AN ABSTRACT OF THE THESIS OF

Michael Nelson II for the degree of Master of Science in Horticulture presented on May 31, 2018.

Title: A Study of Urban Vegetable Garden and their Soils in Corvallis and Portland, OR

Abstract approved:

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Urban agriculture (UA) is defined as the production of food crops or livestock within urban areas. Despite its popularity in the United States, research into UA systems suffers from a general underrepresentation of commercial urban systems. As a result, urban growers often have unique technological needs that are unmet by research and extension. I worked with a particularly ubiquitous group of urban growers, home gardeners, to better understand the current status of urban agricultural soils. Specifically, this study had three parts. First, I documented the current extent of research and knowledge related to urban agricultural soils in the United States (Chapter 1). Second, I noted the characteristics of residential-scale vegetable gardens in Corvallis and Portland, Oregon, to better understand current growing conditions and needs (Chapter 2). Third, I characterized the biological, physical, and chemical characteristics of these same gardens (Chapter 3). Finally, I conclude with potential directions for further research (Chapter 4).

In Chapter 1, I reviewed the academic literature on urban soils and found research which directly analyzed urban *agricultural* soil to be lacking. Only 17 studies directly addressed the characteristics of urban agricultural soils in the United States. Heavy metals were the subject of the vast majority of these articles, with about half the

studies investigating chemical fertility parameters, and even fewer examining biological and physical qualities of agriculturally productive urban soils. Nearly all studies were conducted in residential sites, which potentially limits data-driven urban agricultural policies focused on commercial urban agriculture as a means to supplement locally grown foods.

In order to better inform management recommendations, I recorded garden characteristics of trained urban food growers. In Chapter 2, I report on a survey of surveyed 27 residential food gardens (including two demonstration gardens) in two Pacific Northwest cities. All site managers were trained Oregon State University Extension Master Gardeners. I found 132 unique crops were tended across all gardens, and a variety of management approaches were used. The most noteworthy concern I noted from the site managers was a desire to reconcile the mechanics of crop rotation within a small production footprint.

In Chapter 3, I examined the composition of urban garden soils from those same 27 sites in Corvallis and Portland, Oregon. In addition to recording the physical, biological, chemical fertility, and heavy metal parameters of urban garden soils, I tested for differences between garden sites based upon bed-type (e.g. raised beds versus in-ground beds). Raised beds were significantly different than in-ground beds for nearly one-third of the soil parameters recorded. Further, the mean soil fertility values across all sites were 2-8x above the recommended range for one-third of the parameters examined. I believe excessive applications of organic matter to be the source of this nutrient excess. Excessive organic matter, annually added to small garden spaces, likely promotes soil nutrient imbalances. However, the message many urban growers are given is that adding organic matter to soils is good. My data suggests that urban growers need more nuanced recommendations which account for the unique constraints of small garden spaces. Further, the recommendation to build raised beds to avoid contamination did not hold in this investigation. The matter seems more complicated, and I suggest greater scrutiny be applied to discover the source of contaminated soils in raised beds.

In Chapter 4, I suggest how policy, training, laboratory procedures, and management goals can be adjusted in light of these findings. It seems that the excessive nutrient levels in raised beds is a waste of both economic and environmental resources, with the potential for nutrient leaching as well. I believe that a well-informed site manager can quickly alter the productive capacity of an urban soil. Researchers who wish to contribute to urban agriculture should search for alternative management options which confer the benefits of compost while balancing the varied nutrient content therein. This likely involves using alternative fertilizer sources as well as novel bulking agents which can build but not imbalance a newly productive soil.

A Study of Urban Vegetable Gardens and their Soils in Corvallis and Portland, OR

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Michael Nelson II, Author

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CONTRIBUTION OF AUTHORS

Chapter 1: Michael Nelson II conducted the literature search, oversaw literature scoring, and authored the chapter. Gail Langellotto conceived of the idea and edited the chapter. Isabella Messer and Lucas Costner assisted with the literature scoring.

Chapter 2: Michael Nelson II co-conceived the idea, conducted the field survey of residential garden sites, collected and analyzed data, and authored the chapter. Gail Langellotto co-conceived the idea and edited the chapter.

Chapter 3: Michael Nelson II co-conceived the idea, collected garden soils, processed and analyzed soils, and authored the chapter. Gail Langellotto co-conceived the idea and edited the chapter.

Chapter 4: Michael Nelson II co-conceived the idea and authored the chapter. Gail Langellotto co-conceived the idea and edited the chapter.

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CHAPTER 1: URBAN SOILS AS A NEGLECTED AREA OF STUDY WITHIN AGRICULTURE

Introduction

Urban agriculture (UA) is the production of food crops or livestock within urban areas. UA can take a variety of forms, including commercial and non-profit farms, greenhouses and green roofs, and community and residential gardens (Mohareb et al., 2017). The popularity of UA has historically waxed and waned in response to socio-economic and demographic shifts (Drake & Lawson, 2014; McClintock, Mahmoudi, Simpson, & Santos, 2016). Approximately 30% of the world's population engages in UA, with about one-quarter producing food for sale (Badami & Ramankutty, 2015). Internationally, both the number of people engaged in UA and the number of urban residents producing food for sale are expected to increase (FAO, 2014). In the United States, several recent books have capitalized on the popularity of UA, by advising people on 'how to become a successful market gardener,' (Fortier, 2014; Hartman, 2015; Stone, 2015). These books often have a strong focus on small acreage, peri-urban farming which concentrate on the sale of produce to cities through private citizens and restaurants.

UA has been suggested as a means to increase food production by up to 50% to accommodate global population increases and shifting consumption patterns (Tilman et al., 2002). Because UA occurs within urban communities, urban farmers are positioned to directly support urban populations and can quickly adapt to customer demands (Oberholtzer, Dimitri, & Pressman, 2014). Grewal & Grewal (2012) found that UA positively contributes to the provisioning of fresh food in cities. It can even potentially address food inequality by diversifying urban food sources (Specht et al., 2014). Public policy related to human health and natural resource management, now directly address UA in recognition of its newfound political significance (Mason & Knowd, 2010).

Urban food production has the potential to positively contribute to the sustainability and resilience of local food systems and to transform urban spaces (Moore, Diez Roux, Nettleton, & Jacobs, 2008; Saldivar-Tanaka, 2004). In fact, a case study of Cleveland, Ohio (Grewal & Grewal, 2012) suggests that most post-industrial cities' food needs could be grown within 100 miles of urban areas in North America. Localizing food production in or near city centers would make more efficient use of energy inputs, relative to rural-based food production (Kulak, Graves, & Chatterton, 2013; Vázquez, Sen, & Soto, 2015), and would also make urban areas more resistant and resilient to natural and political disturbances or disasters (Specht et al., 2014). If we can find ways to amplify the positive contribution of and production opportunities in urban farming, it may be possible to affect positive change in urban systems.

The challenges faced by new urban farmers are a somewhat distinct subset of the challenges faced by rural growers. For example, most policy regarding urban agriculture is designed to manage conflict between land-uses rather than focusing on facilitating crop production (Pearson, Pearson, & Pearson, 2010). The relatively small size of urban agriculture sites (compared to more conventional agriculture), limits growers' ability to allocate area to hedgerows, beetle banks, or similar features, which are known to directly and indirectly benefit both pollinators and pest control agents (Philpott et al., 2014). At the same time, the greater diversity of crop and ornamental plants within or proximal to urban agriculture sites (Matteson & Langellotto, 2010) may benefit urban food production via local increases pollinators and other beneficial insects (Hall et al., 2016). The urban heat island effect could add 3-6ºC (Pickett et al., 2011) to urban farms and extend their growing season, but can also stress plants and promote pest outbreaks (Dale & Frank, 2017). Together, these factors challenge urban growers to produce high quality harvests. The potential of urban farmers to sustainably produce food for the growing population in urban centers is often further limited by a lack of research-based information that is appropriate to the scale, composition, and context of urban food production sites.

Urban soils

The notoriously heterogeneous composition of urban soils is a significant challenge confronting urban growers, who often don't know the soil's content and/or historical context. Amundson, Guo, and Gong (2003) warn that urban soils have been so heavily modified that they should be considered separate from native, undisturbed soils in the region. It is this view of a fractured soil web that prompted Pouyat et al. (2010) to coin the term ‘urban soil mosaic.’ This mosaic is formed by the cumulative effects of anthropogenic factors in an urban area. Models must thus account for extreme heterogeneity across small urban parcels (Yadav, Duckworth, & Grewal 2012) in ways that accurately represent the diversity of biological, physical, and chemical processes in the urban soil mosaic (Leguédois et al., 2016).

Academic recognition of this mosaic as a popular topic within urban soil science has not improved urban growers’ access to accurate data about local soil. This seems to be the chronic position of the urban grower: referencing soil maps can be unreliable, even misguiding (A. Gallagher-, personal communication, March 1, 2018). This is in stark contrast to traditional or rural farming operations who have a long history of soil management and instead rank marketing or legal issues above problems presented by their soil (L. Hailey, personal communication, April 9, 2018). Residential and community gardeners, a ubiquitous group of urban agriculturalists (McClintock, Young, Evans, Simpson, & Santos, 2013), generally eschew soil tests due to cost (Whitzling, Wander, & Phillips, 2010). Without an accurate soil assessment, growers are working blind. They may seek to manage their crops, but can only guess at their soils’ content.

The need for UA soils research

Multiple literature reviews have pointed out that UA is underrepresented in the scholarly literature (Gerster-Bentaya, 2013; Pearson et al., 2010; Taylor & Lovell, 2014). Additionally, a mixed methods survey across 15 United States cities found that urban farmers consistently report that local resources fail to address their unique needs (Oberholtzer et al., 2014).

Given how little we know about urban soils, in general, it is important to point out that we know even less about urban soils in the context of urban agricultural production. Soil science focuses on two main fields: forestry and agriculture (Kaye, Groffman, Grimm, Baker, & Pouyat, 2006). Despite their numerical dominance in urban agriculture (McClintock et al., 2013), urban community gardens are rarely the subject of agricultural research. Instead, they are most frequently examined by social scientists who are interested in aspects regarding culture, politics, and human health (Guitart, Pickering, & Byrne, 2012).

This has led to calls that UA soils research be prioritized as a focal area for soil scientists in the 21st century (Adewopo et al., 2014). In fact, in a nationwide survey of urban farmers, 85% of respondents identified ‘soil health’ as a key production challenge, and 77% identified ‘soil fertility’ as a priority for technical assistance and information (Oberholtzer et al., 2014). Urban farmers need research directly addressing their needs to not only manage fertility, but also determine how best to farm on sub-prime soils.

Objectives

I thus conducted a literature review of urban soil science studies to date, with a focus on what is currently known about urban, agricultural soils. Specifically, I (1) determined the extent urban soil studies have focused on urban agriculture, relative to other urban site types (e.g. industrial areas or urban green space) and (2) identified key research gaps that could be the focus of future studies.

Methods

Literature Search

I conducted a review of the published literature by methodically searching OSU’s 1Search database (Oregon State University, 2017) for various combinations of the words: urban, soil, garden, heavy metal, contamination, urban agriculture, urban farmer, urban food production, nitrogen, carbon, potassium, phosphorus, calcium, boron. I then used the “suggested articles” e-mail feature from Mendeley (Mendeley, 2018) to discover additional articles on urban soils. Throughout this process, I discovered other key articles by cross-referencing the cited works of my article library. I ultimately assembled a library of 247 articles, not counting methods papers.

Study Classification

First, I screened this pool of reference articles for those with study locations inside the United States. International studies were excluded in an effort to reduce variation brought by differences in matters such as national policy.

I further reviewed the remaining articles and scored them using a standardized approach (Appendix **1.1**). Specifically, I categorized articles according to the topic of their research (e.g. urban, agricultural, soil, social), study type (e.g. observational, manipulative, or theoretical), soil parameters studied (e.g. biological, physical, chemical, heavy metals), and general outcomes of the research.

Only studies which focused on urban agricultural soils were retained in the final dataset. In terms of land-use context, agricultural studies were defined as those with productive cropping sites. These studies were further categorized according to whether they focused on soils in urban farms, community gardens, home gardens, or vacant lots.

In terms of study type, observational studies were defined as those which did not apply experimental treatments to study sites. Manipulative studies were defined as controlled experiments with at least one treatment and one control group. All other types (e.g. theoretical, literature review) of studies were excluded from final evaluation in order to focus the review on laboratory assessment of urban agricultural soil.

Studies were also classified according to whether they focused on the biological, chemical, and/or physical parameters of urban soils. Biological parameters included active carbon, potentially mineralizable nitrogen, carbon dioxide respiration, microbial activity, enzyme assays, nematode assessment, etc. Physical parameters included organic matter, soil texture, soil bulk density, penetrometer readings, and wet aggregate stability. Chemical parameters were sub-classified as looking at urban soil fertility (carbon to nitrogen ratio, pH, electrical conductivity, carbon, nitrogen, sulfur, phosphorus, potassium, calcium, magnesium, manganese, copper, zinc, boron), and/or urban soil heavy metal content (arsenic, lead, cobalt, chromium, cadmium, copper, nickel, zinc, barium, uranium, even vanadium).

Finally, studies were summarized with brief conclusions pertaining to the investigated soil parameters, urban characteristics of the site, and general conclusions drawn by the authors. Data were qualitatively analyzed by looking at the percent of studies distributed among review categories (e.g. study type, study context, soil parameters studied, general outcomes) and associated subcategories (for study context).

Results

Of 247 articles scored, only 17 focused on urban agricultural soils (Appendix **1.2**). Most of these manuscripts (71%) were observational studies (Table **1.1**). Only 29% of the studies were manipulative.

Table **1.1**: Distribution of the type of urban soil studies conducted.

Study Type	**Percent of Studies (n=17)**
Observational	71%
Manipulative	29%

Study sites were overwhelmingly focused on residential sites (Table **1.2**). Only three studies (16%) did not take place in community or home gardens. Only one study (5%) addressed urban soils on a commercial farm.

Table **1.2**: Distribution of land-use categories and subcategories of the sites for urban soil science studies. Total percentage exceeds 100% because articles often addressed multiple categories.

Study site category	**Percent of Studies (n=17)**
Community Gardens	47%
Home Gardens	53%
Urban farms	5%
Vacant lots	18%

The overwhelming focus of research regarding urban agricultural in the United States has been heavy metal presence (Table **1.3**). All but one article (94%) addressed heavy metals in relation to urban crop production. The second leading category researched were chemical fertility parameters (47%).

Table **1.3**: Topical categories of urban soil studies conducted in the United States. Total percentage exceeds 100% because articles often addressed multiple categories.

Category examined	**Percent of Studies (n=17)**
Physical	4%
Biological	12%
Chemical fertility	53%
Heavy metals	94%
Garden characteristics	6%

Discussion

The field of urban, agricultural soils is relatively young. Few studies (n=17) have focused on examining agricultural aspects of urban soils in the United States. Those which do exist are heavily biased towards residential garden soils and tend to be observational. Given the popularity of UA, it was somewhat surprising that so few studies have focused on soils from urban farms. This may be due to the scarcity of urban farms, but this also serves to emphasize the need for commercial facilities to be the subject of research endeavors.

In total, I found only four published reviews of urban soils (Kaye et al., 2006; Lorenz, 2015; Meuser, 2010; Pouyat et al., 2010), often drawing upon the same small set of observational studies. In general, these reviews note the unique nature of urban soils, compared to soils in agricultural (typically rural) or natural systems. Urban soils tend to have altered physical, biological, and chemical characteristics (Pavao-Zuckerman, 2008) and contaminants (Meuser, 2010), relative to other systems. The unique nature of urban soils leads to a need to develop a distinct model for the geochemical cycles of urban soils (Kaye et al., 2006). This view is well defended by De Kimpe and Morel (2000) who point out that urban soils are necessarily different from farm and forest soils. Urban soils are often under relatively frequent disturbance from various land use and management, and material used in urban soils are incredibly diverse (De Kimpe & Morel, 2000), such that each human activity uniquely alters the trajectory of the soil (Effland & Pouyat, 1997).

Many more reviews have been published on UA, but very few address the issue of urban soils. When urban soils are addressed in UA reviews, they are given cursory attention, at best. For example, Taylor and Lovell (2014) reviewed urban gardens but included limited information on soils. Lorenz (2015) focused on organic management recommendations for UA, and notes the need for and lack of information regarding the productive capacity of urban soils. Scheyer and Hipple (2005) provide an instructional ‘primer’ for urban soil managers, but they are wholly focused on the physical parameters of urban soils.

The urban ecosystem convergence hypothesis (Pouyat et al., 2010) suggests that ecosystem response to factors or urbanization will begin to homogenize soils and increase similarity between sites. Many authors have found data which support this position (e.g. Maechling, Cooke, & Bockheim, 1974; Samaha, Neill, Ward, & Wheeler, 2013). An explanation of this homogeneity may be that fill soils are typically more alike than the native soils they replace (Herrmann, Shuster, & Garmestani, 2017).

However, Sharma, Basta, and Grewal (2015) found unique soil profiles between two demographically similar neighborhoods in Ohio. Given the paucity of research regarding varied land-use in urban agricultural settings (Table **1.2**), it seems too early to draw conclusive characteristics regarding urban soil profiles.

My review of the literature shows that most studies of urban agricultural soils are observational, focused on non-commercial sites (e.g. home and community gardens), and heavy metal pollutants. The dominance of observational studies is likely due to the relatively young age of urban soil science. Scholarly investigation must first document the general nature of urban soils before they can begin to examine the mechanisms which might influence urban these newly documented soil characteristics or functions. The prevalence of non-commercial sites is likely a consequence of the relative rarity of commercial urban farms. Urban farmers face substantial barriers (Oberholtzer et al., 2014) to form a successful urban farming business, including land access and tenure, market access, labor, and startup costs.

Investigations regarding heavy metals dominated the studies of urban agricultural soils in the United States (Table **1.3**). Some studies found raised beds to offer significantly lower contamination than IG (Gorospe, 2012; Hopwood et al., 2012; Mitchell et al., 2014; Whitzling et al., 2010). Mielke, Anderson, and Berry (1983) discovered a trend in urban environments whereby heavy metals became concentrated in the urban center of a city. As recently as 2015, Clarke, Jenerette, and Bain found that proximity to roadways significantly correlated with numerous elevated heavy metal parameters.

The research regarding crop safety in contaminated soils is inconclusive. While (Sterrett, Chaney, Gifford, & Mielke, 1996) demonstrated that heavy metal content in vegetables increases with heavy metal content in soils, they conclude that risk of lead poisoning is low until soil-lead exceeds 500ppm. Further, Cheng et al. (2015) found that safe handling practices and cleaning techniques could significantly decrease the risk of heavy metal consumption, but still advises that all growers obtain a soil test for their site before growing and consuming crops—a tenet further supported by Walker, Skelly, and Mcadoo (2009). The matter is complicated further when we see that heavy metal content varies depending on the portion of the crop examined, with lead content highest in crop roots and lowest in fruits (Defoe, Hettiarachchi, Benedict, & Martin, 2014; Finster, Gray, & Binns, 2004). Heavy metals display variable degrees of mobility, such that arsenic seems to be minimally transported throughout plant tissue (Defoe et al., 2014), while roots have been found to contain 2-51% of soil lead. Defoe et al. (2014) makes a risky conclusion that 700-1900ppm of lead in the soil is still safe for gardening, as they assume that people don’t eat that many vegetables and that consumption of garden produce is particularly low.

Those who grow produce in soil must remain wary, despite these studies which downplay the concern regarding heavy metals in agricultural soil. For example, Stilwell, Rathier, and Musante (2008) analyzed produce samples and found Cd above the detection limit for all samples, with arsenic, copper, chromium, nickel, and zinc at safe levels and lead at safe levels but greater in garden produce than supermarket produce. Also, McBride et al. (2014) showed that vegetable barium content was much higher than lead or cadmium content, although soil barium was lower than soil lead, and vegetable lead correlated with soil aluminum.

In my review of the literature, urban soils were noted for extremes of excess and deficiency. Gardens in Chicago were found to contain excessive levels of nitrogen, phosphorus, and potassium (Whitzling et al., 2010), and the greater metro area of Baltimore was determined to be extremely enriched in calcium (Pouyat, Szlavecz, Yesilonis, Groffman, & Schwarz, 2010). Concerning nutrient-poor sites, Beniston, Lal, and Mercer (2014) found that importing even minute amounts of organic matter can significantly alter an urban soil’s parameters to greater crop receptivity. However, these benefits provide diminishing returns. Reeves et al. (2014) found the soils of an urban farm to contain slightly more organic matter (~9%) than community gardens (~6%), but found no sites to be nutrient limited and yet the urban farm tended to outperform the community gardens' yield.

Urban soils, while generally existing in a degraded state, can be quickly remediated and turned into productive sites. Behind any sustainably productive soil is a robust set of tests to track soil quality to best inform management decisions. Two articles investigated potential methods to increase the feasibility to test for heavy metals in soils. Whitzling et al. (2010) found significant correlation between Mehlich-3 and Environmental Protection Agency assessments of lead content. Minca and Basta (2013) also found significant correlation between Mehlich-3 and two other assessments of lead content. This increases the chance than a common nutrient assessment can also be extended at minimal cost to also check for lead.

Despite concern over lead contamination from old buildings, demolition of houses was not observed to increase soil lead (Beniston et al., 2014).

Conclusion

Due to the apparent rarity in the current literature, future studies should seek to complement the accounting of biological and physical parameters of urban agricultural soils. Also, the body of literature regarding heavy metals could perhaps enable more controlled studies in order to better understand the mechanisms of accumulation within crops. Finally, the field could benefit from more holistic studies which investigate a broad suite of soil parameters in the same soils.

I suggest that we develop guidelines for geographic areas which provide guidance on if/when heavy metals are correlated with other local soil parameters. For example, both McBride et al. (2014) and Cheng et al. (2015) found correlations between some heavy metals and fertility elements. Additionally, Minca and Basta (2013) found that microwave digestion (as in Chapter 3) reports half the value that an Mehlich-3 analysis of soil lead does. This could potentially enable an urban grower to submit a standard soil test for fertilizer parameters yet still gain insight regarding potential heavy metal contamination at their site.

The fact that urban agricultural research focuses so heavily on non-commercial settings highlights a problem with efforts which proclaim urban agriculture will produce food for the burgeoning urban population. If we seek to support this effort, the field of urban soil science must investigate limits to production and agroecosystem characteristics of real urban farms, operated in a commercial capacity within or next to urban development boundaries.

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CHAPTER 2: CHARACTERISTICS OF URBAN VEGETABLE GARDENS IN TWO WESTERN OREGON CITIES

Introduction

In 2007, for the first time in human history, more people lived in urban areas than in rural areas (United Nations Population Division, 2017). This demographic shift towards urbanization continues, with the 2015 global population estimated to be 7.3 billion people, and increasing annually by 1.95% (United Nations Population Division, 2017). Although annual increases are somewhat less in the United States (estimated to be 0.71% for 2015-2020), the population is still growing (United Nations Population Division, 2017). The recent adoption of a ‘New Urban Agenda’ highlights the international importance of including an urban perspective in planning and policy (Acuto, Parnell, & Seto, 2018).

In an increasingly urbanized world, urban agriculture (UA) is suggested as a means of building local food systems to meet future food needs (Tilman et al., 2002), building sustainable, resilient cities (De Zeeuw, Van Veenhuizen, & Dubbeling, 2011), promoting public health and food justice (Morgan, 2015; Specht et al., 2014), and helping to promote an appreciation for agriculture within the general public (FAO, 2014; Morckel, 2015). Approximately 30% of the world’s population engages in UA, with about one-quarter producing food for sale (Badami & Ramankutty, 2015). In the United States, UA has once again gained traction, due in large part to increased awareness of and desire for local foods (Mason & Knowd, 2010; McClintock et al., 2016; Wortman & Lovell, 2013), but also because of policy initiatives (Taylor & Lovell, 2014).

UA is defined as the production of food crops or livestock within urban areas. Despite its popularity in the United States, research into UA systems suffers from a general lack of funding for research in urban systems (Acuto et al., 2018). As a result, urban farmers often have unique technological needs that are unmet by research and extension (Oberholtzer et al., 2014).

Residential food gardens are perhaps the most common form of UA in the United States (McClintock et al., 2016; Taylor & Lovell, 2012). Residential food gardens represented 89% of all urban agricultural sites in Chicago, covering 29 acres (Taylor & Lovell, 2012). In Portland, a conservative count of more than 3,000 residential food gardens cover more than 20 acres (McClintock et al., 2013). In Madison, WI, 45,193 residential food gardens cover more than 121 acres of land (Smith, Greene, & Silbernagel, 2013). The importance of residential food gardens within the urban landscape is expected to grow, as interest in food gardening, particularly among millennials, is a major driver of yard and garden center sales (Research Now SSI, 2018).

Given the ubiquity and popularity of residential food gardening, it is somewhat surprising that so little research has been conducted in home-garden study sites. Notable exceptions include efforts to map the spatial distribution of residential food gardens (McClintock, Young, & Simpson, 2013; Smith, Ng, & Popkin, 2013; Taylor & Lovell, 2012) or to describe the social or economic benefits of home food gardens (Gray, Guzman, Glowa, & Drevno, 2014; Langellotto, 2014; Schupp & Sharp, 2012).

At best, we currently have a coarse, landscape-level understanding of the characteristics of residential-scale urban agriculture. Before we can understand the potential role that residential gardens might play in urban sustainability and resiliency, it is important to first understand the basic characteristics of urban food gardens. I thus surveyed 27 residential food gardens (including two demonstration gardens) in two Pacific Northwest cities to describe crop diversity, mulching techniques, bed dimensions, season extension, and livestock within each garden.

Methods

Recruitment

I recruited Oregon State University (OSU) Extension Master Gardener volunteers to participate in this study. Study participants agreed to have me visit their yard, so that I could visually assess their garden characteristics. To screen study participants, I created an online survey (Qualtrics, 2017). I provided this survey to the Master Gardener Extension Faculty in Benton, Lane, Marion, and Multnomah counties, and asked them to distribute the survey to current Master Gardener volunteers. I received 87 total responses to my first request for study sites.

Study Sites

I screened out those sites that did not grow edible plants, where the respondent had managed their site for less than one year, or when the respondent did not have authority to grant access to their site. This left 79 potential study sites, which I mapped on Google Maps (Google Inc., 2017). While I had hoped to study gardens from four major cities in the Willamette Valley (e.g. Corvallis, Eugene, Salem, and Portland), mapping efficient sampling routes eliminated Eugene and Salem as logistically viable options. Of the 34 remaining potential study sites, seven did not respond to attempts to schedule site visits. This left me with 11 sites in Corvallis and 16 sites in Portland, for a total of 27 participating sites (

Table **2.1**), all of which had vegetable gardens. Twenty five of the gardens were in private yards, while two of the gardens (one in each city) were demonstration gardens on public land. These demonstration gardens are used to help teach the general public how to design and maintain a home vegetable garden. In total, six sites hosted both raised bed and in-ground bed-types.

Table **2.1**: Location and garden type for the 27 vegetable garden sites. Some sites contained multiple garden bed types, bringing the total number of samples to 35.

Garden Location	**Garden Type**			**Number of Soil Samples**
	Raised-bed	**In-ground**	**Container**	
Corvallis (n=11 gardens)	7	6	0	**13**
Portland (n=16 gardens)	14	6	2	**22**
Total (n=27 gardens)	**21**	**12**	**2**	**35**

Compared to Corvallis, Portland is an order of magnitude larger in both population and land area, making their population density relatively even (

Table **2.2**). Due to their proximity to each other (approximately 80 miles) the cities are in the same climactic zones (USDA Hardiness Zone 8), and thus experience similar weather patterns.

Table **2.2**: Census details for Corvallis and Portland. (U.S. Census Bureau, 2018a) (U.S. Census Bureau, 2018b)

City	**Population (2010)**	**Land area (mi^2)**	**Population/mi^2**
Corvallis	54,462	14.13	3,854.4
Portland	583,776	133.43	4,375.2

My initial site visit took place over August 23-26, 2017. During these visits, I noted bed type, measured bed area, and recorded bed height. I also recorded crops under production, evidence of season extension and/or composting, and site cleanliness in regards to plant debris and weed pressure.

I surveyed bed characteristics if the area was predominantly used for production of annual crops. For example, a bed planted with many peppers and one rhubarb would be included. A bed with an apple tree and bulb flowers was not included in the survey of garden characteristics.

The area of each bed was measured and categorized as either raised bed (RB) or in-ground beds (IG). RB were those with an installed border which physically delineated the productive space from the lawn and often elevated the soil within its borders. In-ground beds were those without protective borders. While other articles (Edmunds, 2016; Reeves et al., 2014) have classified beds with mounded media as RB, I chose to use physical borders as the defining aspect because I believe this barrier limits mechanical options for management. Bed height was determined as the elevation change between the soil outside the garden area and the highest level of the soil within the production area. I recorded absence/presence and composition of mulch both within and between bed areas.

I recorded the presence of all crops that were growing at my study sites. I did not record quantity nor cultivars (for example, a sauce tomato plant, cherry tomato plant, and slicer tomato plant would all be recorded as a single ‘tomato’ entry for a site). If there was a bare patch in the garden bed, I asked the gardener what had recently been harvested. I categorized all crops as annual or perennial. This division generally reflected the dichotomy between the garden area I measured and sampled and the lawn area not analyzed. Most gardeners accompanied me during my initial visits, and thus were on hand to query for identification of obscure crops.

I noted the presence of season extenders, such as cold frames, greenhouses, and dark plastic mulch. I asked the gardener if they produced compost on site. I had intended to gather site information in order to group the participants by management approaches.

I recorded any evidence of livestock on the property and asked every manager I met if they had any livestock which interacted with their gardens. Livestock was defined as a domestic animal which the manager cared for and observed interactions between this animal and their garden.

Statistical Analyses

I used SigmaPlot (Systat Software, San Jose, CA) to run ANOVA comparisons between the two bed-types. I used paired t-tests to compare bed characteristics for the six sites with both bed-types. If the data failed a Shapiro-Wilk normality test, I ran a Kruskal-Wallis ANOVA on ranks or a Wilcoxon signed rank test.

Results

In total, the gardens had 830.6m^2 of garden beds. The area of garden bed surveyed in Corvallis (445.8m^2) and in Portland (384.8m^2) was fairly equitable, even though I only surveyed 11 Corvallis gardens and 16 Portland gardens. Individual vegetable garden area ranged from 0.71-75.44m^2 (mean=25.17m^2). There was no significant difference between the area of garden planted as IG (29.9m^2 ± 17.4) versus RB (24.2m^2 ± 19.7) (H_1=0.56, p=0.454). Bed height ranged from 0-81cm, across all garden beds. As expected, the height of RB (23.4 ± 17cm) was significantly greater than IG (4.6 ± 8.6cm) (H_1=14.525, p<0.001).

A diversity of mulch types was used by gardeners, both within beds as well as between beds (Table **2.3**). All but two sites (93%) had mulch between the beds with one of each bed-type with just bare ground between their beds. The most common mulch between beds was wood chips (n=15) followed by turf (n=9) and gravel (n=8). Less common mulches included hazelnut shells, burlap, and landscape fabric. Twelve sites (44%) had mulch within the border of a garden bed. Six RB used within-bed mulch, and six IG used within-bed mulch. Organic materials (e.g. compost, leaves, straw) were most often used as within-bed mulch, although there was one instance of sheet plastic being used as mulch.

Table **2.3**: Frequency and location of mulch types. Mulch use ‘within beds’ is less than the number of garden sites (n=27) due to a low occurrence of mulch application within the vegetable garden area. Mulch use ‘between beds’ is greater than the number of garden sites because sites could have more than one type of mulch in use.

Within beds		**Between beds**	
Mulch	**Count (n=15)**	**Mulch**	**Count (n=39)**
Compost	2	Wood chips	15
Sheet plastic	2	Turf	9
Leaves	2	Gravel	8
Straw	2	Bark chips	3
Bark chips	1	Hazelnut shells	2
intercropping	1	Burlap	1
Peat moss	1	Compost	1
Grass clippings	1	Landscape fabric	1
Wood chips	1		
Fine bark mulch	1		
Cardboard	1		

I recorded a total of 74 different annual crops and 58 perennial crops (Appendix **2.1**). Tomatoes were grown at all but one site. Kale, basil, and beans were widespread as well. There were 43 different crops which were only grown at a single site within this study. This number grows to 87 unique crops reported at 18.5% of the sites.

Fourteen of twenty-seven sites had some kind of livestock present. The composition of this livestock was predominantly chickens (n=8), followed by bees (n=4). Some sites did respond with interesting self-assessments of what livestock interacted with their gardens, with ‘tortoise’ being the single most noteworthy response I encountered.

Manager concerns

When touring the gardens, many gardeners voiced their concerns to me. Their responses covered a wide range of gardening topics (e.g. competing with trees and buildings for sunlight/shade, unauthorized harvesting, or a desire to extend their growing season). I thus selected an abbreviated number concerns to show here. Three managers expressed a knowledge of the benefit of crop rotation, but lamented a lack of space to facilitate proper rotation while still growing all the crops they wanted. In particular, managers were in need of a solution to plant tomatoes in their garden every year without suffering significant pest pressure. Many managers spoke to the peculiarities of their microclimate at their site. For several, this involved shade restrictions imposed by neighboring trees and buildings, with some of those trees sending roots throughout the gardens' soils. One manager spoke to several aspects of beneficial microclimates, including distant trees to slow the wind and a sloping valley to carry frost away. One site was a side yard which had been installed by the city by pouring soil directly over an old asphalt road.

Discussion

Residential vegetable gardens are diverse and unique. Among the gardens I surveyed, there was no such thing as a 'typical' garden. Perhaps this is one reason that research regarding urban agriculture tends to focus upon more abstract issues like food security and social mobility (e.g. Gray et al., 2014; Oberholtzer et al., 2014; Specht et al., 2014). While the world of conventional agriculture is often focused on soil fertility and crop management, research in UA is often based in the social sciences. The research instead attempts to forecast the great productive potential of urban agriculture, even suggesting remedies to societal food issues like malnutrition (Duží, Frantál, & Simon Rojo, 2017).

The results of my survey suggest that management actions affect an incredibly diverse outcome of garden properties. This can be seen by examining the fate of compostable waste at garden sites, as Dewaelheyns et al. (2013) did in Belgium. Many sites with gardens would export their compost using their city's service. Others would produce their own compost but not use their own green waste. Still others sought to keep all green waste on site, while still importing compost for use in their gardens.

Even communal gardens can fundamentally differ between community, allotment, and opportunistic gardens (Parece & Campbell, 2017). It seems a descriptive accounting of garden sites may be insufficient to properly categorize gardens and that a more detailed assessment of garden management actions would prove beneficial (Loram, Warren, Thompson, & Gaston, 2011) to any assessment of productive urban soils.

Instead, perhaps the field of urban agricultural science should discern which parameters are noteworthy enough to allow classification of garden areas and study sites. In general, we need a cohesive research system to address the needs of urban vegetable growers. A better understanding of the configuration of beds, the composition of imported material, and the priorities of site managers will greatly facilitate more precise and informative research and advice for urban agricultural soils.

The most interesting aspect to come of this assessment of urban garden characteristics is the unrelenting reinforcement of heterogeneity among sites. My study sties were all tended by OSU Extension Master Gardeners, who received similar training, related to vegetable gardening. Still, relatively few trends or characteristics seemed applicable among gardens. This may be due to the varied economic resources (McClintock et al., 2016) and other considerations of a private gardener.

Garden diversity can be examined through the diversity of crops grown at my study sites. These crops constitute agrobiodiversity, a facet Guitart, Pickering, and Byrne (2012) have noted as lacking from the research literature.

Almost all sites maintained some kind of mulch between productive soil spaces, suggesting management efforts are consciously concentrated within garden spaces. Less than half mulched within their bed spaces, offering a potential aspect of further study to understand motivations and possible benefits of extensive mulching. Interestingly, some managers claimed their RB helped the soils drain more quickly, while others were adamant that the raised construction equated to increased water retention within the productive soils.

By definition, raised beds are expected to be taller than in-ground beds. What was interesting about this study was the range and the variance of bed heights. I recorded an in-ground bed with an 11” bed height as well as seven raised beds with a height <6”. I defined bed-type in an effort to group beds by management style, as I suspected the physical border would dictate some of the garden maintenance options available, like tillage options.

Some publications make little distinction between shaping media into mounds and constructing raised borders (Edmunds, 2016). However, I believe there is great potential for these two bed-types to diverge. Especially in a raised bed, bed height is indicative of how much media was imported to fill the void and build the soil matrix. The choice of input is essentially determining the entire ecosystem of the garden bed. Physical and chemical parameters draw directly from the parent material, and biological parameters follow. Perhaps a better categorization of garden beds would account for both the method of establishment (raised or in-ground beds) but also contain ranges of bed heights which might also further correlate with expected fertility parameters within the soil.

Ultimately, the effort to categorize urban agricultural soils must be a broad, holistic attempt to address all factors of a site. The enormous heterogeneity of urban areas leads directly to incredibly diverse urban site managers. If we seek to maximize our utility from urban agriculture, we must contextualize the relationships between soil content, management efforts, manager training, education, and research, all within the frame of an urban environment in a high state of flux.

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CHAPTER 3: CHARACTERISTICS OF URBAN SOILS FROM VEGETABLE GARDENS IN TWO WESTERN OREGON CITIES

Introduction

Soil science arose as a distinct discipline within agriculture in the late 1800s. This signified a time when soil was becoming recognized as worthy of study in its own right and not just to assess its growing potential (Singer, 2015). In 1879, Vasily Vasilyevich Dokuchaev demarked five soil forming factors which would be popularized as CLORPT (**CL**imate, **O**rganisms, **R**elief, **P**arent material, **T**ime) by Hans Jenny (1941). Soil science initially developed based upon interpretations of physical properties of soils, such as horizons, color, texture, structure, and consistency at various moisture contents (Singer, 2015).

The study of soil evolved with and was segmented by the emerging technology employed by various disciplines; some researchers were more focused on chemical properties—led by Eugene Hilgard—while others focused their efforts to accurately model the interactions of soil physics—led by Milton Whitney—as scientific thought progressed (Warkentin, 2006). The premise of CLORPT stood for many decades, but recent global changes have prompted researchers to revisit this basic tenet of soil science. In 2010, Pouyat et al. proposed f(a)CLORPT, suggesting environmental factors to be a function of anthropocentric management. They suggested that the urban environment is so profoundly different from a natural or undisturbed location, that ‘urbanization’ of an area represented a new ‘time zero’ for soil formation. The reigning direct effect of urbanization was the parcelization of land which led to differing environmental regimes across time, ultimately creating extreme heterogeneity in the environment. Indirect effects were predominantly changes in the abiotic and biotic environment, including the urban heat island effect (Pickett et al., 2011), soil compaction (Pitt, Lantrip, & O’Connor, 2000), introduction of exotic species (Ehrenfeld, Kourtev, & Huang, 2001; Steinberg, Pouyat, Parmelee, & Groffman, 1997), atmospheric pollutant deposition (Antisari, Orsini, Marchetti, Vianello, & Gianquinto, 2015; Pickett &

Cadenasso, 2009; Sharma et al., 2015), and heavy metal contamination (Meuser, 2010).

Parcelization promotes heterogeneity in urban soils, to the point that widespread generalizations, such as ‘urban soils are compacted’ or ‘urban soils have a low nutrient content’, may not be appropriate. The ‘urban soil mosaic’ theory asserts that as population density increases, urban soil heterogeneity should increase, as the number of stakeholders making management decisions on individually owned lots increases (Pickett et al., 2011). The extent of this heterogeneity in urban soils offers “natural experiments” to investigate the effect of human management at differing scales (Pouyat et al., 2010). This investigation led them to the conclusion that the closer the scale of observation, the closer human activity can be seen to affect specific soil (Pouyat, et al., 2010). However, to date, we know relatively little about the status of urban soils, and even less about the status of urban agricultural soils (Chapter 1).

The unique nature of urban soils likely impacts the ability of urban farmers and gardeners to successfully and sustainably produce food. Soil maps in urban areas are notoriously unreliable (A. Gallagher, personal communication, March 1, 2018). Although several sources recommend that growers test their soils prior to establishing a garden (Horneck, Sullivan, Owen, & Hart, 2011; Marx, Hart, & Stevens, 1999), soil tests are often cost-prohibitive to many urban growers (Whitzling et al., 2010). Without reliable information on the physical, chemical, and biological characteristics of their soil, urban growers are left to guess at best management practices. The consequences of uninformed and ill-advised management practices can include: increased nutrient leaching (Dai, Wang, Cheng, Zhang, & Cai, 2017) and/or pesticide run-off (Hanke, Wittmer, Bischofberger, Stamm, & Singer, 2010) and/or exposure to pollutants and toxins, such as lead (Whitzling et al., 2010).

Pouyat et al. (2010) provides one of the most comprehensive reviews about urban soils to date. They report that urban soils are incredibly heterogeneous as they are subject to a wide diversity of human management. Meuser (2010) compiled an exhaustive report concerning the contamination of urban soils. This contamination often comes in the form of lead (Mielke, 1994; Mielke et al., 1983; Mitchell et al., 2014; Spliethoff et al., 2016; Whitzling et al., 2010) and other heavy metals (Antisari et al., 2015; Chaney, Sterret, & Mielke, 1984; Gardiner & Harwood, 2017; Sterrett et al., 1996). Compaction of the soil profile is ubiquitous to the urban environment (Effland & Pouyat, 1997; Pavao-Zuckerman, 2008). Although this research has greatly expanded our understanding of urban soils, it is important to note that these studies have concentrated on compromised soil: roadsides and former industrial sites (Pouyat et al., 2010). While this knowledge is useful in assessing the urban environment, it fails to address the needs of urban growers (Oberholtzer et al., 2014). I could find no study that conducted a comprehensive assessment of urban garden soils, which included a soil health assessment including physical, chemical, and biological characteristics.

Urban agriculture not only exists within an environment not seen in conventional agriculture, but also operates in a distinct manner as well. Kaye et al. (2006) asserted that urban ecosystems are fundamentally distinct from their nonurban counterparts because human actions control the pivotal points of urban systems. Heneghan et al. (2008) emphasizes the role of urban soil in relation to any attempt to harness urban ecosystem services. The reason for this pivotal position of human management is the ability to exert a “redirection of soil development trajectories,” (Pavao-Zuckerman, 2008). This creates a feedback loop where the more intensive the management the less can be accurately inferred from natural systems. Even within a city’s altered hydrology (Kodešová et al., 2014; Pickett et al., 2011), no assumptions can be made. Water may be thought to be tamed within pipes, but pressurized water systems from municipal services can leak as much as 20-30% of the water they carry into adjacent soils (Law, Band, & Grove, 2004).

This diverse world of UA is amply practiced by the citizens of Oregon. Urban gardening is particularly popular in western Oregon, where the majority of the state’s population resides. Residential and school vegetable gardens are ubiquitous throughout the region, and are particularly clustered in the cities of Portland, Corvallis, Salem, and Eugene (McClintock, Young, Evans, Simpson, & Santos, 2013; Oregon Department of

Education, 2018). In addition, 89% of the state's certified Extension Master Gardener volunteers reside in Western Oregon, where they support home, community, and school gardeners with sustainable gardening advice and educational opportunities (Langellotto, 2017). Currently, the soils advice given by state university programs avoid direct management suggestions (Cogger, 2005) and instead seem to simply scale-down agricultural recommendations from acres to square-feet (Hart, Mcneilan, Acreages, & Oregon, 2000), asking gardeners to copy small-farmer operations (Collins, Miles, Cogger, & Koenig, 2013). More specific information is needed for home-scale systems, in order to improve the success and sustainability of urban growers, as well as the overall quality of the recommendations available to urban gardeners by the Extension Master Gardener Program or other sources.

This project

I thus sampled soils and measured soil characteristics from 27 vegetable gardens in western Oregon, in order to develop baseline understanding of the current status of urban soils in this area. I compared the results of my soil survey to the recommendations provided by an OSU Extension publication (Marx et al., 1999) as well as Cornell's Comprehensive Assessment of Soil Health (CASH) system (Appendix **3.1**) (Moebius-Clune et al., 2016) to assess the proportion of Extension Master Gardener-tended gardens that fell within recommended guidelines for various soil parameters. Cornell's CASH system is a method of quantifying soil health parameters that was developed in New England in effort to relate a holistic view of soil properties (Moebius-Clune et al., 2016).

I sampled soils from both raised beds and in-ground vegetable garden beds to discover if any key differences exist between the two garden types. Raised beds are often recommended to urban gardeners, specifically (Edmunds, 2016; Finster et al., 2004), and to home gardeners, in general (Bell, Detweiler, Noordijk, & Bubl, 2014; Langellotto-Rhodaback et al., 2011), as a means of working around soil issues, and concentrating soil management efforts to a small, defined space. I expected that nutrient levels would generally be higher for raised beds than for in-ground vegetable beds. Similarly, I expected raised beds to have lower levels of soil contaminants—heavy metals, including lead—compared to in-ground vegetable beds. Finally, I expected in-ground beds to have a more balanced C:N ratio, compared to raised beds. These hypotheses are based upon the assumption that raised beds receive large amounts of material input. I assume this material is of high-fertility and focuses on nitrogen rather than carbon, thus leading an over-fertilized site to be nitrogen-rich and carbon-poor.

I conducted a controlled experiment to determine the effectiveness of OM oxidation at elevated organic matter levels.

Methods

Recruitment

As described in Chapter 2, I recruited Oregon State University (OSU) Extension Master Gardener volunteers to participate in this study. Study participants, all of whom have received at least three hours of instruction in soil health and management, allowed me to come to their garden and sample their soils. In exchange for their participation, all gardeners were provided the results of their site-specific soil analysis. Participants in this study were the same group of individuals that allowed me to census their garden characteristics (Chapter 2).

Study Sites

I sampled soils from residential vegetable gardens in two Oregon cities: Corvallis and Portland (see Chapter 2: Study Sites for a full description of garden sites). Due to their proximity to each other (approximately 80 miles) the cities experience similar weather patterns and thus are in the same climactic zone (United States Department of Agriculture, 2018a) (Table **3.1**).

Table **3.1**: Descriptive weather data from 2017, for both Corvallis and Portland, Oregon. (National Oceanic and Atmospheric Administration, 2018)

City, Climate Zone	**Precipitation (2017)**			**Temperature (2017)**		
	Low	**High**	**Annual**	**Low**	**High**	**Mean**
Corvallis, 8b	0.48cm (August)	31.69 (February)	136.07cm	-10ºC (Jan. 6)	40ºC (Aug. 3)	11.7ºC
Portland, 8b	0.15cm (August)	26.31cm (February)	116.33cm	-11.7ºC (Jan. 13)	40.56ºC (Aug. 3)	12.3ºC

Soil Sampling

I collected soil samples in Corvallis on August 30, 2017, and in Portland on August 31, 2017. The timing of soil samples was chosen to ensure that samples were collected prior to fall rains in Western Oregon but well after peak plant growth and most crops were harvested. Soil compaction was measured in the field. All other soil parameters were calculated from soil samples collected in the field and assayed in the lab.

I sampled the garden soils using a 1m long, 2cm diameter auger to collect 30cm cores. I took a soil sample every 2m of bed length. If the bed was less than 2m I took a single sample. I aimed to sample soils toward the center of the beds, but adjusted as needed to avoid irrigation material as well as the base of plants.

All samples were collected into a bucket where I manually scooped the collected soil into a polyethylene bag labeled with the site number and bed-type. In an effort to preserve sensitive biological and chemical data (Barker, Nusbaum, & Nelson, 1969), I kept the bags of samples in a cooler with ice until the end of the day, when I moved them into an industrial cold room at 3.3°C , where they were held until processing.

Soil Sample Testing

All samples were processed and analyzed at the Oregon State University Central Analytical Laboratory (CAL). In the lab, each site's samples were homogenized by passing the media through a 2mm sieve. Especially sticky samples were passed through an 8mm sieve and left to air dry at ~30°C for one day, before rejoining the intake process. The material that didn't pass through a sieve was examined for identifiable rock and organic matter, which were set aside in separate containers. The remaining material was subjected to mild crushing by ceramic mortar and pestle. This material was once again passed through the 2mm sieve. After the final sieving, total matter >2mm was weighed, recorded as organic matter or rock fragments as determined by visual assessment, and discarded (Appendix **3.2**). Each sample was placed in a large tin then set in a drying rack to air dry at ~30°C. I then put the dried sample inside a labelled plastic bag and held at room temperature (21~23°C). These dried samples were used for subsequent physical, biological, and chemical soil assays. The specific soil parameters that were measured are summarized in Table **3.2**.

Table **3.2**: Physical, biological, and chemical parameters measured for each site's sample. Chemical parameters are subdivided into general characteristics, soil fertility parameters, and heavy metals.

Physical characteristics	Site compaction, bulk density, wet aggregate stability, particle size and soil texture
Biological markers	Active carbon, potentially mineralizable nitrogen, carbon dioxide respiration
Chemical characteristics	Suspended ions and soil salts, total carbon total nitrogen, organic matter
Chemical: soil fertility	sulfur, phosphorus, potassium, calcium, magnesium, manganese, plant-available copper, zinc, boron
Chemical: heavy metals	Arsenic, lead, cobalt, total copper, chromium, cadmium, nickel

I could not find both recommended thresholds for many parameters (e.g. bulk density, wet aggregate stability, penetrometer, active carbon, PMN, manganese, copper, zinc, and CO_2 respiration). Some, like manganese and zinc, are likely without an upper limit because excess of these nutrients is rare in conventional agriculture. With other parameters, such as active carbon and soil respiration, growers and gardeners are currently advised using a ‘more is better’ approach (Moebius-Clune et al., 2016). For these parameters, levels exceeding established thresholds are not often recognized.

Physical Characteristics

Site compaction

I used a penetrometer in the field to measure compaction within garden beds. I recorded the highest compaction rating in the top 40cm, or the depth of the rating exceeded 300psi (Duiker, 2002), and I recorded resistance to the nearest 25 psi. I probed within a square meter of both ends of all beds. If the beds were longer than 4m, another probe was inserted every 2m. If the length of a bed was smaller than 2m, a single probe was used. I used a table prepared by Duiker (2002) to translate a site’s penetrometer readings into a compaction category for the whole site.

Bulk density (D_b)

The bulk density (D_b) of sites were determined using the best fitted revised empirical model proposed by De Vos, Van Meirvenne, Quataert, Deckers, & Muys (2005). It uses organic matter percentage as determined by loss-on-ignition (LOI) testing (see *Organic matter*, below):

$$(1)\ D_b = 1.775 - [0.173 * (LOI)^{½}]$$

Wet aggregate stability

I used a rain simulator (Ogden, van Es, & Schindelbeck, 1997) with minor adaptations (Moebius-Clune et al., 2016) to determine the percentage of wet-stable aggregates in a sample.

Particle size and Soil Texture

I followed the pretreatment procedure as outlined in (Day, 1965), using 20mL of 10% sodium hexametaphosphate as dispersant and I conducted an extended oxidation phase consisting of repeated H_2O_2 additions every 2-4 daylight-hours, 4-6 days a week, for five weeks. Over this time, some samples stopped bubbling, indicating oxidation had decreased and that most of the organic matter was likely dissolved. At this point, I reduced the frequency of H_2O_2 additions to once a week. After five weeks, some samples had not yet ceased to bubble. I left the samples to settle for five weeks at 21-23°C. Upon return, many had grown mold, which indicated residual organic material in the sample. I administered H_2O_2 for one more week, both to disrupt the mold and as a last effort to oxidize remaining organic matter. I lost sample #33 due to unexpected over-bubbling of the sample and subsequent unknown particle loss from the flask.

Hydrometer readings were made using an adjustment to the procedure of Gee & Bauder, (1986). Soil texture was determined by calculating the percent of sand, clay, and silt particles in each sample, and then using a soil texture calculator (United States Department of Agriculture, 2018b).

Biological markers

I measured several soil biological parameters as indicators of soil microbial activity. Potentially Mineralizable Nitrogen (PMN) represents how much organic nitrogen is being consumed and excreted by microbes; this process produces nitrate which facilitates nitrogen uptake by plants. Carbon dioxide respiration is a direct measure of carbon respired by microbes. This carbon sources almost entirely from the active carbon fraction of the organic material. Active carbon is the most readily available fraction of the soil organic carbon pool to both microbes and plants. This parameter is incredibly responsive to changes in management (Moebius-Clune et al., 2016) and thus is a useful tool to assess outcomes of site management.

Active carbon

A CAL lab technician measured active carbon following the protocol outlined in Moebius-Clune et al. (2016).

Potentially Mineralizable Nitrogen

PMN is a proxy measure of microbial activity by quantifying how much inorganic nitrogen is created over a specified incubation period. It compares final nitrate and ammonia levels to initial concentrations and thus is a composite of four measurements (Appendix **3.4**). I used an adaptation of the protocol outlined in Moebius-Clune et al. (2016), such that I incubated the samples in an aerobic environment for one month. I added enough DI to bring the samples to approximate field-capacity, as determined by equation (1). The difference between day 30 and day 0, divided across 30 days, is recorded as PMN.

Carbon dioxide (CO_2) respiration

I followed the protocol outlined by Franzluebbers (1999) except that I used a Picarro CO_2 Isotope Analyzer to measure the concentration of CO_2 gas produced by the samples five minutes after rewetting, again after 24 hours of incubation at ~22°C, and once more after 72 hours of incubation. One RB site was not analyzed as I ran out of sample.

The Picarro reports concentration of 12- and 13-CO_2 for two minutes per sample as a rolling average. I recorded a reading from the final 10 seconds of each sample, then determined total respiration by summing the two isotope concentrations ($^{12}CO_2$ + $^{13}CO_2$) and plotting them across time. A sample of this data can be found in Appendix **3.3**.

Chemical concentrations

Suspended ions and soil salts (pH, EC)

I used methods outlined by Moebius-Clune et al. (2016) for both soil pH and electrical conductivity with adjustments because of necessary dilution of the soil slurry beyond a water to soil ratio of 1:1. The raw and adjusted (Conyers & Davey, 1988) values of soil pH, as well as the raw and adjusted (Rhoades, Chanduvi, & Lesch, 1999) EC values, are included in Appendix **3.7**.

Combustion (C, N, S)

I followed an adapted protocol for sample preparation (Tiessen, Bettany, & Stewart, 1981) and a CAL technician prepared and calibrated an Elementar Vario MACRO Cube before processing my samples. This process drives out all carbon, oxygen, sulfur, and water from the samples. This allows for a measure of both total ash and total organic matter. Total ash are the minerals left behind while total organic matter is the mass which is combusted away.

Organic matter

Organic matter was determined by multiplying soil carbon by two (Pribyl, 2010).

Mehlich-III nutrient analysis (P, K, Ca, Mg, Mn, plant-available Cu, and Zn)

I chose the Mehlich-III (M3) extraction process to assess potassium, sodium, magnesium, phosphorus, manganese, iron, copper, and aluminum. I followed standard protocol (Mehlich, 1984) and placed the resulting filtrate solution in a sample-preservation fridge. A CAL technician ran the filtrate on a PerkinElmer 2100 DV ICP-OES (inductively coupled plasma, optical emission spectrometer). ICP-OES uses a plasma flame technique to excite atoms and ions which then emit light where the wavelength is characteristic of particular elements and the intensity conveys the concentration of the element.

Boron Content

I used a hot water bath to perform a calcium chloride extraction (Bingham, 1982) with an adjustment (Jones Jr., 2001). I placed the resulting solution in a vial in the fridge for a CAL technician to analyze them with the ICP-OES (Horneck, Hart, Topper, & Koepsell, 1989).

Heavy metal content (As, Pb, Co, Cu, Cr, Cd, Ni)

I put approximately 5g of each sample into individual vials made of polytetrafluoroethylene. These were loaded for microwave digestion using an Anton Par Multiwave GO. I followed procedure (Kingston & Jassie, 1986) with adjustment (Sah & Miller, 1992). I labeled the filtered solution and placed it in the fridge for ICP analysis.

Oxidation experiment

I chose two samples (~20g) from each level of OM presence: high, medium, low (see Table **3.3**). I subjected a replicate of each sample to one of three different periods of H_2O_2 oxidation: two, nine, and twelve days. I applied H_2O_2 in 2mL additions as permitted by the most reactive sample. At predetermined times, I removed a sample from each site and set it in an oven to dry. I then conducted a combustion analysis, as determined separately (see Chapter 3: Combustion). In some cases, the values from the first timepoint of oxidation exceed the pre-determined initial value of a sample's organic matter. This is due to experimental variance, which is ±3% for this test (Tiessen, Bettany, & Stewart, 1981).

Table **3.3**: The categories of the samples in the oxidation experiment. OM%=organic matter, as determined separately (see Chapter 3: Combustion). OM category represents the low, middle, and high points of organic matter in this project's samples. A repetition from each sample was subjected to one of three treatment lengths: 2 days and 9 H_2O_2 administrations, 9 days and 20 H_2O_2 administrations, 12 days and 41 H_2O_2 administrations.

Site #	**OM%**	**OM category**
31	5.1	Low
32	5.7	Low
14	15.5	Medium
25	15.9	Medium
19	28.7	High
22	30.3	High

Statistical Analyses

I used SigmaPlot (Systat Software, San Jose, CA) to test all groups for normality using Shapiro-Wilk's test and examined equal variance using Levene's Median test. I used ANOVA comparisons between the two bed-types. I used paired t-tests for those sites with both bed-types. If the data failed a Shapiro-Wilk normality test, I ran a Kruskal-Wallis ANOVA on ranks or a Wilcoxon signed rank test. Due to small sample size, container garden samples were omitted from analyses.

I also used the Cornell system (Moebius-Clune et al., 2016) to score each site's soil health qualities. Except, where that system runs from 0-100, I collapsed the ratings into their five color-coded groups and rated parameters on a scale from 1-5, with five being the best. Finally, I compared descriptive statistics, for each soil sample, to the recommended ranges for various soil parameters.

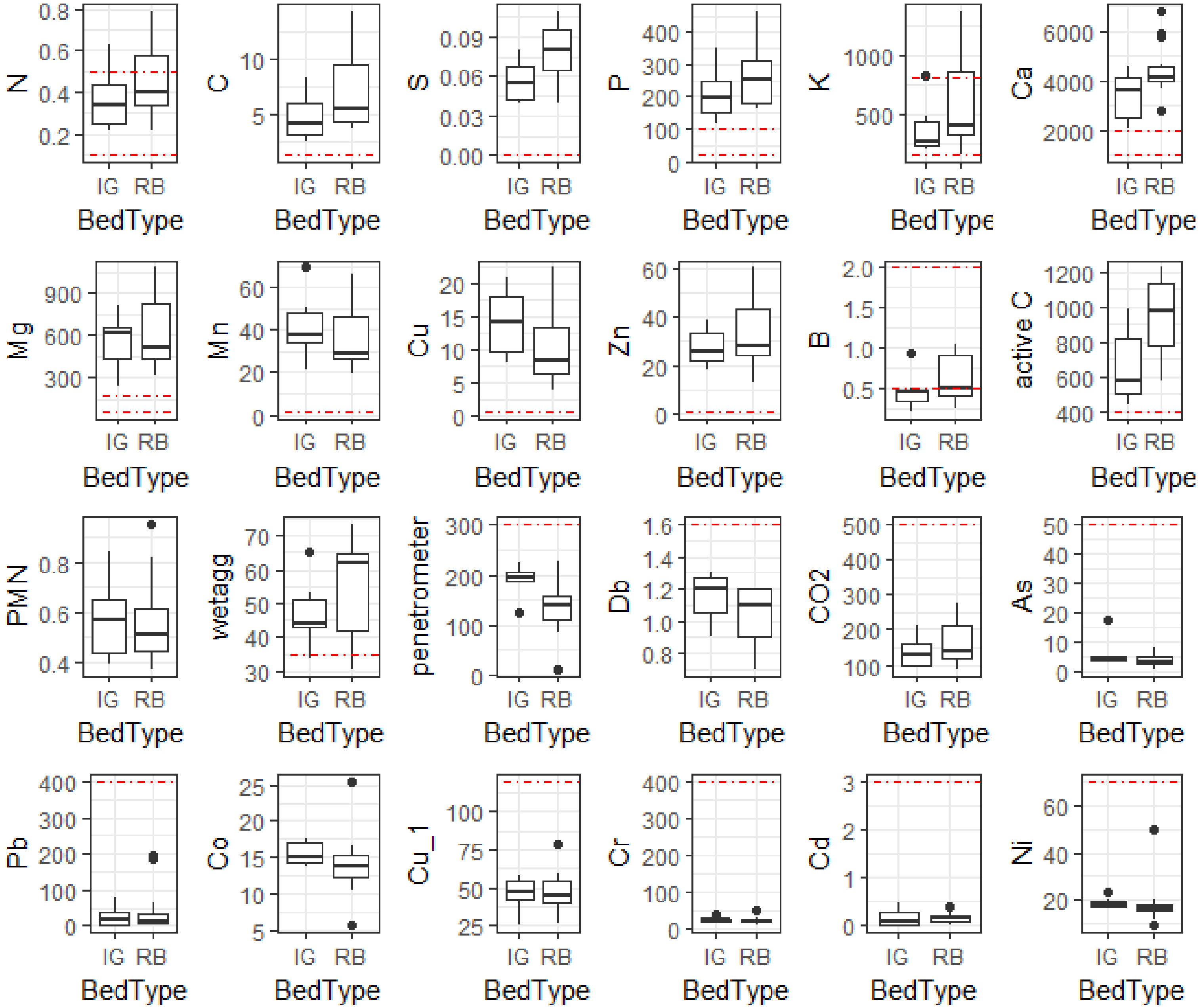
Results

On average, sites exceeded recommended fertility ranges for agricultural soils (Figure **3.1**). I selected some fertility parameters, displayed in Table **3.4**, to convey the state of excess of my study sites.

Table **3.4**: Percent of garden study sites (n=33) that are within, above, and below recommended ranges for various soil parameters (see Table **3.6**Table **3.9** for more information on recommended ranges).

Soil Parameter	**# of Sites**		
	Within Recommended Range	**Above Recommended range**	**Below Recommended Range**
organic matter	6%	94%	0%
EC	18%	82%	0%
C:N	9%	0%	91%
N	70%	30%	0%
S	0%	100%	0%
P	0%	100%	0%
K	73%	24%	3%
Ca	0%	100%	0%
Mg	0%	100%	0%
Mn	100%	No upper limit, but lowest value was an order of magnitude greater than the rec	0%
Plant-available Cu	100%	No upper limit, but the fourth lowest value exceeds the minimum recommendation by an order of magnitude	0%
Zn	100%	No upper limit, but lowest value was an order of magnitude greater than the rec	0%
B	42%	3%	55%

Figure **3.1**: Boxplots displaying the tested parameters of all the sites. Beds are grouped along the X-axis, where IG=in-ground beds and RB=raised beds. The Y-axis shows the name or element measured. The dotted lines display the recommended ranges (see Table **3.6**Table **3.9** for the source of recommendations). I did not discover a recommendation for PMN nor cobalt. N = nitrogen (%), C = carbon (%), S = sulfur (%), P = phosphorus (ppm), K = potassium (ppm), Ca = calcium (ppm), Mg = magnesium (ppm), Mn = manganese (ppm), Cu = plant-available copper (ppm), Zn = zinc (ppm), B = boron (ppm), active C = active carbon (ppm), PMN = potentially mineralizable nitrogen (ppm/day), wetagg = wet aggregate stability (% of soil mass), penetrometer = penetrometer reading (psi), Db = bulk density (g/cm^3), CO2 = carbon-dioxide respiration (ppm), As = arsenic (ppm), Pb = lead (ppm), Co = cobalt (ppm), Cu_1 = total copper (ppm), Cr = chromium (ppm), Cd = cadmium (ppm), Ni = nickel (ppm).


N
0.8
0.6
0.4
0.2
C
10
5
S
0.09
0.06
0.03
0.00
P
400
300
200
100
0
K
1000
500
Ca
6000
4000
2000
Mg
900
600
300
Mn
60
40
20
0
Cu
20
15
10
5
0
Zn
60
40
20
0
B
2.0
1.5
1.0
0.5
active C
1200
1000
800
600
400
PMN
0.8
0.6
0.4
wetagg
70
60
50
40
30
penetrometer
300
200
100
0
Db
1.6
1.4
1.2
1.0
0.8
CO2
500
400
300
200
100
As
50
40
30
20
10
0
Pb
400
300
200
100
0
Co
25
20
15
10
5
Cu_1
100
75
50
25
Cr
400
300
200
100
0
Cd
3
2
1
0
Ni
60
40
20
IG
RB
BedType

Across all garden sites, where differences between bed types were found, there was a tendency for raised bed soils to be higher for various soil parameters, compared to in ground beds (Figure **3.1**). In addition, several soil parameters fell outside of recommended ranges for vegetable garden soils, regardless of bed type.

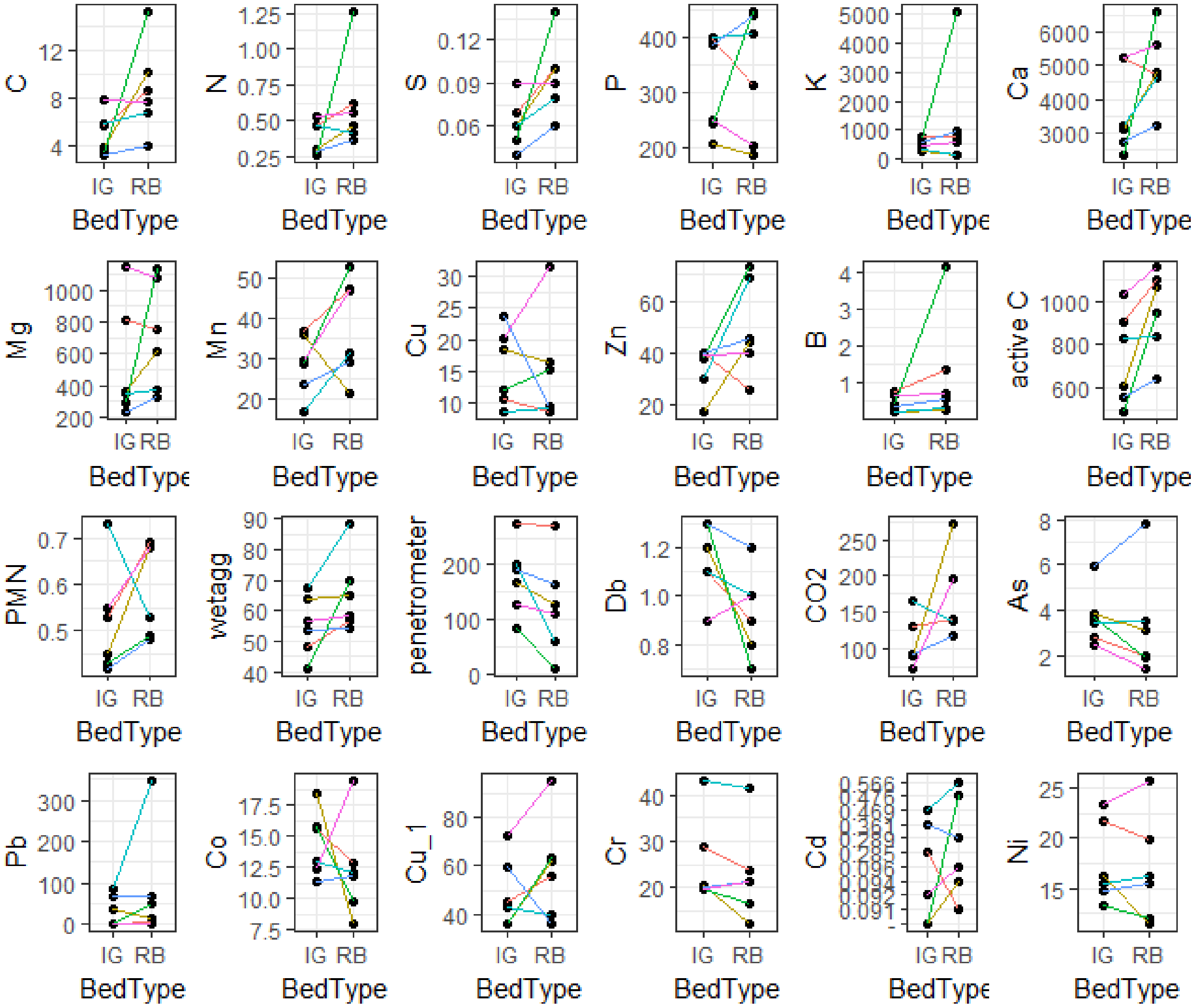
Between paired beds under a single manager

I found statistically significant differences between raised beds and in-ground bed pairs under the same manager across eight parameters. RB had greater concentrations of organic matter (t_5=2.063, p=0.047), carbon (t_5=2.026, p=0.049), sulfur (t_5=2.654, p=0.045), active carbon (t_5=2.8, p=0.019), and aggregate stability (t_5=2.137, p=0.043). IG led in concentrations of boron (Z=-2.201, p=0.031), greater penetrometer resistance (t_5=-2.417, p=0.030), and higher levels of bulk density (t_5=-2.076, p=0.046). For the six sites with both bed-types, soil texture was fairly consistent between soil samples (Table **3.5**). Texture was either consistent between soil samples within a site (i.e. loam and loam), or else textural classes were in adjacent categories (i.e. loam and sandy clay loam).

Table **3.5**: Textural class of paired bed-types. The first column denotes which bed-types were at the same site. RB are raised beds. IG are in-ground beds.

Site	**Bed-type**	**Textural class**
5	RB	Loam
	IG	Loam
7	RB	Loam
	IG	Sandy clay loam
17	RB	Sandy loam
	IG	Loam
22	RB	Sandy loam
	IG	Loam
24	RB	Sandy loam
	IG	Loam
26	RB	Loam
	IG	Loam

Figure **3.2**: Graphs representing the six sites with paired beds. IB are on the left and are connected by a site-specific color to the corresponding RB on the right. ‘Cu’ represents the measurement of plant-available copper, the ‘Cu_1’ parameter is a measure of total copper. N = nitrogen (%), C = carbon (%), S = sulfur (%), P = phosphorus (ppm), K = potassium (ppm), Ca = calcium (ppm), Mg = magnesium (ppm), Mn = manganese (ppm), Cu = plant-available copper (ppm), Zn = zinc (ppm), B = boron (ppm), active C = active carbon (ppm), PMN = potentially mineralizable nitrogen (ppm/day), wetagg = wet aggregate stability (% of soil mass), penetrometer = penetrometer reading (psi), Db = bulk density (g/cm^3), CO2 = carbon-dioxide respiration (ppm), As = arsenic (ppm), Pb = lead (ppm), Co = cobalt (ppm), Cu_1 = total copper (ppm), Cr = chromium (ppm), Cd = cadmium (ppm), Ni = nickel (ppm).



Physical Characteristics

Garden beds (12.9 ± 6.3%), whether raised (14.8 ± 6.8%) or in-ground (9.6 ± 3.9%), had an overabundance of organic matter (Table **3.6**). Raised beds were significantly more enriched in organic matter compared to in-ground beds (H_1=5.739, p=0.017).

Although garden soils had penetrometer readings that would not be considered compacted, I found significant differences in soil compaction between bed-types ($F_{1,32}$=4.814, p=0.036). In-ground beds were more compacted (181.1 psi ± 50.7) than raised beds (133.6 psi ± 64.3). However, it is important to note that mean compaction

(150.9 psi ± 63.3) was well below the recommended threshold for garden soils (<300 psi). Of 33 beds (21 RB and 12 IG), 91% showed no evidence of compaction. There were no significant differences between bed types for wet aggregate stability or bulk density (Table **3.6**). Soil texture was fairly similar among garden sites (Appendix **3.5** and **3.6**). A majority of soil samples (59%) were classified as loamy soil. The rest of the sites were classified as sandy loam (24%), clay loam (12%), silt loam (3%), and sandy clay loam (3%).

Table **3.6**: Physical parameters of soils sampled from Corvallis and Portland, Oregon, as well as recommended ranges. Mean physical parameters (and standard deviations) are presented for all garden beds, raised beds, in-ground beds, and containers. Recommended ranges were derived from ([1]*(Daddow & Warrington, 1983)*, [2]*(Moebius-Clune et al., 2016)*, [4]*(Fenton, Albers, & Ketterings, 2008)*). Recommended range for sand, silt, and clay values were set to values consistent with a [3]Loam textural class. Several physical parameters could not be calculated for the container garden (x), due the small volume of soil collected from the single container.

Physical Parameter	Recommended level	All beds (n=33)		Raised beds (n=21)		In-ground beds (n=12)		Containers (n=1)
		Mean (s.d.)	Range	Mean (s.d.)	Range	Mean (s.d.)	Range	Range
Bulk density (g/cm^3)	<1.6[1]	1.2 (0.1)	0.8-1.4	1.1 (0.2)	0.8-1.3	1.2 (0.1)	1.1-1.4	x
Wet aggregate stability (% of soil)	>35[2]	55.4 (13.3)	30.7-88.2	57.8 (14.3)	30.7-88.2	51.1 (10.7)	33.8-67.5	67
Penetrometer (psi)	<300[2]	150.9 (63.3)	10-275	133.6 (64.3)	10-273.3	181.1 (50.7)	81.8-275	x
Sand %	25-55[3]	43.4 (10.5)	21.9-63.3	45 (9.7)	32.1-63.3	41.1 (11.8)	21.9-59.8	x
Silt %	25-50[3]	36 (8.6)	20.8-51.4	19.6 (3.9)	13.9-30.2	20.9 (5.7)	14.1-32	x
Clay %	25-40[3]	20.5 (5.3)	13.9-33.9	35.4 (7.9)	20.8-47.9	38 (8.7)	21-51.4	x
Organic matter (% of soil)	3-6[4]	12.9 (6.3)	5.1-30.3	14.8 (6.8)	7.2-30.3	9.6 (3.9)	5.1-16.7	x

Biological Markers

Active carbon was significantly (H_1=8.090, p=0.004) greater in raised beds (950.1 ±203.3 ppm) than for in-ground beds (699.1 ± 212.9 ppm). In addition, microbial respiration was significantly (H_1=9.218, p=0.002) greater in raised beds (47.1 ± 15.5 µg CO_2-C/g dry soil/day) than in the in-ground beds (31.1 ± 11.6 µg CO_2-C/g dry soil/day).

PMN is a combination of four parameters—initial and final concentrations of both ammonia and nitrogen. Only the final ammonia concentrations were significantly (H_1=3.858, p=0.050) greater in RB (0.04 ± 0.03 ppm) than IG beds (0.02 ± 0.02 ppm). Ultimately, PMN did not differ significantly between bed-types (Table **3.7**).

Table **3.7**: Biological parameters of soil sampled from Corvallis and Portland, Oregon, as well as recommended ranges. Mean biological parameters (and standard deviations) are presented for all garden beds, raised beds, in-ground beds, and containers. Recommended ranges were derived from ([1]*(Moebius-Clune et al., 2016)*). Two biological parameters could not be calculated for the container garden (x), due the small volume of soil collected from the single container.

Biological Parameters	Recommended level	All beds (n=33)		Raised beds (n=21)		In-ground beds (n=12)		Containers (n=2)
		Mean (s.d.)	Range	Mean (s.d.)	Range	Mean (s.d.)	Range	Range
Active carbon (ppm)	>400[1]	68.8 (237.6)	445.9-1225.2	950.1 (203.3)	575.1-1225.2	699.1 (212.9)	445.9-1032.2	x
PMN (ppm NO_3-N + NH_4-N/g soil/day)	None found	0.563 (0.146)	0.370-0.945	0.573 (0.151)	0.370-0.945	0.544 (0.142)	0.394-0.836	x
CO^2 respiration (µg CO_2/g dry soil/day)	500-1500[1]	198.5 (221.4)	71-1327.2	172.6 (56.8)	105.9-273.7	114 (42.4)	71-213.6	602.4-1327.2

Chemical Concentrations

With the exception of pH (overall: 6.4 ± 0.3, raised beds: 6.4 ± 0.3, in-ground beds: 6.5 ±0.2; Table **3.8**), most gardens had chemical characteristics that were outside of the recommended range for vegetable garden soils (**Error! Reference source not found.**).

For example, electrical conductivity (EC) fell well outside of the recommended range of 100-200 µS/cm across all garden beds (301.7 µS/cm ± 351.2), and was elevated in raised beds (332.5 µS/cm ± 431.6) relative to in ground beds (247.7 units ± 123.4) (Table **3.8**). However, it is important to point out that the overall mean was strongly influenced by the EC of a single soil sample (site #22), which recorded an EC of 2279 µS/cm. The median response was 225.3 µS/cm. Excluding that single sample, EC ranged from 121-536 across all sites, with only six samples falling within the recommended EC range.

Carbon content of all beds (6.5 ±3.2%) showed a wide range (2.5-15.2%), and raised beds (7.4 ±3.4%) were found to be significantly (H_1=5.741, p=0.017) greater than in-ground (4.8 ±1.9%) (Table **3.8**). The carbon to nitrogen ratio of the sites (14.1 ± 2.8) was significantly different (H_1=6.576, p=0.010), with raised beds (15 ± 3.1) at a greater value than in-ground beds (12.6 ± 1.1).

Sulfur and calcium were both significantly ($F_{1,31}$=8.815, p=0.006 and $F_{1,31}$=7.720, p=0.009, respectively) more concentrated in raised beds (0.08 ± 0.2% and 4589 ±1043ppm) than in-ground beds (0.06 ±0.02% and 3510± 1128ppm).

Most soil elements were not significantly different between bed-types, including: nitrogen, phosphorus, potassium, magnesium, manganese, copper, zinc, and boron. However, several soil nutrients had means that were well outside the recommended range for vegetable garden soils, including sulfur, phosphorus, calcium, and magnesium (Table **3.8**).

Table **3.8**: Chemical parameters of soil sampled from Corvallis and Portland, Oregon, as well as recommended ranges. Mean chemical parameters (and standard deviations) are presented for all garden beds, raised beds, and in-ground beds. Recommended ranges were derived from ([1]*(Marx et al., 1999),*[2]*(Keesling, 1954)*, [3]*(Pribyl, 2010))*.

Chemical Parameters	**Recommended range**	**All beds (n=33)**		**Raised beds (n=21)**		**In-ground beds (n=12)**		**Containers (n=2)**
		Mean (s.d.)	**Range**	**Mean (s.d.)**	**Range**	**Mean (s.d.)**	**Range**	**Results**
pH	6-7.5[1]	6.4 (0.3)	5.6-7	6.4 (0.3)	5.6-7	6.5 (0.2)	6.2-7	x
EC (µS/cm)	100-200[1]	301.7 (351.2)	116.6-2187	332.5 (431.6)	130.8-2187	247.7 (123.4)	116.6-515	x
C:N	20-50:1[2]	14.1 (2.8)	10.9-22	15 (3.1)	11.2-22	12.6 (1.1)	10.9-14.7	x
C%	>1.25[3]	6.5 (3.2)	2.5-15.2	7.4 (3.4)	3.6-15.2	4.8 (1.9)	2.5-8.3	x
N%	0.1-0.5[1]	0.45 (0.21)	0.2-1.3	0.49 (0.23)	0.2-1.3	0.38 (0.13)	0.2-0.6	x
S%	0.0002-0.001[1]	0.07 (0.02)	0.04-0.14	0.08 (0.02)	0.04-0.14	0.06(0.02)	0.04-0.09	x
P (ppm)	20-100[1]	281 (102)	117.7-465.6	279 (102)	160.5-465.6	262 (99)	117.7-400.7	390-440
K (ppm)	150-800[1]	660 (830)	134-5089	780 (1048)	134-5089	448 (230)	199.3-827.2	517-839
Ca (ppm)	1000-2000[1]	4363 (1350)	2042-7889	4589 (1043)	2773-6821	3510 (1128)	2042-5209	6343-7889
Mg (ppm)	60-180[1]	627 (276)	235.4-1142	646 (267)	324.2-1137	545 (283)	235.4-1142	844-1015
Mn (ppm)	>1.5[1]	36.1 (13.4)	17.1-69.2	37 (13.9)	19.8-66.2	35.2 (13.9)	17.1-69.2	31.2-33
Cu (ppm)	>0.6[1]	13.7 (7.4)	3.8-33.6	11.7 (6.8)	3.8-31.3	14.9 (5.4)	8.2-23.7	22.3-33.6
Zn (ppm)	>1[1]	37.3 (16.4)	12.9-72.8	38.2 (17.2)	12.9-72.8	30.7 (8.8)	17.2-40	63.3-71.8
B (ppm)	0.5-2[1]	0.67 (0.69)	0.2-4.1	0.8 (0.83)	0.3-4.1	0.46 (0.23)	0.2-0.9	x

Heavy Metal Content

Heavy metals fell well below recommended maximums for all gardens (Table **3.9**). In addition, I found no significant differences in heavy metal content between bed-types. Arsenic levels were concerning for an in-ground bed in Corvallis which had an arsenic level (17.1 ppm) that was four times the sample average (3.8 ± 9 ppm), and above the recommended threshold of 16 ppm.

Across all sites, lead levels were below 400 ppm; the level at which when restrictions on gardening activities are recommended. However, four sites had lead levels above 50ppm; the level at which gardeners are cautioned to limit dust exposure (Brewer, Sullivan, Deol, & Angima, 2016). These soils came from a container in Portland (140 ppm), a raised bed in Corvallis (197 ppm), and two raised beds in Portland (185 ppm and 346 ppm).

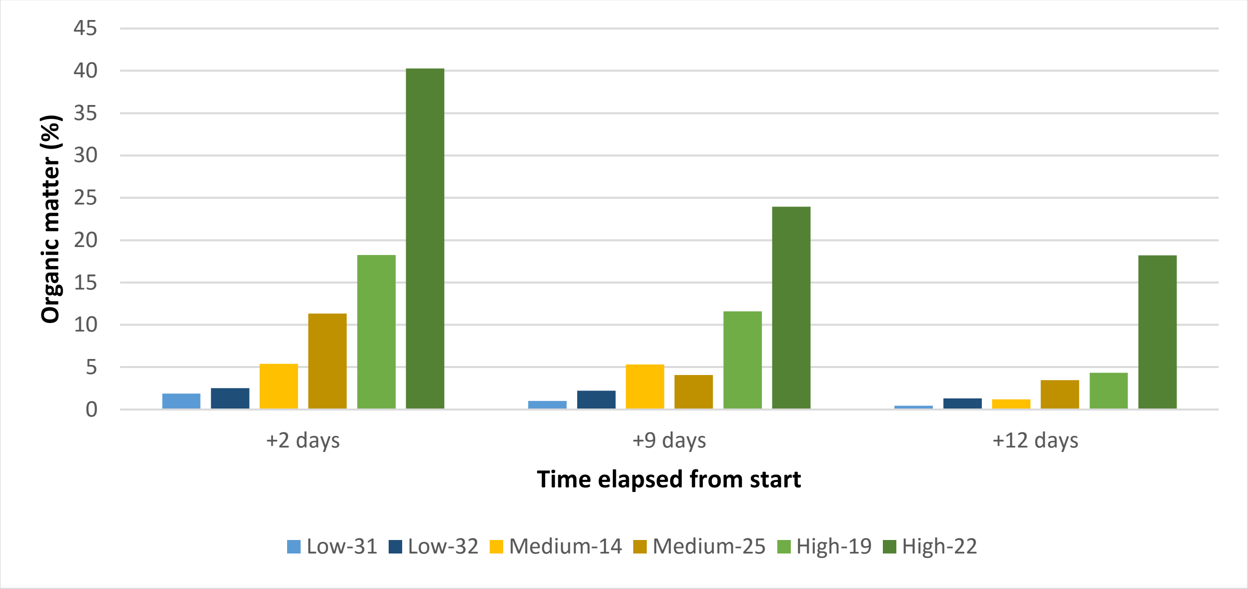
Table **3.9**: Chemical heavy metal parameters of soil sampled from Corvallis and Portland, Oregon, as well as recommended ranges. Mean heavy metal parameters (and standard deviations) are presented for all garden beds, raised beds, in-ground beds, and containers. Recommended ranges were derived from ([1]*(Moebius-Clune et al., 2016)*).

Heavy Metal Parameters	Recommended maximum	All beds (n=33)		Raised beds (n=21)		In-ground beds (n=12)		Containers (n=2)
Arsenic (ppm)	16 ppm[1]	3.8 (2.9)	0.2-17.1	3.6 (2.1)	0.6-7.8	4.9 (4)	2.5-17.1	0.19-1
Lead (ppm)	400 ppm[1]	45.7 (72.3)	0.2-346.8	52.2 (87.1)	0.2-346.8	29.5 (32.2)	0.2-83.9	7.8-140.1
Cobalt (ppm)	None found	13.6 (4.1)	3-25.4	13.7 (4.1)	5.6-25.4	15 (2.2)	11.4-18.3	3-7.3
Copper (ppm)	270 ppm[1]	51.8 (17.9)	25.1-109.1	50.6 (16)	27.3-95	47.4 (12.8)	25.1-72.4	72.9-109.1
Chromium (ppm)	36 ppm[1]	24.3 (8.5)	8.5-48.2	23.1 (8.8)	8.5-48.2	25.4 (8.2)	18.4-43.2	23.9-37.2
Cadmium (ppm)	2.5 ppm[1]	0.2 (0.15)	0-0.57	0.19 (0.15)	0-0.57	0.2 (0.17)	0-0.47	0.28-0.39
Nickel (ppm)	140 ppm[1]	17.6 (6.7)	9-49.5	17.8 (8.1)	9-49.5	18.2 (3.3)	13.2-23.6	10.4-12.3

Oxidation experiment

All samples decreased in organic matter content with increasing addition of hydrogen peroxide (Figure **3.3**). By nine days, the low and medium groups were at or below 5% organic matter. At the end of the experiment, all but the highest organic matter samples were around or below 5%. Of particular note is site #22 which, after 12 days and about 82mL of hydrogen peroxide yielding a loss of about half the organic matter, is still near 20% organic matter content.

Figure **3.3**: Results from a controlled oxidation experiment. The legend shows the site number (14, 19, 22, 25, 31, and 32) and the level of organic matter in the original sample. The X-axis shows three consecutive time points when a sample from each site was pulled for analysis. The Y-axis shows organic matter percent in the samples.



Discussion

To my knowledge, this study presents the first comprehensive reporting of the characteristics of residential-scale urban agriculture soils which includes physical, biological, and chemical characteristics. In addition, I examined the differences between garden soils in raised beds versus in-ground beds. I found that gardens are generally over-enriched in several soil parameters, including organic matter, phosphorus, calcium, magnesium, and potassium. These results suggest that routine compost applications have led to nutrient build-up over time (Seiter & Horwath, 2004), leading to high soil electrical conductivity, which is indicative of a build-up of soil salts. These results are particularly notable, as all soils were sampled from the gardens of certified Extension Master Gardeners, all of whom have received similar training regarding soil health and fertility.

Relatively little is known about the consequences of excessive organic matter in agricultural soils. Such excesses are not common in commercial agriculture, where loss of soil organic carbon is often a concern (see Lal, 2007 or Magdoff & Weil, 2004). Researchers have discovered accelerated nitrogen mineralization in organic soils (Broadbent, 1986), but these are Histosols, bog-type soils which generally experience extended anaerobic conditions. However, urban gardens have been noted to apply compost in excess in order to meet fertility needs (Lorenz, 2015), resulting in elevated levels of phosphorus and potassium levels in their soils and subsequent leaching to local watersheds (Goss, Williams, & Howse, 1991). The excesses in calcium, phosphorus, and potassium that we documented from garden soils in this study are unlikely to harm crops, nor is this excess likely to encourage rapid growth (Browne, 1942). Instead, these over-enriched soils that exceed agricultural recommendations are not only economically wasteful, but may also promote nutrient leaching (Dewaelheyns et al., 2013; Riaz, Murtaza, Farooq, & Farooq, 2018). This matter can be further affected by the amount of residue and the species of the previous crop (Goss, Williams, & Howse, 1991).

Walsh, Fletcher, and Ladson (2005) examined “urban stream syndrome,” a model describing the consistently observed ecological degradation of streams which drain from urban landscapes. Gittleman et al. (2017) estimate that 0.09” and 1.60” of water runs off per square inch of New York City community garden during a typical (i.e. 1.5” rain event) and heavy storm (i.e. 5” rain event). However, we don’t yet know the extent to which excess nutrients might leach from urban gardens, following a rain or irrigation event. However, the combination of over-enriched soils in a landscape surrounded by impervious surfaces suggests that urban gardeners might be contributing to urban-runoff and waterway contamination.

Beneath this excess of soil nutrients, I found stable soil parameters, such as bulk density, pH, and texture. These factors are important as they affect nearly all aspects of chemical and biological interactions within the soil matrix (Mengel & Kirkby, 2001). This indicates that results from this study should be comparable across sites. Differences between sites or bed types are likely not related to the underlying, native soils, but are instead likely due to management practices.

Although researchers have suggested that urban soils are expected to have low levels of soil microbial activity (Lorenz 2015), high levels of soil compaction (Lorenz, 2015; Pavao-Zuckerman, 2008), and high levels of contamination (Pickett & Cadenasso, 2009), I found the opposite for the soils in this study. All gardens sampled had evidence of highly active microbial communities, which could benefit crop production via cycling nutrients out of organic matter and into plant-accessible forms of nitrogen, phosphorus, or other elements, but may also promote leaching of mobile compounds, like nitrates. Nearly all soils sampled had no to low compaction. All soil samples were below recommended thresholds for heavy metals.

Bed-type

Despite anecdotal claims to the benefits of raised beds avoiding poor soil texture (Langellotto-Rhodaback, 2011), I found little evidence to suggest raised beds are superior to in-ground beds. Compared to in-ground beds, raised beds tended to be over-enriched in multiple soil parameters (e.g. organic matter, electrical conductivity, nitrogen, sulfur, phosphorus, potassium, calcium, magnesium, manganese, copper, zinc). Although I did not specifically query gardeners about their gardening practices, the most obvious explanation for this difference is that gardeners who used raised beds had to fill their beds with large volume of growing media. Gardeners who grew crops using in-ground beds likely did not have to add as much media to their soil before they could begin planting. In-ground gardeners could thus be expected to have decreased application of organic matter as well as the dilution of organic matter when it is tilled into the native soil.

Unexpectedly, the three highest lead levels were found within raised beds. Raised beds are recommended as a way for gardeners to grow food in areas where metals in the soil are a concern (Brewer et al., 2016). Soil samples adjacent to these sites (located from 0.4mi to 0.8mi away) did not exhibit elevated levels of lead, which suggests that environmental deposition is not the cause of the elevated lead levels. I do not know the source metals in soil samples. However, given the wide variety of compost products on the market, it is possible that the growing media used to fill the raised beds contained heavy metals. Gardeners should be wary of their compost purchases. If the compost makes no nutritional claim, then it is exempt from analysis and contamination limits (Association of American Plant Food Control Officials, 2018). If it does assert content-claims, then it must be registered and appropriately labelled, but the disclosure of heavy metal content is allowed to be veiled behind an ‘internet statement,’ meaning the heavy metal content is only online and not on the bagged product (Oregon Department of Agriculture: Pesticides Program, 2018).

Imbalanced Organic Matter in Urban Garden Soils

Perhaps the most noteworthy result from this study was the elevated levels of organic matter (average of 13% by mass) across study sites. This high level of organic matter complicated soil processing and analysis in the laboratory, and required modifications from standard protocols. For example, while lab technicians typically spend about 20 minutes (A. Villaseñor, personal communication, May 3, 2018) to intake a soil sample and screen it to remove organic matter, I spent about two hours per sample meticulously separating fine pieces of mulch from my soil sample. To prepare soil samples for textural analysis, samples are usually oxidized with hydrogen peroxide for one to three days (A. Villaseñor, personal communication, May 3, 2018) while I spent over five weeks oxidizing samples. Even at this length of time samples were still showing evidence of active oxidation, which is indicative of remnant organic matter. I also found reason to suspect the wet aggregate stability was over-estimated.

The elevated amount of organic matter in residential-scale garden soils makes sense, when considered in the context of garden size. In small garden plots, gardeners can easily over-apply products which have been recommended for successful, large-scale, agricultural production. For example, an analysis of pesticide labels for home-use versus agricultural-use of imidacloprid has shown that label directions could result in home-scale application rates that are up to 120 times higher than the maximum label rate approved for agricultural crops (Hopwood et al., 2012). This is because commercial growers treat plants per acre, whereas home gardeners are treating individual plants. It is easy to imagine that the over-abundance of organic matter in soils results from large amounts of compost added to a relatively small area. However, the response of garden soils to organic matter additions also demonstrates the ability of small-site managers to redirect the trajectory of their soils.

Oxidation experiment

While Leifeld and Kögel-Knabner (2001) found oxidation to be an acceptable preparation for soil textural analysis, their maximum starting value was ~8% organic matter content. In light of discovery that even an exceptionally lengthy oxidation treatment may not always bring a soil sample’s organic matter content within expected levels. It may benefit soil scientists to audit laboratory procedures in relation to analysis of the high organic content of urban garden soils.

Implication for management

Compost brings variable supplies of nutrients. While some research suggests organic matter can provide an adequate supply of micronutrients (Chen & Stevenson, 1986), I found a notable lack of boron in my samples. In a study characterized by excess, boron stands unique in that only one site exceeded recommendations, while more than half fell below the minimum concentration. Phosphorus in manure-based compost, for example, is more mobile than synthetic or mineral phosphorus (Seiter & Horwath, 2004), which may lead to nitrogen-phosophorus imbalance in soils.

The over-reliance upon organic matter to fertilize home garden soils, combined with the ease at which soil nutrients can be applied in small-plot gardens, likely contributed to the documented excess of several garden nutrients. Assuming a cost of $50/yard of compost (Mother Earth News, 2018), at 3.3 pounds of compost per square foot (Cogger, 2005; Collins et al., 2013), the final price comes to about $6/100ft^2. This is equates to just over $1,300 per acre to maintain a similar application rate (see

Table **3.10**). A hobby grower can likely afford residential-scale expenditures to improve the soil quality of their private garden. For example, one site (#22) in my study had a raised bed which, according to the manager, was filled entirely “with compost.” The electrical conductivity of this bed was an order of magnitude above all others (2279 µS/cm). Excessive salts, indicated by the high conductivity reading, can inhibit seed germination (Vázquez et al., 2015). Such high electrical conductivity values are typically only found in compost mediums (400-5000 µS/cm) (Costello, 2011).

Table **3.10**: Hypothetical scenario exploring costs to apply compost at a recommended application rate([1]*Cogger, 2005; Collins et al., 2013*)

Production type	**Arable land**	**[1]Cost to apply compost at 2lbs-N/1000ft^2**
Rural farm	100 acres	$130,680
Urban farm	2 acres	$2,613
Urban garden	100 ft^2	$6

Urban gardeners are often advised and trained to manage their soils with the same research which informs commercial agriculture. For example, cover crop calculators for farms and for gardens differ only the in the units (acres for farms, square feet for gardens) (OSU Small Farms, 2018). Soil sampling instructions assume that gardeners will sample over a large area (Fery & Murphy, 2013), rather than in the discrete, small beds that were typical for gardeners in this study. Home gardeners might not understand that commercial farms rely on cover crops and rotation, in addition to compost importation to maintain soil organic matter (Hodges, 1991; Weil & Magdoff, 2004).

I suggest that soil management be taught to urban gardeners as a two-phase approach: establishment and maintenance. Establishment involves converting the land from some other use into a garden. This should start with a test of the native soil to determine the starting point of fertility parameters. The primary concern should be matching the soil pH to the productive range of the desired crops. Additionally, this conversion should ensure acceptable bulk density for crop survival as well as texture for nutrient and water retention. The next step will likely involve a high degree of inputs in both material and labor in order to remediate a likely degraded soil into one of high-fertility. The timing of this phase will likely be short and will be controlled by the degree of labor involved in this process. After a site is determined to have become a productive garden, it is time to move to a maintenance approach regarding the soil fertility. The focus should shift to routine soil testing as both a check against existing or experimental management efforts as well as to track trends or shifts in soil content. From this point forward, it is likely that managers will simply need to use focused applications of specific nutrients to maintain typical production (Bradfield, 1942; Seiter & Horwath, 2004). Fine-tuning of the fertilizer inputs, in response to organic matter mineralization (Weil & Magdoff, 2004), can dramatically increase soil productivity for very little cost (Hodges, 1991). These suggestions run contrary to previous research (Domsch, 1985, as cited in Seiter & Horwath, 2004) which argued to attain the highest possible value of organic matter in a productive field.

I conducted an observational study of soil health in residential vegetable gardens in Corvallis and Portland, Oregon. The relatively small sample size (27 gardens from two cities) of this observational study limits my ability to make broad generalizations. Nonetheless, several interesting patterns emerged, which could be the focus of future research. For example, future studies could: (1) analyze the chemical characteristics of commercial compost to identify potential sources of contaminants in residential gardens, (2) develop an alternative set of laboratory tests for soils with elevated levels of organic matter, (3) examine the leaching potential of urban garden soils, (4) develop data-driven models for sustainable management of urban garden fertility, and (5) investigate how to modify Extension Master Gardener education materials to better enable gardeners to sustainably manage their soils. Despite increased interest in urban agriculture (Adewopo et al., 2014), the field of urban soils is relatively young (Kaye et al., 2006). Nearly any investigation will advance our knowledge in the field, and will help gardeners and other urban growers make more informed decisions for their land.

The single overlap between conventional agricultural soils and UA soils that I read (Setälä et al., 2014) pointed out that such soils share common interactions between ecosystem services and trade-offs. These interactions are shaped by human intervention, such that the manner and method of conversion of vacant lot to garden, or building to vacant lot, plays a large role in the future trajectory of that site (Beniston et al., 2014; Gardiner, Prajzner, Burkman, Albro, & Grewal, 2014). For example, residential development over previously forested soils showed a greater C and N density than in similar forested sites over time (Raciti et al., 2011). Rainey (2012) suggests the development of best management practices for both pre- and post-construction to improve soil services.

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CHAPTER 4: CONCLUSION

This project contributes to the field of urban agriculture and urban soil in the following ways:

- By conducting a holistic assessment of urban gardens, including site characteristics, management practices, and soil content.
- Being the first, to my knowledge, to examine a group of site managers with a common core of training and knowledge—in this case, OSU Extension Master Gardeners.
- Demonstrating that managers trained in best practices still create gardens with excessive soil nutrient content
- Highlighting a deficiency of boron in soils amidst a study awash in excess.
- Raising doubt on the efficacy of utilizing raised beds to avoid heavy metal contamination.
- Solidifying the case for urban agricultural research as distinct from conventional agricultural knowledge.
- Displaying a paucity of controlled, experimental research regarding urban agricultural soil.
- Pointing out which laboratory procedures are least appropriate when analyzing the high organic content of urban garden soils.

In 2007, the balance of human residence shifted to favor urban living over rural locations for the first time in recorded history (United Nations Population Division, 2017). This trend shows no sign of stopping as every year more cities are upgraded to mega-cities and the global population rises (United Nations Population Division, 2017). The location of most of these major cities is atop prized agricultural land (Imhoff et al., 1997). As urban areas expand, there is a further loss of farmland to make way for housing developments and associated infrastructure (Pérez & García, 2016). Increased urban dwelling has resulted in two phenomena: urban sprawl (the unplanned spreading of urban development into adjoining areas) and urban density (the number of people per meter squared of land). Urban agriculture is often suggested as a means of meeting global food needs (Lorenz, 2015; Tilman et al., 2002), localizing food production (Kontothanasis, 2017; Moore et al., 2008; Schupp & Sharp, 2012), and reducing food transport miles (Kulak, Graves, & Chatterton, 2013b; Martellozzo et al., 2014; Vázquez et al., 2015). Urban neighborhoods are often under-served by centralized grocery stores (Horowitz, Colson, Hebert, & Lancaster, 2004; Powell, Slater, Mirtcheva, Bao, & Chaloupka, 2006). Urban agriculture is thus also seen as a critical component of public health initiatives, by providing access to fresh, nutrient-dense foods.

Despite the popularity and potential benefits of urban agriculture, we know surprisingly little about the characteristics of one particularly prominent form of urban agriculture: home vegetable gardens. Research on home gardens has tended to focus on the social, political, and health benefits of gardening (Taylor & Lovell, 2014). We have limited reports and anecdotal data, at best, on what crops home gardeners are growing, how they manage these crops, and the impediments to residential-scale production.

Via an observational study, I documented the characteristics of 27 residential-scale vegetable gardens in Corvallis and Portland, OR. Specifically, I noted the diversity of crops, mulches, and general methods used by home gardeners. Even though all gardens were tended by individuals who belong to the same group (e.g. Oregon’s certified Extension Master Gardeners) there were relatively few garden elements that were shared across all gardens (Chapter 2). Gardeners used 16 different mulches and 132 different crops, including 74 annuals and 58 perennials.

Despite differences in individual gardens, there was a tendency for gardens to be over-enriched in organic matter, which likely contributed to soil fertility levels that were 2-8 time the upper recommended range for vegetable garden soil fertility (Chapter 3). There are several possible, non-mutually exclusive explanations for this over-enrichment. First, gardeners are not necessarily concerned with maximizing the economy of their garden, while commercial growers might pay more attention to balancing investments on inputs (e.g. organic matter, fertilizer) against crop returns.

Second, gardens tend to be small spaces (on average, <27.8m^2 in this study) that can quickly respond to additions or soil organic matter or nutrients. It may be that gardeners don’t necessarily understand how little input they need to optimize the soil fertility in small garden bed. Third, most gardeners do not regularly test their soil, yet they habitually add organic matter to their plots. Over time, this contributes to an excess of organic matter and some soil nutrients. Finally, the messaging of the OSU Extension Master Gardener Program has long been ‘just add organic matter’, when teaching gardeners how to manage home garden soils. My results suggest that the importance of testing garden soils before applying inputs, and as needed, perhaps moving away from compost additions and instead applying more focused fertilizers, such as feather meal or synthetic options.

In order to improve the sustainability and capacity of urban agriculture to meet local food needs, it is important to first understand gardeners’ current growing conditions and practices before we can identify areas of improvement. For example, crop rotation is often recommended as a best practice for sustainable gardening (Lorenz, 2015). However, most of the gardeners in my study reported that crop rotation was a particular challenge, give the small space they had available for production.

Current research and extension efforts don’t meet the technical needs of urban growers at the home scale or at commercial scales (Oberholtzer et al., 2014). Gardens and small scale urban farms differ in both scale and composition, relative to production agriculture in more rural areas. Yet many of the recommendations that we provide to urban growers are based upon research conducted in rural systems. There is a paucity of research on urban agricultural soils, in particular (Chapter 1). These soils have been identified as a key production challenge and priority need for future research and extension (Adewopo et al., 2014; Oberholtzer et al., 2014).

It seems the advice offered to urban growers are recommendations based upon a presumption that the soil needs drastic remediation to become productive. My findings suggest even trained land managers do not recognize when they might be able to stop establishing their site and shift into sustainable maintenance. This bias can be seen in the numerous fertility parameters which still lack an upper boundary and advice parrots a ‘more is better’ mentality. There are no easy answers to this fertility problem. Compost is ubiquitous and confers numerous beneficial properties to a soil. But scientific research must offer guidance to address the ensuing fertility imbalance which follows excessive reliance upon compost.

Laboratory practices

An unexpected outcome of this research was discovering a need to modify standard soil sampling and laboratory procedures for garden soil tests. The extremely high levels of organic matter in garden soil samples complicated analyses in several ways. First, I spent over a week and a half meticulously screening *each* soil sample in an effort to intercept and remove the abundance of organic material incorporated in the sample. This organic matter was mostly fine particles from the mulch which covered most garden beds. While I brushed most mulch aside prior to sampling, the sheer abundance of organic matter at the sample sites meant that much of it was captured in the initial soil sample, and needed to be screened out prior to analysis. Lab technicians do not typically have the luxury of spending 10 days processing a single soil sample prior to analysis. This points to the importance of communicating the need to take clean soil samples, without garden mulch, to gardeners who are collecting soils for a soil test.

Second, the abundance of organic matter in soil samples complicated analyses of soil texture. The standard procedure is to oxidize organic matter using hydrogen peroxide over the course of a week, or less. Under typical levels or organic matter (e.g. 5% or less), one week is adequate to oxidize organic matter. However, a majority of my samples continued to display signs of active oxidation even after five weeks of hydrogen peroxide applications. As a result of my experience in the lab, the Oregon State University Central Analytical Laboratory is beginning to formulate alternative processing procedures for garden soil samples. For example, processing soil samples in a muffle furnace guarantees complete organic matter combustion but risks altering mineral structures within the sample, which could alter the textural profile. However, for samples with high organic matter, it may be that the variance introduced by mineralization may be preferred to the variance introduced by incomplete organic matter oxidation. While Leifeld and Kögel-Knabner (2001) found organic matter to oxidize at a rate consistent with the initial concentration, they did not test samples above approximately 8% organic matter.

High garden soil organic matter also impacted analyses of wet aggregate stability. Once again, residual organic matter in soil samples complicated results. The bits of organic matter which made it past the initial sieving show resilience against the rain simulator. While organic matter contributes to aggregation factors and provides the feed for microbes which exude the extra-cellular polysaccharides, it is not the organic matter itself we are seeking to test for stability. Examining the remaining 'stable aggregates' suggests that a large portion of this media is in fact finely shredded organic matter.

Based upon the results of my research, I suggest that soil analytical labs amend their standard operating procedures to include an alternative processing track for garden soil samples, to account for the high level of organic matter that is typifies these samples. For example, additional time could be allocated to processing garden samples (to remove fine organic matter) prior to analysis. We might also ask gardeners to submit a soil sample that does not include the top 1-2cm of garden soil, in order to exclude organic mulches from the soil sample, and to yield more accurate results.

Future directions

If we want to support and grow UA, we need to keep crop production central to our effort, and not view UA as an architectural amenity (Eigenbrod & Gruda, 2015). In turn, this will require investing efforts in UA production research and extension, at multiple scales (e.g. residential, community, commercial). Luckily, research and extension opportunities abound in the rapidly growing field of urban agriculture. Relatively few land grant universities have extension or research programs focused upon urban agriculture. Notable exceptions include the University of California's extension urban agriculture program and the University of Illinois' extension master urban farmer training. Oregon State University extension supported a beginning urban farming apprenticeship program from 2011-2017, until the program was no longer financially feasible to deliver. These extension efforts are critically reliant upon research from lab groups in Illinois (e.g. Dr. Sarah Taylor Lovell), Ohio (e.g. Dr. Mary Gardiner), and California (e.g. Drs. Stacy Philpott and Gordon Frankie). As more researchers document develop system- and scale-appropriate practices that serve the needs of urban growers, the success of UA will grow. Luckily, plentiful research needs abound, including the open area of urban agricultural soils.

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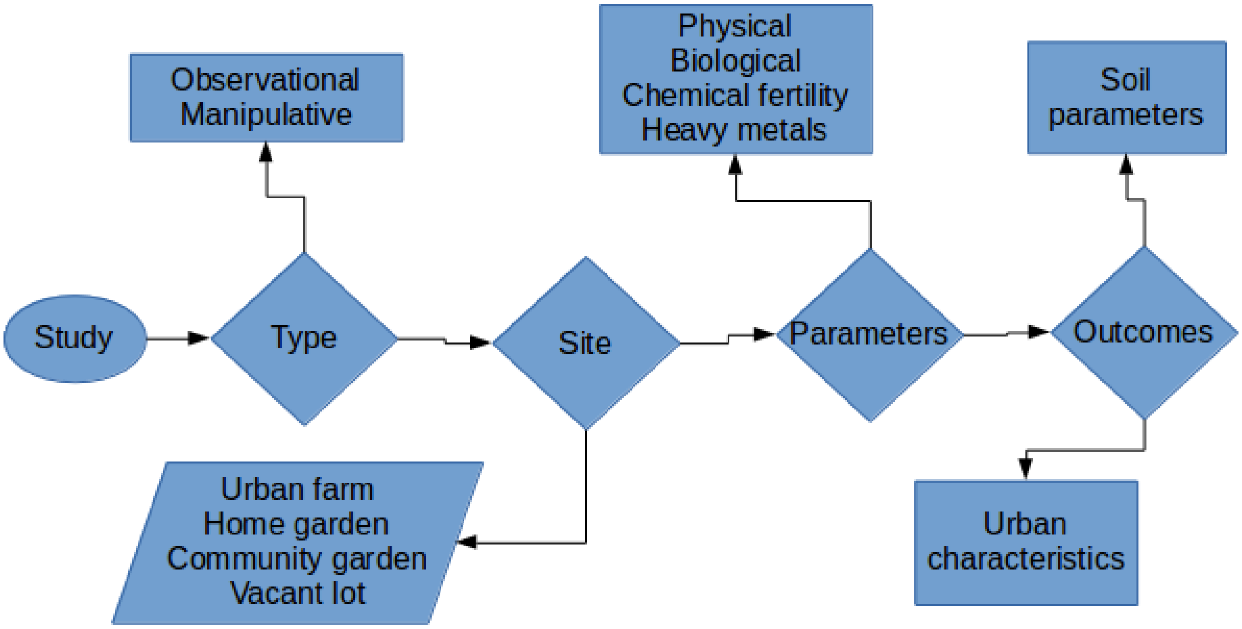
APPENDICES

Appendix **1.1**: A flow chart which represents the manner used to score the reviewed literature. Studies were scored according to study type, site type, parameters studied, and general outcomes.



Appendix **1.2**: A table displaying the 17 articles in the United States which directly address urban, agricultural soil. Regarding study types, M = manipulative study, O = observational study. Study sites are abbreviated as follows: C = community garden, H = home garden, U = urban farm, V = vacant lot.

Author and year	**Location**	**Study type**	**Study site**	**Specific parameters examined**	**Findings or conclusions.**
Beniston et al., 2015	OH, MI	M	V	pH, carbon, phosphorus, potassium, organic matter, texture, lead	Importing organic matter improves physical properties. Degraded soil can be rapidly amended into productivity.
Beniston, 2014	OH	M	V	pH, active carbon, microbial biomass, electrical conductivity, carbon, nitrogen, organic matter, bulk density, wet aggregate stability, arsenic, lead, cadmium	Demolition of vacant houses results in high bulk density. Application of large amounts of organic matter can benefit numerous soil properties. Vacant land in shrinking industrial cities holds significant potential for urban agriculture.
Cheng et al., 2015	NY	O	C, H	Chromium, cobalt, nickel, copper, zinc, arsenic, cadmium, lead	Correlation between chromium and other heavy metals. Good cleaning techniques decrease heavy metal ingestion risk, soils should be tested before cultivation.
Clarke et al., 2015	CA	O	C	arsenic, lead, cadmium	Proximity to roads increased all heavy metal parameters. Lead increased with neighborhood age. exchangeable arsenic increased with cultivation

Defoe et al., 2014	WA	M	C, H	Lead, arsenic	Lead was highest in roots, lowest in fruits. Arsenic remained low and may not translocate through plants. They claim 700-1900ppm of soil lead is still safe for gardening.
Finster et al., 2004	IL	M	H	lead	Heavy metal content is greatest in roots>stem/leaves>fruit if the metals source from the local parent material. Roots contained 2-51% of soil lead. Urban gardeners should test the lead levels in their soils and develop strategies to ensure safety.
Gorospe, 2012	CA	O	H	pH, arsenic, lead, cobalt, chromium, cadmium, nickel, zinc, barium, vanadium	In-ground beds had the highest readings for every heavy metals parameter. Arsenic, cadmium, and lead were significantly lower in raised beds.
McBride et al., 2014	NY	O	H	lead, cadmium, barium, aluminum	Vegetable barium was much higher than lead or cadmium, although soil barium was lower than soil lead. Vegetable lead correlated with aluminum; soil particle adherence/incorporation was more important than lead uptake via roots.
Mielke et al., 1983	MD	O	H	pH, zinc, lead, copper, cadmium, nickel	Heavy metals were concentrated and ubiquitous particularly in the urban center
Minca et al., 2012	OH	O	V	pH, carbon, nitrogen, texture, arsenic, lead, copper, chromium, cadmium, nickel, zinc, salinity	Significant linear regressions between total lead and Mehlich 3.

Mitchell et al., 2014	NY	O	C	pH, carbon, nitrogen, sulfur, phosphorus, potassium, calcium, magnesium, manganese, cobalt arsenic, lead, copper, chromium, cadmium, nickel, zinc , aluminum, iron, lithium, sodium, titanium, vanadium, barium, beryllium	Barium and lead most frequently exceeded guidance values and along with cadmium were strongly correlated with zinc. Most samples (78%) did not exceed guidance values, though at least one sample exceeding health-based guidance values in 70% of gardens. Contaminants were associated with visible debris and a lack of raised beds; management practices (e.g., importing uncontaminated soil) have likely reduced metals concentrations.
Reeves et al., 2014	OH	O	C, U	pH, carbon, nitrogen, organic matter, texture, nematodes	Urban farms (~9%) had more organic matter than community gardens (~6%). Neither location were nutrient limited, but urban farms tended to outperform community gardens.
Spliethoff et al., 2016	NY	O	C	lead	Children are more likely to be exposed to lead due to inhalation/digestion of dust particles. recommend replacing the rooting-depth with new media as a means to avoid contamination
Sterrett et al., 1996	MD	M	C, H	pH, phosphorus, manganese, zinc, lead, copper, cadmium, nickel, iron	Heavy metals content is higher in produce from contaminated/urban sites. Risk is low until soil lead >500ppm.
Stilwell et al., 2008	CT	O	C	arsenic, lead, copper, chromium, cadmium, nickel, zinc, titanium, uranium	Cadmium was above detection limits in all samples. Arsenic, copper, chromium, nickel, zinc at safe levels.

Walker et al., 2009	NV	O	H	arsenic, lead	An informational article about the potential affects that arsenic could have on crops in Nevada.
Whitzling et al., 2010	IL	O	H	pH, nitrogen, phosphorus, potassium, copper, lead	Gardens contained excessive fertility, with raised beds containing less heavy metals than in-ground beds. They also found a correlation between Mehlich-3 and Environmental Protection Agency methods of lead assessment.

Appendix **2.1**: Full list of crops recorded from all sites.

Annual crops		**Perennial crops**	
common name	**# of sites**	**common name**	**# of sites**
Tomato	25	Raspberry	16
Basil	22	Blueberry	15
Bean	20	Apple	14
Kale	20	Fig	14
Squash, summer	19	Strawberry	14
Pepper, hot	18	Rhubarb	12
Lettuce	17	Sage	12
Eggplant	15	Asparagus	11
Cucumber	14	Artichoke	10
Pepper, sweet	14	Chive	10
Onion	13	Lavender	9
Potato	13	Rosemary	9
Squash, winter	13	Grape	8
Carrot	12	Pear	8
Chard	12	Currant	7
Pea	12	Marion berry	7
Cabbage	11	Oregano	7
Garlic	11	Thyme	7
Parsley	11	Blackberry	6
Sunflower	11	Mint	6
Beet	10	Hop	5
Broccoli	9	Persimmon	5
Nasturtium	8	Cherry	4
Leek	7	Peach	4
Echinacea	6	Marjoram	3
Arugula	5	Plum	3
Borage	5	Prune	3
Brussels	5	Tarragon	3
Cilantro	5	Aronia	2
Fennel	5	Gooseberry	2
Parsnip	5	Hardy kiwi	2
Cauliflower	4	Lemon	2
Shallot	4	Lemon verbena	2
Bok choy	3	Tayberry	2
Celery	3	Asian pear	1

Corn	3	Chamomile	1
Dill	3	Choke cherry	1
Ground cherry	3	Elderberry	1
Horseradish	3	Fern, fiddle heads	1
Kohlrabi	3	Pineapple guava	1
Radish	3	Goji	1
Shiso	3	Gumi	1
Spinach	3	Hazelnut	1
Tomatillo	3	Honey berry	1
Cabbage, napa	2	Josta berry	1
Chicory	2	Lemongrass	1
Collard	2	Lime	1
Mustard	2	Mulberry	1
Oca	2	Papaya	1
Okra	2	Passion fruit	1
Pumpkin	2	Paw paw	1
Purslane	2	Quince	1
Strawberry	2	Savory	1
Sunchoke	2	Sea berry	1
Sweet potato	2	Serviceberry	1
Turnip, salad	2	Snow berry	1
Yacon	2	Thimbleberry	1
Amaranth	1	Walnut	1
Barley	1		
Burnet	1		
Celeriac	1		
Gai lan	1		
Kalettes	1		
Melon	1		
Papalo	1		
Perilla	1		
Rhubarb	1		
Romanesco	1		
Scallion	1		
Sorrel	1		
Stevia	1		
Thistle	1		
Vietnamese corriander	1		
watercress	1		

Appendix **3.1**: Comprehensive Assessment of Soil Health (CASH) scores (*Moebius-Clune et al., 2016*) for all sites. Only methods which were similar to those employed in my study were scored according to the CASH rating. RB=raised bed, IG=in-ground bed, organic matter=organic matter, C=carbon, P=phosphorus, K=potassium, micronutrient score is a composite ranking of magnesium, manganese, and zinc. A score of five is the best, a score of 1 is the worst. Micronutrients were unable to reach a full five points because Iron was not assessed and thus missing from the final score.

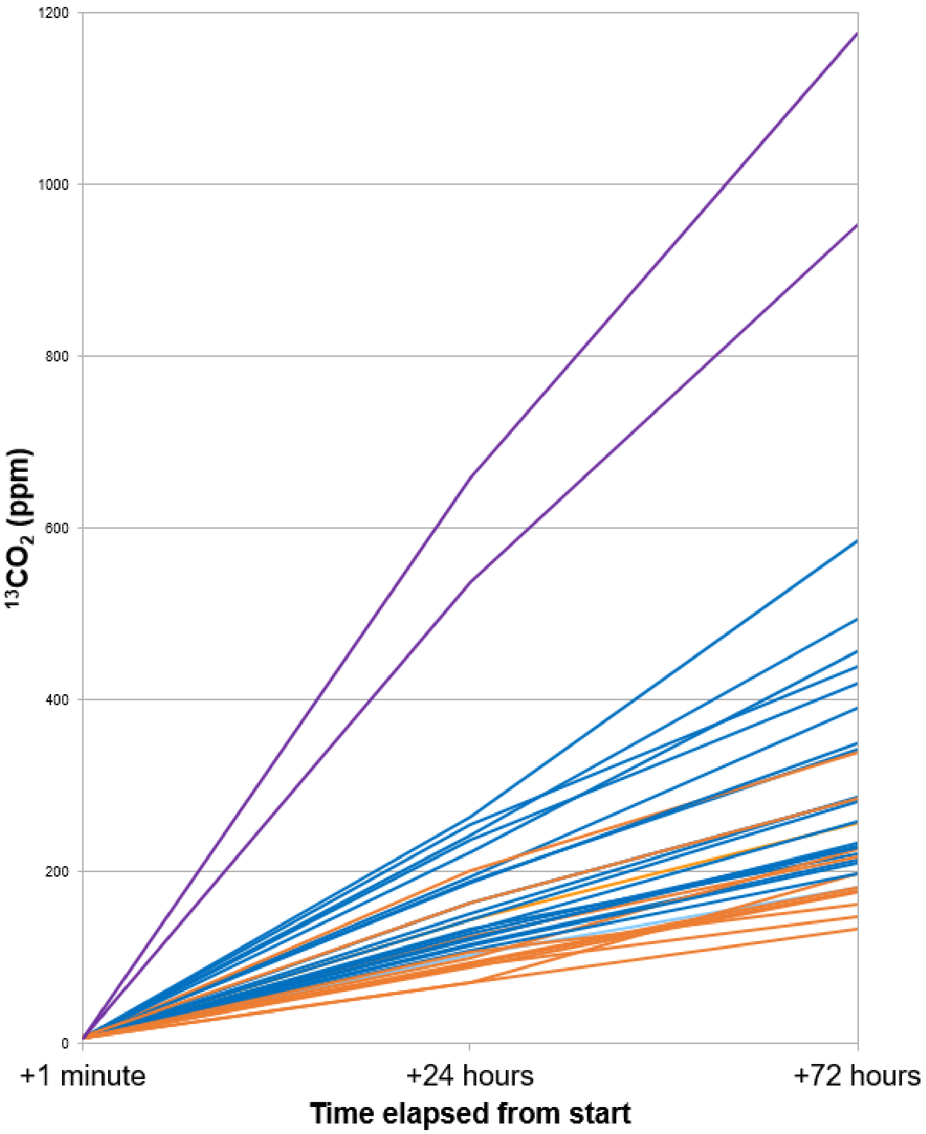
Site #	Bed-type	Textural range	Subsurface hardness	Wet aggregate stability	Organic matter	CO_2	Active carbon	Acid-pH	Normal-pH	P	K	Micronutrient score
1	RB	medium	5	5	5	3	5	5	5	1	5	4
2	RB	fine	4	5	5	3	5	5	5	1	5	4
3	RB	fine	4	2	1	1	3	5	5	1	5	2
5	IG	medium	5	4	5	1	5	2	5	1	5	2
5	RB	medium	4	2	5	2	5	5	5	1	5	4
6	RB	medium	5	4	2	3	5	1	5	1	5	4
7	IG	fine	4	5	2	4	5	5	5	1	5	4
7	RB	medium	5	5	1	3	5	5	5	1	5	4
8	RB	medium	4	3	4	2	5	3	5	1	5	4
9	IG	medium	4	4	2	2	5	3	5	1	5	4
10	IG	medium	5	2	5	1	4	1	5	1	5	4
12	IG	fine	5	3	1	1	3	2	5	1	5	2
13	IG	medium	5	4	5	1	5	3	5	1	5	4
15	RB	medium	5	3	3	1	5	1	5	1	5	4
16	RB	medium	5	5	1	2	5	2	5	1	5	4
17	IG	medium	5	4	5	4	5	4	5	1	5	2
17	RB	coarse	5	5	5	1	5	4	5	1	5	4
18	RB	coarse	5	5	5	3	5	5	1	1	5	4

19	RB	medium	5	2	5	2	5	5	4	1	5	2
20	RB	coarse	5	5	3	3	5	2	5	1	5	4
21	RB	coarse	5	5	4	x	5	1	5	1	5	4
22	RB	coarse	5	5	5	2	5	5	5	1	5	4
22	IG	coarse	5	4	5	2	5	3	5	1	5	4
23	RB	medium	5	5	5	3	5	4	5	1	5	2
24	RB	medium	5	3	2	1	4	4	5	1	5	4
24	IG	medium	5	4	5	1	5	1	5	1	5	4
25	RB	medium	5	5	5	4	5	4	5	1	5	4
26	IG	medium	5	5	3	1	3	4	5	1	5	4
26	RB	medium	5	3	2	1	4	5	5	1	5	4
27	RB	coarse	5	3	2	1	3	5	5	1	5	4
28	RB	medium	4	4	2	1	3	5	5	1	5	4
31	IG	medium	5	5	4	3	5	5	5	1	5	4
32	IG	medium	5	4	2	1	3	2	5	1	5	4

Appendix **3.2**: Weights of rock fraction and organic matter from fresh samples.

sample #	**rock weight (g)**	**organic matter wet weight (g)**
1	179.5	18.0
2	79.7	4.4
3	59.1	3.9
4	137.6	0.3
5	91.1	3.3
6	31.8	4.4
7	76.4	2.7
8	134.3	9.4
9	19.8	10.1
10	138.9	2.6
11	87.1	2.8
12	20.2	1.9
13	114.0	4.8
14	107.4	5.1
15	36.2	2.6
16	69.5	8.6
17	190.4	4.8
18	29.7	4.2
19	130.7	6.6
20	62.5	6.2
21	71.5	2.2
22	55.1	7.1
23	106.7	6.5
24	91.1	1.0
25	107.1	3.7
26	47.7	4.7
27	81.4	1.6
28	7.5	79.8
29	160.1	1.3
30	70.0	4.8
31	28.1	3.9
32	55.7	8.8
33	194.6	11.8
34	74.3	3.9
35	4.5	43.7
36	7.1	113.0

Appendix **3.3**: Respiration of soil samples across five days. Only $^{13}CO_2$ is shown, with concentration in ppm displayed on the Y-axis. The X-axis begins one minute after rewetting the samples and ends 72 hours later. The two purple lines represent the two container samples. Blue lines are RB, while orange lines are IG.



Appendix **3.4**: The initial and final concentrations from potassium chloride extractions to determine PMN.

	Initial extraction		**Final concentration**	
Sample#	**Ammonia (ppm)**	**Nitrate (ppm)**	**Ammonia (ppm)**	**Nitrate (ppm)**
1	1.4	6.3	0.2	28.3
2	1.0	1.9	0.3	14.3
3	1.7	9.1	0.2	27.1
4	0.6	2.0	0.2	9.5
5	0.7	3.2	0.2	22.7
6	0.7	3.6	0.2	15.5
7	0.9	6.4	0.2	25.5
8	2.4	4.2	0.2	18.5
9	1.1	6.8	0.2	30.2
10	0.9	2.3	0.2	20.9
11	0.7	6.8	0.2	21.7
12	0.6	2.0	0.2	17.0
13	2.5	2.3	0.2	17.4
14	0.7	9.2	0.2	24.6
15	0.7	2.6	0.2	16.8
16	0.8	3.5	0.2	17.4
17	1.7	8.0	0.2	26.2
18	0.9	3.7	0.2	15.1
19	2.3	4.6	0.3	26.5
20	0.7	4.2	0.2	18.1
21	0.6	4.7	0.2	15.0
22	3.9	38.2	0.4	48.7
23	0.9	3.1	0.2	14.4
24	0.9	5.4	0.2	20.3
25	1.0	10.6	0.2	28.8
26	1.0	13.1	0.2	26.2
27	1.0	3.4	0.2	18.5
28	2.0	1.1	0.4	15.8
29	0.9	5.0	0.2	17.3
30	0.7	1.4	0.2	13.2
31	0.7	3.7	0.2	14.6
32	0.9	0.9	0.2	11.9

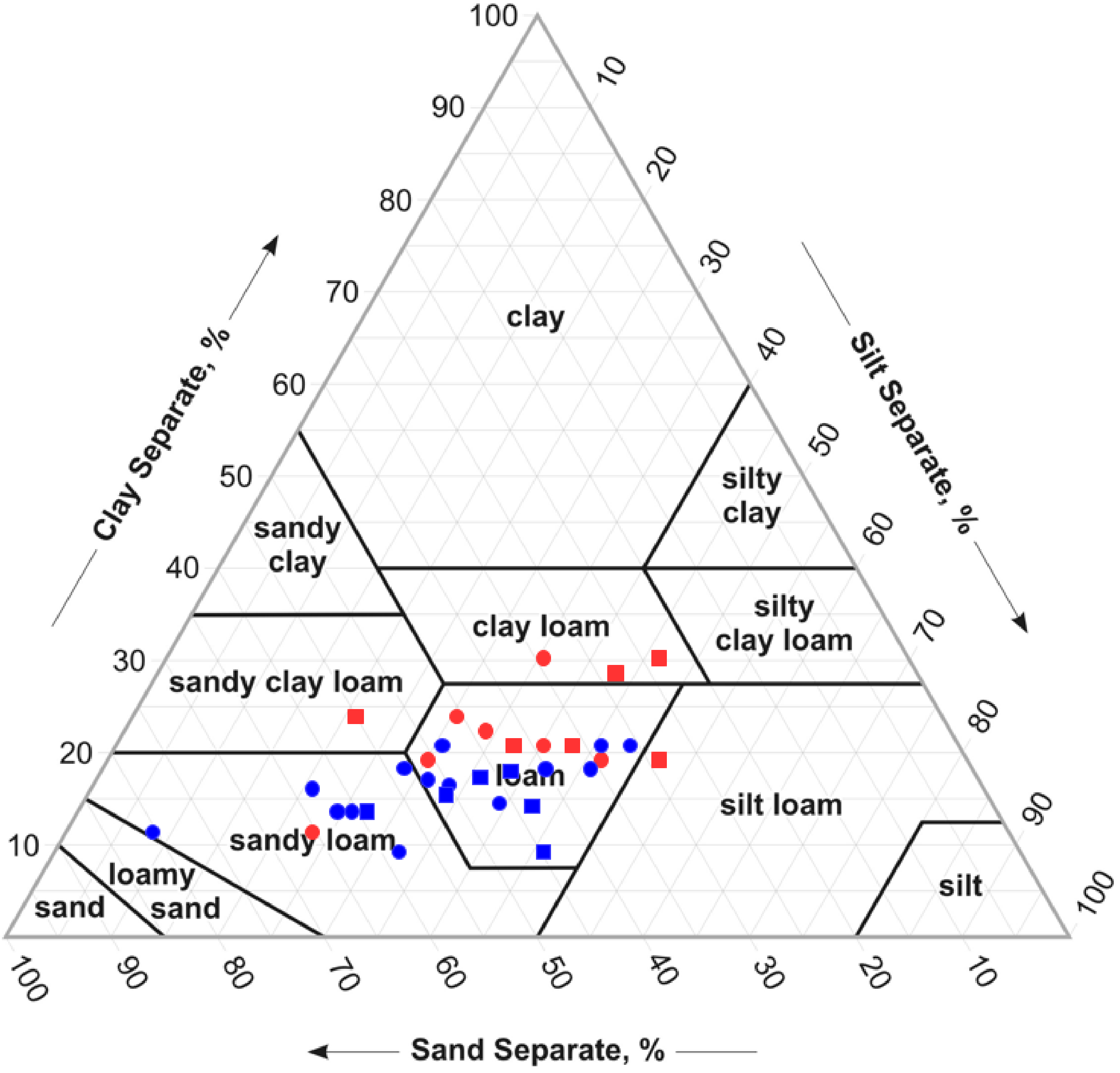
33	0.9	4.6	0.3	25.3
34	0.7	3.5	0.2	15.0

Appendix **3.5**: Raw data for physical characteristics of all sites. For bed-type, ‘RB’ represents for raised bed, ‘IG’ represents for in-ground beds, ‘cont’ represents container samples. ‘Compromised’ indicates the samples were irreparably disrupted in the course of lab work. The ‘x’s represent a lack of data from the container samples due to very limited sample volume.

Site #	Bed-Type	Wet aggregate stability (%)	Textural class	Sand (%)	Silt (%)	Clay (%)	Penetrometer (psi)	Compaction rating	Bulk density (g/cm^3)
1	RB	64.3	loam	44.2	33.9	21.9	140.3	little to none	1.0
2	RB	65.1	clay loam	66.3	24.1	9.6	227.8	little to none	1.0
3	RB	30.7	clay loam	34.7	35.1	30.2	218.8	little to none	1.3
5	RB	56.8	loam	50.5	29.7	19.8	273.3	moderate	1.1
5	IG	48.4	loam	35.7	42.5	21.8	275.0	little to none	1.2
6	RB	34.4	loam	34.8	43.5	21.7	112.1	little to none	1.3
7	RB	58.4	loam	38.0	40.0	22.0	109.4	little to none	1.1
7	IG	56.6	sandy clay loam	54.9	21.0	24.0	126.4	little to none	1.1
8	RB	64.2	loam	46.1	31.0	23.0	139.2	little to none	1.0
9	IG	65.0	clay loam	28.8	43.1	28.1	204.7	little to none	1.1
10	IG	43.5	loam	40.0	37.0	23.0	222.5	little to none	1.2
12	IG	33.8	silt loam	27.4	51.4	21.2	187.5	little to none	1.3
13	IG	42.5	clay loam	21.9	46.1	32.0	125.0	little to none	1.3
15	RB	42.0	loam	32.9	45.1	22.0	158.3	little to none	1.3
16	RB	61.8	loam	47.2	32.9	19.9	185.0	little to none	1.2
17	RB	64.8	sandy loam	63.3	20.8	15.9	125.9	little to none	1.0
17	IG	63.9	loam	44.0	38.0	18.0	168.8	little to none	1.3
18	RB	51.8	loam	32.1	47.9	20.0	129.2	slight	1.3
19	RB	68.7	sandy loam	80.0	9.0	11.0	12.5	little to none	0.8

20	RB	35.6	loam	47.4	38.0	14.6	158.3	little to none	1.2
21	RB	66.6	sandy loam	60.1	25.9	14.0	90.9	little to none	1.1
22	RB	69.7	sandy loam	53.4	27.5	19.1	10.0	little to none	0.8
22	IG	41.2	loam	46.1	37.0	17.0	81.8	little to none	1.3
23	RB	57.8	sandy loam	56.8	33.2	10.0	143.8	little to none	1.2
24	RB	88.2	sandy loam	62.3	23.8	13.9	58.3	little to none	1.1
24	IG	67.5	loam	44.8	46.2	9.0	200.0	little to none	1.2
25	RB	73.2	loam	51.9	31.1	17.0	110.0	little to none	1.1
26	RB	54.4	loam	35.8	46.2	18.1	165.3	little to none	1.3
26	IG	53.3	loam	42.9	42.3	14.8	191.3	little to none	1.3
27	RB	41.7	loam	39.9	42.1	18.0	83.3	little to none	1.3
28	RB	64.6	loam	50.3	33.8	15.9	154.2	little to none	1.0
31	IG	44.1	sandy loam	59.8	26.1	14.1	187.5	little to none	1.4
32	IG	53.5	loam	50.0	34.0	16.0	203.1	little to none	1.4
33	cont	x	x	x	x	x	x	x	x
34	cont	67.3	x	x	x	x	x	x	x

Appendix **3.6**: Soil textural triangle with sites as dots. Squares represent in-ground beds while circles represent raised beds. Corvallis sites are in red. Portland sites are in blue. Raised beds are indicated by circles. In ground beds are represented by squares. Figure adapted from: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054311.


100
90
80
70
60
50
40
30
20
10
Clay Separate, %
10
20
30
40
50
60
70
80
90
100
Silt Separate, %
100
90
80
70
60
50
40
30
20
10
Sand Separate, %
clay
sandy
clay
silty
clay
clay loam
silty
clay loam
sandy clay loam
loam
silt loam
sandy loam
loamy
sand
sand
silt

Appendix **3.7**: Raw and adjusted values of both soil pH and electrical conductivity (EC). Readings were recorded directly from the equipment then adjusted if necessary due to varied levels of dilution in the soil sample.

sample #	**initial pH**	**adjusted pH**	**initial EC**	**adjusted EC**
1	6.5	6.2	233.7	243.6
2	6.4	6.1	195.2	203.5
3	6.3	6.1	426.4	444.4
5	6.9	6.6	229.2	238.9
6	6.3	6.3	258.6	269.5
7	7.1	6.7	257.2	268.1
8	6.5	6.1	311.8	325.0
9	6.3	6.3	515.0	536.8
10	6.5	6.5	286.8	298.9
11	6.5	6.5	474.0	494.0
12	7.0	7.0	184.7	192.5
13	6.6	6.6	194.9	203.1
14	6.9	6.5	245.4	255.8
15	6.7	6.7	209.2	218.0
16	7.0	6.6	165.2	172.2
17	6.7	6.4	208.9	217.7
18	6.4	6.4	231.4	241.2
19	5.9	5.6	196.8	205.1
20	6.3	6.0	133.6	139.2
21	6.6	6.6	235.7	245.7
22	7.4	7.0	2187.0	2279.4
23	6.6	6.2	130.8	136.3
24	6.5	6.5	217.8	227.0
25	6.4	6.4	214.5	223.6
26	6.4	6.4	405.7	422.8
27	6.7	6.7	331.5	345.5
28	6.8	6.4	202.9	211.5
29	6.3	6.3	211.8	220.8
30	6.4	6.4	140.2	146.1
31	6.2	6.2	199.9	208.3
32	6.2	6.2	116.6	121.5
33	6.3	6.3	209.1	217.9
34	6.6	6.6	194.3	202.5