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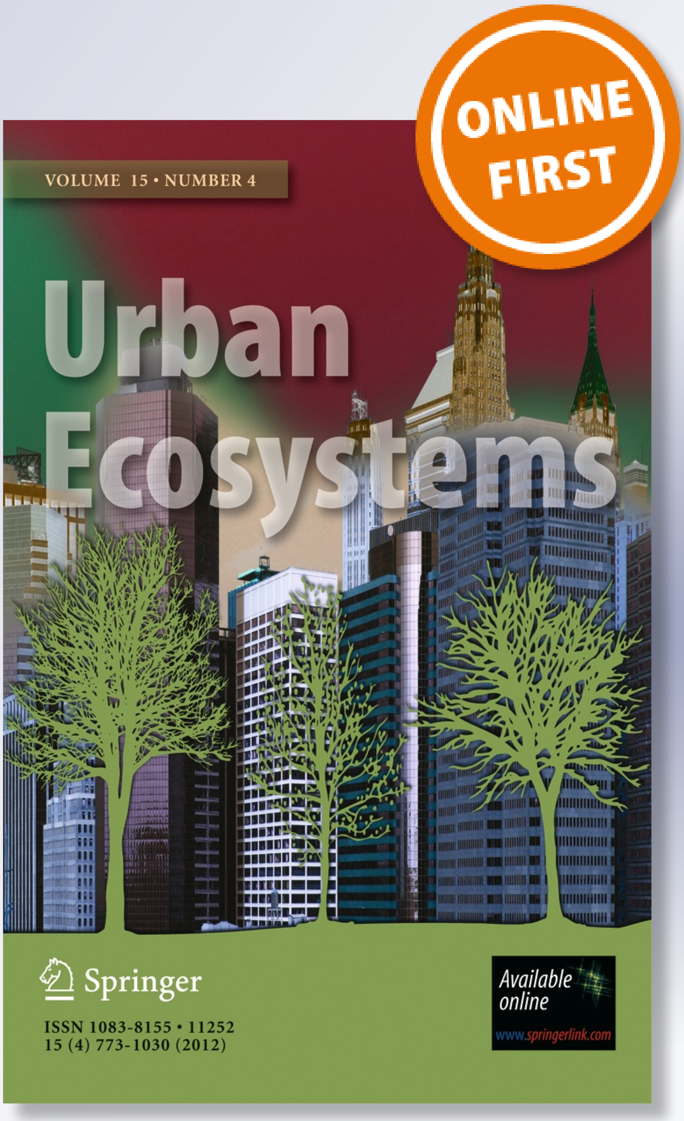

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Soil health as a predictor of lettuce productivity and quality: A case study of urban vacant lots

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Abstract Urban agriculture offers a framework for local self-reliance and resilience in cities. However, there is a concern over the capacity of urban soil to provide sustainable and safe food production. We tested the effectiveness of several soil health indicators to predict food crop productivity and quality in vacant lots in a disadvantaged neighborhood in the city of Cleveland, Ohio. We defined soil health as a state of composite well being in terms of biological, chemical, and physical properties of the soil as they relate to crop productivity. Twelve city-owned vacant lots, three close to each of the four city schools, were selected for soil properties and plant growth analyses. Soil samples were analyzed for pH, moisture content (θv), soil texture, soil organic matter (SOM), active carbon (AC), ammonium (NH_4-N), nitrate (NO_3-N), microbial biomass N (MBN), and nematode community parameters including total (TNN), bacteria-feeding (BFN), fungal-feeding (FFN), and plant-parasitic (PPN) nematodes, number of nematode genera (NNG), and nematode food web enrichment index (EI) and structure index (SI). Lettuce was planted in the selected vacant lots and its growth was documented through measures of dry biomass, numbers of leaves/plant, and complementary subjective appearance scores related to physiological status. All measured parameters varied considerably among vacant lots except soil pH. Principal components analysis revealed that among the primary soil physical, chemical, and biological parameters, soil clay, NO_3-N, MBN, SOM, AC, TNN, BFN, FFN, and PPN contributed most to the variance of the entire dataset. There were also several positive correlations among these key soil health predictor variables: AC was positively correlated with clay, SOM, MBN, TNN, BFN, FFN and PPN, and TNN was positively correlated with

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AC, SOM, MBN, BFN, FFN and PPN. Of the identified primary soil health indicators, only clay, SOM, and MBN positively correlated with lettuce dry biomass, which was also positively correlated with a secondary soil health indicator, the nematode food web EI. Lettuce leaf necrosis was negatively correlated with clay, AC, SOM, MBN, TNN, FFN, and PPN, and the proportion of withered leaves was negatively correlated only with SOM. It is concluded that AC, PPN, TNN, SOM, MBN, clay, and nematode food web EI can serve as important soil health indicators that have potential for predicting crop productivity and quality in urban soils. It is also concluded that lettuce can serve as an important indicator of soil health with respect to crop productivity and quality in vacant lots.

Keywords Urban soil · Urban agriculture · Lettuce productivity · Soil active carbon · Nematodes · Bioindicators · Cleveland

Introduction

Interest in urban agriculture has reemerged particularly in post-industrial North American cities due to the increased need to provide access to healthy food in disadvantaged neighborhoods and to productively manage the accumulating vacant land (Grewal and Grewal 2012). Urban agriculture in the form of community gardens has long been shown to allow citizens to become self-reliant in fresh produce (Patel 1991), provide access to fresh and healthy food (Blaine et al. 2010), improve dietary intake of fresh produce (Blaine et al. 2010), increase personal wellness (Brown and Jameton 2000), and bring communities together and reduce crime (Armstrong 2000). Grewal and Grewal (2012) reported that post-industrial cities such as Cleveland have the necessary space including vacant land and flat rooftops to entirely meet their demand for fresh produce, poultry, shell eggs, and honey. Such levels of self-reliance in food can not only enhance urban food security but can also prevent hundreds of millions of dollars in annual economic leakage from local economies, leading to enhanced socio-economic resilience of communities (Grewal and Grewal 2012).

Urban soils are however greatly altered due to accelerated human activity and there are concerns about their capacity for sustainable and safe food production. During urban development, existing vegetation is removed, and topsoil is often completely stripped off exposing subsoil to the surface. The exposed subsoil has lower plant nutrient and organic matter content, lacks structural and functional complexity of the soil food web, and produces low plant biomass and quality compared to the topsoil (Cheng and Grewal 2009). Urban soils often have low aeration, porosity, and drainage due to compaction by heavy construction equipment (Cogger 2005). In addition, there are concerns of soil contamination with lead and other pollutants associated with demolition of buildings and vehicle emissions (Belluck et al. 2003; Petersen et al. 2006). Indeed, proximity to the road and anthropogenic factors such as the number of houses on a street or the level of traffic passing through a neighborhood also influence physical, chemical, and biological properties of the soil (Zhu et al. 2006; Park et al. 2010a, b).

Soil health encompasses biological, chemical, and physical properties (Moebius-Clune et al. 2011), but biological properties are considered more critical due to their potential as early and sensitive indicators of alterations in ecosystem structure and function (Kennedy and Papendick 1995; Weil et al. 2003; Aziz et al. 2011). Currently, the properties most commonly included in soil health assessment from agricultural production perspective are microbial biomass and activity, enzymes, soil organic matter (SOM), total nitrogen, available nutrients, porosity, aggregate stability, and compaction (Islam and Weil 2000a; Weil et al. 2003; Schindelbeck et al. 2008; Aziz et al. 2011; Moebius-Clune et al. 2011), however promising new soil health indicators have been identified more recently. For example, the active carbon (AC) has been developed as a composite measure of soil health based on selected biological, chemical, and physical properties of a wide range of soils (Islam and Weil 2000a, b; Weil et al. 2003). AC is the most usable (biologically labile) form of soil total organic carbon (TOC) which, contributes greatly to the functionality of the soil food web (Weil et al. 2003) and has been shown to be more sensitive to soil management practices and ecological disturbances than TOC (Weil et al. 2003). Jokela et al. (2009) reported that the greater sensitivity of AC to management systems was reflected in relationships with microbial and physical properties. It has also been shown to correlate with water-stable aggregates, soluble carbohydrate, soil microbial biomass, and basal and substrate-induced respiration (Schindelbeck et al. 2008), and has thus been proposed as a measure of soil health, capable of detecting changes in the labile C pool of soil (Schindelbeck et al. 2008). The AC test is currently being incorporated as one of the direct measures of routine soil quality in both managed and disturbed agroecosystems (Card 2004; Islam and Sundermeier 2008; Schindelbeck et al. 2008; USDA 2011; Stiles et al. 2011). However, at present there is no information on the use of this test as a measure of soil quality in urban ecosystems.

Soil nematodes have also emerged as effective environmental bioindicators which, have tremendous potential in soil health assessment (Yeates et al. 1993; Bongers and Bongers 1998; Ritz and Trudgill 1999; Ferris et al. 2001; Briar et al. 2007). As the most abundant metazoans in the soil and occurring at multiple trophic levels (Yeates et al. 1993), the nematodes provide important insights into the condition of the soil food web (Ritz and Trudgill 1999; Ferris et al. 2001; Ferris 2010; Neher 2001). Ferris et al. (2001) developed a faunal profile framework that relates nematode community to soil food web condition by integrating nematode feeding groups (trophic ecology) and the *colonizer-persister* scale (cp scale akin to the *r* and *k* strategists) into a matrix classification of functional guilds. The cp value is based on the life strategy of nematode species and the scale is composed of five levels (Bongers and Bongers 1998). The colonizers, whose reproduction rates are high and body sizes are small, receive a low value; while the persisters, which reproduce slowly but have larger body sizes, are placed in high cp categories. Thus, the basal condition of the soil food web is represented by the dominance of Ba_2 and Fu_2 guilds (bacterivores and fungivores which are in cp-2 categories) from which it develops into two distinct trajectories: the enrichment trajectory and the structure trajectory. Opportunistic non-herbivorous guilds, Ba_1 and Fu_2, are considered as indicators of enriched food webs, while high cp guilds (cp 3–5) are indicators of structured food webs that have more complex trophic links and where recovery from stress is occurring. According to Ferris et al. (2001), the enrichment index (EI) provides an indication of the response of primary decomposers to the available resources in the soil food web while structure index (SI) suggests trophic linkages in a food web as indicated by the presence of higher c-p value nematodes particularly predatory and omnivores. Therefore, plotting EI and SI provides a graphic representation of nematode faunal profile depicting the likely condition of the soil food web in a given habitat (Ferris et al. 2001). The faunal profile model can be graphically represented into four quadrats (A to D), where quadrat D represents a depleted food web after a major disturbance event; quadrat A indicates a disturbed and N-enriched food web (e.g. following compost amendment) with only limited trophic linkages; quadrat B represents a maturing food web with diverse trophic linkages; and quadrat C indicates a matured food web (Ferris et al. 2001). Thus, the nematode faunal profile model has the potential to reflect the developmental condition of the soil food web following human activities such as urban development and demolition. However, information about soil nematodes has not been integrated into any of the routine soil health assessments.

Plants, especially well-studied agricultural crops with wild relatives, can also be used as effective bioindicators of soil health. It is well established that crops respond to abiotic factors (including soil condition) in their nearby microenvironment (e.g., Bumgarner et al. 2011a, b). Lettuce (*Lactuca sativa*) has been used as a bioindicator plant (Brown et al. 1998; Charles et al. 2011) because it is grown worldwide and clearly responds to soil and aerial microenvironments. These responses have been tested in nearly every setting from zero-gravity chambers in space flight, highly engineered plant factories in Asia, sophisticated growth chambers in academic and government labs, and commercial, academic, and government greenhouses and open fields (Bumgarner et al. 2011a, b; Jenni and Dubuc 2002; Lee et al. 2002; Mackowiak et al. 2009). Moreover, these responses tend to manifest readily. In addition, lettuce is comprised of a relatively simple root-shoot axis the growth and development of which has been exhaustively described and modeled (Salomez and Hofman 2007; Wheeler et al. 1993). Further, seedlings of lettuce hybrids, such as the one used in this study, are essentially clones (Mou 2011). Therefore, the low genetic variation among "indicator" plants across experimental units minimizes experimental error to an extent difficult to achieve with many natural populations. Lastly, although heavily studied, responses by lettuce to abiotic and biotic factors, including the physical, chemical and biological properties of its rooting medium, remain of interest to scientists and farmers.

The question that still remains unanswered is the predictive relationship between the various soil health indicators (including physical, chemical, and biological parameters) and crop productivity and quality, particularly in the highly disturbed urban ecosystems. To address this question and to determine the validity of using the well established and emerging soil health indicators including AC and soil nematode community as tools to predict capacity of urban soils to sustain food production, our hypothesis was that selected soil health indicators will positively correlate with plant productivity and quality. This hypothesis was tested through the following set of specific objectives: (i) evaluate soil health in urban vacant lots using selected standard and emerging soil health indicators; (ii) identify a set of soil health indicators that contribute most the variation in the data set obtained; and (iii) determine relationships between soil health and lettuce productivity and quality parameters.

Materials and methods

Site selection and characterization

This study was conducted in the Hough neighborhood in the city of Cleveland (41 29′58″ N latitude and 81 41′37″ W longitude), Ohio, USA. The Hough neighborhood consists of 7.04 sq km area and is home to an economically disadvantaged population. Total population in the neighborhood had declined from 76,000 in 1960 to under 20,000 in 1990 (www.nhlink.net 2012) and was only 16,306 in 2009 (www.city-data.com 2012). The median annual household income in 2009 was $13,971, and the percentage of population below poverty level was 40.8 % compared to 26.3 % for the entire city (www.city-data.com 2012). Due to the continuing population exodus coupled with recent U.S. economic crisis, many homes in the neighborhood that had remained vacant and physically deteriorated over time have been demolished. Consequently, a relatively large number of "vacant lots" have accumulated in the neighborhood. For this study, a total of 12 (out of over 300) city-owned vacant lots, three close to each of the four city schools were selected and the address, latitude and longitude coordinates, overall visual condition, and dominant plant species were recorded. The main reason for selecting vacant lots close to the schools was to potentially use them to establish gardens to engage students in gardening and enhance access to healthy food. All lots were mowed by the city at 7–10 day intervals during the growing season and all clippings were returned to the soil.

Site characteristics

All vacant lots used in this study were previously used as home sites for nearly a century. The front and back yards were planted by homeowners with diverse urban plantings consisting mainly of turfgrasses, flowering plants, shrubbery and some trees. The homes from these lots were demolished within the past 10 years and the foundation areas were either left to be colonized by natural vegetation or seeded with turfgrass seed mixtures. At the time of sampling all lots were owned by the city and were mowed once every 7–10 days during the growing season. Site addresses, area in acres, nearest school, latitude and longitude coordinates, and dominant plant species recorded at each site are provided in Table 1. Each site used was previously the site of a house. The most abundant plant species found on the sites included red clover (*Trifolium pratense*), white clover (*Trifolium repens*), bluegrass (*Poa pratensis*), fine fescue (*Festuca* sp.), mulberry (*Morus* sp.), cherry (*Prunus avium*), buckhorn (*Plantago lanceolata*), chicory (*Cichorium intybus*), wild carrot (*Daucus carota*), morning glory (*Ipomoea* sp.), black medic (*Medicago lupilina*), dandelions (*Taraxacum officinale),* cottonwood (*Populus deltoides*), perennial rye grass (*Lolium perenne*), and crabgrass (*Digitaria* sp.).

Collection of soil samples

Composite soil samples were randomly collected from 0 to 10 cm depth from all vacant lots. For soil sampling, each lot was arbitrarily divided into three approximately equal subplots. Ten core samples (10 cm deep and 2 cm internal diameter) were taken from each subplot, placed in a sealable polyethylene bag, mixed to form a composite sample, and placed in a cooler for transport back to the lab. This resulted in three composite soil samples from each site with a total of 36 samples for all selected sites.

Soil sample processing and analysis

A portion of the field-moist soil was passed through a 2 mm sieve and homogenized to stabilize biological activity followed by analysis of total microbial biomass. Another portion of the soil was spread on a polyethylene sheet and air-dried for 14 days at room temperature and analyzed for selected chemical and physical properties.

Antecedent soil moisture content (θv) was determined by following the gravimetric method. Particle size analysis was performed to measure the relative proportions of sand, silt, and clay for determining soil texture (Gee and Bauder 1986). Soil pH was determined using a combination glass electrode in a 1:1 soil and deionized water mixtures. Soil ammonium (NH_4-N) and nitrate (NO_3-N) were extracted by 0.5 M K_2SO_4 solution followed by alkaline persulfate oxidation (Cabrera and Beare 1993) and indophenol blue technique (Sims et al. 1995). Soil organic matter (SOM) was determined by ignition loss method (Storer 1984). Soil active carbon (AC) was measured using the 0.02 M $KMnO_4$ mild oxidation method (Weil et al. 2003), in which dilute, neutral buffered $KMnO_4$ solution (pH7.2) was reacted with the most readily oxidizable (active) forms of total organic carbon (TOC), converting Mn^{+7} to

Table 1 Characteristics of the vacant lots in the Hough neighborhood of Cleveland, Ohio, USA used in this study

Site address	Area (acres)	Closest school	Latitude–longitude	Plant species recorded	Other characteristics
7115 Lawnview	0.11	Martin Luther King High School	(41.51332, −81.63898)	Red clover (*Trifolium pretense*), White clover (*Trifolium repens*), Buckhorn (*Plantago lanceolata*)	Partially shaded; no litter
7111 Linwood	0.14	Martin Luther King High School	(41.51271, −81.63917)	Buckhorn (*Plantago lanceolata*), Red clover (*Trifolium pretense*), Chicory (*Cichorum intybus*), Crabgrass (*Digitaria sp.*), Mulberry tree (*Morus sp.*)	Mostly sunny; no litter
1798 E 89th St	0.11	Mary B. Martin Middle School	(41.50850, −81.62643)	Red clover (*Trifolium pretense*), Morning glory (*Ipomoea sp.*), Black medic (*Medicago lupilina*), White clover (*Trifolium repens*), Buckhorn (*Plantago lanceolata*)	Mostly sunny except in rear of the site; no litter
10307 Churchill Ave	0.09	Wade Park Elementary School	(41.52137, −81.61615)	Red clover (*Trifolium pretense*), Chickory (*Cichorum intybus*), White clover (*Trifolium repens*), Buckhorn (*Plantago lanceolata*), Mulberry tree (*Morus sp.*), Maple (*Acer sp.*), Annual bluegrass (*Poa annua*), Cherry (*Prunus avium*)	Mostly sunny; some litter present
7920 Pulaski Ave	0.07	Willson Elementary School	(41.52487, −81.63295)	Red clover (*Trifolium pretense*), Chicory (*Cichorum intybus*), Queen Anne's lace (*Daucus carota*), Buckhorn (*Plantago lanceolata*), Dandelion (*Traxacum officinale*), Maple (*Acer sp.*), Mulberry tree (*Morus sp.*)	Mostly open, sunny and flat lot; some litter present
1316 E 92nd St	0.16	St. Thomas Aquinas Middle School	(41.52073, −81.62364)	Red clover (*Trifolium pretense*), Chicory (*Cichorum intybus*), White clover (*Trifolium repens*), Buckhorn (*Plantago lanceolata*)	Steep slope; scattered bushes
9020 Superior St	0.14	St. Thomas Aquinas Middle School	(41.520783, −81.624683)	Buckhorn (*Plantago lanceolata*), White clover (*Trifolium repens*), Red clover (*Trifolium pretense*), Mulberry tree (*Morus sp.*), Morning glory (*Ipomoea sp.*), Chicory (*Cichorum intybus*), Perennial ryegrass	Mostly open and sunny; one area had a large hole; the site filled with litter
1359 E 105th St.	0.04	Wade Park Elementary School	(41.519795, −81.615448)	Red clover (*Trifolium pretense*), Buckhorn (*Plantago lanceolata*), Chicory (*Cichorum intybus*), Dandelion (*Taraxacum officinale*), Morning glory (*Ipomoea sp.*)	Sunny and relatively flat corner lot
Crawford	0.22	Mary B. Martin Middle School	(41.511325, −81.625473)	Red clover (*Trifolium pretense*), White clover (*Trifolium repens*), Black medic (*Medicago lupilina*), Buckhorn (*Plantago lanceolata*), Chicory (*Cichorum intybus*), Crabgrass (*Digitaria sp.*), Grapevine (*Vitis sp.*)	Enclosed with trees and fencing; some litter and concrete present
8109 Pulaski Ave.	0.06	Willson Elementary School	(41.524961, −81.631379)	White clover (*Trifolium repens*), Red clover (*Trifolium pretense*), Dandelion (*Taraxacum officinale*), Bluegrass (*Poa annua*),, Black medic (*Medicago lupilina*), Broad leaf plantain (*Plantago major*), Curled dock (*Rumex crispus*)	Mostly open and sunny; relatively flat; some litter present
8401 Brookline	0.05	Mary B. Martin Middle School	(41.508726, −81.629233)	Red clover (*Trifolium pretense*), Bluegrass (*Poa annua*), Fine fescue (*Festuca sp.*), Mulberry tree (*Morus sp.*), Cherry (*Prunus avium*), White clover (*Trifolium repens*)	Mostly sunny; some litter present

Table 1 (continued)

Site address	Area (acres)	Closest school	Latitude–longitude	Plant species recorded	Other characteristics
7817 Myron	0.06	St. Francis Elementary School	(41.52090, −81.63404)	Red clover (*Trifolium pretense*), Chicory (*Cichorum intybus*), White clover (*Trifolium repens*), Annual bluegrass (*Poa annua*), Wood sorrel (*Oxalis sp.*), Black medic (*Medicago lupilina*), Buckhorn (*Plantago lanceolata*), Cottonwood (*Populus deltoides*)	Mostly open with patchy grass; some litter present

Mn^{+2}, and proportionally lowering absorbance of the solution. The absorption of the solution was measured spectrophotometrically at 550 nm light.

Soil microbial biomass was determined using a modification of the chloroform fumigation extraction method (Brookes et al. 1985) using the extraction efficiency of 0.45 (Jenkinson 1988). Soil nematodes were recovered by extracting 10 g of homogenized soil with distilled water using the Baermann funnel technique (Flegg and Hooper 1970). Nematodes were collected from the funnels in plastic vials after 72 h. The nematodes were left overnight at 4 °C to settle, and the top layer of water was carefully removed from the plastic vial until only 5 mL of each collected sample was left. The settled nematodes were then killed by quickly adding 5 mL of boiling water into each vial. The nematodes were then identified to the genus level using an inverted microscope. Nematodes were identified using morphological characteristics and published keys (Goodey 1963; Mai and Lyon 1975). After being identified to genera, the nematodes were assigned one of the five trophic categories based on their feeding habit: Bacteriovores (Ba), Fungivores (Fu), Plant parasites (Pp), Predators (Pr), and Omnivores (Om). All nematodes were also given a colonizer-persister (c-p) value between 1 and 5 following Bongers and Ferris (1999). Nematode food web maturity index (MI), combined maturity index (CMI), structure index (SI), enrichment index (EI), and plant-parasitic index (PPI) were calculated according to Bongers (1990), Yeates (1994), and Ferris et al. (2001).

Lettuce productivity and quality

A uniform set of 3 week old, greenhouse-grown lettuce *Latuca sativa* “Romaine-type” seedlings containing two to three true leaves were planted in the 12 vacant lots between 15 and 20 July, 2011. Each vacant lot was divided into three sub-plots blocked in the direction of the nearest road and nine seedlings were planted in each sub-plot with a total of 27 plants per lot. Seedlings were set in place at random locations within the sub-plots at a minimum of 1.5 m from each other using a five-step process. First, a 10 cm diameter × 10 cm deep soil plug was removed using a golf course cup cutter. A seedling was then set in the hole, filling the volume with crumbled native soil removed from the same hole such that the seedling growing point remained approximately 3 mm above the soil surface. Next, a 20 cm × 20 cm section of black, nylon, semi-permeable landscape fabric containing a 4 cm diameter hole in the middle was centered over the plant and fixed in place with ground staples. Seedling leaves were then threaded through the hole in the fabric, which allowed for water to penetrate but significantly inhibited weed growth. Finally, plants were watered immediately and then every other day thereafter depending on rainfall. No fertilizer or organic amendments were applied. Data on the number of leaves/plant, proportion of withered leaves, greenness index (1–5 scale, 5 being most green), necrosis (0–3 scale, 3 being most severe necrosis), and chlorosis (0–3 scale, 3 being most severe chlorosis) of each plant were recorded weekly. Lettuce were harvested by cutting at ground level four weeks after planting, oven-dried at 55 °C until a constant weight was obtained.

Statistical analysis

Principal component analysis (PCA) was performed on soil physical, chemical, and biological properties (soil moisture, NH_4-N, NO_3-N, MBN, SOM, clay, sand, silt, pH, active C, total number of nematodes, number of nematode genera, and abundances of nematode trophic groups) to account for the variance and to identify the parameters contributing most to this variation. Then Pearson's correlations between the identified key soil parameters as well as PC1 and PC2 as independent variables and lettuce growth parameters, and Pearson's correlations between the nematode food web enrichment as well as structure indices and lettuce parameters were determined using MINITAB v.15 (Minitab, Inc, State College, PA, USA). Natural log transformation was performed on all nematode abundance data to normalize the dataset. An alpha level of <0.05 was considered significant.

Results

Soil physical, chemical, and biological properties

The physical, chemical and biological properties measured on the sites had wide ranges except soil pH (6.5–7.5) (Table 2). Sand (44–84 %), silt (10–36 %) and clay (5–23 %) contents varied so widely that several different soil textural classes could be recognized. SOM varied from 2 to 7.3 % and AC from 413 to 695 mg/kg (Table 2).

Among the soil biological parameters, MBN varied from 40 to 218 mg/kg, TNN/10 g of soil from 49 to 988, and NNG/10 g soil from 12 to 20 (Table 2). A total of 33 nematode genera representing all five trophic groups and all five cp classes were identified (Table 3). Most nematode genera belonged to plant parasitic and bacterial feeding groups. Among the nematode food web indices, the SI showed the largest variability from 0 to 65 followed by EI, which varied from 54 to 93 (Table 2). The nematode faunal profile showed that the soil food webs in urban vacant lots were highly enriched, but poorly to moderately structured (Fig. 1).

Identification of soil physical, chemical and biological parameters contributing most to the variability

The first three components in the principal components analysis cumulatively accounted for 69 % of the total variance in the dataset (Table 4). Soil AC, SOM, TNN, MBN, and abundance of plant-parasitic nematodes contributed most to the first component, whereas soil NO_3-N, clay, abundance of bacteria-feeding nematodes, and abundance of fungal-feeding nematodes contributed most to the second component

Table 2 Summary statistics of soil microbial biomass, physical and chemical properties, nematode community parameters, and lettuce growth and quality in vacant lots (n=36) in the Hough neighborhood in Cleveland, Ohio, USA

Variable	Mean	SE Mean	Minimum	Maximum
Clay (%)	9.1	0.9	4.1	33.2
Sand (%)	68.1	2.0	43.8	85.5
Silt (%)	22.9	1.5	10.3	50.4
Soil moisture (%)	8.8	0.9	1.5	18.8
pH	7.1	0.04	6.5	7.5
NH_4-N (mg/kg)	9.0	0.6	4.0	20.0
NO_3-N (mg/kg)	11.6	1.0	3.0	35.0
Active C (mg/kg)	623.6	13.2	413.3	694.8
Soil organic matter (%)	4.0	0.2	2.0	7.3
Soil microbial biomass N (mgN/kg)	114.5	7.8	40.2	218.1
Nematode abundance (10 g soil)	263.0	32.7	49.0	988.0
Nematode genera number (10 g soil)	16.1	0.4	12.0	20.0
Free-living nematode abundance (10 g soil)	192.4	27.2	39	851
Plant-parasitic nematode abundance (10 g soil)	70.7	11	6	376
Bacteria-feeding nematode abundance (10 g soil)	141.8	19.8	27	607
Fungal-feeding nematode abundance (10 g soil)	43.61	7.69	4	235
Omnivorous nematode abundance (10 g soil)	8.05	1.12	0	24
Predatory nematode abundance (10 g soil)	0.98	0.30	0	7
Enrichment index	79.0	1.4	54.2	93.4
Structure index	27.4	3.0	0.0	65.1
Lettuce dry weight (g/plant)	9.2	0.8	1.9	21.8
Number of leaves/plant	11.2	0.4	6	16
Proportion of withered leaves/plant	0.12	0.01	0.00	0.38
Greenness index (1 to 5 scale)	2.8	0.09	2.0	3.9
Necrosis (0 to 3 scale)	0.46	0.02	0.38	1.43
Chlorosis (0 to 3 scale)	0.56	0.03	0.09	1.85

(Table 4 and Fig. 2). Therefore, these nine soil parameters were selected to determine their correlation with lettuce parameters.

Relationships among soil physical, chemical and biological parameters contributing most to the variability

The results of the Pearson's correlation among the soil physical, chemical, and biological parameters found to be contributing most to the variability in the soil dataset are presented in Table 5. Results show that NO_3-N is only positively correlated with MBN, SOM and clay whereas MBN is positively correlated with NO_3-N, SOM, AC, clay, TNN, and PPN. Similarly, SOM is positively correlated with AC, NO_3-N, MBN, clay, TNN, and PPN, whereas AC is positively correlated with SOM, clay, MBN, TNN, BFN, FFN, and PPN. Interestingly, TNN is positively correlated with AC, SOM, MBN, BFN, FFN, and PPN, and Clay is positively correlated with NO_3-N, MBN, SOM, AC, and PPN.

Table 3 Nematode genera identified in soil (0–10 cm) in vacant lots in the Hough neighborhood in Cleveland, Ohio, USA (number in parentheses is nematode colonizer-persister [c-p] value)

Bacteria feeders	Fungal feeders	Omnivores	Predators	Plant feeders
Rhabditis (1)	*Aphelechoides (2)*	*Eudorylaimus (4)*	*Monochus (4)*	*Filenchus (2)*
Pelodera (1)	*Aphelechus (2)*	*Dorylaimus (4)*		*Tylenchus (2)*
Monohystera (1)		*Alaimus (4)*		*Paratylenchus (2)*
Diplogaster (1)		*Pungentus (4)*		*Psilenchus (2)*
Panogralaimus (1)		*Nygellus (4)*		*Aglenchus (2)*
Acrobeloides (2)				*Hoplolaimus (3)*
Acrobeles (2)				*Helicotylenchus (3)*
Cephalobus (2)				*Rotylenchus (3)*
Eucephalobus (2)				*Tylenchorynchus (3)*
Plectus (2)				*Pratylenchus (3)*
Wilsonema (2)				*Criconemoides (3)*
Chiloplacus (2)				*Heterodera (3)*

Lettuce productivity and quality

Lettuce dry biomass per plant varied from 1.9 to 21.8 g, the number of leaves per plant from 6 to 16, the proportion of withered leaves from 0 to 0.38, greenness index from 2 to 3.9, necrosis index from 0.4 to 1.4, and chlorosis index from 0.1 to 1.9 (Table 2). The temporal dynamics indicated that the proportion of withered leaves generally decreased from week 1 to week 4, whereas the total number of leaves per plant and greenness index increased.

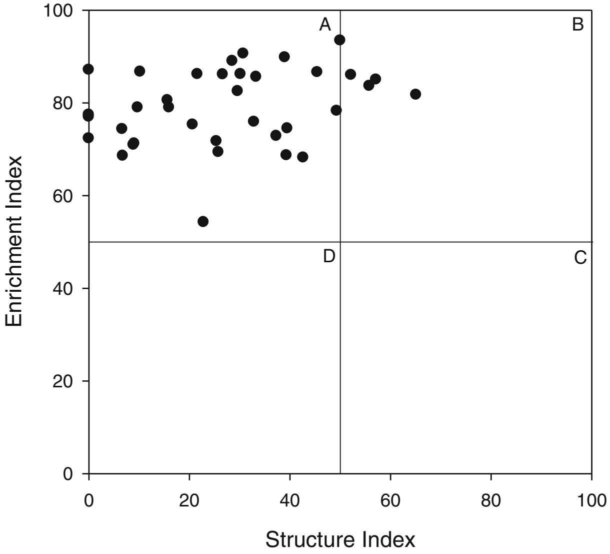

Fig. 1 Nematode faunal profile showing the enrichment and structure indices of the soil food webs in vacant lots (n=3 per lot) in the Hough neighborhood in Cleveland, Ohio, USA

Table 4 Principal component analysis for predicting soil parameters contributing to variation in the dataset

Component	1	2	3
Eigenvalue	5.5158	3.4787	2.0507
Variation explained	0.345	0.217	0.128
Cumulative variation	0.345	0.562	0.69
Attribute loading for eigenvectors[a]			
Variable	PC1	PC2	PC3
Soil moisture	0.057	−0.279	0.017
NH_4-N	0.241	0.017	−0.418
NO_3-N	0.142	−0.323	0.036
Soil Microbial biomass	0.314	−0.149	−0.262
Soil organic matter	0.367	−0.114	−0.129
Clay	0.263	−0.325	0.06
Sand	−0.203	0.303	−0.411
Silt	0.108	−0.203	0.51
pH	0.05	−0.269	−0.151
Active C	0.331	0.008	−0.195
Total nematode abundance	0.339	0.293	0.077
Nematode genera number	−0.082	0.294	0.324
PPN abundance	0.371	0.078	0.171
BF nematode abundance	0.238	0.392	0.015
FF nematode abundance	0.249	0.331	−0.041
Omnivore and Predator nematode abundance	0.268	0.172	0.319

[a] Eigenvector loading for components 1, 2 and 3 only are shown. These three components account for 69 % of the total variation in the data sets

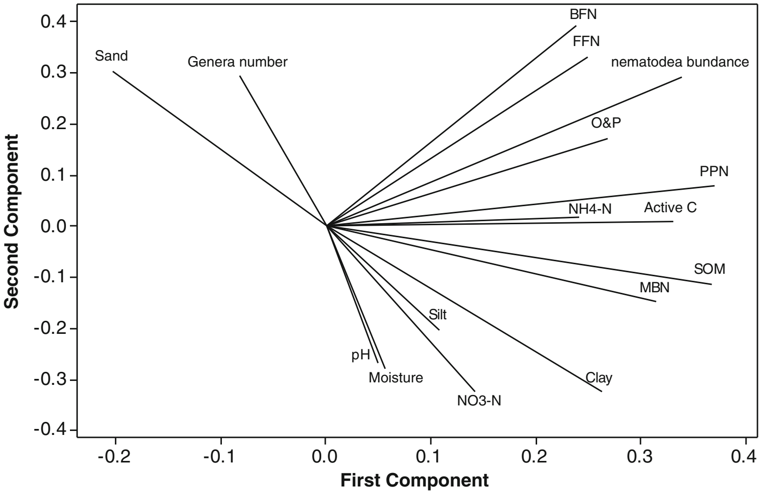

Fig. 2 Principal component analysis (loading plot) for predicting soil parameters in vacant lots in the Hough neighborhood in Cleveland, Ohio, USA. * Abbreviations: MBN: microbial biomass N; SOM: soil organic matter; PPN: plant-parasitic nematode abundance; BFN: bacteria-feeding nematode abundance; FFN: fungal-feeding nematode abundance; O&P: omnivorous and predatory nematode abundances

Table 5 Person's correlation (r) and level of significance (p) among the soil physical, chemical, and biological properties in urban vacant lots in Cleveland, Ohio, USA (*n*=36)

Variable	NO_3-N		Microbial biomass N		Soil organic matter		Active C		Clay		Total nematode abundance		Bacteria-feeding nematode abundance		Fungal-feeding nematode abundance		Plant-parasitic nematode abundance	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p
NO_3-N			0.44	0.01	0.34	0.04	0.23	0.17	0.57	0.00	−0.03	0.88	−0.14	0.40	−0.14	0.43	0.11	0.51
Microbial biomass N	0.44	**0.01**			0.81	0.00	0.60	0.00	0.57	0.00	0.35	0.04	0.11	0.52	0.28	0.09	0.54	0.00
Soil organic matter	0.34	**0.04**	0.81	**<0.01**			0.75	0.00	0.64	0.00	0.50	0.00	0.24	0.16	0.27	0.12	0.69	0.00
Active C	0.23	0.17	0.60	**<0.01**	0.75	**<0.01**			0.38	0.02	0.57	0.00	0.43	0.01	0.33	0.05	0.60	0.00
Clay	0.57	**<0.01**	0.57	**<0.01**	0.64	**<0.01**	0.38	**0.02**			0.16	0.36	−0.10	0.55	−0.02	0.92	0.46	0.01
Total nematode abundance	−0.03	0.88	0.35	**0.04**	0.50	**<0.01**	0.57	**<0.01**	0.16	0.36			0.91	0.00	0.84	0.00	0.80	0.00
Bacteria-feeding nematode abundance	−0.14	0.40	0.11	0.52	0.24	0.16	0.43	**0.01**	−0.10	0.55	0.91	**<0.01**			0.83	0.00	0.52	0.00
Fungal-feeding nematode abundance	−0.14	0.43	0.28	0.09	0.27	0.12	0.33	**0.05**	−0.02	0.92	0.84	**<0.01**	0.83	**<0.01**			0.52	0.00
Plant-parasitic nematode abundance	0.11	0.51	0.54	**<0.01**	0.69	**<0.01**	0.60	**<0.01**	0.46	**0.01**	0.80	**<0.01**	0.52	**<0.01**	0.52	**<0.01**		

Bold letters indicate significant *p* values

Relationship between lettuce productivity and quality parameters and selected soil health parameters

Results of the Pearson's correlation between the lettuce growth and quality parameters and the soil parameters found to be contributing most to the variability in the soil dataset are summarized in Table 6. Lettuce dry biomass was positively correlated with soil clay, SOM, MBN, and nematode food web EI. Lettuce leaf necrosis was negatively correlated with soil clay, AC, SOM, MBN, TNN, FFN, and PPN. The proportion of withered leaves was negatively correlated with SOM. In addition, significant correlations were found between PC1 (which is highly related to soil AC, SOM, TNN, and PPN) and lettuce dry weight (positive), total number of leaves (positive), and leaf necrosis (negative), but not to PC2 (which is highly related to NO_3-N, clay, BFN, and FFN). In fact, PC1 explained more of the variation than any single variable alone (Table 6).

Discussion

The results of this study suggest that several standard and emerging measures of soil health can be employed as early indicators of lettuce productivity and quality in urban vacant lots. Interestingly, significant correlations were found between PC1 (which included contributions by soil AC, SOM, TNN, and PPN) and lettuce dry weight (positive), total number of

Table 6 Pearson's correlation coefficients (r) and level of significance (p) between soil parameters and lettuce growth and quality parameters, and soil nematode community in vacant lots in the Hough neighborhood in Cleveland, Ohio (*n*=36)

Variable	Total plant dry weight		Total number of leaves/plant		Leaf greenness		Leaf necrosis		Leaf chlorosis		Proportion of withered leaves	
	r	p	r	p	r	p	r	p	r	p	r	p
NO_3-N	0.17	0.31	−0.05	0.77	0.31	0.07	−0.03	0.85	0.03	0.87	0.16	0.37
Microbial biomass	0.35	**0.04**	0.20	0.24	0.30	0.07	−0.49	**<0.01**	−0.13	0.44	−0.16	0.36
Soil organic matter	0.36	**0.03**	0.31	0.07	0.26	0.13	−0.58	**<0.01**	−0.07	0.68	−0.36	**0.03**
Clay	0.36	**0.03**	0.28	0.10	0.21	0.22	−0.43	**0.01**	−0.08	0.66	−0.32	0.06
Active C	0.19	0.26	0.19	0.28	0.03	0.85	−0.45	**0.01**	−0.08	0.64	−0.14	0.42
Total Nematode abundance	0.28	0.10	0.31	0.07	−0.00	0.98	−0.41	**0.01**	−0.01	0.94	−0.15	0.40
Plant-parasitic nematode abundance	0.18	0.29	0.24	0.17	−0.08	0.66	−0.51	**<0.01**	−0.09	0.60	−0.21	0.22
Bacteria-feeding nematode abundance	0.32	0.06	0.32	0.06	0.02	0.91	−0.25	0.15	0.04	0.80	−0.08	0.64
Fungal-feeding nematode abundance	0.25	0.14	0.25	0.14	0.04	0.82	−0.34	**0.04**	−0.14	0.41	−0.12	0.50
Enrichment index	0.35	**0.04**	0.29	0.09	0.25	0.15	−0.21	0.22	0.14	0.41	−0.20	0.24
Structure index	0.15	0.38	0.17	0.32	0.04	0.82	−0.21	0.22	0.18	0.29	−0.12	0.50
PC1	0.39	**0.02**	0.33	**0.05**	0.14	0.42	−0.58	**<0.01**	−0.10	0.55	−0.25	0.15
PC2	−0.03	0.88	0.13	0.46	−0.19	0.27	0.03	0.87	0.06	0.73	0.01	0.93

Bold letters indicate significant *p* values leaves (positive), and leaf necrosis (negative). In fact, PC1 explained more of the variation than any single variable alone. Although, PCA analysis identified eight primary soil health indicators (four each in PC1 and PC2) contributing most the variability in the soil properties data set only clay, SOM, and MBN correlated positively with lettuce dry biomass and clay, AC, SOM, MBN, TNN, FFN, and PPN correlated negatively with lettuce leaf necrosis and withering. In addition, a secondary (i.e. deduced) soil health indicator, the nematode food web EI, positively correlated with lettuce biomass. Several of these eight (seven primary and one secondary) soil health indicators also positively correlated with each other. For example, AC and PPN positively correlated with all the other six primary soil health indicators, TNN positively correlated with all except clay, SOM and MBN with all except FFN, and clay with all except TNN and FFN. Therefore, it is concluded that clay, AC, SOM, MBN, TNN, FFN, and PPN, and nematode food web EI can serve as important soil health indicators with potential for predicting crop productivity and quality in highly disturbed soils in urban vacant lots. A brief discussion supporting the potential use of the identified soil health indicators as predictors of crop productivity and quality is provided below. In addition the potential of lettuce as a bioindicator of soil health conditions is also discussed.

The positive relationship between clay content and lettuce dry weight is probably due to the soil's improved aggregate stability, cation exchange capacity, nutrient availability, especially N, and water holding capacity under higher clay conditions compared to higher proportions of sand in urban soils. Clay enhances moisture retention in the soil leading to greater water availability for plant roots to meet the transpiration demand, thereby leading to improved plant growth (Saxton et al. 1986). Clay also improves nutrient retention capacity of soil enabling a more steady release of nutrients which results in sustained plant growth. Indeed, several studies have reported that variations in CEC associated with nutrient availability could be explained by the variation in clay contents of soil (Drake and Motto 1982; Bell and van Keulen 1995). However, it should be noted that there is a fairly low threshold for the proportion of clay in soils before its positive impact on plant productivity is diminished.

AC was found to be negatively correlated with lettuce leaf necrosis in the present study. AC was also positively correlated with clay, SOM, MBN, TNN, FFN, and PPN in this study and has shown a positive correlation with available N, microbial biomass, and SOM in previous studies (Dilly et al. 2003; Weil et al. 2003; Schindelbeck et al. 2008; Jokela et al. 2009). Since C is stoichiometrically linked with N in SOM (Asner et al. 1997), an increase in AC invariably increases the soil available N. A significant relationship between AC and microbial biomass suggests that soil microbes contain a substantial amount of AC in their cells. This is not surprising as AC was measured on air-dried soil which would have also lysed the microbial cells. Similarly, extractable C was measured in partially dried soil after microwave irradiation treatment applied to lyse cells to determine microbial biomass (Islam and Weil 1998). The significant positive relationship between AC and SOM affirms that C is the main component of SOM in the regulation of soil quality (Johnston et al. 2009). Considering that AC, SOM, and microbial biomass are individual indicators of soil quality, significant positive correlations among these parameters reinforce the utility of AC as an effective and broader predictor of urban soil's capacity for supporting crop productivity and quality.

SOM positively correlated with lettuce dry biomass and negatively correlated with lettuce leaf necrosis and leaf withering. SOM also positively correlated with AC, MBN, clay, TNN, and PPN in this study. As C is the main component of SOM that determines soil quality and agricultural sustainability (Johnston et al. 2009), and labile fraction of C in SOM is a preferred substrate for soil heterotrophic microorganisms, a higher content of microbial biomass is usually associated with efficient SOM decomposition (Marumoto et al. 1982;

Islam and Weil 2000a, b) with resulting greater availability of nutrients in soil. SOM is also a core indicator of soil health due to its association with higher water-holding capacity, sink of C, improved soil structural stability, long-term productivity and improved soil tilth (USDA 1980; Naeth et al. 1991). Therefore our finings reinforce the significance of SOM as a general predictor of crop productivity and quality.

MBN positively correlated with lettuce dry biomass and negatively correlated with lettuce leaf necrosis. MBN also positively correlated with AC, SOM, clay, TNN, and PPN in this study. The higher concentration of N associated with higher content of MBN in the vacant lots suggests greater availability of N from SOM decomposition (Aber et al. 1995). Generally, increase in SOM diversifies food sources and increases energy availability for the soil microbes, thereby increasing microbial biomass and efficient biological activities (Powlson et al. 1987; Lundquist et al. 1999). Thus, the increase in both microbial biomass and SOM and the consequent efficiency in microbial activity and nutrient availability can promote plant growth and health as revealed by the correlation results in this study. It should also be pointed out that higher microbial biomass and SOM lead to an increase in total nematode abundance as found in this and previous studies (Griffiths et al. 1994; Bulluck et al. 2002), which could further improve soil nutrient mineralization and recycling leading to sustained crop productivity. In addition, it has been suggested that higher soil microbial biomass and SOM may contribute to “reduced disease severity” in urban lawns (Cheng et al. 2008b). Therefore, MBN has potential as a predictor of crop productivity and quality.

The total number of nematodes (TNN) in soil is considered to be a measure of overall productivity or carrying capacity of the ecosystem (Ritz and Trudgill 1999). Also the relative TNN in different soils can provide an indication of the extent of N mineralization and potential plant productivity. The opportunistic bacteria-feeding and fungal-feeding nematodes are one of the metazoans contributing most to N mineralization in soil detrital food webs. Due to their higher body C/N ratio compared to their food sources (bacteria and fungi), these nematodes excrete extra mineralized N into the soil. It has been estimated that bacteria-feeding nematodes alone can contribute 10 % of the total net N mineralization in soil (reviewed by Griffiths 1994), making soil nematodes as important as collembolans in soil N mineralization and cycling. In a newly proposed nematode metabolic footprint concept (Ferris 2010) TNN has been included as an additional factor in the well-established nematode faunal profile model (Ferris et al. 2001) to reinforce their overall contributions to soil nutrient mineralization and cycling. As nematodes essentially act as “slow-release” mechanisms for N in the soil, TNN has tremendous potential to serve as tool for predicting sustained crop productivity in the soil.

The positive relationship of PPN with AC, SOM, MBN, and clay observed in the present study suggests that the numbers of PPN in the soil are indicative of the level of available plant nutrients. This is most likely due to the bottom up control of nutrients on plant growth. While greater number of PPN per unit of soil is reflective of greater amount of available plant resource (i.e. current or past ecosystem productivity), PPNs can reduce future crop productivity when their numbers exceed a certain threshold. The lack of negative relationship between PPN and lettuce biomass production in the current study suggests that PPN numbers did not exceed a damage threshold in the studied vacant lots. Further, PPN showed a negative relationship with lettuce leaf necrosis, as opposed the expected positive relationship, again showing that the average densities of PPN in the studied sites were low and did not result in any significant leaf necrosis or lettuce biomass reduction. Therefore, the use of PPN as a predictor of plant productivity and quality would depend upon their actual density and the species involved relative to the crop species being grown.

The nematode faunal profile analysis indicated that soil food webs in urban vacant lots were highly enriched but poorly to moderately structured, as opposed to the natural grasslands and forest systems which exhibit moderately enriched but highly structured nematode food webs (Ferris et al. 2001). The observed high enrichment of the soil food webs in urban vacant lots suggests that these sites are dominated by bacteria-driven decomposition pathways as opposed to fungal dominated decomposition pathways that occur in more stable forest and natural grassland ecosystems (Ferris et al. 2001). Therefore, the observed food webs in urban vacant lots indicate a disturbed food web condition compared to natural grasslands and forest ecosystems as we have found in our previous studies on urban landscapes (Cheng et al. 2008a, b; Park et al. 2010a; Grewal et al. 2011). EI is a measure of nutrient availability in the soil because low cp value opportunistic bacteria-feeding and fungal-feeding nematodes that contribute to EI help in N release from SOM (Chen and Ferris 2000) and regulate N flows, resulting in a sustained plant growth (Ferris et al. 2001). Thus, the positive relationship between nematode food web EI and lettuce dry weight observed in the present study is predictive of high nutrient availability to plants in the vacant lots. As the studied vacant lots were frequently mowed with clippings returned to the soil, the soil food webs were likely maintained in enriched condition dominated by opportunistic nematode guilds that contribute to high N mineralization.

Lettuce growth and quality correlated with specific soil health indicators. This suggests that lettuce can be a useful indicator of soil health conditions. Lettuce rapidly responds to abiotic and biotic factors within its growing environment, including root-zone conditions. Not surprisingly, lettuce remains a favorite species in studies of the following: a) nearly all forms of soil and soil fertility management (e.g., Coria-Cayupan et al. 2009; Kohler et al. 2006), b) environmental contamination (e.g., Ascher et al. 2009; Cantrell and Lindermann 2001; Nali et al. 2009; Shah and Belozerova 2009; Tambasco et al. 2000; Yu et al. 2004), especially as it may relate to human health and c) shifts in soil microbial populations (e.g., Kohler et al. 2006; Shah and Belozerova 2009). Lettuce is already firmly positioned as a bioindicator of heavy metal (Conesa et al. 2010; Gaw et al. 2008; Kashem and Warman 2009; Le Guedard et al. 2008; Pillay and Jonnalagadda 2007; Tambasco et al. 2000) and major macronutrient (Montemurro 2010; Ribeiro et al. 2010) levels and of potential plant-microbe interactions (Ponce et al. 2008; Shah and Belozerova 2009). Based on the results of this study and of the above mentioned previous studies, it can be concluded that lettuce could be employed as a simple and sensitive indicator of soil health conditions.

Conclusions

The results of this study support the overall hypothesis that the selected soil health indicators can serve as useful and early predictors of crop productivity and quality in urban vacant lots. Although, PCA analysis identified eight primary soil health indicators contributing most the variability in the soil properties data set only clay, SOM, and MBN correlated positively with lettuce dry biomass and clay, AC, SOM, MBN, TNN, FFN, and PPN correlated negatively with lettuce leaf necrosis and withering. In addition, a secondary (i.e. deduced) soil health indicator, the nematode food web EI, positively correlated with lettuce biomass. It is also evident from results of this study that lettuce may be a simple and useful indicator of general soil health conditions in urban vacant lots.

The results of this study also show that the health of the soil in urban vacant lots in Cleveland, Ohio is variable, but suitable for food production. In fact, MBN (114.5 vs 36.3–48.16 mgN/kg) was higher in the vacant lots compared to the agricultural soils

(Nahar et al. 2006) in the Northeast Ohio region. Further, TNN (263 vs 126/10 g soil) and PPN (71 vs 43/10 g soil), two nematode-based measures of ecosystem productivity, in vacant lots were also higher compared to agricultural soils (Briar et al. 2007) in the region. Thus, barring any contamination with heavy metals and organic compounds, which we plan to address in future studies, soils in urban vacant lots in the city of Cleveland should be able to sustain food production activities.

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