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Crop diversity and plant–plant interactions in urban allotment gardens

Matthew E. Woods[1]‡, Rehman Ata[1]‡, Zachary Teitel[1]†, Nishara M. Arachchige[1], Yi Yang[1], Brian E. Raychaba[1], James Kuhns[2,3] and Lesley G. Campbell[1]*

[1]Department of Chemistry and Biology, Ryerson University, Toronto, ON M5B 2K3, Canada
[2]Toronto Urban Growers, http://www.torontourbangrowers.org/
[3]Centre for Studies in Food Security, Ryerson University, Toronto, ON M5B 2K3, Canada
*Corresponding author: lesley.g.campbell@ryerson.ca

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Abstract

Allotment food gardens represent important sources of food security for urban residents. Since urban gardeners rarely receive formal agricultural education and have extremely limited space, they may be relying on readily available gardening advice (e.g., seed packet instructions), inventing cultural strategies that consider inter-specific competitive dynamics, or making poor planting decisions. Knowledge of garden crop diversity and planting arrangements can aid in designing strategies for productive urban gardens and food systems. We surveyed 96 individual plots in 10 allotment gardens in the Toronto region, assessed crop diversity within gardens and recorded planting practices used by urban gardeners by measuring the proximity of individual plants relative to similar or different crop species. We also compared planting densities used by urban gardeners with those recommended by major seed distributers. Collectively, Toronto urban agriculture contributes substantially to urban plant diversity (108 crops), but each plot tends to be relatively depauperate. Carrots and lettuce were three to five times more likely to be planted in clusters than intermingled with other crops ($P < 0.05$); whereas gardeners did not appear to use consistent planting arrangements for tomatoes or zucchini. Gardeners tended to plant tomatoes and zucchini 56–62.5% more densely than recommended by seed distributers ($P < 0.001$), whereas they planted 147 times fewer carrots in a given area than recommended ($P < 0.05$). Furthermore, neither crop planting density nor crop diversity changed with plot size. The planting arrangements we have documented suggest gardeners using allotment plots attempt plant densely in extremely limited space, and are employing cultural strategies that intensify competitive dynamics within gardens. Future research should assess the absolute and relative effect of altered cultural practices on yield, such that any modifications can be prioritized by their impact on yield.

Key words: crop diversity, domestic gardens, intercropping, planting density, polyculture, urban agriculture

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Introduction

As global food demands increase, food production methods must become increasingly efficient, a challenge that requires diverse solutions[1,2]. Urban agriculture converts unproductive land to productive gardens and moves food production closer to dense human populations[3,4]. Whereas most agricultural research has focused on improving crop yield of large, monocultural fields found on rural farms, urban gardens typically contain a diversity of crops and the methods to improve yield in rural monocultures may not easily transfer to small, urban, polyculture systems[4]. Instead, synthesizing new or revisiting traditional methods of small-scale agriculture may be more appropriate strategies for maximizing yield[5]. Furthermore, it may be especially important to use a different approach than rural agriculture since urban agroecology offers an accessible opportunity for the public to participate in scientific knowledge acquisition and dissemination, firsthand[6–9]. For this to happen, a clear understanding of the gardening practices of modern, urban gardeners is required but currently does not exist, to our knowledge.

In polycultures, two or more crops grow in close proximity such that they interact agronomically[10]. Diverse

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‡ These authors contributed equally to this work.
† Current address: Department of Integrative Biology, University of Guelph, Guelph, ON N1G 2W1, Canada.

cropping systems can facilitate nutrient cycling[11] and reduce pest outbreaks[12]. Still, mechanization of tilling and harvesting is often difficult due to the complexity of spatial arrangements and phenological variation of crops within an intercropped plot[13]. Thus, polycultures are typically more labor-intensive than monocultures and labor costs limit their widespread adoption[14]. However, polycultures are often adopted in small garden plots intended for domestic use and may even benefit overall garden yield.

Spatial arrangements of plant species within polycultural systems vary; plants may be clustered within species-specific groupings or intermingled. In mixed intercropping, gardeners haphazardly disperse a variety of crops within a given plot[15]. Alternatively, row cropping divides two or more crops into alternating rows during a single field season[16]. Further, vertical layering, common in tropical home gardens and increasingly common in home gardens in the global north, combines crop species that grow within the same soil but use different portions of the above-ground vertical strata to efficiently use space[17]. Finally, relay intercropping is employed when gardeners plant crops at different stages of their life cycle, maximizing light and soil efficiency[18] as well as reducing weed competition[19]. Each of these planting strategies will affect the type and intensity of plant–plant competition (and thus yield) within the plot. Therefore, understanding the spatial arrangement of plants within urban garden plots and their consequent effect on yield will be important to identify successful urban gardening approaches that can improve urban food production more broadly.

Often urban garden plots are composed of multiple, neighboring compact polycultures and thus represent a unique form of polycultural farming. Beyond increasing the sustainability and food security of urban populations[20], urban gardens have also been shown to promote positive social environments. They support and reinforce cultural identity[7], create a cultural hub within a community and decrease youth delinquency[21], by providing youth with opportunities to feed themselves and their families[22]. Finally, urban gardening tends to increase the frequency of healthy behaviours[22,23]. Yet, productivity of these small plots can be limited by the space available, the experience and interest of the gardener and the cost of managing these plots within cities[24]. Rare reports suggest that urban gardens can produce more food than rural farms on a per area basis[25,26]. When planted in small spaces, urban garden yield may be driven, in part, by the mode and intensity of plant–plant interactions[27]. When planting designs create plant–plant interactions that reduce competition[28] or are facilitative (although evidence for this is less common[29]), yields should improve and, in contrast, decline when interactions are highly competitive.

One physical difference between urban gardens and rural farms that could alter the nature of plant–plant interactions within these forms of agriculture is the size of each garden plot. With dramatically reduced space available in urban gardens, which then also reduces the utility of mechanized help (e.g., tractors, harvesters, etc.), one might expect a higher frequency of inter-specific plant interactions and increased planting density. Plants can sense the presence of their neighbors before competition begins[30,31] and may allocate more energy to competitive traits[32,33], potentially reducing both individual- and population-level yield. Polycultures show an inverse relationship between inter-plant competition and productivity[34]; polycultures may be more productive than monocultures when intra-specific competition is greater than inter-specific competition. Competitive interactions may be reduced in polycultures because species access light and soil resources in different ways[35,36].

Recently, resources have been placed into rebuilding the local food supply chain and restructuring Ontario's food and agriculture system, especially within urban centers, with the intention of creating a food system that is more sustainable through local production, equitable and economically viable[37]. In the city of Toronto, there are more than 100 community gardens in which residents can gain access to a garden plot[38]. In Toronto, one of the most ethnically diverse cities in North America (43% visible minority[39]), there is potential to see a wide variety of crops within community gardens. Many studies have examined the positive impacts of community gardens (see above citations), but fewer have explored which crops are most commonly found in urban gardens (especially in the global north) and the drivers of that diversity[40–45]. Further, there has yet to be a study that closely examines the spatial arrangements of these crops and the effects of competition on yield.

Our long-term goal is to identify polycultural garden planting designs that consistently result in high yield per unit area in urban gardens. As a first step, we measured allotment-plot crop diversity in the Toronto region (Canada), catalogued planting designs, described plant–plant interactions observed, and measured correlates of competitive intensity (density, distance to nearest neighbor) within a garden as baseline information for future urban agricultural research and extension activities. To that end, we asked:

1. What crops do community gardeners in the Greater Toronto Area grow in their urban garden plot?
    - (a) How diverse are allotment plots and what are the most common plants found in gardens?
2. Second, how are crops arranged in Toronto allotment plots?
    - (a) Are crops planted in crop clusters or intermingled among other crops?
    - (b) Are gardeners planting at densities consistent with the plant spacing recommended by major seed distributers?
    - (c) Do gardeners alter crop diversity or planting density based on the size of their allotment plot?

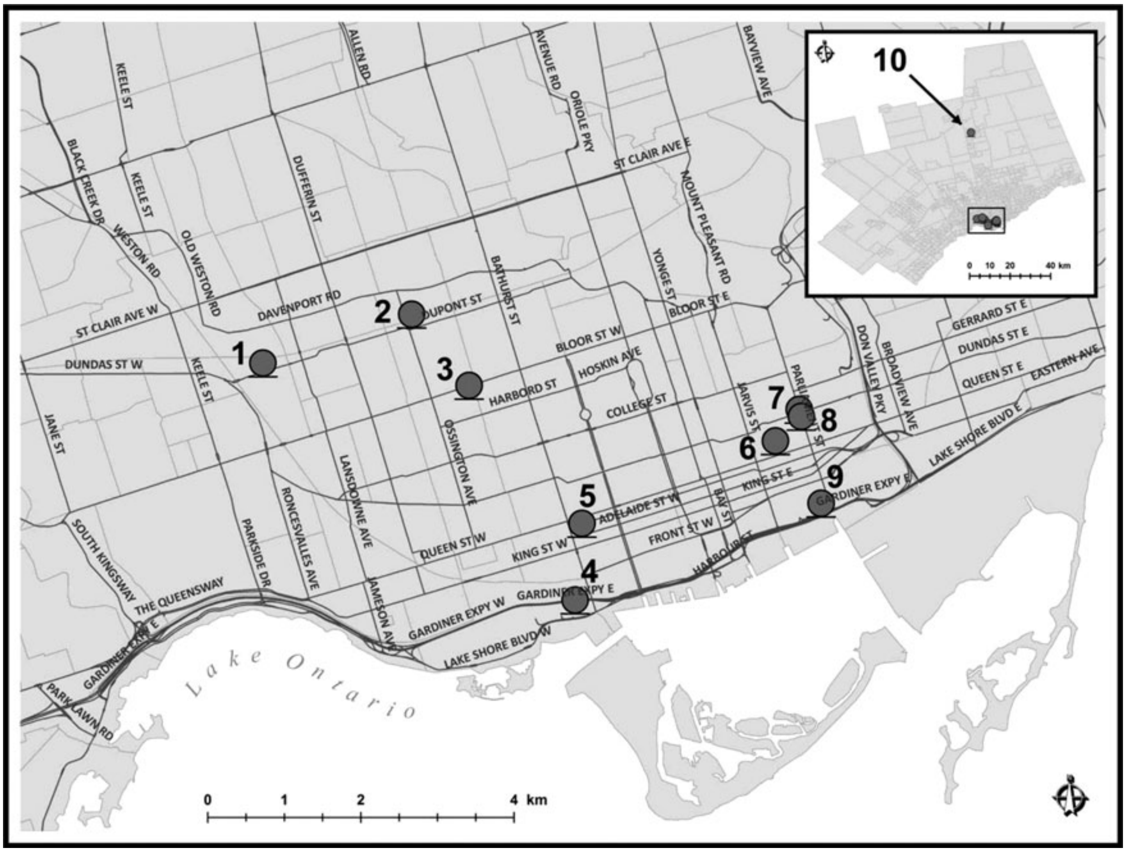

Figure 1. Distribution map of the sampled community gardens in the city of Toronto, Canada with inset map of all sample community gardens located within the broader Toronto census metropolitan area. Sampling performed across Toronto involved 96 individual plots from the following 10 allotment gardens: (1) Perth–Dupont, (2) Garrison Creek, (3) Christie Pits, (4) Fort York, (5) Alex Wilson, (6) Moss Park, (7) Regent Park, (8) 295 Parliament Street, (9) Harmony Gardens and (10) Newmarket. Major roads, highways and census tract boundaries are also shown. Map projection: NAD 1983 UTM Zone 17N.

Materials and Methods

Study sites

The study was conducted in Toronto, Ontario, Canada over the summers of 2013–14 (Fig. 1), which experiences a temperate climate, and an ~195 day growing season (Frost-free dates: April 22–November 3, 2013 and April 16–November 1, 2014). Toronto hosts over 100 community gardens that have a diversity of missions, including education, food production for food banks, community building, etc.[38] We first identified all gardens that explicitly provided plots for individual use and contacted garden coordinators for permission to visit gardens (contact was initiated through phone or email first, depending upon which contact information was listed; in cases where we didn't receive a reply, we visited the garden). Our study included the first 10 gardens from which we received a positive response from the coordinator: Alex Wilson, Christie Pits, Dupont Perth, Fort York, Garrison Creek, Heritage Gardens, Moss Park, New Market, Regent Park and 295 Parliament St. Community Gardens (Fig. 1).

Garden surveys

Within each community garden, we randomly selected 10 individual plots from which we recorded crop and ornamental plant diversity and planting arrangement (100 plots sampled in total). To assess crop and ornamental plant diversity within individual plots, we first surveyed each plot to identify all intentionally planted crops within its boundaries. While we understand that this could underestimate the crop diversity of plants used in gardens (e.g., excluding foraged wild or weedy plants), we expected this to have a minimal effect on our results. Plant identities were determined using a flipbook tool with pictures of possible crops using common names, allowing us to differentiate between crops such as zucchini and pumpkin (both *Cucurbita pepo*). Subsequently, these crops were grouped according to species. Student surveyors were informally tested on their ability to identify plants. Some groups were inconsistently recorded (specifically, surveyors could not consistently differentiate between bean species [*Phaseolus* spp.] and also had trouble differentiating pepper species [*Capsicum* spp.]), so we grouped species within each genus

Table 1. List of crops encountered (with latin binomials) in gardens and their assignment to crop type categories.

Crop type	Crops included
Root vegetables	Carrot (*Daucus carota*), Garlic (*Allium sativum*), Ginger (*Zingiber officinale*), Green onion and Onion (*Allium cepa*), Leek (*Allium ampeloprasum*), Red beet (*Beta vulgaris* ssp. *vulgaris*), Taro (*Colocasia esculenta*)
Leafy vegetables	Arugula (*Eruca sativa*), Bok choy (*Brassica rapa* ssp. *chinensis*), Callaloo (*Amaranthus* spp.), Celery (*Apium graveolens*), Collards, Kale and Kohlrabi (*Brassica oleracea*), Crown Daisy (*Glebionis coronaria*), Lettuce (*Lactuca sativa*), Lovage (*Levisticum officinale*), Mustard greens (*Brassica juncea*), Red Spinach (*Amaranthus dubius*), Spinach (*Spinacia oleracea*), Swiss chard (*Beta vulgaris* ssp. *vulgaris*)
Tomato	Tomato (*Solanum lycopersicum*)
Cucurbits	Bitter gourd (*Momordica charantia*), Buttercup squash (*Cucurbita maxima*), Butternut squash (*Cucurbita moschata*), Cucumber (*Cucumis sativus*), Acorn squash, Pumpkin, Summer squash and Zucchini (*Cucurbita pepo*)

together which had the effect of reducing our estimate of crop diversity. When a plant was unknown to the surveyors, we would either ask the gardener (when present) or photograph the plant and a more seasoned gardener on our team would identify the plant. Maps of each garden plot were hand drawn, for future reference. In four plots, data collectors overlooked recording the plot identity and plot size; these four plots were removed from data analysis, reducing our sample size to 96 plots.

Based on previous observations, we noticed that gardeners commonly planted tomatoes (*Solanum lycopersicum* cvs.), root vegetables, cucurbits and leafy vegetables within their gardens (Table 1, i.e., crop type). Of those broad groups, we expected carrots to be a common root vegetable, zucchini to be a common cucurbit and lettuce to be a common leafy vegetable in gardens (see the ‘Results’ section below) and arbitrarily chose these crops to explore the tendency for gardeners to polyculture these crop types. We then gathered information about planting arrangement for these four crops. First, for all the plants of a given crop, we identified whether urban gardeners clustered plants from the same crop together (hereafter referred to as clustered), intermingled them with other crops (hereafter referred to as intermingled), or if the gardener planted only a single plant of that crop (hereafter referred to as solo). Note, if there was only one plant, we could not consistently determine whether or not a gardener had planted more than one individual per crop and subsequently experienced loss of that plant through mortality. Thus, solo plants were considered an intermingled planting arrangement. We also described whether each of the four crops tended to have more distance between conspecific individuals or individuals of another crop by identifying the nearest plant neighbor of most individuals of a given crop type within the plot (both weedy and crop species). When the nearest plant neighbors tended to be members of the focal species, this was considered clustered and when the nearest plant neighbors were always non-focal species, this was considered intermingled. Distance was always assessed from the point at which the plant stem made contact with the soil (i.e., where it was planted).

To measure planting densities, we selected the tallest individual of the focal crop in the plot, identified its nearest neighbor, and measured the distance between the focal plant and its nearest neighbor. Finally, we counted the number of plants within a 30 cm radius around the focal plant, keeping track of crop and weedy plants separately. Nearest neighbors were identified as a particular crop or categorized as ‘weed’ (i.e., individuals not intentionally planted by the gardener).

Hypothesis testing

To address our research objectives, we performed several analyses, outlined individually below. For all analyses reported here, we used SPSS (version 21; SPSS Inc., Chicago, IL, USA) unless otherwise specified. Throughout all analyses, variables were transformed when they violated assumptions of normality (as noted below). Plants grown within the same plot lacked statistical independence. Therefore, measurements of planting arrangement within a plot across crop types were considered repeated measures. We used a Tukey HSD test to perform *post-hoc* pairwise comparisons of treatments.

Agricultural decisions made by a single gardener could be due to the information available to them and likely arrives in different forms: e.g., planting density instructions on a seed packet (which should be similar for all Toronto gardeners) or influential and experienced gardeners chatting with neighboring gardeners (which may involve much more local information transfer, that is, a single community garden). First, we tested for differences in number of crops per plot among community gardens, where community garden was treated as a random effect (to explore the role of non-specific local and social influences on gardening practices). Plot size was treated as a covariate in the model. Next, we performed four logistic regressions (one per crop type) to determine whether each of the four crops were planted in clusters or intermingled with other crops, where community garden was treated as a random effect.

To determine the effect that garden plot size had on planting density, we used a repeated-measures, mixed, general, linear model with an auto-regressive covariance matrix that included community garden (random, between-subjects effect) and crop type (within-subjects factor) and their interaction, as well as the covariate, plot size. As a response variable, we used a measure of plant density: number of plants within the 30 cm radius discounting weeds.

To determine whether gardeners favored particular intercropping strategies, we compared the observed frequency of clustered versus intermingled planting arrangements for each of the four crops using a chi-square (χ^2) test. The expected value was calculated as an equal frequency of clustered and intermingled planting arrangements.

Finally, we ran a series of analyses to determine whether gardeners used planting densities similar to those recommended by major seed distributers. We compared recommended planting densities between Stokes seeds (http://www.stokesseeds.com, last accessed November 25, 2014) and McKenzie seeds (http://www.mckenzieseeds.com, last accessed November 25, 2014); upon finding them very similar for most and identical for some crops, we collected planting densities only from Stokes seeds. To estimate recommended planting densities, we recorded the recommended spacing, for tomato, lettuce, zucchini and carrots from 10 cultivars per crop. For each crop, we recorded recommended spacing for 10 cultivars and averaged this value. When a range of spacings were provided for a given cultivar, we chose the midpoint value. Only gardens growing a given crop type were included in each analysis. These values served as the reference against which the distribution of planting densities measured in community gardens were compared using one-sample *t*-tests. When necessary to meet test assumptions, planting densities were natural logarithm transformed.

Results

Crop diversity and composition in community gardens

We recorded 108 crops from 24 plant families within the 96 community garden plots surveyed, with 8.11 ± 0.6 crops per plot (mean ± SE, median = 8, min = 1, max = 26). On average, plots contained 0.30 ± 0.90 crops per plot that did not occur in any other plot surveyed (i.e., a unique occurrence of a crop, median = 0, min = 0, max = 5). We were unable to identify 13 plants across eight plots that we believe were grown intentionally (non-weed species) and these unidentified crops were not included in subsequent analyses. The species accumulation curves and fitted models for the gardens surveyed (Fig. 2A) reached an asymptote, using the Chao presence/absence richness estimator, estimating 137 crops across the urban gardens we censused. Tomatoes were the most commonly planted crop followed by peppers, beans, basil (*Ocimum basilicum*), lettuce, Swiss chard, cucumber, onion, carrot and zucchini (Fig. 2B).

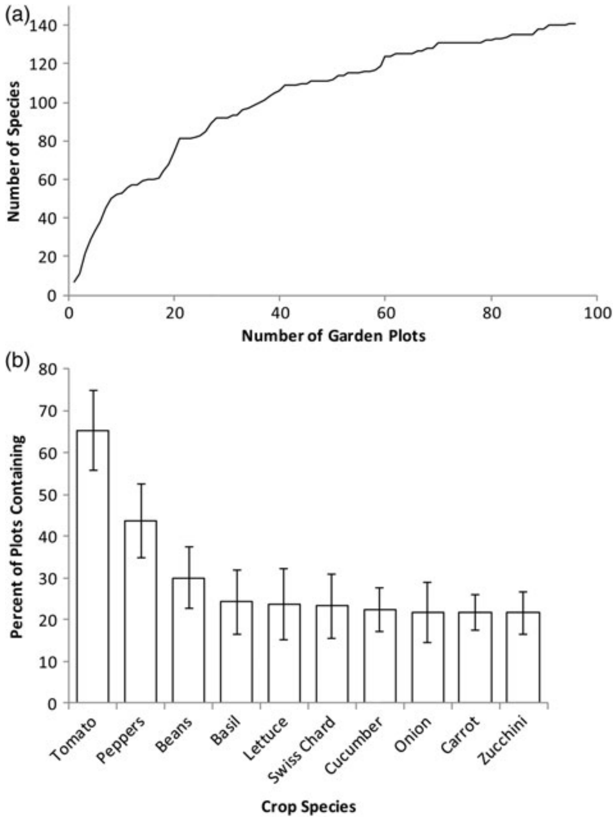

Figure 2. Crop richness in 96 individual garden plots distributed across 10 allotment gardens in Toronto, ON. (A) Species accumulation curve of the 96 gardens, with a predicted asymptote of 137 crops across all plots in the 10 community gardens using the Chao presence/absence richness estimator. (B) The mean percentage (±SE) of gardens containing the 10 most commonly encountered crops in Toronto, ON after recording crop presence at 96 community garden plots.

Planting arrangements within individual plots

When present in plots surveyed, gardeners tended to cluster lettuce ($\chi^2 = 4.26$, df = 1, $P = 0.039$) and carrots ($\chi^2 = 5.33$, df = 1, $P = 0.021$) but did not show a significant preference for clustered or intermingled planting arrangements for tomato ($\chi^2 = 2.32$, df = 1, $P = 0.13$) or zucchini ($\chi^2 = 0.05$, df = 1, $P = 0.82$, Fig. 3).

Do gardeners follow the spacing recommendations of seed distributors?

The average urban gardener did not follow the spacing recommendations made by major seed distributors. First, seed distributors suggested spacing tomatoes 41–60 cm apart (midpoint = 50, SD = 0, *n* = 10), but, on average, urban gardeners planted tomatoes significantly closer, at 23.66 cm from their nearest neighbor (Fig. 4,

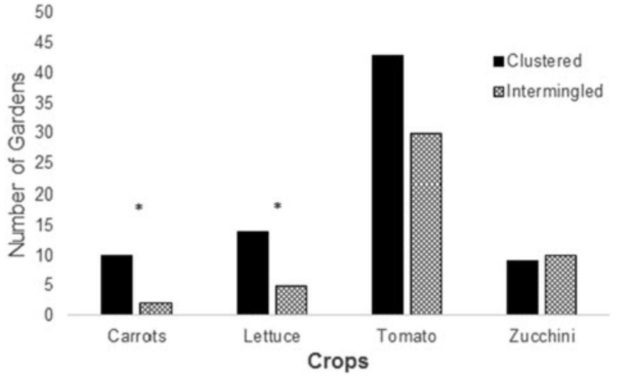

Figure 3. Number of garden plots where vegetables were arranged in homogenous crop clusters (black bars) or intermingled with other crops (patterned bars) for carrots, lettuce, tomatoes or zucchini. Asterisks indicate where clustering planting practices were significantly more common than intermingled planting practices ($P < 0.05$).

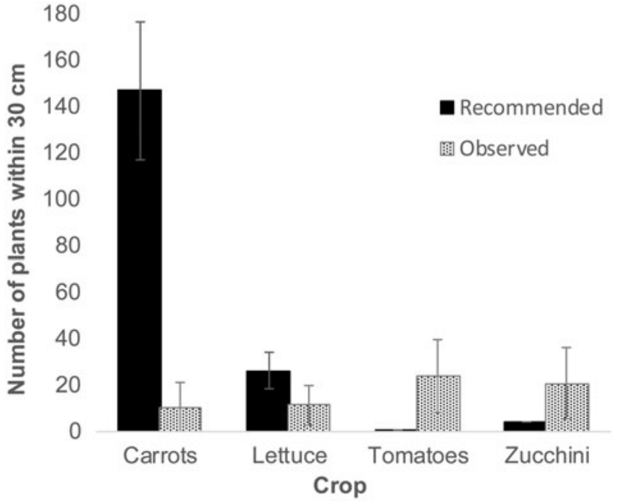

Figure 4. The number of plants within 30 cm of a crop (mean ± SD) based on seed package recommendations from Stokes seed company (black bars) and observed in Toronto allotment plots (patterned bars).

$t = 14.36$, df = 72, $P < 0.0001$). Similarly, where the recommended density for lettuce was 26.1 plants (SD = 7.87, $n = 10$) in 30 cm radius around a central lettuce plant, urban gardeners planted significantly less lettuce in that area (Fig. 4, $t = 3.75$, df = 19, $P = 0.014$). Gardeners planted more zucchini than recommended within the 30 cm radius around the focal zucchini (mean = 2, SD = 0, $n = 10$) (Fig. 4, $t = 2.6189$, df = 17, $P = 0.018$). Finally, seed distributors suggest planting one row (5 cm wide) of carrot seeds (each 4.7 mm apart ± 0.95 mm) in the 30 cm radius around a central carrot (~1470 seeds), but on average, urban gardeners planted significantly fewer carrots in that space (Fig. 4, mean = 9.73 plants, SD = 8.60, $t = 588.20$, df = 11, $P < 0.001$).

The effect of plot size on diversity and competitive interactions in urban gardens

Plot sizes ranged from 1.34 to 16.49 m^2 (mean = 6.24 m^2, SD = 4.34 m^2). We detected a marginally significant trend whereby gardeners tended to plant more crops in larger garden plots ($\beta = 0.067$, SE = 0.035, $F_{1,6} = 3.52$, $P = 0.10$). However, overall, gardeners did not change plant density of any crop type as plot size increased ($P > 0.05$).

Discussion

Across Toronto, crop diversity was relatively high (Fig. 2A) but within individual urban garden plots, diversity was relatively low. Crops were often, but not always intermingled with other crops (Fig. 3). When plants of one crop were clustered (lettuce and carrots), these arrangements tended to reflect crop types that are typically densely planted, whereas those crops that were planted as either intermingled or clustered plantings (tomatoes and zucchini) are typically planted at lower planting densities (Fig. 2B). Gardeners tend to plant crops less densely than recommended by seed distributors (Fig. 4). Furthermore, neither crop planting density nor crop diversity, changed with plot size.

The contribution of agriculture to urban plant diversity

Urban centers tend to support high species diversity relative to nearby rural areas that also support human populations, often because of the non-native species collected in urban centers[46]. Economic, cultural and historical variation in neighborhoods may drive species richness gradients within urban centers[47]. In fact, cities can be extremely diverse; in Germany, Kuhn et al. documented 580 native plant species, 116 alien plant species introduced before the discovery of the Americas (pre-1500s) and 85 post–1500 alien plant species in German urban places[48]. When comparing across the full range of land-use types within cities, gardens may be hotbeds of plant diversity within the broader landscape[47,49]. Domestic gardens from four urban centers in the UK supported 438 species (largely non-native), far outnumbering species diversity found in nearby native ecosystems[50]. Even lawns in the UK can support substantial numbers of plant species; a total of 159 species were recorded[51]. So, to what extent does urban agriculture contribute to species diversity within city boundaries?

With perhaps still the highest proportion of immigrants than any other city in the world, Toronto is a culturally diverse metropolis[52,53]. The city's increasing human diversity may be reflected in Toronto's gardens. In Toronto, food production occurs in backyards and allotment plots[38,54]. Importantly, the average garden size of backyard food gardens in Toronto is much larger (41 m^2, $n = 125$[54]) than that available to gardeners with allotment plots (5.8 m^2, $n = 8$[26]; 6.2 m^2, $n = 91$, results presented above). Interestingly, the allotment plots we censused (108 crops in 96 plots) were much more diverse than backyard gardens in Toronto, where a census recorded only 27 crops[54]. With similar results to our findings, Taylor and Lovell[17] recently inventoried 121 edible plant species in 59 home gardens in Chicago. These differences likely reflect socio-economic and cultural differences between the homeowners and allotment gardeners[38,47]. Our allotment plots also tend to be radically smaller than gardens censused in other studies (e.g., 37–10,000 m^2, Niamey Gardens, Niger[55]; 225–3400 m^2, Balzaporte Gardens, Mexico[41]) and yet crop diversity in Toronto was similar to that in Niamey[41].

When one compares regional estimates of food prices by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) to the most abundant crops found in Toronto home gardens, several common garden crops (i.e., zucchini, tomatoes, cucumbers and lettuce) are also considered some of the most expensive crops sold in Ontario[56]. This suggests that urban gardeners may be planting with food security in mind (although see[57]). Further, five of the most abundant crops in Toronto home gardens (i.e., tomatoes, cucumbers, carrots, peppers and onions) fall within the top six of most produced crops in Ontario[56]. This suggests that what urban gardeners grow in their gardens is not influenced by what is readily available in Toronto markets[56].

The consequences of polyculture for urban garden yield

Gardeners planted tomatoes and zucchini in both clustered and intermingled arrays equally, but planted lettuce and carrots in clustered more than in intermingled arrays (Fig. 3). Interestingly both tomatoes and cucurbits benefit from intercropping, especially with each other; intercropping tomatoes and cucumbers is thought to be beneficial for plant yields[58] and has achieved a land equivalent ratio (LER, i.e., a ratio describing the area under monoculture versus the area under intercropping required to give equal amounts of yield at the same management level, where values above one suggest a relative yield benefit to intercropping) of 1.14 compared with growing both crops in monoculture[59]. Intercropping tomatoes in other combinations has achieved a beneficial LER of 1.08[60]. Other intercropping systems that have garnered economically profitable LERs of greater than one include cauliflower[61] and cabbage[62], among others.

In contrast to when agricultural extension and research started in North America[63], today, the greater part of North Americans live within urban and suburban areas. Although the vast majority of food will continue to be produced by rural farmers, extension programming and research programs must be updated to serve the public good[64]. Although urban gardeners receive gardening information from a diversity of places (e.g., nongovernmental websites and virtual communities of gardeners[65]), most information provided to gardeners by agricultural extension (e.g., http://www.gardening.cornell.edu/) often assumes relatively large garden size (e.g., 97 m^2, http://www.ces.ncsu.edu/depts/hort/hil/pdf/ag-06.pdf) and subsequently focuses on row crops, thus encouraging clustered planting. Yet, in the urban gardens we visited, we rarely found garden plots large enough to require walk-ways to access even the most central spaces and hence row cropping was rarely used as a planting design consistent throughout the plot, although clustered planting was common for lettuce and carrot crops. Differences in arrangement between urban and rural gardens apparently have dramatic effects on the way gardeners arrange plants within gardens, and thus on the potential for interspecific interactions.

The consequences of plot size and planting densities for urban garden yield

Urban gardens in Toronto and elsewhere, despite their coordination by non-professionals, can be very prolific, in some cases producing five times more food than expected for rural farm yields[26] but this success may not necessarily be consistent[57]. Differences in yield in either direction between rural and urban producers suggest that gardeners may be making different cultural decisions than rural farmers. We suspect there are several reasons for this. For instance, rural farms may not be as space efficient as urban gardens; spacing recommendations from seed suppliers may reflect the need to accommodate machinery on large rural farms. Further, urban gardeners may employ trellising or staking to maximize the use of vertical space, whereas rural farmers often do not. Alternatively, as noted earlier, gardeners may have a range of motivations for gardening, and their goals may not be to maximize yield[45,57]. Instead, they may plant at high densities in polycultures because they wish to grow a wide range of foods[45]. Since increased plant density increases crop susceptibility to disease[66] and increased plant diversity reduces crop susceptibility to disease[67], it is difficult to understand the role that disease plays in urban garden yield relative to rural farm yield. Meanwhile, competition may be elevated due to high planting densities[68,69], and yield in these gardens may be reduced.

In many crops, including carrots, a basic pattern in agronomy has emerged, that of the parabolic relationship between harvestable yield and density[70,71]. Although total crop biomass asymptotically increases with density and then levels off ('Law of constant final yield'), harvestable yield in many plants that produce fruit, declines with the highest planting densities. Since this pattern reflects the allometry of reproductive allocation[72], increased planting densities may be a successful strategy when growing leafy vegetables, like lettuce. However, when fruiting plants (tomato or zucchini) are crowded, as in our gardens, these plants will be smaller, and more of them will be close to, or even under, the minimum size for reproduction[72], perhaps limiting the yield of these gardens. However, the degree to which yield was impacted in each garden was likely influenced by planting arrangements. Highly dense plantings of clustered conspecifics may have more severe reductions in yield than crowded gardens where plants with complementary growth habit and resource use were intermingled. More research is required on the role of facilitation and complementarity between crops in polyculture to understand the conditions that promote improved yield for common garden crops. Further, competition for nutrients may be reduced in urban gardens compared with rural farms because of the use of compost mixes in raised beds and the liberal application of compost and fertilizers to in-ground beds. Several studies found high levels of phosphorus in vegetable gardens[17,73,74]. Additionally, gardeners may try to avoid wasting seeds or seedlings purchased in controlled units (e.g., six-packs of seedlings, 100 seeds/packet) when individual plot size cannot change. Alternatively, increasing plant density in tomatoes may be one method of weed control that reduces manual labor by the gardeners[75].

Conclusions

Urban allotment gardens feed people from a diversity of economic and cultural backgrounds, and, in some cases, provide access to fresh food where it is otherwise unavailable, potentially improving the health and welfare of urban citizens[23,39]. By maximizing the yield of these gardens, cities can maximize the positive benefits of these spaces. Clearly, urban gardeners in the Greater Toronto Area are growing food differently than their rural counterparts. Before suggesting modifications, future work should assess the absolute and relative effect of altered cultural practices on yield, such that any modifications can be prioritized by their impact on yield specifically focusing on: (1) optimal planting densities under urban allotment garden conditions, (2) the role of trellising and staking in urban garden yield and (3) combinations of crops that overyield because of facilitation or complementarity. Furthermore, we suspect that the relative benefit of those acting as knowledge sources in communities (e.g., Master Gardeners or urban agricultural extension agents[37]) will depend on their ability to listen to and communicate effectively with gardeners, especially since urban gardeners are not generally professional, full-time farmers[64]. This is no small task, since access to data and gardeners is limited because of the private nature of domestic gardens, even those in community spaces. Datasets to describe gardening techniques, even with a regional perspective, will require the involvement of many individual garden owners[73]. In addition, urban gardeners are often immigrants[17,76] with limited facility in English. Special approaches will be needed to educate these gardeners about how to garden productively and safely or to learn more about how their highly productive gardening practices could be adapted for wider use[17]. The urban agriculture movement exemplifies participatory science and provides applied ecologists with a mandate to explore issues in inter-specific interactions, allometry and scientific communication.

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