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Agroecological and social characteristics of New York city community gardens: contributions to urban food security, ecosystem services, and environmental education

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Abstract There is growing public interest and participation in food-producing urban community gardens in North America, yet little research has examined agricultural production and ecological processes in these spaces. We describe the agroecological and social characteristics of 61 food-producing gardens in New York City, drawing on gardener interviews, land-use maps, plant species inventories, arthropod scouting, and soil sampling and analysis. Gardens contained agricultural crops, food production infrastructure, ornamental plants, and recreational areas in varying proportions, indicating that gardens serve multiple and distinct purposes depending on community needs and interests. On average, gardeners devoted the greatest proportion of garden area (44 %) to food production, and supplied a large share of their households' produce needs from their community gardens. Solanaceae, Brassicaceae, and Cucurbitaceae crops dominated food crop areas, hindering effective crop rotation to prevent disease and pest problems. Most gardeners grew crops in raised beds constructed with clean fill and compost. These soils generally had sandy textures, low water-holding capacity, high organic matter levels (with a large proportion from recent inputs) and excessive nutrient levels. Soil water content at field capacity increased exponentially with total soil carbon, suggesting that organic matter enhances water-holding capacity. Insect pest densities greatly exceeded action thresholds in nearly all gardens for aphids and whiteflies on Brassica crops, aphids on

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Cucurbit crops, and two-spotted spider mites on tomatoes. Predator and parasitoid densities were generally low (less than one per plant on average), perhaps partially due to low floral and woody perennial cover in most gardens (12 % and 9 % on average, respectively). Dominant groups of natural enemies were minute pirate bugs, spiders, and parasitoid wasps. A wide variety of people of differing experience levels, incomes, and ethnicities participate in community gardening in NYC, and most gardens host multiple languages. Promising directions for urban gardening research, education, and practice include: 1) Cover cropping to improve soil quality and nutrient management, and diversify crop rotations; 2) Improving access to soil testing and guidance on appropriate use of soil amendments, 3) Enhancing habitat for arthropod natural enemies that provide biological control of insect pests with floral and woody perennial plantings; and 4) Incorporating ecological knowledge and inquiry-based approaches into gardening workshops, educational materials, and technical support, and offering these resources in multiple languages.

Keywords Community gardens · Ecological knowledge · Ecosystem services · Food security · Gardening education · Insect pest management · Land-use · New York City · Soil fertility · Soil quality · Urban agriculture · Urban arthropods

Introduction

City dwellers, civil-society organizations, and policymakers show growing interest in food-producing community gardens for their potential to improve nutrition and public health, enhance urban environmental quality, and provide opportunities for urban residents to experience the natural world (Alaimo et al. 2008; Drake and Lawson 2015; Krasny and Tidball 2009; U.S. House of Representatives 2010). Community gardens are public spaces managed by member-volunteers who grow food crops and/or flowers, shrubs, and trees in individual plots and communal growing spaces (Cohen et al. 2012). Where they host vegetable and fruit production, community gardens may foster food access and healthy eating, in addition to physical and mental health, environmental stewardship, and community organizing (Armstrong 2000; Blair et al. 1991; Draper and Freedman 2010; Litt et al. 2011). Supporting and expanding community gardens could benefit many urban dwellers in neighborhoods where people lack access to affordable healthy foods and opportunities for interactions with nature (Larson et al. 2009; Miller 2005).

Since the late 1800's, food production in community gardens has been a prominent part of urban life in the United States, particularly during times of social and economic change (Lawson 2005). In New York City (NYC), the contemporary community gardening movement began in the 1970's. In the wake of urban decline and housing abandonment, residents transformed vacant lots into gardens that integrated community development, green space, and local food production (Saldivar-Tanaka and Krasny 2004; Schmelzkopf 2002). During this time, a robust network of city-sponsored programs and nonprofit gardening support and advocacy organizations took shape in response to the groundswell of grassroots community gardening efforts (Cohen et al. 2012).

In recent years, these networks have grown as participation in food-producing community gardens increased once again throughout the United States and Canada. Almost 90 % of 445 surveyed community gardening support organizations in North America established new gardens from 2007 to 2011, and existing gardens increased their size and membership

(Lawson and Drake 2012). Seed companies reported increased vegetable seed sales in 2009 (Horowitz 2009), reflecting renewed interest in food gardening in general. The economic recession of 2008–2009 and increased food prices likely stimulated interest in gardening as people sought to save money on produce (Draper and Freedman 2010; Horowitz 2009). However, public interest in gardening may also reflect enduring social movements for sustainable food systems, food justice, and civic environmentalism (Levkoe 2006; Svendsen and Campbell 2008; Teig et al. 2009; Wekerle 2004).

Urban gardens: Social benefits and challenges

Urban dwellers engage in community gardening for multiple reasons. Many gardeners participate partly to grow healthy, fresh, affordable produce (Armstrong 2000; Draper and Freedman 2010). Gardeners also value the opportunity to cultivate organically grown and culturally significant vegetables, which may be too expensive or unavailable in low-income neighborhoods (Armstrong 2000; Baker 2004; Carney et al. 2012; Wakefield et al. 2007). Access to garden produce may facilitate improved nutrition through increased vegetable consumption (Alaimo et al. 2008; Blair et al. 1991; Carney et al. 2012; Litt et al. 2011). However, food access is rarely the sole motivation for community garden participation. Gardeners also seek to improve health and wellness, practice environmental stewardship, build relationships with neighbors, and organize around other neighborhood issues and needs (Armstrong 2000; Blair et al. 1991; Drake and Lawson 2015; Draper and Freedman 2010; Gittleman et al. 2011; Ohmer et al. 2009; Saldivar-Tanaka and Krasny 2004).

Challenges associated with urban community gardening stem from access to various types of resources, including material resources (e.g., land, soil) and non-material resources (e.g., human resources, technical assistance). Underlying many of these resource needs are insufficient sociopolitical resources – access to and influence with policymakers, government agencies and other funders – particularly for communities of color and low-income neighborhoods (Cohen and Reynolds 2015).

Among material resource needs, access to land and land tenure are widespread concerns, as most garden spaces are not owned by gardeners and are subject to residential and commercial development (Guitart et al. 2012; MacNair 2002; Saldivar-Tanaka and Krasny 2004; Teig et al. 2009; Wakefield et al. 2007). In many cases, uncertainty about continued access to land limits crop selection and discourages investment in infrastructure and perennial plantings (Pfeiffer et al. 2014; Wakefield et al. 2007). Community gardeners also express difficulty obtaining materials (particularly clean soil) and financial resources to garden successfully (Drake and Lawson 2015; Saldivar-Tanaka and Krasny 2004; Wakefield et al. 2007).

Even with land and materials, successful community gardens require human and educational resources, including staff and volunteer commitment, labor, experience, knowledge and skills. In general, community gardens rely on volunteers to maintain common areas, fundraise, procure materials, and advocate for land access – all in addition to cultivating plots of vegetables and flowers. Getting new people involved and sustaining participation in common labors are frequent concerns for most garden leaders (Drake and Lawson 2015), and the inability of many community gardens and farms to afford paid, skilled staff constrains both production and programming (Cohen and Reynolds 2015). Furthermore, urban gardening support organizations struggle to meet the demand for technical assistance due to small staff size and resources, and language and cultural barriers (Baker 2004; Krasny and Tidball 2009;

Saldivar-Tanaka and Krasny 2004; Svendsen and Campbell 2008). This leaves many gardeners eager for further assistance in horticulture, garden organization and administration, community outreach and networking, and program evaluation (Cohen and Reynolds 2015).

Urban gardens: Agroecological characteristics and challenges

In contrast to the well-documented social and institutional aspects of urban gardening, agricultural production and ecological processes in food-producing spaces have only recently received attention (Guitart et al. 2012). Insights from the broader field of urban ecology, combined with initial work on the agroecological characteristics of urban gardens, suggest that gardeners face challenges for sustainable food production, including soil quality concerns, nutrient excesses, and unique insect pest pressures. Building soil quality is a challenge for urban growers, who often plant in raised beds to create a suitable growing medium on compacted lots and minimize exposure to soil contaminants (Clark et al. 2008; Mitchell et al. 2014; Pfeiffer et al. 2014; Witzling et al. 2010). The use of imported substrates (e.g., wood chips, clean fill) may result in suboptimal soil structure, coarse textures, low water-holding capacity, and high potential for nutrient leaching losses (Cameira et al. 2014; Pfeiffer et al. 2014). Furthermore, nutrient applications in urban gardens are often excessive, leading to high levels of soil nutrients which can be lost to the environment and cause nutrient imbalances for crop growth (Cameira et al. 2014; Dewaelheyns et al. 2013; Witzling et al. 2010). Finally, studies of urban forests and vacant lots show that cities have low arthropod natural enemy (predator and parasitoid) populations and higher densities of herbivorous insect pests than surrounding rural areas (McIntyre 2000; Pickett et al. 2001), which may decrease crop productivity and quality if the same trend holds in urban vegetable gardens.

Despite these challenges for food production and environmental quality, recent research also suggests that gardeners' management decisions may enhance ecological processes underlying urban food production. For example, gardeners may be able to augment arthropod natural enemy populations and biological control of insect pests by providing suitable non-crop habitat (Gardiner et al. 2014; Philpott et al. 2014). Ecologically-based soil management approaches such cover cropping could also be integrated into urban gardening practices. Cover crops provide many benefits in other agricultural systems, including improved soil quality and nutrient cycling (Blesh and Drinkwater 2013; Snapp et al. 2005; Tonitto et al. 2006; Wander 2004).

Increasing reliance on ecological processes in urban gardens could enhance ecosystem services and improve agricultural production while preventing negative environmental impacts. To contribute to the knowledge base for developing ecologically-based management practices tailored to urban gardens, we characterized food-producing community gardens in New York City (**NYC**). Through survey interviews with gardeners and systematic collection of ecological data, we explored three over-arching questions: 1) What are the agroecological and social characteristics of food-producing community gardens in NYC? 2) What are the key constraints to food production in NYC community gardens? 3) Are gardener knowledge systems adequately developed to overcome production challenges and what information sources do urban gardeners use to inform management decisions?

Materials and methods

We used social and ecological data collection methods in a nested design to characterize 61 food-producing community gardens across NYC (Fig. 1). Of NYC's approximately 490

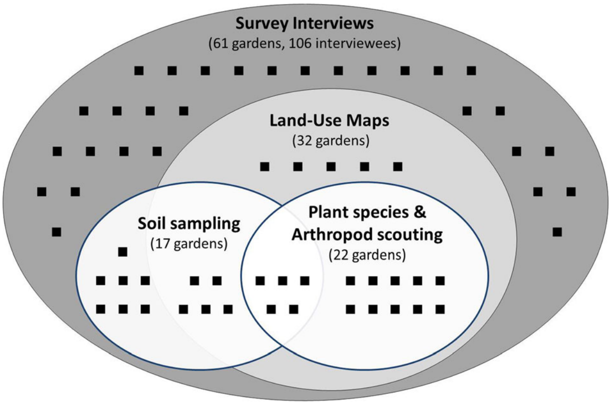

Fig. 1 Nested research design for characterizing 61 food-producing gardens in NYC. Each square represents one garden. Seven additional gardens (not within the survey interview dataset) are included in our land use, plant species, and arthropod scouting datasets

community gardens, about 80 % (392) host food production while 20 % grow only ornamental plants (Gittleman et al. 2011). For our survey and subsequent ecological sampling, we selected gardens growing vegetables and fruits. Other food-producing spaces in the city include 350 institutional gardens (associated with the New York City Housing Authority and public schools), seven community farms, and three commercial farms (Cohen *et al.* 2012). Thus, while our findings represent only community gardens, some of our recommendations may provide useful insights for growers at other urban agriculture sites, particularly when they share key characteristics with community gardens (e.g., use of raised beds with imported soil).

The community gardens participating in this study represent about 15 % of food-producing community gardens in the city and are located in all five of NYC's boroughs, with a distribution roughly proportional to the number of community gardens found in each borough. To describe agroecological features of these gardens, we combined information from gardener interviews with ecological measurements of land use, soil properties, plant species richness, and arthropod communities. We relied on interviews with gardeners and fieldwork experiences to provide insight into gardening challenges, gardener knowledge systems, and social and organizational features of NYC gardens.

During the initial survey interview phase of the study, we worked with 61 food-producing community gardens administered by GreenThumb (www.greenthumbnyc.org), a program of the NYC Department of Parks and Recreation that provides materials and workshops for gardens. We then selected a subset of gardens for land-use mapping, plant species richness surveys and arthropod scouting. We chose sites where gardeners agreed to facilitate regular access for arthropod scouting, and to represent a range of land-use practices and landscape contexts (i.e., varying degrees of urbanization) that we hypothesized would affect arthropod communities. Finally, we sampled and analyzed soils from 17 Brooklyn gardens where gardeners and local organizations expressed interest in participatory research on cover crops and soil management.

Survey interviews

From January 2010 through February 2012, we interviewed 61 garden coordinators and 66 gardeners using two distinct survey instruments. Given that almost all garden coordinators are also gardeners, we administered both surveys to some garden coordinators, resulting in 106 interviewees. Interviews were conducted in either English or Spanish, according to the interviewee's preference.

The survey for garden coordinators focused on general questions about the community garden, including: garden age and size, membership, languages spoken, types of garden beds and sources of soil and compost used to grow food crops, composting, and land tenure. The gardener survey contained more detailed questions about crops grown, gardening experience and practices, reliance on garden produce, information sources, knowledge and use of ecologically-based management practices, and socioeconomic and demographic information. Both surveys included questions about challenges to producing food in urban community gardens.

Garden land-use maps

For each garden selected for land-use mapping, we measured the areas devoted to four major categories of land-uses: 1) 'Agricultural crops' included annual food crops (primarily vegetables), and perennial food crops (fruit trees, berry bushes, asparagus, etc.). 2) 'Ornamental plants' included annual and perennial flowers and woody perennials (shade trees and shrubs). 3) 'Food production infrastructure' consisted of land-uses supporting food production, including paths to facilitate food crop maintenance, compost bins, rainwater harvesting tanks, and structures (toolsheds, chicken coops, and beehives). 4) 'Open/Recreational areas' included open grassy areas, recreational structures (e.g., gazebos, stages), and other non-gardening areas (e.g., picnic areas).

Using measurements from our site surveys, we constructed scale maps showing the land-uses in each garden. A small percentage of land in some gardens (average = 2 %) was in rubble (leftover from the vacant lots where most gardens were created) or weeds. We subtracted this 'unmanaged' area from total garden area and then calculated the percentage of each garden devoted to each land-use.

Soil properties

We took soil samples from 266, 1.9-m^2 (20-ft^2) research plots in 17 Brooklyn gardens. Samples were collected in August and September of 2011 and 2012. For each plot, we collected 8–9 soil cores (2 cm diameter by 20 cm depth, except where the depth of the raised bed was <20 cm) and composited them for processing and analysis. Composite samples were air-dried and then passed through a 2-mm sieve prior to analysis.

Representative subsamples of each soil were sent to the Agricultural Analytical Services Laboratory at Penn State University (University Park, PA) for measurements of soil particle size, pH, and available phosphorous (P), potassium (K), magnesium (Mg), and calcium (Ca). Samples were analyzed for particle size using the hydrometer method (Gee and Bauder 1986). Available P, K, Mg, and Ca were determined using the Mehlich 3 (ICP) method (Wolf and Beegle 1995). To determine total C and N content, we roller-ground representative subsamples of each soil and analyzed them by dry combustion using a LECO 2000 CN Analyzer (LECO Corporation, St. Joseph, MI).

We also selected a subset of soil samples for more intensive characterization: 36 plots from four gardens in 2011, and 54 plots from six gardens in 2012. In these plots, we measured bulk density, soil water content at field capacity (g water/g moist soil, expressed as **%H_2O**), and the C and N contents of particulate organic matter (**POM**; organic matter >53 μm, usually derived from recent inputs). We took triplicate measurements of bulk density and soil water content at field capacity in each plot using gravimetric methods. Samples of known volume were weighed moist in the field 48 h after wetting with a standard volume of water, dried at 60 °C for 48 h, and re-weighed. We calculated bulk density and soil water content at field capacity as follows:

$$\text{Bulk density} = \frac{\text{g field moist soil}}{\text{soil volume } (\text{cm}^3)}$$

$$\%\text{H}_2\text{O, field capacity} = \frac{(\text{g field moist soil} - \text{g oven dry soil})}{\text{g field moist soil}}$$

We extracted POM fractions from the soils using the size and density separation method presented in Marriott and Wander (2006) with slight modifications to accommodate the large quantity of free POM in raised-bed soils constructed with a high proportion of compost (Gregory and Drinkwater, in preparation). We then analyzed each POM fraction for C and N by dry combustion, as outlined above.

Plant species richness inventories

In each garden participating in arthropod scouting (see below), we identified and tallied the number of species of agricultural plants, ornamental plants, and weedy plants (not sown or tended by gardeners). Knowledgeable gardeners at each site and horticulturalist C. Day assisted with plant identifications; we also consulted references to confirm ornamental and weedy plant identifications (Day 2007; Del Tredici 2010; Uva et al. 1997).

Arthropod scouting

Based on discussions with gardeners and consultation with an Extension educator (J.M. Ameroso), we adapted scouting procedures used for integrated pest management on commercial farms to characterize arthropod pest and natural enemy populations and pest damage on crops (Castagnoli et al. 2003; Nihoul et al. 1991; Seaman et al. 2000). We focused on three crop families: Brassicaceae ('Brassicas,' e.g., collards, kale, cabbage, bok choy), Cucurbitaceae ('Cucurbits,' e.g., cucumber, summer squash, and winter squash), and Solanaceae (tomatoes). From June through September of 2011 we collected scouting and yellow sticky card data on these crop families in 22 community gardens. During each garden visit, we examined ten randomly selected Brassica, Cucurbit, and tomato plants and recorded information on arthropod pests and natural enemies present using standard scouting procedures (Table 1). To monitor parasitic wasps, we also placed six yellow sticky cards (two per crop family) within 15 cm of the plant, 15 cm above the ground. After 48 h, we collected the cards, covered them with saran wrap, and froze them for later identification and counting of parasitic wasps under a microscope. Table 1 summarizes the arthropod pests and natural enemies scouted on each crop, scouting protocols and population metrics reported.

Data analysis

We analyzed data from interviews and ecological sampling using JMP Pro 11 statistical software (SAS Institute, Cary, NC). For interview data, we compiled basic descriptive statistics from gardeners' responses to all questions. We also investigated questions about gardener

Table 1 Arthropod pests and natural enemies (predators and parasitoids) monitored and metrics used to characterize their populations. All metrics were calculated from garden-level averages (i.e., the average per-plant arthropod population or damage index across the 10 plants scouted in each garden). For pests, we report metrics from the scouting week in which each pest reached its seasonal peak. For natural enemies, we report average metrics across all scouting weeks

Arthropod common name	Scientific name(s)	Population metrics reported
Brassica pests		
Whiteflies	Homoptera: Aleyrodidae	# whitefly pupae/leaf[a]
Aphids	*Aphis gossypii*, *Myzus persicae*	# aphids/plant
Flea beetles	*Phyllotreta spp.*	# flea beetles/plant
Lepidopteran larvae	Lepidoptera	# larvae/plant
Cucurbit pests		
Aphids	*Aphis gossypii*, *Myzus persicae*	# aphids/10 leaves
Squash bugs	*Anasa tristis*	# nymphs/10 leaves
Tomato pests		
Aphids	*Aphis gossypii*, *Myzus persicae*	# aphids/leaf [b]
Two-spotted spider mite	*Tetranychus urticae* Koch	Spider mite leaf damage index/plant [c]
Natural enemies		
Ladybird beetles	Coccinellidae (e.g., *Coccinella septempunctata*, *Stethorus punctum*)	# ladybird adults and # larvae/plant
Syrphid fly larvae	Diptera: Syrphidae	# syrphid fly larvae/plant
Lacewing larvae	*Chyrsoperla oculata*, etc.	# lacewing larvae/plant
Minute pirate bugs	*Anthocoridae* (e.g., *Oris insidiosus*)	# minute pirate bugs/plant
Parasitic wasps	Hymenoptera	# parasitic wasps/plant (sticky cards)[d]
Spiders	Araneae	# spiders/plant

[a] Average of three leaves

[b] Average of three randomly selected complete (compound) leaves, one from each third of the plant (upper, middle, and lower) (Seaman et al. 2000)

[c] The Leaf Damage Index (**LDI**) is a score of the intensity of visual damage from spider mite feeding on a tomato leaf. It ranges from 1 to 5, with 1 representing <10 % damage and 5 representing 80–100 % damage to the leaf. These visual assessments of leaf damage have been shown to be a closely correlated with spider mite abundance and population structure on tomato plants (Castagnoli et al. 2003; Nihoul et al. 1991). For each plant scouted, we averaged the LDIs from three randomly selected complete leaves, one from each third of the plant

[d] Average of 2 yellow sticky cards per plant family per garden in each scouting week

motivations and knowledge by examining relationships between key categories of information. To determine if gardeners experiencing economic stress relied on garden produce to a greater extent than other gardeners, we compiled data from questions about reliance on garden produce by food security status (food insecure or food secure)[1] and household income bracket (less or greater than $50,000/year). We coded gardeners' responses to open-ended questions about crop rotation and cover cropping to characterize their knowledge and use of ecologically-based management practices. To evaluate if gardeners practiced adequate crop

[1] For this analysis, food insecurity was indicated by a "yes" response to at least one of three interview questions (all relating to food security or insecurity in the past year): (1) if the gardener had worried that her/his household would not have enough food, (2) if the gardener or other household member had been unable to eat sufficient fruits and vegetables due to lack of resources, and/or (3) if the gardener or other household member ate smaller meals or less frequent meals than s/he would have preferred due to lack of resources.

rotation, we analyzed sequences of crops planted in a particular bed over at least three years, as reported by gardeners ($n = 24$). We defined "adequate crop rotation" as crop sequences that do not repeat plant families more than once every three years, which is considered effective for disease management in most cases (Mohler and Johnson 2009).

For land-use and arthropod populations, we calculated summary statistics from garden-level data. We calculated summary statistics for soil properties from beds (management units) sampled within each garden, and report averages by garden. We also used univariate and multiple regression models to assess relationships among soil properties at the plot level. Where scatterplots suggested nonlinear relationships between soil properties, we fitted appropriate curves using the Nonlinear Regression platform in SigmaPlot 10 (Systat Software, San Jose, CA).

To explore potential influences of garden size and neighborhood socioeconomic status on land-use allocation at the garden level, we ran simple regressions. Predictor variables (in separate regressions) included total garden area and median household income in the ZIP code where each garden is located. Response variables included area and percent garden area in vegetable crops, ornamental plants, and recreational areas. ZIP codes were determined from garden addresses given in the Open Accessible Space Information System (http://www.oasisnyc.net/). Median household income was obtained for each ZIP Code Tabulation Area from the U.S. Census Bureau's American FactFinder (http://factfinder2.census.gov), Selected Economic Characteristics as estimated by the 2008–2012 American Community Survey.

Results

Agroecological characteristics and gardener practices

Garden size and land-use

Community gardens in New York City are relatively small. Forty percent of gardens where we conducted interviews were under 500 m^2 (0.12 acres) and nearly 70 % measured less than 1000 m^2 (0.25 acres) (Online Resource 1). Gardens contained agricultural crops, food production infrastructure (mainly paths for maintaining food crops), ornamental plants, and open/recreational areas (Figs. 2 and 3, Online Resource 2). While allocation of land to different uses varied across gardens (Fig. 2), gardeners devoted the greatest proportion of garden area to food production. On average, food crops and supporting infrastructure occupied nearly half of garden area, more than any other land-use (Fig. 3). Almost all agricultural crop area was annual vegetables, with little area in perennial crops (Fig. 3). Since almost 70 % of gardens did not use cover crops between annual cropping cycles (data not shown), most agricultural crop area is bare over the winter. Area in paths was positively correlated with agricultural crop area ($r^2_{adj} = 0.93$, $p < 0.0001$; data not shown). On average, gardeners maintained little area in flowers (12 %) and woody perennials (9 %), though some gardens did maintain substantial ornamental plant areas (Fig. 2, Online Resource 2). Areas devoted to recreation and community gatherings composed just over one-third of garden area, on average (Figs. 2 and 3).

Factors influencing allocation of garden space varied for different land-uses. There were few clear patterns in land-use allocation based on total garden area or median income in the surrounding neighborhood, with several exceptions. Total garden area was not correlated with the percentage of garden area devoted to vegetable crops, ornamental plants, or other non-gardening

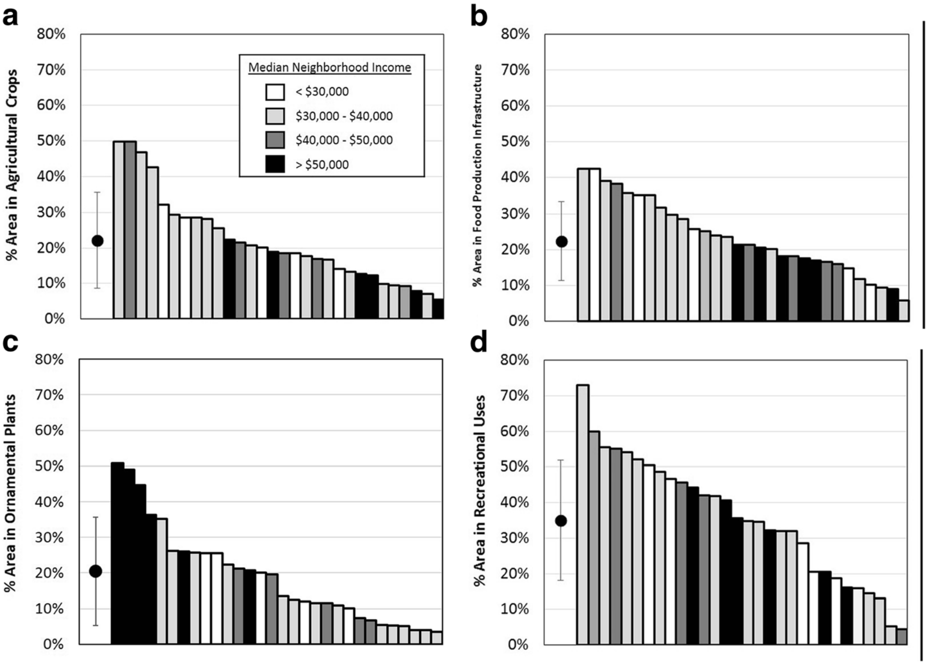

Fig. 2 Percent area allocated to four categories of land uses in mapped gardens varying in median neighborhood income: **a** agricultural crops, **b** food production infrastructure (mainly paths), **c** ornamental plants, and **d** recreational areas. The dot represents the average allocation to each land use and standard deviation. Each bar represents percent area allocated to a given category in a single garden. Bars are color-coded by median household income in the neighborhood where the garden is located: white, < \$30,000; light gray, \$30,000 - \$40,000; dark gray, \$40,000 - \$50,000; black, > \$50,000

areas, or with ornamental plant area. Garden size significantly influenced vegetable crop area ($r^2_{adj} = 0.75$, $p < 0.0001$) and area devoted to paths for maintaining vegetable crops ($r^2_{adj} = 0.85$, $p < 0.0001$). Thus, large gardens had more area in vegetable crops and associated paths compared to small gardens, but did not host larger areas of ornamental plants. Median income in the garden neighborhood was positively correlated with the percentage of garden area in ornamental plants ($r^2_{adj} = 0.47$, $p < 0.0001$) and (weakly) negatively correlated with the percentage of garden area in vegetable crops ($r^2_{adj} = 0.13$, $p = 0.027$).

Crops grown

Food crop areas in NYC gardens are dominated by crops in the Solanaceae, Cucurbitaceae, and Brassicaceae families. When we asked gardeners to list their "six most important crops," seven of the ten most frequently cited crops belonged to these three families (Fig. 4). Tomatoes were by far the dominant crop, appearing on 94 % of gardeners' lists. However, despite the dominance of several plant families, gardeners in NYC collectively grow a wide variety of crops. Gardeners' "top six" lists included 37 crops, and our plant species inventories documented an average of 43 agricultural crops per garden (range, 18–70) and nearly 100 food crops across the 22 surveyed gardens. These included ethnic specialties such as bitter melon (*Momordica charantia*), long beans (*Vigna unguiculata subsp. Sesquipedalis*), luffa or sponge gourd (*Luffa* spp.) and Malabar spinach (*Basella alba*), among others.

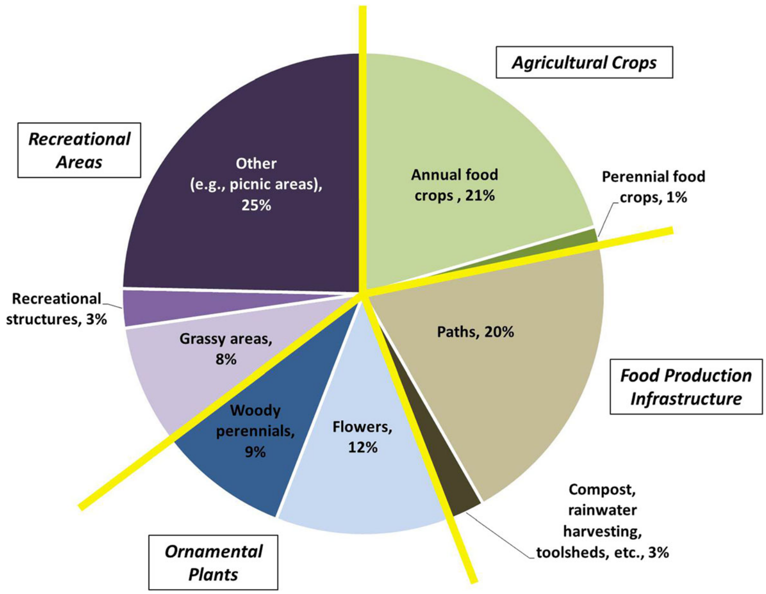

Fig. 3 Pie chart showing a detailed breakdown of the average percent allocation to different land uses within the major categories of agricultural crops (green shading), food production infrastructure (brown shading), ornamental plants (blue shading), and recreational uses (purple shading)

Soil sources, management and properties

Ninety-one percent of the gardeners we interviewed grew food crops only in raised beds (Table 2). Most gardeners used amendments to improve soil quality and to provide nutrients for vegetable crops, most commonly compost from GreenThumb or the garden (Table 2).

Selected soil properties for raised-bed Brooklyn garden soils are summarized by garden in Table 3. Most soils were sandy loams or loamy sands, with a slightly alkaline pH and very high nutrient levels. Brooklyn garden soils also had high average total C and N, though C and N levels varied widely (Table 3). On average, POM accounted for nearly half of total soil C and N reserves, and free POM (POM not associated with soil aggregates, usually from very recent organic inputs) accounted for approximately three-quarters of POM-C and –N (data not

Fig. 4 Most common crops in NYC gardens and the percentage of gardeners growing each as one of their "six most important" crops (n = 66). Plant family abbreviations (in parentheses) are: S = Solanaceae; C = Cucurbitaceae; B = Brassicaceae; F = Fabaceae; M = Malvaceae

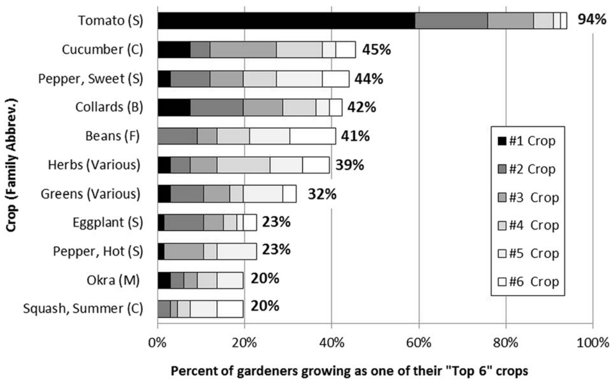

Table 2 Soil sources and management in NYC community gardens (n = 66). Percentages of gardeners using particular soil amendments add to >100 %, since many gardeners use multiple amendments

Soil management practice	% Gardeners	Notes/Examples
Garden beds		
Raised beds	91 %	Constructed with clean fill & compost (78 %) or clean fill only (22 %)
In ground	6 %	
Raised beds & in-ground	3 %	
Soil amendments		
Compost	58 %	Compost from GreenThumb or the garden
Chemical fertilizers	24 %	Miracle-Gro
Manure	24 %	Horse manure from stables
Organic fertilizers	20 %	Granular organic fertilizers, blood meal, fish emulsion
Topsoil	17 %	Bagged topsoil from Home Depot
Mulch	9 %	Straw, leaf mold

shown). These soils generally had very low bulk densities (range, 0.54–1.61 g/cm^3) and water contents at field capacity (range, 0.15–0.40 g H_2O/g moist soil).

Soil texture and pH were consistent across gardens, while properties that respond strongly to management (i.e., nutrients and organic matter) showed high variability. Reflecting the fact that most gardeners grow crops in 'constructed' soils, texture was consistently sandy; the overall coefficient of variation (**CV**) for percent sand was only 10 %. Soils in this concrete-rich, urban environment also had consistently neutral-to-alkaline pH levels (overall CV = 3 %). In contrast, nutrient levels and organic matter-related soil properties showed large variation at all spatial scales (across gardens, within gardens, and within beds). For these properties, variation between different sampling areas in the same bed was only slightly smaller than variation between beds in the same garden, indicating that urban garden soils are heterogeneous at fine scales. For example, total C had average CVs of 21 % within beds, 28 % within gardens, and 60 % overall. POM-C was even more variable, with average CVs of 29 % within beds, 41 % within gardens, and 92 % overall (data not shown).

Soil organic matter content impacted several related soil characteristics which support plant productivity. Total soil C showed significant, positive relationships with total N, Mg, Ca, and CEC, but not with P or K (data not shown). Soil water content at field capacity increased exponentially with total soil C to an upper limit of ~0.37 g H_2O/g moist soil (Fig. 5). Sand content did not exhibit a significant correlation with water content, at least over the range found in the subset of plots selected for field capacity measurements (56–88 % sand).

Arthropod management and populations

The most common insect management strategy – used by 32 % of gardeners – was application of a 'natural' pesticide or repellent (e.g., soap and water, cayenne pepper) (Table 4). Repellent crops, primarily marigolds, were the second-most common strategy with 29 % of gardeners, although many expressed doubt about their efficacy. Interestingly, 27 % of gardeners did not take any steps to manage insect pests, although this was one of the most commonly cited challenges for growing food (see below, "Constraints to urban food production").

Table 3 Summary statistics for soil properties measured in cover crop research plots in 17 Brooklyn gardens. Data on texture (% sand, % clay), pH, P, K, Total C, and Total N are based on 157 beds containing 266 research plots, sampled in the Fall of 2011 and 2012. Data on bulk density and % H_2O (water content at field capacity) are based on triplicate samples from a subset of 57 beds containing 90 research plots across six gardens, sampled in the Fall of 2011 and 2012

Garden	% Sand	% Clay	pH	P (mg/kg)	K (mg/kg)	Soil C (g/kg)	Soil N (g/kg)	Bulk density (g/cm^3)	% H_2O, field capacity (g H_2O/g moist soil)	# beds/samples
1	69.7	10.8	7.1	123.0	498.3	77.1	4.5	–	–	4/4
2	66.7	9.6	6.9	470.5	391.5	67.2	4.2	–	–	2/2
3	72.8	11.0	7.4	209.6	272.6	62.5	3.4	–	–	5/5
4	63.4	10.6	7.2	314.0	134.6	35.8	2.3	–	–	5/12
5	74.9	10.4	7.2	190.7	367.3	136.2	7.0	–	–	3/3
6	69.9	11.1	7.0	234.6	155.2	109.8	7.1	0.95	0.24	10/40
7	61.1	14.7	7.2	179.7	181.8	37.6	1.6	1.37	0.19	29/59
8	65.0	9.7	7.5	139.7	140.8	29.0	1.0	–	–	3/8
9	73.7	9.6	7.1	272.7	160.7	59.1	4.0	0.87	0.27	32/32
10	77.6	10.0	6.7	152.0	104.0	21.5	1.3	–	–	1/3
11	70.4	9.9	7.4	185.5	117.8	42.6	2.0	1.11	0.21	21/21
12	75.3	5.0	7.1	216.1	202.7	102.6	5.7	0.88	0.29	10/23
13	64.5	11.3	7.3	292.8	316.3	50.8	2.7	–	–	21/21
14	67.3	9.9	7.0	290.6	113.7	74.7	3.9	1.05	0.29	4/21
15	69.6	7.4	7.1	353.3	165.7	29.6	1.5	–	–	3/5
16	77.5	9.6	6.3	59.0	63.0	17.6	0.5	–	–	1/3
17	76.6	5.0	7.0	340.7	238.7	71.4	3.9	–	–	3/3
Overall	68.7	10.6	7.2	235.6	199.2	58.2	3.3	1.0	0.25	157/266

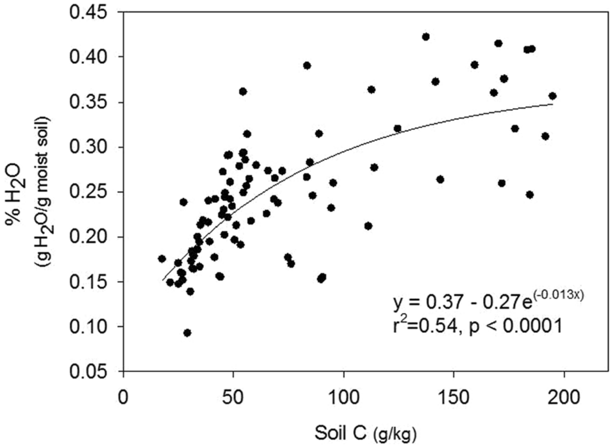

Fig. 5 Relationship between total soil C and water content at field capacity (g H_2O/g moist soil) for 90 research plots across six Brooklyn gardens, sampled in the Fall of 2011 and 2012

Summary statistics for arthropod pest and natural enemy populations are reported in Table 5. In general, pest populations were high, while natural enemy populations were relatively low. Peak populations of whiteflies and aphids on Brassica crops and aphids on Cucurbit crops greatly exceeded action thresholds[2] in 90–100 % of gardens. All gardens also showed leaf damage from two-spotted spider mite feeding in excess of action thresholds. Insect pests that were problematic in some gardens, but not others, included: flea beetles on Brassicas, squash bugs on Cucurbits, and aphids on tomatoes. Arthropod predators were rare, with an average of less than one per plant. Minute pirate bugs and spiders were the most commonly observed natural enemies during scouting. Sticky card data also indicated substantial numbers of parasitic wasps.

Social garden characteristics

Garden age

All of the gardens in our study, with one exception, were founded after 1970. More than 80 % were started after 1980, with the greatest number (41 %) established during the 1990's.

Gardener characteristics

A wide variety of people of differing experience levels, incomes, and ethnicities participate in community gardening in NYC. As might be expected in gardens with culturally diverse membership, most gardens where we conducted interviews hosted multiple languages. Ninety-three percent hosted at least two languages, with 41 % hosting three or more. Some gardens had up to seven languages represented. The most commonly spoken languages were English (found in 100 % of gardens), Spanish (89 %), Mandarin (16 %), French (15 %), and Creole (11 %).

[2] An action threshold is the "point at which pest populations… indicate that pest control action must be taken," and corresponds to pest populations that, left unchecked, will cause economic damage (U.S. EPA 2012).

Table 4 Insect management strategies used by community gardeners in NYC ($n = 66$)

Insect management practice	% Gardeners	Examples
Natural/botanical pesticide or repellent	32 %	Soap & water, essential oils (peppermint, rosemary, etc.), vinegar & water, lime, ashes, garlic, cayenne pepper, baking soda & water
Repellant crops	29 %	Marigolds, basil, nasturtium, herbs (rosemary, lavendar, etc.)
None	27 %	
Hand-picking	18 %	
Chemical pesticide	11 %	Boric acid, pyrethrin, various unknown powders or sprays from local hardware stores
Biocontrol agents	5 %	Praying mantis, ladybugs

Table 5 Summary statistics for arthropod pests and natural enemy populations, measured with scouting and sticky cards in 22 gardens during the summer of 2011. All pest insect metrics were calculated from garden-level average per-plant insect populations during the week in which each pest population reached its peak. All natural enemy population metrics were calculated from garden-level average per-plant or per-sticky card populations over the entire season

Arthropod common name	Metric	Average ± SE	Range	% Gardens Exceeding Threshold[a]
Brassica pests				
Whiteflies	# pupae/leaf	15.8 ± 3.3	0.2 - 57.9	91 %
Aphids	#/plant	8.7 ± 3.6	0.2 - 75.2	100 %
Flea beetles	#/plant	5.8 ± 1.9	0.0 - 34.9	33 %
Cucurbit pests				
Aphids	#/10 leaves	25.3 ± 4.4	1.4 - 64.7	100 %
Squash bug nymphs	#/10 leaves	0.9 ± 0.3	0.0 - 5.8	29 %
Tomato pests				
Aphids	#/leaf	4.2 ± 0.9	0.6 - 19.0	18 %
Two-spotted spider mites	Mean LDI	3.6 ± 0.2	1.5 - 4.8	100 %
Natural enemies				
Scouted natural enemies,[b] Brassicas	#/plant	0.4 ± 0.1	0.0 - 1.5	n/a
Scouted natural enemies,[b] Cucurbits	#/10 leaves	0.9 ± 0.1	0.0 - 2.4	n/a
Scouted natural enemies,[b] Tomatoes	#/plant	0.4 ± 0.1	0.0 - 1.5	n/a
Minute Pirate Bugs	#/sticky card	6.3 ± 1.0	0.0 - 16.8	n/a
Parasitic Wasps	#/sticky card	72.7 ± 7.0	32.8 - 139.5	n/a
Natural enemy: Pest (sticky cards)	ratio	0.61 ± 0.04	0.28–0.96	n/a

[a] Thresholds are pest populations at which pest control actions are recommended to prevent economic losses and are as follows: whitefly nymphs on ≥40 % of Brassica leaves (Diehl et al. 1997); 1 aphid/10 Brassica plants (Dimson 2001); 2–5 flea beetles/Brassica plant (Grubinger 2005); aphids on ≥20 % of Cucurbit runners (Reiners and Petzoldt 2014); ≥ 1 squash bug egg mass/Cucurbit plant (Reiners and Petzoldt 2014); 6 aphids/tomato leaf (Reiners and Petzoldt 2014); mean spider mite Leaf Damage Index (LDI) of 2.0–2.5 (Nihoul *et al.* 1991)

[b] Scouted natural enemies include (in decreasing order of overall abundance): minute pirate bugs, spiders, ladybird beetles, syrphid fly larvae, lacewing larvae

Contributions of community gardens to food security and nutrition

While community gardens are not the only sources of produce for gardeners, they supply a substantial portion of gardeners' produce needs (Table 6). During the growing season, 55 % of gardeners harvested more than two-thirds of the vegetables eaten in their households from their community gardens, and 22 % harvested between one- and two-thirds of their household's produce needs.

Gardeners reporting food insecurity or annual household income below $50,000/year showed slightly greater reliance on garden produce compared to food-secure and higher-income gardeners. A greater percentage of gardeners struggling with food insecurity relied on their gardens for more than two-thirds of their vegetables during the growing season compared to food-secure gardeners (63 % vs. 52 %) and more than one-third of their vegetables during the winter (32 % vs. 11 %). Ninety percent of food-insecure gardeners ranked their garden as their first or second produce source, compared to 72 % of food-secure gardeners. We found similar patterns for gardeners living on low incomes compared to higher-income gardeners (Table 6).

Constraints to urban food production

While many NYC gardeners grow enough produce to make important contributions to food security and nutrition, they face many challenges for agricultural production. The most commonly cited challenges among gardeners we interviewed included: building and maintaining soil quality and fertility, insect pest damage, weed management, limited time for gardening, reliable access to water, and mammalian pests (Fig. 6). Specific insect pest problems frequently mentioned by gardeners or observed in subsequent fieldwork are outlined in Table 7.

Table 6 Reliance on garden produce by food security status and annual household income. Percentages of gardeners giving particular responses were calculated separately for food security status (food-insecure and food secure gardeners) and for annual household income level (less or greater than $50,000)[1]

Food security status/Household income →	Food-insecure (n = 19)	Food-secure (n = 47)	< $50,000/yr. ($n$ = 42)	> $50,000/yr. ($n$ = 17)	Overall (n = 66)
% of household vegetable consumption from garden during the GROWING SEASON					
Less than 1/3	21 %	24 %	21 %	31 %	23 %
1/3–2/3	16 %	24 %	24 %	25 %	22 %
More than 2/3	63 %	52 %	55 %	43 %	55 %
% of household vegetable consumption from garden during the WINTER					
Less than 1/3	68 %	89 %	88 %	81 %	83 %
1/3–2/3	32 %	7 %	10 %	19 %	14 %
More than 2/3	0 %	4 %	2 %	0 %	3 %
Community garden ranking as OVERALL produce source					
Primary produce source	37 %	23 %	29 %	19 %	27 %
2nd produce source	53 %	49 %	57 %	38 %	50 %
3rd produce source	5 %	21 %	12 %	25 %	17 %

[1] Response percentages by income level were calculated out of the total number of gardeners who chose to report their annual household income (n = 59); this is lower than the total number of interviewees (n = 66)

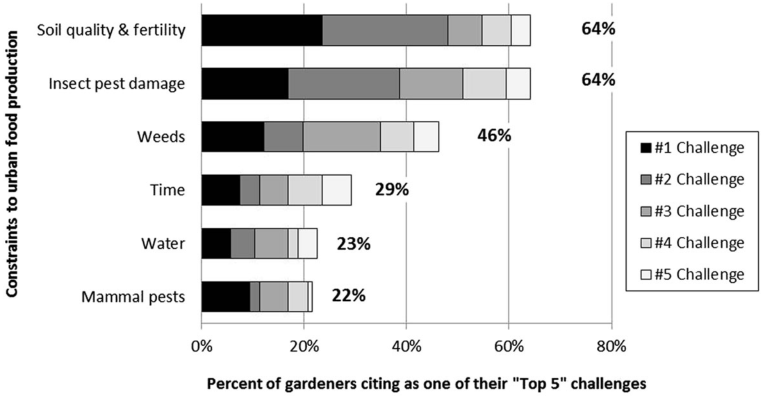

Fig. 6 Most commonly cited challenges for growing food in NYC community gardens and the percentage of gardeners citing each as one of their "top five" challenges (n = 106)

Gardener knowledge systems

Knowledge & use of ecologically-based management practices

We used questions about crop rotation and cover cropping to provide insight into gardeners' understanding and use of agroecological practices. Gardeners varied in their understanding and use of crop rotation (Table 8). Eighty percent were familiar with the basic definition of crop rotation (not planting the same crop in the same location year after year). However, only three percent of gardeners understood the importance of rotating botanical families. Many gardeners also struggled to articulate the multiple functions of crop rotation. The most commonly understood function was to support soil fertility by avoiding repeated planting of heavy-feeding crops. Only 5 % of gardeners mentioned disease and insect pest management as potential functions of crop rotation and none mentioned weed management, although crop rotation is a key strategy for managing diseases, insects, and weeds (Liebman and Dyck 1993; Mohler and Johnson 2009).

These gaps in gardeners' understanding of crop rotation were reflected in their practices. Of all gardeners who could report a three-year sequence of crops planted in a particular bed

Table 7 Commonly mentioned or observed insect pest problems in NYC community gardens, 2010–2011

Insect common name	Insect scientific name	Crop hosts
Whiteflies	Homoptera: Aleyrodidae	Brassica crops, especially collards
Flea beetles	*Phyllotreta* spp.	Brassica crops, Eggplant
Lepidopteron larvae, e.g.: • Imported cabbageworm • Diamondback moth • Cabbage looper	Lepidoptera, e.g.: • *Pieris rapae* • *Plutella xylostella* • *Trichoplusia ni*	Brassica crops, esp. collards and cabbage
Squash bugs	*Anasa tristis*	Cucurbit crops
Squash vine borer	*Melittia cucurbitae*	Cucurbit crops, especially summer squash/zucchini
Two-spotted spider mite	*Tetranychus urticae* Koch	Tomatoes
Aphids	Homoptera: Aphididae	Many crops

Table 8 Gardener knowledge and use of agroecologial management practices. Based on open-ended questions asking gardeners to define and list the potential benefits of crop rotation and cover cropping (crop rotation questions: $n = 66$, cover cropping questions: $n = 102$)

Agroecological practice/Knowledge & Use	% Gardeners
Crop Rotation	
Heard of crop rotation	80 %
Practiced adequate crop rotation[a]	21 %
Understands rotation of botanical families	3 %
Identified functions of crop rotation:	
Soil fertility	65 %
Pest control	5 %
Disease suppression	5 %
Weed management	0 %
Cover Cropping	
Heard of cover crops	58 %
Has used cover crops	29 %
Identified functions of cover crops:	
Soil fertility	43 %
Soil protection	15 %
Weed suppression	8 %
Soil tilth/structural improvement	5 %

[a] Gardener's practice of "adequate crop rotation" was evaluated from the group of respondents who could remember a three-year sequence of crops planted in a particular management unit ($n = 24$). We defined "adequate crop rotation" as crop sequences that do not repeat plant families more than once every three years, which is considered effective for disease management in most cases (Mohler and Johnson 2009)

($n = 24$), only 21 % reported a sequence that did not repeat a plant family (Table 8). Even many gardeners who believed that they *did* practice crop rotation planted crops in the same family for multiple years, or with insufficient intervals for disease prevention. Of the gardeners who believed they were practicing crop rotation *and* could remember a three-year sequence of crops ($n = 13$), 70 % reported sequences that repeated a plant family in consecutive years (for example, pepper – tomato – eggplant, a sequence containing only Solanaceous crops) or waited only one year before repeating a plant family.

As with crop rotation, many gardeners had heard of cover cropping (58 %), but fewer gardeners used cover crops or understood their multiple functions (Table 8). Soil fertility was the most commonly identified function of cover cropping, recognized by 65 % of gardeners. However, many gardeners did not realize that not all cover crops add nutrients (expressing, for example, the misconception that the non-legumes rye and wheat "put nitrogen back in the soil" when in fact only legumes fix nitrogen). Furthermore, very few gardeners (< 10 %) recognized other functions of cover crops, such as weed suppression and improvement of soil tilth.

Gardening information sources

The most commonly used source of gardening information was other gardeners (59 %), followed by websites (47 %), print materials (41 %), and GreenThumb workshops (30 %) (data not shown). Interestingly, when we asked gardeners to name their preferred ways to obtain new information, workshops were the favorite by far (Fig. 7). Nearly half of gardeners

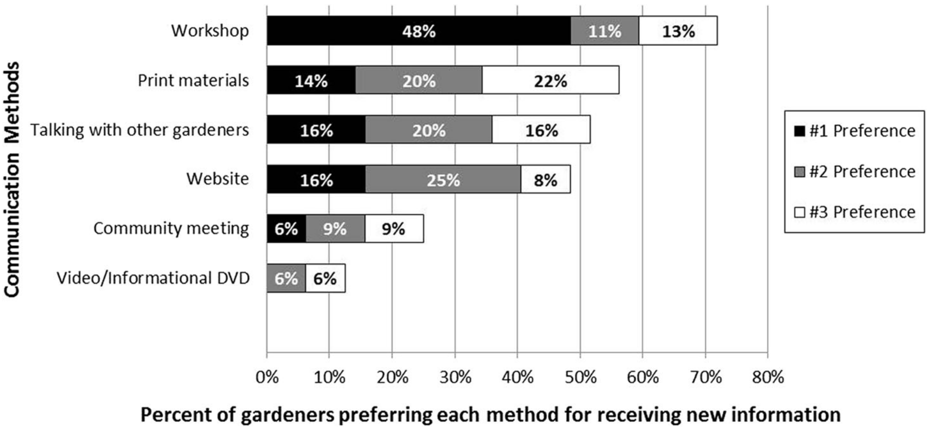

Fig. 7 Potential communication methods and the percentage of gardeners who chose each as their 1st, 2nd, or 3rd preference for getting new gardening information

identified workshops as the best way to obtain new information, and about 70 % identified workshops as one of their top three choices. Print materials, talking with other gardeners, and websites were among the top three choices for about half of gardeners (Fig. 7).

Discussion

Taken together, our findings provide insight into the value of community gardens in urban neighborhoods, the unique characteristics of urban garden soils and arthropod communities that affect ecological processes in these gardens, constraints on food production and opportunities for addressing these problems. While food production and access are important for many urban community gardeners, these spaces also serve other functions that enhance quality of life in cities. The urban setting of NYC gardens imposes unique production constraints, including difficulties building soil quality in 'constructed' raised-bed soils, and landscape factors and environmental stressors that favor herbivorous pest populations over arthropod natural enemies. However, we see many opportunities for using agroecological practices to address these production challenges and expand ecosystem services in these gardens. To support gardeners in adapting agroecological practices to urban conditions, gardening educators can incorporate ecological knowledge and inquiry-based approaches in their programming.

Food production, gardener priorities, and social research needs

In keeping with other studies of urban settings, we found that community gardens are important sources of fresh produce in NYC. Gardeners devoted the greatest proportion of garden space to crops and supporting infrastructure, and relied on their gardens for a substantial amount of their families' fresh produce. These findings are consistent with studies documenting the productivity of urban community gardens; crop yields can sometimes exceed national averages for commercial vegetable production (Algert et al. 2006; Baker 2002; Blair et al. 1991; Gittleman et al. 2012; Vitiello and Nairn, 2009). The significance of garden produce is two-fold. First, community gardeners achieve considerable cost-savings by growing their own produce (Algert et al. 2006; Armstrong 2000; D'Abundo and Carden, 2008;

Saldivar-Tanaka and Krasny 2004; Wakefield et al. 2007). Second, our study and others have found that urban gardeners grow culturally significant crops that may be difficult to find or expensive elsewhere (Baker 2004; Saldivar-Tanaka and Krasny 2004; Shava et al. 2010). The fact that NYC gardens supply a significant proportion of gardeners' household produce needs is impressive, particularly in light of the unique challenges for agricultural production posed by the urban environment and lack of research and extension focused on urban agriculture (Guitart et al. 2012; Pfeiffer et al. 2014).

Given that garden produce was particularly important for food-insecure and low-income gardeners in NYC, our findings suggest that increased support for community gardens may improve food security in ways that foster the agency and dignity of individuals, families, and communities (Levkoe 2006; Teig et al. 2009). Future research might explore how to design effective programs and policies that enhance the capacity of community gardens to promote food security and nutrition. This research could identify essential technical and material assistance, as well as supportive funding and policy processes to ensure equitable distribution of resources that support gardening as a strategy to achieve community food security (Cohen and Reynolds 2015).

While gardeners placed high value on the contributions of gardens to food access and better nutrition in their communities, the diversity of land-uses we documented in NYC gardens – including food production, ornamental plantings, and recreational spaces – demonstrates that community gardens serve multiple purposes in urban neighborhoods. In addition to serving as a source of fresh produce, community gardens in NYC and other urban areas conserve green space and biodiversity and provide opportunities for recreation, cultural expression and socializing with neighbors (Armstrong 2000; Blair et al. 1991; Draper and Freedman 2010; Saldivar-Tanaka and Krasny 2004; Shava et al. 2010). The variation in land-use allocation we observed suggests that the importance of these functions varies across gardens and depends on local context and community needs and interests (Drake and Lawson 2015).

Several patterns in land-use were influenced by garden size and neighborhood income. The consistent increase in vegetable crop area with garden size may reflect widespread demand for food-growing space in NYC neighborhoods. In contrast, the percentage of garden area devoted to ornamental plants increased with neighborhood income rather than garden size. Gardeners in higher-income neighborhoods may be more able to afford – and devote time to maintaining – ornamental plantings compared to gardeners in lower-income neighborhoods, who may also prioritize other land uses (e.g., food-growing areas or recreational spaces). Our interview data on vegetable consumption suggest that lower-income gardeners rely on garden produce to a greater extent than higher-income gardeners, and therefore may prioritize food production over other land uses. Furthermore, as median neighborhood income decreases, allocation of garden area to food production increases slightly, even within this subset of gardens selected for active food production areas. Had we included gardens dedicated solely to ornamental plantings (many of which are located in higher-income neighborhoods), the increased importance of food production in lower-income neighborhoods may have been more apparent. Recreational land-uses (e.g., picnic areas, grassy play areas) may also be more highly valued than ornamental plantings in lower-income neighborhoods if there are few other suitable areas for community gatherings or for children to play. This may be the case, as parks in poor areas tend to be smaller, more crowded, and have less amenities and more concerns regarding park quality and safety compared with parks in higher-income areas (Miyake et al. 2010; Vaughan et al. 2013).

Gardeners' land-use decisions are also likely shaped by factors that we did not investigate, such as the number of interested gardeners, physical constraints associated with available garden space (e.g., existing infrastructure, underlying concrete or shade from buildings), the time gardeners can devote to maintaining plantings, proximity of the neighborhood to other green spaces, and personal and cultural preferences. Thus, it is not surprising that space allocation in NYC community gardens varies among food production, ornamental plants, and recreational uses in ways that are nuanced and difficult to fully understand without more in-depth, qualitative methods.

Production constraints and potential agroecological solutions

Gardeners in NYC viewed soil quality and fertility and insect pests as the most important problems impacting crop production in community gardens, and our data confirm that there are widespread challenges in both of these arenas. Our data also indicate that ecological properties and processes in these gardens differ from those in rural areas where most agricultural research has been conducted. Therefore, effectively addressing soil quality challenges in urban gardens requires understanding how the unique characteristics of raised-beds and constructed soils impact the cycling of organic matter, water, and nutrients. Similarly, an understanding of the environmental and management drivers of arthropod community composition should underlie efforts to address insect pest damage through cultural practices.

Farmers and researchers have developed agroecological approaches to improve soil quality and manage pests in commercial farming operations, and we see opportunities for adapting this knowledge to urban gardens. Agroecological management approaches are based on locally appropriate suites of practices that enhance biological processes (e.g., internal nutrient cycling, biological control of insect pests by predators and parasitoids) to support crop productivity and ecosystem health. This allows growers to avoid relying on expensive and environmentally damaging external inputs such as chemical fertilizers and pesticides (Kanyama-Phiri et al. 2008; Shennan 2008).

Our interview results indicate that many NYC community gardeners have some knowledge of the ecological processes governing crop production, and, like gardeners in other cities, are motivated to minimize or avoid chemical use for health and environmental reasons (Armstrong 2000; Carney et al. 2012; Wakefield et al. 2007). Furthermore, most gardens are intensively managed and some exhibit significant crop diversity. Thus, there is great potential for implementing agroecological management strategies. To tap this potential, researchers and educators should partner with gardeners to provide sustained technical assistance that supports gardeners in effectively implementing, adapting, and refining agroecological practices to fit their urban setting and specific management goals.

Start with the soil

Fertile soil is the foundation of any agricultural endeavor, and urban community gardeners face formidable challenges in this arena because available garden sites are often contaminated with heavy metals and other toxins. To mitigate exposure to these contaminants, city gardeners usually construct raised beds with imported growing media (New York State Department of Health, 2011; Shayler et al. 2009; Witzling et al. 2010). Raised beds are often expensive to build (Pfeiffer et al. 2014; Witzling et al. 2010) and must be maintained with regular additions of soil and compost to keep contaminant concentrations low (Clark et al. 2008). As in other cities (Baker 2004), gardeners in NYC cited access to clean soil and compost as a key production constraint, at times limiting the number of raised beds built when additional garden space was available (Cohen and Reynolds 2015).

Even where gardeners can procure sufficient growing media, the unusual composition of raised-bed soils presents management challenges not found in natural soils. In NYC gardens, most raised beds are constructed with a mix of sandy clean fill and compost in varying proportions. Due to their coarse texture, these soils are well-drained but have poor water-holding capacity: Ninety-five percent of water-holding capacity measurements in our study were below the optimum level for preventing water limitation in sandy loam soils (~0.42 cm^3 H_2O/cm^3 soil) (Brady and Weil 2008). Cameira et al. (2014) also found that sandy textures in raised-bed allotment gardens in Lisbon were associated with low water-holding capacity and high potential for drainage and nutrient leaching.

Despite their sandy textures, community garden soils in NYC have high organic matter contents (approximately 12 % on average[3]) due to the high proportion of compost mixed with the sand. Given the coarse textures and lack of silt and clay in these soils, the large SOM reserves likely play an even greater role in these soils than is typical for natural soils (Haynes 2005; Marriott and Wander 2006; Po et al. 2009; Wander 2004). For example, in Brooklyn garden soils, water content at field capacity increased exponentially with total soil C, whereas in natural soils both SOM and clay content influence water-holding capacity. High SOM levels cannot completely compensate for the lack of silt and clay in raised-bed soils, however. Most gardeners reported that their soils dry out quickly, despite the fact that 98 % of beds had SOM levels in excess of the 4 % SOM (2 % C) level considered optimal for coarse-textured field soils (Gugino et al. 2009).

In addition to these impacts on soil structure and soil-water dynamics, very large SOM reserves in NYC garden soils lead to nutrient excesses, thus presenting another soil management challenge for gardeners. Total soil C showed positive correlations with N, Mg, and Ca, indicating that SOM reservoirs of these nutrients are of primary importance in these soils. In the plots we tested in Brooklyn, all P, Mg, and Ca values, and most K values, greatly exceeded optimum levels for vegetable production (NJAES 2014). As such, they may cause nutrient imbalances for crops and environmental pollution. Our findings concur with other studies documenting excessive nutrient levels in urban garden soils. Researchers also found excessive P and K fertility in urban community gardens in Chicago (Witzling et al. 2010) and home vegetable gardens in Flanders (Dewaelheyns et al. 2013). In urban gardens in Lisbon, N inputs were two to three times higher than crop uptake, leading to N losses via leaching and denitrification (Cameira et al. 2014).

Clearly, NYC community gardeners face a dilemma. To improve soil structure and water-holding capacity, organic matter additions are recommended. However, in this case, adding composts (typically rich in nutrients) would exacerbate the nutrient excesses present in most gardens. Incorporating cover crops into urban gardens may improve soil-water dynamics and soil structure without adding nutrients (with the exception of legumes, which add new N through biological fixation). In the short term, cover crops could also be grown and the shoots used as surface mulch to retain soil moisture by reducing evaporation (Teasdale and Mohler 1993). Over time, adding plant residues from cover crops to soils increases SOM levels

[3] This is based on our measurements of total soil C, which averaged 58.2 g/kg (~6 % of soil mass), and the common 'rule of thumb' that SOM is approximately half carbon by weight (Brady and Weil 2008). Average SOM content in Brooklyn soils can therefore be estimated as 6 % × 2 = 12 %.

(McDaniel et al. 2014), which is related to improved soil structure and water- and nutrient-holding capacity (Snapp et al. 2005; Wander 2004). Furthermore, cover crops have dense root systems, and thus improve soil tilth and nutrient cycling through physical and biological processes associated with root growth and decomposition (Haynes and Beare 1997). However, given that soil texture influences relationships between organic inputs, SOM levels, and soil function (Gentile et al. 2010), further research is needed to understand the long-term effects of cover cropping in these coarse-textured, raised-bed soils. Understanding how cover crop residue additions and residue management practices impact C and N accrual in organic matter fractions, aggregation, water-holding capacity and nutrient availability could inform recommendations for improving soil quality and fertility in raised beds through cover cropping.

Improved access to soil testing and guidance on appropriate use of soil amendments could also help address the problem of excessive nutrient levels and identify soils where nutrient levels are suboptimal. Facilitating soil testing and interpretation would allow gardeners to make more informed decisions about when, and which, nutrient-containing amendments are needed to support crop production. Integrated social and ecological research might investigate the impact of providing assistance with soil testing, interpretation, and nutrient management planning on actual nutrient balances (the difference between nutrient inputs and exports in harvested crops) (Drinkwater et al. 2008) and environmental impacts of urban garden plots.

Unique challenges and strategies for pest management in NYC community gardens

Gardeners also cited insect pests among their top challenges for food production, and we found that pest populations are high enough to cause substantial crop damage and yield loss. This is consistent with previous studies of urban forests and vacant lots, which show that cities exhibit higher densities of herbivorous insects and reduced populations of arthropod natural enemies (predators and parasitoids) compared to surrounding rural areas (Cregg and Dix 2001; McIntyre 2000; Pickett et al. 2001). Our findings suggest that this pattern also holds in urban food-producing community gardens. The key drivers of severe pest pressure in urban settings may stem from 1) reduced plant diversity and abundance (both within gardens and in the surrounding landscape) which limit populations of natural enemies that would control pests, and 2) increased environmental stressors which allow pest species to proliferate.

Because predators and parasitoids need larger contiguous areas of high-quality habitat than herbivorous pests to gain enough food resources, natural enemies suffer more than pests in fragmented urban habitats (Gibb and Hochuli 2002; McIntyre 2000). In rural and sub-urban agricultural landscapes, large expanses of vegetation and diverse habitats (e.g., forested and riparian areas and hedgerows) provide natural enemies with shelter from environmental extremes, over-wintering sites, and food when pests are absent (Chaplin-Kramer et al. 2011; Isaacs et al. 2009; Landis et al. 2000). Such habitats are small and fragmented in urban environments, thus reducing the resources available to support arthropod predators and parasitoids. Generally low floral and woody perennial cover in many community gardens may further exacerbate the negative effect of habitat fragmentation on these taxa, leading to low abundance and diversity of natural enemies that would otherwise regulate pest populations (Gardiner et al. 2014).

Floral and woody perennial plantings can be used to restore natural enemy populations and promote biological control in agricultural systems, provided that suitable plant species are chosen – that is, species that are attractive to arthropod predators and parasitoids and provide critical resources at the right points in their life cycles to support optimal survival and reproduction (Fiedler and Landis, 2007a; Fiedler and Landis, 2007b). Most studies showing an increase in natural enemy populations with such ‘habitat management’ efforts have taken place on rural farms. For example, borders of undistributed vegetation around field edges serve as refuges for insect predators such as ladybird beetles, spiders, and predatory mites (Mohler and Johnson 2009) and may enhance pest control in adjacent crops, in some cases up to 200 m from hedgerows (Morandin et al. 2014). If locally-adapted ‘insectary plantings’ in urban gardens were to have similar effects on natural enemies and pests, biocontrol benefits from a single hedgerow could extend throughout an average-size garden in NYC.

That said, increasing landscape complexity in urban community gardens may not always result in the same outcomes as those documented for rural farms, particularly if fragmentation of the urban landscape prevents natural enemies from colonizing gardens when suitable habitat is provided (Tscharntke et al. 2005). However, the limited research available suggests that habitat management is a viable option and successful practices could be developed for city gardens. We documented several natural enemy taxa in NYC gardens that are effective biocontrol agents against problematic insect pests. These included minute pirate bugs and spiders (both generalist predators) as well as ladybird beetle adults and larvae, syrphid fly larvae, and lacewing larvae, all which consume aphids, spider mites, whiteflies, and other soft-bodied insects (Altieri et al. 2010). Though we did not observe high densities of these arthropod predators, their presence in the gardens suggests that providing additional resources through habitat management could augment their populations and biocontrol activity. Indeed, in a parallel study in NYC gardens, we found that increasing floral area significantly increased the density of natural enemies on some crops (Gregory et al., In Preparation). In urban gardens and lots in Ohio, the abundance of predatory long-legged flies (Dolichopodidae) was positively correlated with bloom abundance, and the abundance of minute pirate bugs was positively correlated with vegetation height (Gardiner et al. 2014). This provides further support for the idea that floral and perennial plantings could contribute to enhanced biological control in urban gardens, though further research (particularly longitudinal study) is needed to evaluate the impacts of habitat management strategies on natural enemy abundance, diversity, predation and parasitism rates, and ultimately crop health in urban gardens.

Incorporating cover crops into vegetable rotations could also enhance conservation biological control in NYC community gardens (in addition to the soil-related benefits discussed above). Over-wintering cover crops such as vetches and clovers supply moisture, physical protection, and food for generalist natural enemies like minute pirate bugs and ladybird beetles, which allows them to establish large populations before key pests of summer vegetables arrive (Clark 2007) (p. 28). Adding cover crops would also diversify rotations in gardens where the dominance of Solanaceous, Brassica, and Cucurbit crops may worsen pest pressure. Widespread and repeated planting of crops in these three families may be partially responsible for insect pest problems, as plantings dominated by a single crop or family support larger pest populations and suffer greater yield losses than mixed stands containing lower densities of different crops (Andow 1991). We found that the most severe insect pest problems in NYC gardens affect the dominant plant families, which supports the hypothesis that resource concentration exacerbates pest damage. Beyond adding cover crops, implementing crop rotations that utilize a diversity of botanical families, and properly rotating these families, could help break pest and disease cycles (Mohler and Johnson 2009).

Urban gardeners may need to be particularly conscientious about habitat management and rotation planning to support natural enemies and discourage pests, as there are several environmental factors beyond gardeners’ control that contribute to urban insect pest populations. First, the increased heat typical of urban environments may contribute directly to the growth of some pest populations (Dale and Frank 2014). Urban plants also experience stressors that increase their susceptibility to pest colonization. For example, urban plants often suffer water stress due to increased vapor pressure deficit and transpiration (a result of warmer urban temperatures), and/or limited soil water availability in shallow, coarse-textured substrates. Water stress, in turn, may interfere with plant defenses and cause plants to produce sap with high concentrations of amino acids, making them more attractive to sap-feeding insects such as aphids (Cregg and Dix 2001; McIntyre 2000). Combined with low natural enemy densities, these microclimatic factors may play an important role in allowing pests like whiteflies – which are typically considered a greenhouse pest (Cole et al. 2009; Klass 1996) – to proliferate in outdoor settings in urban gardens.

Gardening education: Content and program design considerations

Successfully implementing agroecological practices (such as cover cropping, habitat management, and crop rotation) requires ecological knowledge and skills for adapting the practices to local conditions and management goals (Settle 2000; Shennan 2008). To support gardeners in developing sustainable practices for urban food production, we suggest that garden educators: 1) incorporate ecological concepts in educational programming, 2) provide follow-up support as gardeners implement, monitor, refine, and share new practices; 3) enhance the accessibility of gardening education.

Our interview findings indicate that most gardeners have general familiarity with ecologically-based practices such as crop rotation and cover cropping, but there are significant gaps in their understanding of ecological concepts that underlie successful implementation of these practices. To address these gaps, garden educators could incorporate ecological knowledge and observations into workshops, educational materials, and technical assistance. Gardeners should understand the functions of a given practice, traits and ecological niches of relevant species (e.g., food crops, cover crops, weeds, arthropod pests and natural enemies, etc.), and ecological processes being managed (Table 9). Such knowledge provides a strong basis for making informed choices about agroecological practices to achieve management goals – for example, which cover crops will effectively compete with weeds in a highly fertile garden soil or which floral and woody perennial plantings will provide resources for natural enemies.

In addition to basic ecological knowledge, gardeners also need skills for testing and refining agroecological practices to fit local environmental conditions, a strategy known as 'adaptive management' (Peterson 2005). The experiences of farmers and natural resources managers suggest that experimentation, observation, and reflection in a community of practice may promote learning that enables ecologically-based, adaptive management (Braun and Duveskog 2008; Krasny and Tidball 2009; Kroma 2006; Warner 2007). To support development of adaptive management skills, educators can engage gardeners in monitoring the outcomes of new practices (for example, natural enemy abundance and pest damage on crops before and after the introduction of habitat management plantings) and reflecting in groups on improvements that might be made in gardening practices.

As garden educators work to enhance their programming with ecological knowledge and adaptive management skills, it is important to ensure that such programming is accessible to a broad range of community gardeners. In our interviews, gardeners expressed a strong preference for workshops as the best way to obtain new gardening information, but reported talking

Table 9 Agroecological practices, goals of using them, and key species traits and ecological processes that gardeners should be familiar with to successfully implement and refine agroecological practices

Agroecological practice	Functions/Goals	Ecological knowledge needed to use the practice successfully	
		Species traits	Ecological processes
Cover cropping	• Improve soil quality though organic matter inputs [a] • Improve soil fertility and nutrient cycling through N fixation by legumes, and nutrient retention by non-legumes [b] • Suppress weeds [c] • Provide resources for arthropod pollinators and natural enemies [d]	• Cover crops: Family groupings, seasonal niches, biomass production, N-fixation ability (legumes), competitiveness (germination and growth rates, allelopathic chemicals produced) • Weeds: Life cycles (especially when seed is produced), seasonal niches	• Primary productivity • Nutrient assimilation • Legume nitrogen fixation • Decomposition and nutrient mineralization • Competition (cover crops vs. weeds)
Habitat management (for arthropod natural enemies)	• Reduce herbivorous pest populations and crop damage through conservation biological control [e]	• Arthropod pests: Life cycles, resources requirements, and existing natural enemies (predators and parasitoids) • Arthropod natural enemies: Life cycles, resource requirements (alternative food, shelter, over-wintering), dispersal ranges • Noncrop plants for providing natural enemy habitat: phenology, resources provided,[e] attractiveness to natural enemies (often related to floral area)[f]	• Trophic structure and trophic cascades (indirect interactions across multiple trophic levels; e.g., augmented predator populations increase plant productivity by suppressing herbivore populations)[g] • Over-wintering • Foraging • Predation and parasitism
Crop rotation	• Prevent build-up of diseases and pests specific to particular crop families [h] • Improve soil fertility and nutrient cycling by planting crops with different nutrient requirements, rooting depths, and N-fixing ability [h] • Enhance weed management by planting crops with varying patterns of resource use, allelopathy, and soil management [c, h]	• Crops: Family groupings, seasonal niches, disease and pest susceptibilities, nutrient requirements • Diseases and insect pests: Life cycles, alternate hosts, nonhost period required to eliminate inoculum or eggs/larvae, dispersal capabilities • Weeds: Life cycles (especially when seed is produced), seasonal niches	• Disease and insect pest survival and reproduction • Nutrient assimilation • Legume nitrogen fixation • Competition (crops vs. weeds)

[a] Snapp et al. 2005

[b] Drinkwater and Snapp, 2007

[c] Liebman and Dyck 1993

[d] Clark 2007

[e] Landis et al. 2000

[f] Fiedler and Landis, 2007b

[g] Shennan 2008

[h] Mohler and Johnson 2009

with other gardeners and consulting website and print materials more frequently. The gap between gardeners' preferred method for obtaining information (workshops) and the information sources used most frequently (other gardeners, websites, and print materials) likely reflects the additional time and travel commitment associated with attending workshops. Numerous agencies throughout New York City offer workshops on gardening topics, from growing techniques to food preservation to garden organization and leadership.[4] Thus, scarcity of workshops is not likely a problem. Future gardening education efforts might focus on tailoring workshops to the interests of specific gardening groups, enhancing workshop accessibility in terms of scheduling and geographic locations, and providing follow-up support to assist gardeners in implementing new, knowledge-intensive management practices.

Given the diversity of languages and cultures in NYC gardens, educators should also strive to provide resources in appropriate languages and develop culturally sensitive programs. While the diversity of languages in NYC community gardens indicates rich opportunities for cross-cultural learning, it likely presents a challenge for organization, communication, and education in gardens. Several authors have cited language and cultural barriers (e.g., lack of seeds and information on ethnic specialty crops) as challenges for gardening education in urban areas (Baker 2004; Saldivar-Tanaka and Krasny 2004). Our results indicate strong interest in gardening education materials and support in languages besides English, particularly Spanish.

Conclusions

Despite strong public interest in urban community gardens as sources of healthful produce and sites for environmental stewardship, little research has investigated gardeners' planting and management practices or the ecological characteristics affecting food production in these gardens. Our integrated agroecological and social characterization of NYC community gardens provides insight into challenges for sustainable agricultural production posed by the urban environment and current growing methods, and suggests promising directions for future urban gardening research, education, and practice. Specifically, research and education partnerships are needed to develop urban agriculture practices that build soil quality in raised-beds, promote sustainable nutrient management, and address insect pest damage.

Soil and nutrient management are key challenges for community gardeners. Most NYC gardeners grow crops in raised beds constructed with clean fill and compost. These anthropogenic soils tend to have a sandy texture, low water-holding capacity, high organic matter levels with a large proportion from recent inputs, and excessive nutrient levels (including P, K, Mg, and Ca). Cover cropping could improve soil structure and water- and nutrient-holding capacity by adding organic material and promoting aggregation, largely through physical and biological processes associated with root growth and decomposition. Our soil analyses also indicate a need for improved access to soil testing and guidance on appropriate use of soil amendments in order to prevent over-fertilization and associated environmental pollution.

[4] Organizations offering gardening workshops in NYC include: Bronx Green-Up/New York Botanical Garden (http://www.nybg.org/green_up/), Brooklyn Botanic Garden (http://www.bbg.org/greenbridge), East New York Farms! (http://eastnewyorkfarms.org/), Green Guerillas (http://www.greenguerillas.org/index.php), GreenThumb (http://www.greenthumbnyc.org/), GrowNYC (http://www.grownyc.org/), Just Food's City Farms Workshop Series (http://justfood.org/city-farms/community-workshop-series) and Farm School NYC (http://justfood.org/farmschoolnyc).

We also found that insect pests in NYC community gardens cause substantial crop damage and loss, and arthropod natural enemies are relatively scarce. While habitat fragmentation and urban environmental conditions likely contribute to high pest and low natural enemy densities in community gardens, land-use practices and crop choices within gardens may exacerbate pest problems. With just a small percentage of garden area devoted to flowers and woody perennials, most gardens may not provide adequate resources for arthropod natural enemies that provide biological control of insect pests. Furthermore, the dominance of just three crop families (Brassicaceae, Cucurbitaceae, and Solanaceae) in NYC gardens may create ideal conditions for insect pests that affect these crops. Research and education efforts to reduce pest damage in urban gardens could focus on habitat management (planting specific floral and woody perennial species to provide resources for predator and parasitoid insects) and diversifying crop rotations.

As researchers and educators partner with urban community gardeners to develop and share ecologically-based practices, thoughtful program design can increase the impact of these efforts. Gardening educators should incorporate ecological knowledge and inquiry-based approaches in their programming to support gardeners in using agroecological management practices and developing adaptive management skills. Enhancing the accessibility of gardening workshops and technical support (in terms of geographic location, scheduling, and languages offered) is also crucial to ensure that educational programming addresses the needs and taps the knowledge of diverse gardening groups. Working together to understand how garden practices and characteristics impact ecosystem services can inform community garden design and management to achieve food production and environmental quality goals.

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Compliance with ethical standards Prior to administering garden coordinator and gardener surveys, we submitted the interview guides (including an oral informed consent protocol) to the Institutional Review Board for Human Participants in the Cornell University Office of Research Integrity and Assurance. They were deemed exempt from review due to the non-sensitive nature of the information sought. Participating gardeners received updates via mailings, a project website (http://blogs.cornell.edu/gep/), and presentations.

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