/s10705-009-9289-0

689 Udawatta, R.P., Motavalli, P.P., Garrett, H.E., Krstansky, J.J., 2006. Nitrogen losses in runoff
690 from three adjacent agricultural watersheds with claypan soils. *Agric. Ecosyst. Environ.*
691 117, 39–48. doi:10.1016/j.agee.2006.03.002

692 United States Environmental Protection Agency, (USEPA), 1986. Quality criteria for water.
693 Office of Water Regulations and Standards. Washington, D.C.

694 United States Environmental Protection Agency, (USEPA), 2000. Ambient water quality criteria
695 recommendations of state and tribal nutrient criteria rivers and streams in nutrient ecoregion
696 XIV EPA 822-B-00-022. Office of Science and Technology Health and Ecological Criteria
697 Division. Washinton, D.C.

698 United States Environmental Protection Agency, (USEPA), 2001. Ambient water quality criteria
699 recommendations lakes and reservoirs in nutrient ecoregion XIV EPA 822-B-01-011.

700 Office of Science and Technology Health and Ecological Criteria Division. Washinton,
701 D.C.

702 United States Environmental Protection Agency, (USEPA), 2003. National management
703 measures for the control of nonpoint pollution from agirculture EPA 841-B-03-004. Office
704 of Water. Washington, DC.

705 United States Environmental Protection Agency, (USEPA), 2007. Aquatic life ambient
706 freshwater quality criteria- copper EPA-822-R-07-001. Office of Water and Office of
707 Science and Technology. Washington, D.C.

708 United States Environmental Protection Agency, (USEPA), 2009a. Developing your stormwater
709 pollution prevention plan: A guide for industrial operators EPA 833-B-09-002. Office of
710 Water. Washington, DC.

711 United States Environmental Protection Agency, (USEPA), 2009b. National primary drinking
712 water regulations EPA 816-F-09-004. Office of Water. Washington, DC.

713 United States Environmental Protection Agency, (USEPA), 2013. Aquatic life ambient water
714 quality criteria for ammonia- freshwater EPA 822-R-13-001. Office of Water and Office of
715 Science and Technology. Washington, D.C.

716 United States Environmental Protection Agency, (USEPA), 2014. National recommended water
717 quality criteria [WWW Document]. URL
718 <http://water.epa.gov/scitech/swguidance/standards/criteria/current/index.cfm#altable>

719 Urban Design Lab, (UDL), 2014. Urban agriculture research in New York City : Phase II Final
720 Report. The Earth Institute at Columbia Univeristy. New York, NY.

721 Van Seters, T., Rocha, L., Smith, D., Macmillan, G., 2009. Evaluation of green roofs for runoff
722 retention, runoff quality, and leachability 44, 33–47.

723 VanWoert, N.D., Rowe, D.B., Andresen, J. a, Rugh, C.L., Fernandez, R.T., Xiao, L., 2005.
724 Green roof stormwater retention: effects of roof surface, slope, and media depth. J. Environ.
725 Qual. 34, 1036–44. doi:10.2134/jeq2004.0364

726 Wang, Q., Li, Y., Klassen, W., Alva, A., 2012. High retention of N P nutrients, soil organic
727 carbon, and fine particles by cover crops under tropical climate. Agron. Sustain. Dev. 32,
728 781–790. doi:10.1007/s13593-011-0054-9

729 Warncke, D., Dahl, J., Zandstra, B., 2004. Nutrient recommendations for vegetable crops in
730 Michigan. Michigan State University Extension Bulletin E2934.

731 Warsaw, A.L., Fernandez, R.T., Cregg, B.M., Andresen, J.A., 2009. Container-grown
732 ornamental plant growth and water runoff nutrient content and volume under four irrigation
733 treatments. HortScience 44, 1573–1580.

734 Whittinghill, L.J., Rowe, D.B., 2012. The role of green roof technology in urban agriculture.
735 *Renew. Agric. Food Syst.* 27, 314–322. doi:10.1017/S174217051100038X

736 Whittinghill, L.J., Rowe, D.B., Andresen, J. a., Cregg, B.M., 2015. Comparison of stormwater
737 runoff from sedum, native prairie, and vegetable producing green roofs. *Urban Ecosyst.* 8,
738 13–29. doi:10.1007/s11252-014-0386-8

739 Wilson, C., Albano, J., Mozdzen, M., Riiska, C., 2010. Irrigation water and nitrate-nitrogen loss
740 characterization in southern Florida nurseries: cumulative volumes, runoff rates, nitrate-
741 nitrogen concentrations and loadings, and implications for management. *Horttechnology* 20,
742 325–330.

743 Wilson, P.C., Albano, J.P., 2011. Impact of fertigation versus controlled-release fertilizer
744 formulations on nitrate concentrations in nursery drainage water. *Horttechnology* 21, 176–
745 180.

746 Wong, N.H., Tay, S.F., Wong, R., Ong, C.L., Sia, A., 2003. Life cycle cost analysis of rooftop
747 gardens in Singapore. *Build. Environ.* 38, 499–509. doi:10.1016/S0360-1323(02)00131-2

748 Wood, B.H., Wood, C.W., Yoo, K.H., Yoon, K.S., Delaney, D.P., 1999. Seasonal surface runoff
749 losses of nutrients and metals from soils fertilized with broiler litter and commercial
750 fertilizer. *J. Environ. Qual.* 28, 1210–1218.

751 Woods, E., 2009. Evaluation of the quantity and quality of storm water runoff released from
752 various green roof systems. Southern Illinois University Edwardsville.

753 Yoder, D.C., Cope, T.L., Wills, J.B., Denton, H.P., 2005. No-till transplanting of vegetables and
754 tobacco to reduce erosion and nutrient surface runoff. *J. Soil Water Conserv.* 60, 68–72.

755 Zhang, M.-K., Wang, L.-P., He, Z.-L., 2007. Spatial and temporal variation of nitrogen exported
756 by runoff from sandy agricultural soils. *J. Environ. Sci. (China)* 19, 1086–92.

757 Zhang, Z., Kong, L., Zhu, L., Xia, J., Patricia, X., 2012. Fate characteristics of nitrogen in runoff
758 from a small agricultural watershed on the south of Huaihe River in China. *Environ. Earth*
759 *Sci.* 66, 835–848. doi:10.1007/s12665-011-1293-4

760

761 **Table**
762 Table 1. Water quality metrics and their average values found in the green roof literature.

Water Quality Metric	Range
pH	5.3-8.3 ^{e-g,k,l,s,t,v}
Conductivity (uS/cm)	83.82-273.31 (1727.8 for intensive green roofs) ^{e,l,t}
Apparent Color (PtCo)	219.04-878.19 ^{e,l}
Suspended Solids (mg/L)	6-482 (to 1026 non-vegetated) ^{g,l,r}
Turbidity (NTU)	4.5-310 (to 568 non-vegetated) ^{e,f,r,t}
Nitrate (mg/L)	0.005-70.3 ^{e,g,h,j,o,s-v}
Ammonium (mg/L)	0-0.125 ^{i-k,m,o,s,t}
Total P (mg/L)	0-22.1 ^{d-g,i-m,o-q,s-u}
K (mg/L)	3-8.5 ^{e,i-k,m,t}
Fe (mg/L)	0.0007-0.8316 ^{a-c,e,i-k,t}
Mn (mg/L)	0-0.45 ^{b,c,e,i,j,t}
Cu (mg/L)	0-0.75 ^{a-c,g,i,j,n,o,t}
Zn (mg/L)	0.002-1.0536 ^{a-c,e,g,i-k,n,o,t}
Ni (mg/L)	0-0.0778 ^{a-c,n,t}
As (mg/L)	0.0005-0.025 ^g
Cd (mg/L)	0-0.0203 ^{a-c,f,g,n,t}
Cr (mg/L)	0-0.0032 ^{b,g,i,t}
Pb (mg/L)	0-0.27 ^{a-c,f,g,i,n,t}

763 ^a(Alsup et al., 2013); ^bAlsup et al., 2010; ^cAlsup et al., 2011; ^dBeck et al., 2011; ^eBerghage et al.,
764 2009; ^fBliss et al., 2009; ^gBuccola et al., 2008; ^hCarpenter and Kaluvakolanu, 2011; ⁱCzemiel
765 Berndtsson et al., 2006; ^jCzemiel Berndtsson et al., 2008; ^kCzemiel Berndtsson et al., 2009; ^lDe
766 Cuyper et al., 2005; ^mEmilsson et al., 2007; ⁿGöbel et al., 2007; ^oGregoire and Clausen, 2011;
767 ^pHathaway et al., 2008; ^qMonterusso et al., 2004; ^rMorgan et al., 2011; ^sTeemusk and Mander,
768 2007; ^tVan Seters et al., 2009; ^uWhittinghill et al., 2014; ^vWoods, 2009

769
770

771 Table 2. Water quality metrics and their average values found in literature on agricultural runoff.

Water Quality Metric	Range
pH	4.4-8.1 ^{a,i,j,x,z,ab}
Conductivity (uS/cm)	162-682 ^{j,r,ab,ac}
Suspended Solids (mg/L)	11-62,250 ^{a,b,f,g,j,k,p-r,v,x}
Turbidity (NTU)	
Nitrate (mg/L)	0-75 (up to 376.4 in nursery production) ^{a,d,h-k,m,q,u-z,ab,ad,af-aj}
Ammonium (mg/L)	0-81.38 ^{a,e,h-k,m,o-v,x,aa,ab,ad-af,ah-aj}
Total P (mg/L)	0.0-17.8 ^{a,c,g,j,l-n,t,v,w,z,ad,ae,ai}
K (mg/L)	<0.1-92.6 ^{c,i,k,o,s,ab,ai}
Ca (mg/L)	1.65-34.8 ^{i,k,ai}
Mg (mg/L)	0-29 ^{i,k,w,ab,ai}
Na (mg/L)	19.6-220 ^{k,w}
B (mg/L)	0.018-0.13 ^{ab}
Fe (mg/L)	0.02-0.24 ^{k,ab}
Mn (mg/L)	0.0-0.29 ^{k,ab,ai}
Cu (mg/L)	0.0-0.48 ^{a,b,k,o,ab,ai}
Zn (mg/L)	0.005-1.04 ^{a,k,o,ab,ai}
Al (mg/L)	0.027 ^k

772 ^aAdeli et al., 2011; ^bBanas et al., 2010; ^cBertol et al., 2007; ^dBeutel et al., 2009; ^eBorin and
773 Tocchetto, 2007; ^fBraskerud, 2001; ^gBraskerud, 2002a; ^hBraskerud, 2002b; ⁱBravo-Espinosa et
774 al., 2009; ^jChan et al., 2010; ^kEdwards et al., 2012; ^lEvanylo et al., 2008; ^mFranklin et al., 2012;
775 ⁿHama et al., 2012; ^oHill et al., 2005; ^pHollinger et al., 2001; ^qJordan et al., 2003; ^rKirkkala et al.,
776 2011; ^sKurz et al., 2005; ^tLiang et al., 2013; ^uMangiafico et al., 2008; ^vMishra et al., 2006;
777 ^wMoreno-Mateos et al., 2010; ^xMustafa et al., 2009; ^yO'Green et al., 2010; ^zOtero et al., 2011;
778 ^{aa}Pierson et al., 2001; ^{ab}Sauer et al., 1999; ^{ac}Stowe et al., 2010; ^{ad}Tanner et al., 2005; ^{ae}Tiessen et
779 al., 2003; ^{af}Tiwari et al., 2009; ^{ag}Udawatta et al., 2006; ^{ah}Wang et al., 2012; ^{ai}Warsaw et al.,
780 2009; Wilson et al., 2010; Wilson and Albano, 2011; ^{aj}Wood et al., 1999; ^{ak}Zhang et al., 2007,
781 2012

Table 3. Annual mass loading (AML) from the Brooklyn Grange and the range average annual mass loading from conventional green roofs and agricultural lands and the number of studies from which they have been taken or derived.

Water Quality Metric	Brooklyn Grange AML (kg/ha)	Green Roofs*		Agricultural Lands⁺	
		AML (kg/ha)	No. of Studies	AML (kg/ha)	No. of Studies
TSS	1513.99	<7.69-514.57	2	0.1-11080	7
NO₃⁻	33.20	0.2-188.59	9	0-57.4	19
NH₄	0.40	0.02-39.79	4	<0.001-15.95	16
P	9.26	0.1-17.31	10	0-113.15	19
K	131.68	0.1-17.31	5	0.09-23.19	4
Ca	275.16	2.65-66.5	3	0.76-13.96	2
Mg	34.08	9.84-41.6	3	0.13-2.89	2
Na	126.64	2.30-35.79	3	0.03-0.88	1

Annual mass loading (AML) for the Brooklyn Grange was calculated from the average concentrations in runoff water times the volume of runoff water. The volume of runoff water was estimated based on the area of the roof, average annual rainfall in New York, City, and a runoff retention of 40 %. Annual mass loading from green roofs and agricultural lands was converted to kg/ha when presented in a study, or calculated in a similar manner when all the necessary information was available in the source.

*(Alsup et al., 2011; Beck et al., 2011; Berghage et al., 2009; Carpenter and Kaluvakolanu, 2011; Culligan et al., 2014; Czemieli Berndtsson et al., 2006; Emilsson et al., 2007; Gregoire and Clausen, 2011; Hathaway et al., 2008; Monterusso et al., 2004; Van Seters et al., 2009; Whittinghill et al., 2015; Woods, 2009)

⁺(Adeli et al., 2011; Banas et al., 2010; Berg et al., 1988; Bravo-Espinosa et al., 2009; Chan et al., 2010; Evanylo et al., 2008; Franklin et al., 2012; Giordano et al., 2010; Hama et al., 2012; Harmel et al., 2006; Hollinger et al., 2001; Jordan et al., 2003; Kovacic et al., 2006, 2000; Langdale et al., 1985; Liang et al., 2013; Lowrance et al., 2007; Mishra et al., 2006; Pierson et al., 2001; Tanner et al., 2005; Tiessen et al., 2003; Tiwari et al., 2009; Udawatta et al., 2006; Warsaw et al., 2009; Wood et al., 1999; Yoder et al., 2005; Zhang et al., 2007)

804 Table 4. United States Environmental Protection Agency water quality guidelines for the
 805 micronutrients and heavy metals examined in this study (USEPA, 2014).

Water Quality Metric	Fresh Water		Human Health
	Acute	Chronic	
Na (mg/L)	-	-	-
B (mg/L)	19,000 ⁺	< 5 ⁺	0.750 ⁺
Fe (mg/L)	1.0 ⁺	1.0 ⁺	0.3**
Mn (mg/L)	-	-	0.05**
Cu (mg/L)	2.73-3573*	3.54-60.4*	1.0**
Zn (mg/L)	0.12	0.12	5.0**
Ni (mg/L)	0.47	0.052	0.61
Al (mg/L)	0.75	0.087	0.05-0.2**
As (mg/L)	0.34	0.15	0.010**
Cd (mg/L)	0.002	0.00025	0.005**
Cr (mg/L)	III: 0.570	III: 0.074	0.1**
	VI: 0.016	VI: 0.011	
Pb (mg/L)	0.065	0.0025	0.015**

806 ⁺ (USEPA, 1986)

807 * (USEPA, 2007)

808 ** (USEPA, 2009b)

809

810 Table 5. Soil test results for substrate sampled from the Brooklyn Grange rooftop farm in March 2013,
 811 before the addition of compost or other fertilizers/amendments. Analysis performed by Logan Labs, LLC
 812 (Lakeview, OH), results provided to us by Ben Flanner and the Brooklyn Grange.

		Result	
Total exchange capacity (M.E.)		14.67	
pH		8.00	
Organic matter (%)		10.15	
Anions	Sulfur (mg/kg)	18	
	Mehlich III phosphorus (kg/hectare)	212 (1154 lbs/acre)	
Exchangable Cations	Calcium (kg/hectare)	Desired value	4480 (3991 lbs/acre)
		Value Found	5541 (4944 lbs/acre)
		Deficit	
	Magnesium (kg/hectare)	Desired value	473 (422 lbs/acre)
		Value Found	412 (368 lbs/acre)
		Deficit	61 (-54 lbs/acre)
	Potassium (kg/hectare)	Desired value	512 (457 lbs/acre)
		Value Found	201 (179 lbs/acre)
		Deficit	311 (-278 lbs/acre)
	Sodium (kg/hectare)		27 (24 lbs/acre)
	Base saturation (%)	Desired value	60 to 70
		Value Found	84.23
		Desired value	10 to 20
		Value Found	10.45
		Desired value	2 to 5
		Value Found	1.56
		Desired value	0.5 to 3
		Value Found	0.35
		Desired value	Variable
		Value Found	3.40
		Desired value	10 to 15
		Value Found	0.00
Trace Elements (mg/kg)	Boron	0.75	
	Iron	99	
	Manganese	25	
	Copper	4.15	
	Zinc	9.72	
	Aluminum	126	

813

814

815 Table 6. Rates of application for nutrients applied to the Brooklyn Grange during the 2012 growing
 816 season (Personal Communication, Gwen Schantz, 6/28/2013) compared to nutrient application
 817 recommendations for green roofs (FLL, 2002) and market gardens at ground level (Warncke et al.,
 818 2004) based on soil testing performed by Logan Labs, LLC (Lakeview, OH).

Nutrient	Sources of Nutrient	Application Rate (g/m ²)	Recommendations	
			Green roofs (FLL, 2002) (g/m ²)	Market gardens at ground level (g/m ²)
Nitrogen	Pro Gro 5-3-4, Fish Emulsion, Compost	4.57-6.93	7.03	15.69
Phosphorus (P₂O₅)	Kelp Meal, Alfalfa Meal, Pro Gro 5-3-4, Fish Emulsion, Compost	6.50-9.6	4.69	3.75
Potassium (K₂O):				
Tomatoes and Peppers	Kelp Meal, Sulfate of Potash, Pro Gro 5-3-4, Fish Emulsion, Compost	46.49-52.86	7.03	Maintenance: 7.50 To build up soil test level: 29.19
Rest of the Roof	Kelp Meal, Pro Gro 5-3-4, Fish Emulsion, Compost	9.14-15.51	7.03	Maintenance: 9.37 To build up soil test level: 31.07
Calcium	Kelp Meal	0.58-0.9	-	-
Magnesium	-	-	0.57	-
Sodium (NaCl)	Kelp Meal	0.14-0.57	-	-
Chlorine (NaCl)	Kelp Meal	0.22-0.88	≤ 0.23	-

819 Applications of Kelp Meal (North Country Organics, Bradford, VT), Alfalfa Meal (North Country
 820 Organics, Bradford, VT), Sulfate of Potash (North Country Organics, Bradford, VT), Pro Gro 5-3-4
 821 (North Country Organics, Bradford, VT), and Fish Emulsion (Neptune's Harvest Organic Fertilizer,
 822 Gloucester, MA) based on the amount of fertilizer used in 2012 and the area of the roof it was applied to
 823 (Personal Communication, Gwen Schantz, 6/28/2013). Application of compost based on the amount
 824 applied at the beginning of the 2013 growing season (Personal Communications, Bradley Fleming,
 825 4/19/2013) and the range of typical compost nutrient contents (DuPont, 2011).
 826

827

828

829

830

Figure 1. (A) An aerial view of the Brooklyn Grange rooftop farm in Long Island City, Queen, New York with the locations of the monitored drain pipe and drainage basin and weather station (from Google Maps, Imagery © 2014 Google) and (B) the weather station used in collecting ambient weather data.

Figure 2. Weekly average temperature and total precipitation measured on the Brooklyn Grange between May 24, 2013 (week 1) and January 2, 2014 (week 32) and 30 year (1981-2010) climatological normals for the same time period (NOAA, 2014).

Figure 3. Average pH, conductivity, apparent color, and turbidity, of water sampled from Brooklyn Grange runoff (BKG). Runoff measurements from extensive sedum green roofs (Green roof), traditional non-vegetated roofs (Non-vegetated), and rain (Rain) samples were collected from a previous study (Culligan et al., 2014). Capital letters indicate statistically significant groupings of means.

Figure 4. Average suspended solids of water sampled from Brooklyn Grange runoff (BKG) and rain from a Manhattan Building (Rain121). Capital letters indicate statistically significant groupings of means.

Figure 5. Average nitrate (NO_3^-), ammonium (NH_4), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) content of water sampled from Brooklyn Grange runoff (BKG). Runoff measurements from extensive sedum green roofs (Green roof), traditional non-vegetated roofs (Non-vegetated), and rain (Rain) samples were collected from a previous study (Culligan et al., 2014). Capital letters indicate statistically significant groupings of means.

Figure 6. Average sodium content of water sampled from Brooklyn Grange runoff (BKG). Runoff measurements from extensive sedum green roofs (Green roof), traditional non-vegetated roofs (Non-vegetated), and rain (Rain) samples were collected from a previous study (Culligan et al., 2014). Capital letters indicate statistically significant groupings of means.