# 13 Biogeochemistry of Rooftop Farm Soils

*Yoshiki Harada, Thomas H. Whitlow,*
*Nina L Bassuk, and Jonathan Russell-Anelli*

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## 13.1 APPROACH

Rooftop farming draws on many specialized fields, each with its own terminology as well as different definitions for the same term. As a prime example, one can argue that there is no soil on a roof, so why should there be a chapter on rooftop farming in a volume devoted to soil science? A simple definition of soil that is universally accepted by agriculturalists, geologists, ecologists, and engineers is a perennial challenge, yet by calling the material placed on a roof in order to grow plants a *soil*, it is appropriate to follow Jenny's (1941) wise choice of leaving the definition open and inclusive.

Among the many subject areas informing rooftop farming are soil science, biogeochemistry, horticultural science, green roof design and management, and potting soils (Figure 13.1). In the biophysical sciences, *soil science* provides the foundation for understanding the physics and chemistry of water and nutrient movement in a rooftop soil while *biogeochemistry* treats these fluxes at the ecosystem scale. In the realm of applied science, production *horticulture* has historically dealt primarily with crops grown in ground in native soils. In contrast, roofs lack native soil, are disconnected from the underlying subsoil and parent material, and are disconnected from upland watersheds. A rooftop farm resembles a *green roof* yet would probably require deeper soil and supplemental irrigation to achieve acceptable yield and quality. A rooftop farm devoted to vegetable production also draws on the technologies developed for *greenhouse production*, including supplemental irrigation and nutrients and the use of artificial soilless or potting mixes. Since the 1950s, an extensive literature has dealt with synthetic soil mixes for greenhouse and nursery production, which provides information that could be used to develop soil for extensive outdoor landscapes like green roofs (Baker 1957; Dasberg 1999; Jozwik 2000; Newman 2008). Finally, *urban planning and design* lends understanding of how rooftop farming both drives and responds to the complex, coupled human and natural systems of modern cities. This literature is large and expanding rapidly. A recent search of bibliographic databases found over 1,000 peer-reviewed papers relevant to growing plants on roofs, while the intersection of the disciplines contains roughly 100 papers.

This chapter is intended for a wide audience, not just for soil scientists. After a review of the context for rooftop farming, the focus is on the influence of soil composition and depth on the water and nutrient budgets of rooftop farms and concludes with a case study from New York City (Figures 13.1 and 13.2).

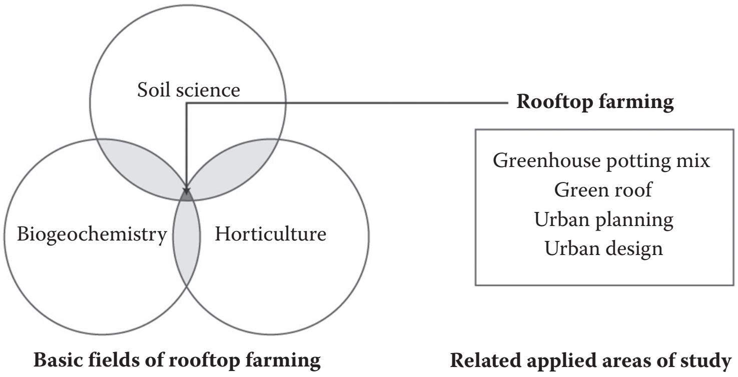
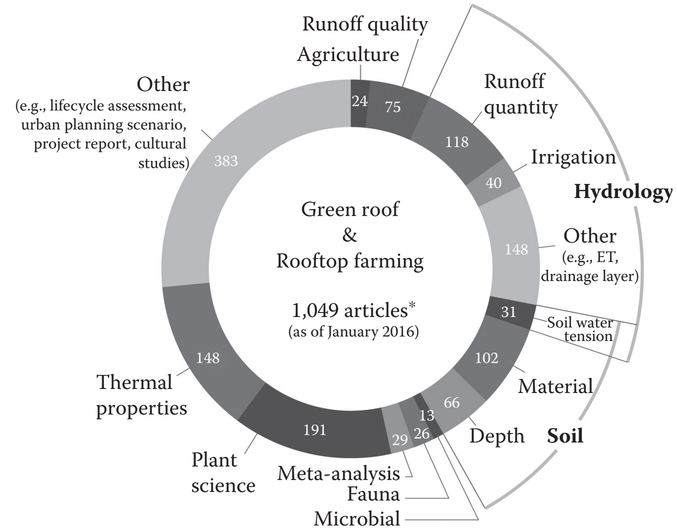


**FIGURE 13.1** Related fields of rooftop farming.



*Based on the Web of Science entry

*Each article can be categorized into multiple topic groups

**FIGURE 13.2** Topic groups in green roof and rooftop farming research.

## 13.2 BACKGROUND

Cities are hotspots for biogeochemical cycles, making them ideal locations for developing and testing novel ecosystems to enhance sustainability (Palmer et al. 2004; Grimm et al. 2008). Among these are a wide variety of green infrastructure projects intended to manage stormwater, save energy, and manage waste. Social dimensions to these practices include environmental education, investment, green job employment, eco-justice, food security, and building more cohesive communities.

Urban rooftop farms could potentially integrate many ecosystem services. These perceived services necessarily involve regulatory and investment sectors as well as public preferences (Plakias 2016). In this regard, urban rooftop farming could be viewed as one of the most creative components of twenty-first century planning for sustainable cities. The “combining” and “stacking” of multiple ecosystem services presents a unique opportunity for cross-disciplinary research (Felson and Pickett 2005; Lovell 2010; Robertson et al. 2014).

In New York City, green infrastructure projects are supported by a 20-year $1.5-billion capital initiative to fund community-based projects across the city (New York City Department of Environmental Protection 2010; Bloomberg 2011; De Blasio 2015). In April 2012, a new zoning code allowed retrofitting rooftops to include vegetable farms (New York City Department of City Planning 2012), prompting an influx of public and private funds into rooftop farms. A prominent example is the Brooklyn Grange, a 70,000-square-foot (0.65 ha) commercial rooftop farm (Figure 13.3), constructed in 2012 with a $592,730 grant from the Community-Based Green Infrastructure Program of the New York City Department of Environmental Protection (2011). This grant was partly based on the expectation that the farm would reduce stormwater runoff and the resulting N pollution caused by combined sewer discharges into surface waters.

Since its inception, the Grange has linked to the local community through businesses, schools, nonprofit organizations, and underrepresented populations by providing organic vegetables, collecting food wastes for composting, and offering educational and green job training programs (Plakias 2016). However, the functional environmental performance of rooftop farms has received little attention from the scientific community and there is little quantitative information on the design and operation of rooftop farms from a resource subsidies perspective. Understanding the water and nutrient budgets could lay the foundation for optimizing the environmental, yield, and economic return of the farm.

### 13.2.1 OPPORTUNITIES

A rooftop is a simple watershed system analogous to the Hubbard Brook experimental watershed. Inputs and outflows of water and nutrients are easiest to measure in watersheds with clear boundaries and topographic gradients, shallow soil overlying impervious rock, and a centralized stream network (Likens 2013). This approach provides a foundation for science to inform policy

**FIGURE 13.3** The Brooklyn Grange Farm at Brooklyn Navy Yard, Summer 2015.

and practice across cities, thereby allowing comparisons of water and nutrient budgets across geographic locations and with varying degrees of human influence (Howarth et al. 1996). The extended community of scientists involved in the Long-Term Ecological Research (LTER) program supported by the US National Science Foundation (NSF) affords an ideal opportunity for generalizing the state of knowledge of urban biogeochemistry and applying this to practice (Fahey et al. 2015).

### 13.2.2 CHALLENGES

Although the biogeochemical processes of rooftop farms resemble those of forested and agricultural ecosystems, because many components of in-ground ecosystems are either *absent* (e.g., ground water recharge), *simplified* (e.g., soil horizonation), or *replaced with artificial materials* (e.g., soilless media), it is difficult to apply knowledge from other systems directly to rooftops.

Even among the horticultural disciplines that contribute to the emerging practice of rooftop farming, the existing scientific understanding of system performance may not translate directly. For example, extensive green roofs typically use soil media that are designed to be lightweight and drain rapidly to minimize roof loads. Nutrient supply after establishment is also relatively unimportant. While these soils may supply adequate water for slow growing, drought-tolerant *Sedum* species typically used on extensive green roofs, they are not optimal for a vegetable production system where yield and quality are important. In order to increase the nutrient and water holding capacity for vegetable cropping, green roof soil is amended with peat, coconut coir, biochar, and spent mushroom media, which are typical components used in greenhouse potting mixes managed for a single crop cycles. In contrast, rooftop farms use the same soil indefinitely under outdoor conditions with diurnal and seasonal cycles of temperature and moisture. Soils in rooftop farms are further amended with organic fertilizers for vegetable production (kelp meal, blood meal) and food-waste compost, which is low in many essential nutrients found in the native soil.

Ideally, each ingredient of a rooftop soil would contribute to optimizing the water and nutrient budgets. Optimum management of existing farms could aim at the steady state of nutrient budget in the traditional sense of biogeochemistry (Likens 2013), while "enhanced" steady state could be achieved by applying scientific understanding of site characteristics (e.g., substrates, irrigation systems) to improve the performance (Fahey et al. 2015). Beyond rooftop farms, similar challenges confront all green infrastructure projects, including green roofs, bioswales, rain gardens, and reclaimed urban parcels.

### 13.2.3 ENVIRONMENTAL QUALITY

New York City alone has about 8,600 ha of flat rooftop surface (Acks 2006), about 25 times the size of the Central Park. Converting even a small fraction of this space to agriculture raises concern about increased N load to surface water bodies draining the city. The appearance of "dead zones" resulting from low oxygen concentration in the Chesapeake Bay and Gulf of Mexico are the legacy of fertilizer runoff from farming practices intended to maximize crop yield (Rabalais et al. 2002; Kemp et al. 2005). In the United States, the passage of the Clean Water Act in 1970 and its subsequent amendments reflects a growing recognition that management practices can have a profound influence on downstream water quality. The establishment of total maximum daily loads (TMDLs) for each governmental jurisdiction in a watershed is intended to eliminate downstream pollution (New York State Department of Environmental Conservation 2000). The need to comply with increasingly stringent regulations has led to the development of best management practices (BMPs) to reduce both concentration and runoff volume from all land uses (Meals et al. 2010). Because urban rooftop farming is in its infancy, there exists an unprecedented opportunity to develop and implement BMPs before problems arise. Soil science is central to engineering soils that satisfy both the concerns of roof bearing capacity and nutrient and water retention. Among the most important soil properties affecting these are depth, composition, and pore-size distribution.

## 13.3 SOIL DESIGN

### 13.3.1 Overview

Over the past decade, reviews of the green roof literature report a wide range of water retention and nutrient loss (Mentens et al. 2006; Berndtsson 2010; Rowe 2011; Li and Babcock 2014; Driscoll et al. 2015). Reviews of green roof performance include both soilless (Ampim et al. 2010) and soil-based media (Best et al. 2015) and irrigation (Van Mechelen et al. 2015). The physical, chemical, and biological properties of the soil are the key factors, which relate the design and management to water retention and nutrient leaching from green roofs (Berndtsson 2010; Rowe 2011; Buffam and Mitchell 2015). It has proven difficult to develop standard specifications for rooftop soil that meet the competing demands of vegetable yield and quality, water retention, and nutrient leaching while keeping weight to a minimum. Green roofs with similar design and management vary widely in performance, yet the key information needed to explain such difference is often unknown or unreported. Studies often do not include statistics for both runoff quantity and quality, while coupled studies often lack details of soil composition. Insufficient detail stems in part from the difficulties of defining each component of green roof soil mixes. Even the standardized industrial-grade products like expanded shale would require laboratory testing to quantify their physical characteristics (e.g., pore-size distribution), and there are many components that are too variable for exact specification (e.g., composts), especially as their properties change over time in response to field conditions and the management history. Those factors present a challenge to synthesize the knowledge from different studies across disparate climactic zones and cultural contexts.

### 13.3.2 Soil Composition

Rooftop farms use a variety of soils, including commercial potting mixes (e.g., planter mixes, garden mixes), commercial green roof mixes, experimental mixes using common/novel ingredients for a green roof, and commercial rooftop farming mixes (Table 13.1). Both commercial potting and green roof mixes use organic (e.g., compost, peat) and mineral (e.g., vermiculite, perlite) soilless materials, and both have been used in the studies on rooftop farming, while expanded shale, clay, and slate (ESCS) is the main mineral component typically used in commercial green roof mixes in order to meet the drainage guidelines and weight limitations (Ampim et al. 2010). Naturally sourced soils (e.g., sand, loam) are sometimes used for green roofs with or without being blended with soilless materials (Best et al. 2015). The review of available literature indicated only one commercial formulation specified for the rooftop farming, Rooflite®, which is reported in the feasibility review of rooftop farming by the New York State Energy Research and Development Authority (2013). It is a blend of heat-treated shale, spent mushroom media, and composts (Kong et al. 2015), and is used in the Brooklyn Grange, a rooftop farm in New York City, that is the subject of the "Case Study" later in this chapter. Given the variety of soils by rooftop farms, it is important to define the components in each study in order to obtain generalizable interpretations of the results.

In a broad sense, interest in rooftop farming is an outgrowth of ecological awareness, including adaptive reuse of waste products. Of 24 rooftop farming studies identified in this review, Grard et al. (2015) studied a rooftop farm in Paris, France that used locally sourced yard waste compost, crushed wood, and coffee grounds in its soil, growing lettuce (*Lactuca sativa*) and tomatoes

**TABLE 13.1**
**Soil Type, Depth, and Plant Growth in Rooftop Farming Research**

| Soil Type | Soil Detail | Crops | Yield[a] | Irrigation[b] | Soil Depth (mm) | Location | References |
|---|---|---|---|---|---|---|---|
| Commercial potting mix | Sunshine Mix #4, Sun-Gro Horticulture (55%–65% peat, 35%–45% perlite) | Lettuce<br>chicory[c] | S | Y | 50, 100, 200 | Korea (rooftop) | Cho (2008) |
| Commercial potting mix | Sunshine Mix #4, Sun-Gro Horticulture (55%–65% peat, 35%–45% perlite) | Lettuce<br>chicory[d] | S | Y | 150 | Korea (rooftop) | Cho et al. (2010) |
| Commercial potting mix | Sunshine Mix Fisons (composition unspecified) | Kale[e] | S | Y | 102 | VA, USA (rooftop) | Elstein et al. (2006) |
| Commercial potting mix | 1. Terre à planter, Brun brand (topsoil, blond sphagnum peat moss, composted bark, brown peat, horse manure and composted seaweed, ratio unspecified) | Lettuce<br>tomatoes | S | Y | 300 | Paris, France (rooftop) | Grard et al. (2015) |
| Experimental mix | 2. 100% yard waste compost, underlain by 100% crushed wood | | | | | | |
| Experimental mix | 3. 100% yard waste compost, underlain by 100% coffee ground layer, 100% crushed wood layer | | | | | | |
| Experimental mix | 4. 50% yard waste compost, 50% crushed wood | | | | | | |
| Commercial green roof mix | Renewed Earth (50% expanded shale, 35% sand, 15% leaf compost) | Tomatoes[f]<br>beans[g]<br>cucumbers[h]<br>peppers<br>chives[i]<br>basil[j] | S (except pepper) | Y | 105 | MI, USA (rooftop) | Whittinghill et al. (2013) |
| Experimental mix | Expanded shale, sand + 0, 20, 40, 60, 80, 100% yard waste compost | Cucumbers[h]<br>peppers | S | Y | 125 | MI, USA (rooftop) | Eksi et al. (2015) |

(*Continued*)

**TABLE 13.1 (*Continued*)**
**Soil Type, Depth, and Plant Growth in Rooftop Farming Research**

| Soil Type | Soil Detail | Crops | Yield[a] | Irrigation[b] | Soil Depth (mm) | Location | References |
|---|---|---|---|---|---|---|---|
| Commercial rooftop farming mix | Rooflite, Skyland (lightweight mineral aggregates, mushroom compost, unspecified organic composted component, ratio unspecified) + (1) yard waste compost, (2) composted poultry manure, (3) vermicompost, (4) controlled-release fertilizer | Swiss chard | S | Y | 110 | NY, USA (greenhouse) | Kong et al. (2015) |

[a] S, satisfactory yield.
[b] Y, irrigated.
[c] *Cichorium intybus* var. *folisum.*
[d] *Cichorium endivia* var. *endivia.*
[e] *Brassica oleracea* var. *acephala.*
[f] *Solanum lycopersicum.*
[g] *Phaseolus vulgaris.*
[h] *Cucumis sativus.*
[i] *Allium schoenoprasum.*
[j] *Ocimum basilicum.*

(*Lycopersicum esculentum* var. *cherry*) with irrigation. This study reports satisfactory yields of both crops and heavy metal levels lower than the European standard. However, the original soil depth of 300 mm soil decreased to 100–150 mm after the first growing season due to settling and decomposition of organic matter (OM). The volume reduction and consumption of urban wastes is an important ecosystem service, yet the changes in soil depth complicate management and point to the need to replenish OM frequently.

In green roof research, Ampim et al. (2010) reviewed the physical and chemical characteristics of recycled soil ingredients and emphasize the need of combining soil material research with observations of plant response, and runoff quantity and quality. More recently, an increasing number of studies have reported satisfactory growth of grass, sedum, and wildflowers in soils made from recycled construction materials (e.g., bricks, tiles) (Bates et al. 2015; Molineux et al. 2015), paper ash, and bark (Young et al. 2014; Molineux et al. 2015).

Biochar (Cao et al. 2014) and hydrogel products (Olszewski et al. 2010; Savi et al. 2014) have also been tested for their ability to increase the plant available water. Biochar could also improve the water and nutrient retention of soil (Beck et al. 2011), while the effects of hydrogel were species-dependent (Farrell et al. 2013). Unlike typical green roofs, which do not produce food, recycled materials used for rooftop farms would need to be tested for toxic residues to ensure public health.

### 13.3.3 PLANT GROWTH EFFECTS

Across a variety of soils, all seven studies of rooftop farms (Table 13.1) report satisfactory yield in all species except pepper (*Capsicum annuum)* (Whittinghill et al. 2013). All studies used irrigation yet none reported the effect of soil composition on irrigation requirements, although Kong et al. (2015) reported that the addition of composted yard waste to Rooflite® resulted in higher yields of Swiss chard (*Beta vulgaris*) and reduced leaching loss of nitrogen.

### 13.3.4 SOIL DEPTH

Among the studies on rooftop farming summarized in Table 13.1, soil depth varied between 50–300 mm. Only Cho (2008) specifically tested different soil depths and reported positive but nonsignificant growth response to deeper soil. It is noteworthy that the manufacturer of Rooflite® specifies a minimum depth of 8 inches (≈200 mm) (Skyland USA LLC 2016), yet six of seven studies report satisfactory yields with soil less than 200 mm deep.

In addition to the studies of rooftop farms, green roof research includes an additional 60+ studies addressing the effect of soil depth both with and without irrigation. Standard extensive and intensive green roofs typically use drought-tolerant plants, which require much less water and nutrients in comparison to vegetable crops; hence, soils designed for green roofs may not be optimal for vegetable production. However, these studies still report important information on soil properties which could reduce the evaporative loss while maintaining plant available water (see "Soil Moisture and Evapotranspiration"). Ten studies using soil depths ranging between 20 and 400 mm reported that increasing depth increased available water and biomass across a wide range of species including *succulents* (VanWoert et al. 2005; Getter and Rowe 2009), *dry grassland species* (Dunnett et al. 2008), *turf grass species* (Nektarios et al. 2010; Ntoulas et al. 2012; Ntoulas et al. 2013), *drought-adapted shrubs* (Nektarios et al. 2011; Kotsiris et al. 2012; Savi et al. 2015), and *olive trees* (Kotsiris et al. 2013).

### 13.3.5 SOIL MOISTURE AND EVAPOTRANSPIRATION

In terms of the water budget of a rooftop farm, the ideal soil reduces runoff volume and minimizes the irrigation demand while achieving commercially viable yield and quality of crops. To this goal, it is important to balance evapotranspiration (ET) demand and soil water holding capacity. In a Mediterranean climate, Nektarios et al. (2011) grew *Dianthus fruticosus* in either 750 mm or 150 mm of pumice-based soil with irrigation. In this field experiment, shallow soil had higher evaporative losses presumably because the zone of capillary rise was closer to the soil surface, therefore both the diffusive resistance of the soil was less and the temperature gradient between the soil surface and capillary water was steeper. Pore-size distribution and soil depth are the key to controlling evaporative losses.

In a controlled greenhouse simulation of spring and summer conditions (Sheffield UK, average temperature 7.1 and 16.7°C, respectively; Poë et al. 2015), ET was positively correlated with the water holding capacity of the soil and was greatest in the soil with the highest OM and fine mineral fractions whose volumetric water content (VWC) was 25% at 33 kPa.

In a greenhouse simulation of summer conditions (Subtropical, New Zealand, average air temperature 22°C), Voyde et al. (2010) monitored ET of *Sedum mexicanum* and *Disphyma australe*, two drought hardy succulents, grown in 70 mm of pumice, zeolite, and compost. Over the first 9 days of the experiment, ET from planted treatments was consistently higher than the evaporative loss from bare soil. After day 17 when ET essentially ceased due to the drought stress, both treatments lost equal amounts of water. In a rooftop farm, transpiration in the absence of water stress could be much higher because of the large leaf area and could decline more rapidly as vegetables close their stomates in response to drought.

### 13.3.6 WATER RETENTION

Soil water tension (SWT) plays important roles in the water retention characteristics of a soil, including the field capacity, plant available water, and the effects of porosity and self-mulching. Compared to greenhouse cropping systems, management of water is more important outdoors because of diurnal and seasonal variation in water supply and demand experienced in the field. Therefore, SWT of green roof and rooftop faming mixes are much less articulated or understood, containing large amount of soilless mixes typical to greenhouse cropping system. In addition, the low range of tension (<10 kPa) is particularly important for rooftop systems, because the soil depth is much shallower (<500 mm) than the in-ground systems (>1000 mm). Also, meta-analysis on SWT-based irrigation criteria reports 6–10 kPa for mustard greens, collard, and leaf lettuce in sandy loam (Shock and Wang 2011), and such leaf greens are important crops for rooftop farming. Therefore, for the effective management of water in rooftop farming, it is important to understand the water of soilless mixes in low range of tension (<10 kPa).

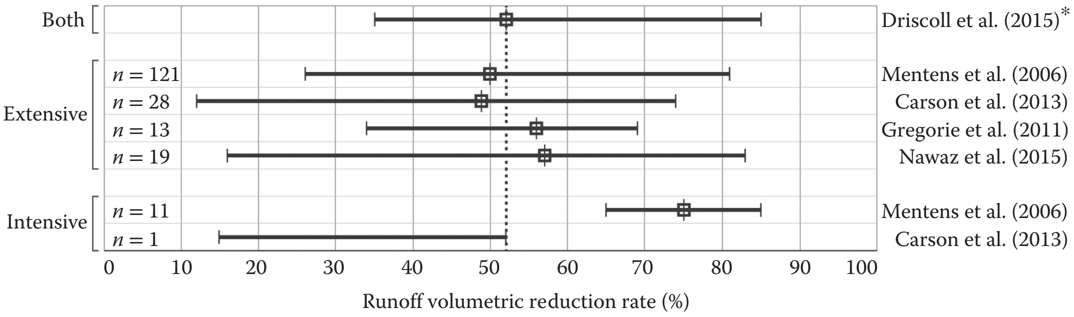
SWT is sensitive to the composition of soil mixes, and it is difficult to characterize the SWT of soil mixes solely based on SWT of each ingredient, yet the key effect of each material could be generalized to some extent. Within the tension range between 2 and 10 kPa, mixes of pumice and thermally treated clay showed 2%–7% VWC, in comparison to the mixes of crushed tile and pumice, which showed VWC between 15% and 20% (Ntoulas et al. 2015). Organic soilless materials and naturally sourced soil could also change VWC. Below 10 kPa, peat often holds more water than compost at the volumetric addition of 15% and 20% (Ntoulas et al. 2012, 2013, 2015), yet compost was more effective at the increased addition rates of 30% (Kotsiris et al. 2012, 2013). The type of compost also has an influence on the moisture contents (Ntoulas et al. 2015). In the mixture of pumice, compost, and zeolite, the 15% volumetric addition of sandy loam increased the VWC above 6.5 kPa tension, while mixes without sandy loam had higher VWC below 2 kPa (Nektarios et al. 2011). Adding 30% sandy loam to peat or compost treatments reduced the VWC above 3 kPa tension (Ntoulas et al. 2013). In order to design the SWT, it is important to establish the critical composition of each material.

## 13.4 RUNOFF VOLUME

The effect of particle size distribution on water retention and drainage is well understood and relatively easy to take for granted in native mineral soils, as are their effects on plant growth. Soils retain the maximum amount of available water in the texture class known as silt loam, where particle size classes, and hence pore sizes, are more or less evenly distributed. However, soils intended for rooftop farms often lack the familiar sand, silt, and clay size fractions and when organic materials (e.g., compost, biochar, highly modified skeletal components like expanded shale) are substituted for these mineral components, designing an optimal soil for rooftop farming becomes quite challenging.

In rooftop farms, surface runoff would not occur under normal conditions, and "runoff" as used in this context indicates the export of drainage water following the lateral flow through the soil and underlying drainage layer and along the impervious roof membrane. Rooftop farms are irrigated and it is important to differentiate "volumetric runoff reduction" from "water budget," which includes all fluxes of water including irrigation, while runoff reduction only compares precipitation to runoff. Irrigation can produce discharge. In green roofs and rooftop farms, irrigation could produce base flow if it is frequent and maintains water content near field capacity. Elstein et al. (2006) report the volumetric runoff reduction of a rooftop farm of 69.2%, while Whittinghill et al. (2015) report a reduction over 85% for 0–10 mm of precipitation, and below 60% for precipitation events over 10 mm. The study does not report the overall volumetric reduction based on the cumulative precipitation and drainage during the entire study period.

In studies of nonproduction green roofs, over 100 studies report volumetric runoff reduction, and five reviews show large variation across individual studies between 12%–85% (Figure 13.4).



*Interquartile range and mean of site means from international stormwater best management practice database.
*Number and media depths of studies not reported.
*Dashed line indicates the mean of site means.

**FIGURE 13.4** Runoff volumetric reduction of extensive and intensive green roofs.

(Carson et al. 2013; Gregoir and Clausen 2011; Mentens et al. 2006; Nawaz et al. 2015; Driscoll et al. 2015) This wide variation defies simple generalizations applicable across climate zones, soils, and plant cover types, but the average reduction is around 50%.

## 13.5 RUNOFF QUALITY

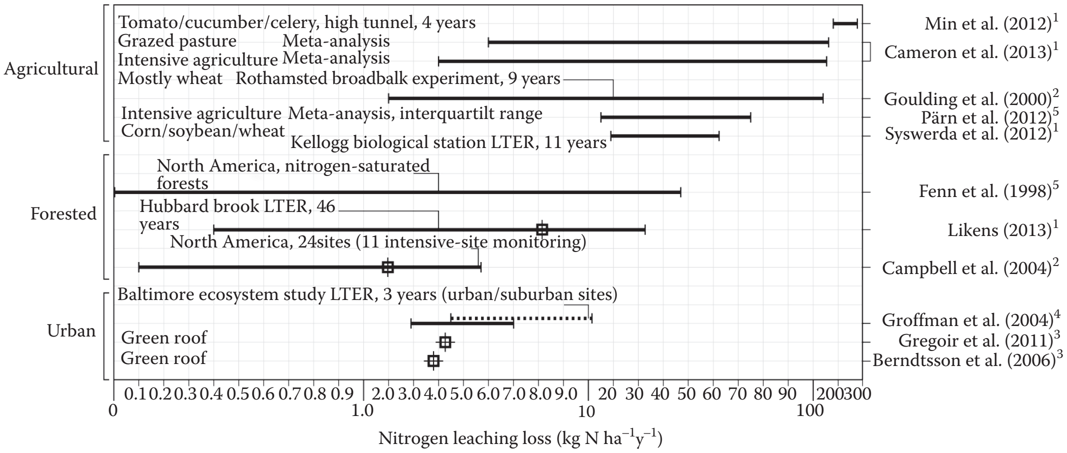
### 13.5.1 Overview

Through industry, agriculture, and urbanization, human activity is a major driver of the global N cycle, affecting the form and function of ecosystems across diverse scales (Howarth et al. 1996; Vitousek et al. 1997). It is useful to put N leaching from urban rooftop farming in the context of other land uses (Figure 13.5). Among 11 studies reporting N loss, including the NSF LTER projects in agricultural, forested, and urban watersheds (Berndtsson et al. 2006; Cameron et al. 2013; Campbell et al. 2004; Fenn et al. 1998; Gregoir and Clausen 2011; Groffman et al. 2004; Goulding et al. 2013; Likens 2013; Min et al. 2012; Pärn et al. 2012; Syswerda et al. 2012), N losses vary from <0.1 kg N $\text{ha}^{-1}$ $\text{y}^{-1}$ from a forested watershed (Fenn et al. 1998), to 277 kg N $\text{ha}^{-1}$ $\text{y}^{-1}$ from a vegetable farm (Min et al. 2012). Green roof losses average between 4 and 5 kg N $\text{ha}^{-1}$ $\text{y}^{-1}$ (Berndtsson et al. 2006; Gregoire and Clausen 2011). Although two studies report the N concentration in leachate from rooftop farms, as of January 2016, there have been no field observations on mass N leaching. Rooftop vegetable production could result in substantial N loss due to rapid soil drainage rates and fertility. Both urban design and policy need to consider N losses in order to quantify the environmental costs and benefits from urban rooftop farms.

### 13.5.2 N Concentration

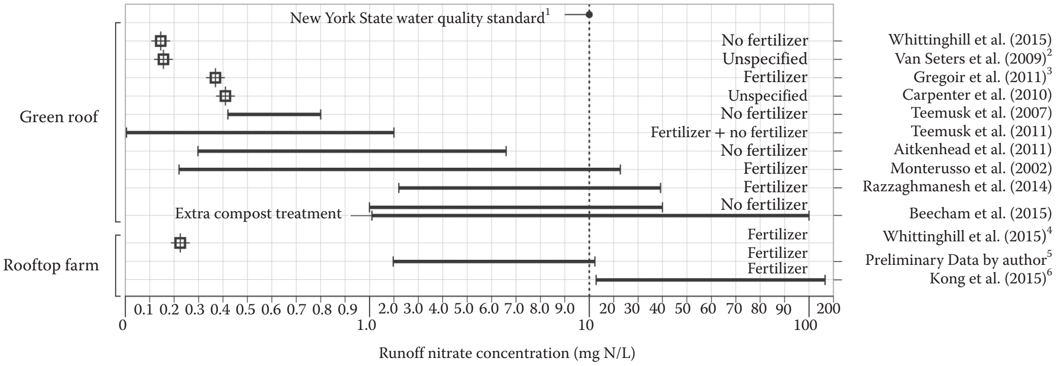
N concentration is a key metric used by environmental regulators to gauge surface water quality (Groffman et al. 2004); hence, N concentration in runoff is a useful indicator of N loading from rooftop farms and green roofs. Two studies report the N concentration relevant to the runoff from rooftop farming. Whittinghill et al. (2015) reported average runoff nitrate concentration of 0.22 mg $\text{L}^{-1}$ from a field experiment while in a greenhouse experiment, Kong et al. (2015) reported maximum nitrate N concentrations of 12.8 mg $\text{L}^{-1}$ from vermicompost and 165.8 mg $\text{L}^{-1}$ using a controlled-release fertilizer. Different nitrate N concentrations between Whittinghill et al. (2015) and Kong et al. (2015) reflect nitrate levels present in the soil products (65 vs. 118 mg $\text{L}^{-1}$), and N addition rates (35 vs. 126–189 kg N $\text{ha}^{-1}$).

Figure 13.6 includes the runoff nitrate N concentrations from these studies as well as the preliminary results from the Brooklyn Grange farm at the Brooklyn Navy Yard in New York City that uses the same soil used by Kong et al. (2015). The results from the Brooklyn Grange farm (2–12 mg $\text{L}^{-1}$) fall between the values from other two studies. With the oversight of the United States Environmental Protection Agency (2016), New York State sets the standard for nitrate N in rivers



[1] Nitrate nitrogen
[2] Dissolved inorganic nitrogen
[3] Total nitrogen
[4] Dotted line for total nitrogen, soillinefro nitrate nitrogen
[5] Nitrogen form varies/unspecified

**FIGURE 13.5** Nitrogen leaching loss from forested, agricultural, and urban watershed.



[1] NYS regulation 6 NYCRR part 703, surface water and groundwater quality standards and groundwater effluent limitations.
[2] Geometric mean.
[3] Nitrate + nitrate concentration, geometric mean.
[4] Vegetable cropping with commercial green roof mix.
[5] Preliminary data on the field sampling of drainage water at the Brooklyn Grange, using commercial rooftop farming mix.
[6] Pour-through sampling in greenhouse experiment, using commercial rooftop farming mix.

**FIGURE 13.6** Runoff nitrate nitrogen concentration of green roofs and rooftop farms.

and streams at 10 mg L$^{-1}$ (6 NYCRR Part 703) (New York State Department of Environmental Conservation 2016). Note that roof drains are not directly subject to regulation.

Among 10 studies of nonproduction green roofs summarized in Figure 13.6 (Aitkenhead et al. 2011; Beecham and Razzaghmanesh 2015; Carpenter and Kaluvakolanu 2010; Gregoir and Clausen 2011; Monterusso et al. 2002; Razzaghmanesh et al. 2014; Teemusk and Mander 2007, 2011; Van Seters et al. 2009; Whittinghill et al. 2015), nitrate N concentration in runoff ranges from below 0.2 (Van Seters et al. 2009; Whittinghill et al. 2015) to 100 mg L$^{-1}$ (Beecham et al. 2015). Teemusk et al. (2011) report higher N concentration in runoff from their fertilized green roof yet this is not reflected in the ranking of maximum nitrate concentrations across all of the studies. The study conducted by Gregoire and Clausen (2011) reported low N concentration in runoff despite using twice the rate of N application used in studies that yielded higher concentrations (Monterusso et al. 2002; Razzaghmanesh et al. 2014).

Composts are another potential source of N leached from green roofs (Hathaway et al. 2008; Toland et al. 2012). In Figure 13.6, the two highest nitrate concentrations were observed in unfertilized treatments that used compost (Beecham and Razzaghmanesh 2015). Most commercial green roof mixes contain sources of organic N, including manure, blood meal, biosolids, and kelp even if it is not reported. In order to make meaningful comparisons among studies it is important for each study to define the levels and sources of soil nutrient, in order to understand how fertilizer and compost contribute to the high N concentration in runoff.

### 13.5.3 N SINK

Urban green infrastructure is intended to be the N sink, reducing the N load to surface waters. Driscoll et al. (2015) reviewed the seven types of green infrastructure projects (Bioretention, Media Filter, Detention Pond, Swale, Wetland, Green Roof), and report only green roofs behave as an N source due to fertilizer application, while rooftop farming was not within the scope of the review. As of January 2016, among 24 studies of rooftop farming, none report the N source/sink relationship. In green roof literature, most studies on N source/sink are based on observations of runoff N concentrations alone.

Table 13.2 compares N concentration of green roof runoff to that of precipitation or runoff from a control roof without vegetation (Aitkenhead-Peterson et al. 2011; Beecham and Razzaghmanesh 2015; Berndtsson et al.2006, 2009; Gregoire and Clausen 2011; Teemusk and Mander 2007; Toland et al. 2012; Van Seters et al. 2009). Results varied across the ranges of soil depths, vegetation, and geographic locations. The first four studies reported lower nitrate and ammonia N concentrations in green roof

**TABLE 13.2**
**Comparison of N Concentration of Green Roof Runoff and Reference Stormwater**

| Green Roof Runoff[a] | | | | | | | |
|---|---|---|---|---|---|---|---|
| **NO3** | **NH4** | **Reference Stormwater[b]** | **Runoff Volume Reported** | **Soil Depth (mm)** | **Plants** | **Location** | **References** |
| Low | Low | Rain | N | 30 | Sedum | Sweden | Berndtsson et al. (2009) |
| Low | Low | Rain | N | 400 | Shrub, tree | Japan | |
| Low | Low | Rain | Y | 30–40 | Sedum | Sweden | Berndtsson et al. (2006) |
| Low | Low | Roof runoff | Y | 140 | Wildflower | Toronto | Van Seters et al. (2009) |
| Similar | Low | Rain | Y | 102 | Sedum | CT, USA | Gregoire and Clausen (2011) |
| Similar | Similar | Roof runoff | N | Unspecified | Sedum, moss | AR, USA | Toland et al. (2012) |
| Similar | High | Rain | Y[c] | 100–300 | Brachyscome, Chrysocephalum, Disphyma spp | South Australia | Beecham and Razzaghmanesh (2015) |
| Varies | Similar | Rain | N | 71 | Sedum, Delosperma, Talinum spp | TX, USA | Aitkenhead-Peterson et al. (2011) |
| High | High | Rain | Y[d] | 100 | Sedum, Thymus, Dianthus, Cerastium spp | Estonia | Teemusk and Mander (2007) |

[a] Comparison of green roof runoff N concentration to reference stormwater (precipitation or runoff from unvegetated roof).
[b] Precipitation is used as a reference stormwater if runoff from unvegetated roof is also reported.
[c] Only retention rates reported.
[d] Rainfall events not specified in concentration.

runoff compared to precipitation or unvegetated roofs, hence green roofs are most likely an N sink. Among the remaining five studies, only Gregoire and Clausen (2011) compared mass N loading, reporting that the green roof was a net sink for N. The other four studies do not report runoff volume in terms that can be used to calculate loading rates. Because rooftop farms are likely sources of N due to the high soil infiltration and the application of irrigation and N fertilizer, it is necessary to measure both runoff volume and N concentration in order to calculate total load to downstream water bodies.

## 13.6 CASE STUDY

The literature review presented herein reveals that the water and N budgets of green roofs and rooftop farms varies widely in relation to soil composition, depth, vegetation, management regime, and regional climate. In an effort to disentangle these variables, a multiyear study was initiated at the Brooklyn Grange, a 70,000-square-foot (0.65 ha) commercial rooftop farm in New York City. The Grange uses Rooflite®, presently the only commercial soil available for rooftop farming in the United States. Observation included monitoring irrigation, ET, VWC, and runoff volume and quality and experimentation with a variety of soil mixes in an effort to optimize the use of water and nutrient subsidies. Even though the farm is irrigated multiple times each day using a combination of drip tape and overhead sprinklers in order to maintain VWC between 25%–35%, during the dry periods, VWC drops to 15%–25%. Irrigation consistently produces base flow even below 25% VWC, suggesting that opportunities exist for optimizing the water and nutrient budgets of the farm by modifying the soil mix currently in use.

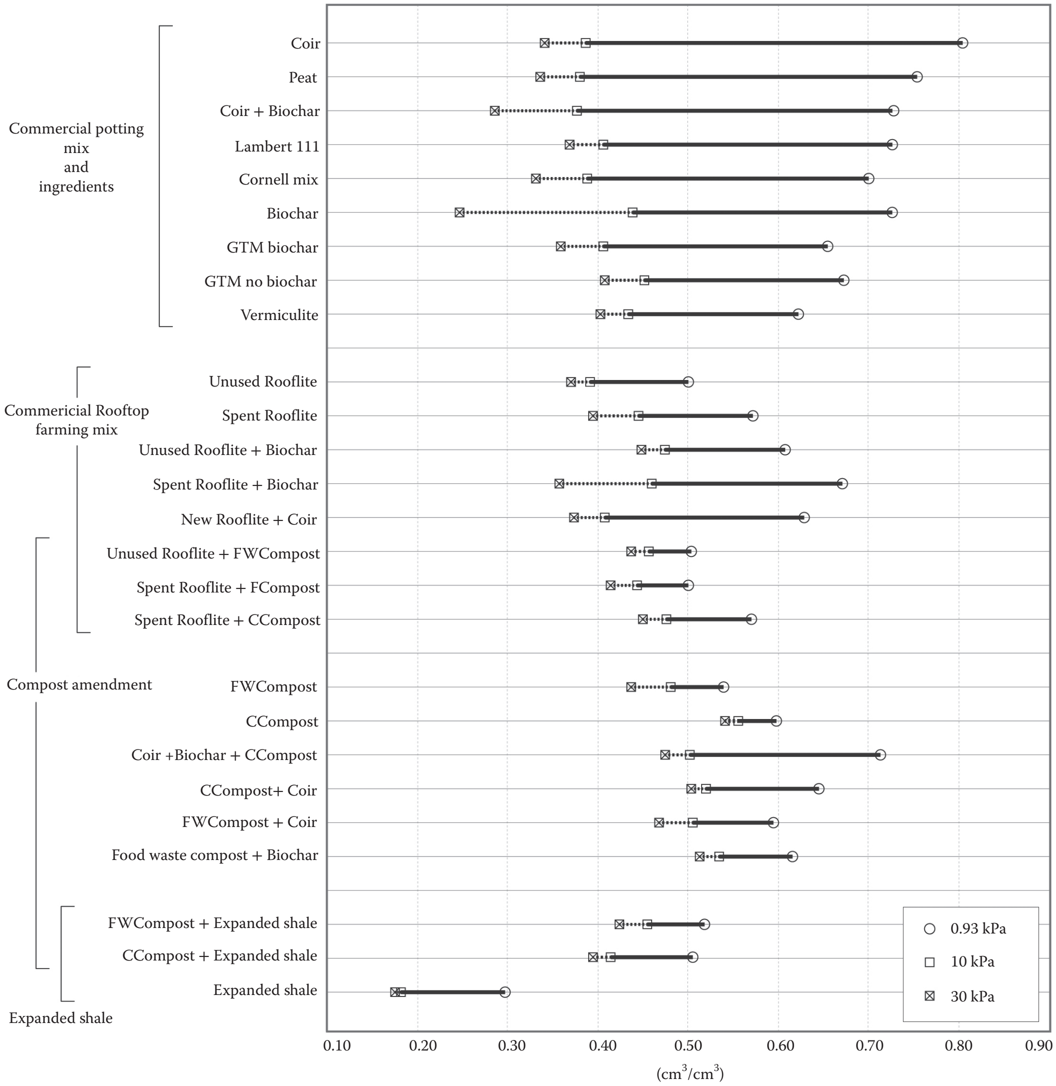
### 13.6.1 SOIL WATER RETENTION

Biogeochemical performance is not the only criterion for rooftop soils. They must also meet construction material guidelines for weight, wind, and fire set by the American National Standards Institute (ANSI). Also, decisions about including reused waste products in soil mixes would ideally be informed by comprehensive life-cycle assessments, including the energy and carbon (C) emission by the transportation and manufacturing processes. The approach adopted in this study is to first narrow down the biogeochemically superior soil design through a controlled laboratory experiment, followed by field experiments, then consider regulatory and life-cycle perspectives.

Figure 13.7 compares the VWC of 26 potential rooftop soils and amendments obtained from replicated tension table experiments. Among 26 mixes, including eight Rooflite® and nine potting mixes, VWC at 0.93 kPa varied from <30% for expanded shale to 80% for coconut coir. The lowest VWC of both unused and spent Rooflite® is ca 35%, exceeding field observations during rainless summer periods. This could be due to nonuniform field conditions caused by preferential flows and hysteresis or by variation in irrigation. Amending Rooflite® with biochar, coir and compost increased maximum VWC up to 60%–70%, while six of nine potting mix treatments had maximum VWM > 70%, which indicates the potential for designing lightweight rooftop soil by substituting organic amendments for expanded shale. Based on these lab results, we are field testing new soils that include coir and biochar.

### 13.6.2 YIELD

Despite the anticipated advantages afforded by local food production systems, if crop yield does equal or exceed conventional agriculture, rooftop farming may do little to advance urban sustainability. A comparison of yields for four of the many vegetable crops grown at the Grange with California, New York, and New Jersey shows that the Grange outperforms statewide averages for conventional farms. On a per hectare basis, the Grange yielded 1.2 times more lettuce than California in 2015 and five times more tomatoes than NY in 2014. Note that California was experiencing a multiyear drought during this period, which could have depressed yields and skewed the data in favor of the Grange. In any case, it appears that rooftop vegetable production can produce high yields with appropriate inputs of water and nutrients.



Coir : Coconut coir
Lambert 111 : Commercial potting mix
GTM : Commercial potting mix (uses coir and biochar tested in the study)
FWCompost : Food waste compost
CCompost : Cornell compost
Rooflite : Commercial Rooftop farming mix (uses expanded shale in the study)

*Each material is mixed in the same volume in the treatment with multiple materials.

**FIGURE 13.7** Volumetric water content of soilless mixes and ingredients at 0.93, 10, and 30 kPa.

### 13.6.3 WATER AND N BUDGET

Field monitoring of the farm's water budget indicates that 38% of the water supplied is lost to drainage (Table 13.4). Because irrigation relies on potable water from Upstate New York reservoirs, it would be desirable to reduce drainage losses. This could be accomplished by varying the soil mix and depth to maximize water retention in the range of plant available soil moisture.

Mass N input to the Grange through the fertilizer application and atmospheric N deposition (Table 13.5) is about 120 kg N $ha^{-1}$ $y^{-1}$, while mass N contained in vegetables leaving the farm as food crops is over 60% of N input. However, the sampled N loss by soil leachate (Table 13.5) is 10 times the initial estimation by this N balance model (Fertilizer application + Atmospheric deposition – Vegetable harvest ≈ 40 kg N $ha^{-1}$ $y^{-1}$). Organic N in soil imported in the original soil mix could

### TABLE 13.3
### Vegetable Yield of the Brooklyn Grange and In-Ground Agriculture

| | | Yield(metric ton/ha) | | | |
|---|---|---|---|---|---|
| **Crop** | **Year** | **Brooklyn Grange** | **New York**[b] | **New Jersey**[b] | **California**[b] |
| Snap beans | 2014 | 20.40 | 7.07 | 3.70 | 12.35 |
| | 2015 | 19.79 | 7.30 | 3.59 | 13.47 |
| Tomatoes | 2014 | 68.58 | 13.47 | 24.14 | 35.36 |
| | 2015 | 47.62 | 14.59 | 25.26 | 34.80 |
| Leaf lettuce | 2014 | 34.22[a] | NA | NA | 26.94 |
| | 2015 | 35.52[a] | NA | NA | 29.19 |
| Bell peppers | 2014 | 128.26 | NA | 38.17 | 54.45 |
| | 2015 | 70.78 | NA | 34.24 | 51.08 |

[a] Based on the yield of leafy greens mix.

[b] Based on the National Agricultural Statistics Service, USDA.

### TABLE 13.4
### Water Budget of the Brooklyn Grange

| **Water Flux Type** | **Water Flux ($10^6$ L $y^{-1}$)** | **Method** |
|---|---|---|
| Irrigation input | ≈1.5 | Flow meter |
| Precipitation input | >5 | Rain gauge |
| ET loss | >4 | Penman–Monteith equation |
| Drainage loss | ≈2.5 | Water Balance Model (Irrigation + Precipitation – ET) |

*Note:* Preliminary data on the water budget of the Brooklyn Grange, a rooftop farm at Brooklyn Navy Yard, NYC 2014–2015.

### TABLE 13.5
### Nitrogen Budget of the Brooklyn Grange

| **N Flux Type** | **N Flux (kg N $ha^{-1}$ $y^{-1}$)** | **N Form** | **Method** |
|---|---|---|---|
| Fertilizer application | >110 | Total N | Inventory analysis (farming record) |
| Atmospheric deposition | <10 | Dissolved inorganic N | Bulk collector (with ion-exchange resin) |
| Soil leachate | >400 | Dissolved inorganic N | Soil mesh bag (with ion-exchange resin) |
| Vegetable harvest | >80 | Total N | Inventory analysis (farming record) |

*Note:* Preliminary data on the N budget of the Brooklyn Grange, a rooftop farm at Brooklyn Navy Yard, NYC 2014–2015.

account for these high leaching losses. Further research will examine the accuracy of the sampling method, and denitrification potential of soil leachate in the drainage layer of the Grange.

## 13.7 CONCLUSION

Rooftop farming requires the synthesis of knowledge from many fields, including soil science, biogeochemistry, horticulture, and urban planning and design, among which soil science is central to both understanding and improving practices. This chapter reviewed the intersection of those fields with an emphasis on their relevance to rooftop farming. The perspective of soil science is central to both understanding and improving rooftop farming.

## 13.8 LIMITATIONS OF CURRENT RESEARCH

As of January 2016, more than 1,000 papers relevant to green roof design and rooftop ecosystems have been published. Of these studies, the bulk are focused on hydrologic responses, media and plant performance as well as climate effects. Green roof practices have been driven by the perceived need to reduce weight, drain rapidly, and contribute to building insulation. Few even attempt comprehensive integration of the many topics shown in Figure 13.2. As of yet, only 24 studies address rooftop agriculture. This review has identified these key gaps in knowledge:

- Commercial/custom potting mixes, conventional roofing ballast, and mineral soil could be important functional components roof infrastructure, but are not systematically studied in green roof or rooftop vegetable cropping systems.
- While there is increasing interest in soil composition, depth, and moisture, key factors are often unreported, preventing understanding of what is actually driving soil water and nutrient dynamics.
- Even when studies include both soil performance and plant growth, they do not include inputs and losses, or runoff volume, quality, and variation necessary to calculate loading rates and other ecosystem-level responses.

## 13.9 FUTURE WORK

Rooftop farms are ideal for investigating urban biogeochemical processes because they are simple enough to be studied in detail but complex enough to yield insights into the way cities function in the global context for food security, environmental quality, and waste management. Studies like the one at the Brooklyn Grange reveal how variables like soil composition, physical characteristics, depth, and application of fertilizer and irrigation subsidies affect the ability of a roof to deliver ecosystem services while at the same time actively informing daily management practices to improve the rapid development of BMPs. Future research should include:

- Detailed studies of engineered soils to conserve water, reduce leachate, and optimize partitioning of water into transpiration
- Systematic analysis of novel/different soil components, including repurposed waste and native soil
- Optimizing plant growth and quality along with ecosystem-level responses
- Applying the small science approach to studying individual farms and expanding to a research network including cities in different climate zones in order to develop a comprehensive framework of BMPs

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