ASSESSING THE IMPACT OF COMPOST AMENDMENT FOR MANAGING NEMATODES AND THE HEALTH OF MINERAL SOIL UNDER CARROT PRODUCTION

By

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ABSTRACT

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In the absence of resistant cultivars and sustainable alternatives to nematicides, soil nutrient amendment is one of the potential alternatives for managing herbivore nematodes and improving soil health in carrot (*Daucus carota* L.) production. Using nematodes as indicators of changes in soil ecosystem, the main goal was to develop integrated compost amendment strategies for managing soil nutrient, nematodes, soil health, and carrot yield and quality. Processing carrot ‘Cupar’ and a fresh market cultivar ‘Sugarsnax 54’ were grown with amendments of plant compost (PC) and animal waste-based compost (AC) use under field and/or glasshouse conditions during 2012-2014 to test a series of hypotheses. Nematode community, five times during the growing season at approximately four-week intervals, soil physicochemical properties and respiration at planting and at harvest, and carrot yield were standard parameters.

The first series of experiments compared AC and PC applied at 135, 203 and 270, and 112, 168 and 224 kg nitrogen (N) per ha for Cupar and Sugarsnax 54, respectively, in sandy clay loam soil. Urea and non-amended check were included as controls. The hypothesis was that compost amendment would enhance soil food web structure index (SI), improve soil biological and physicochemical properties, and increase carrot yield and quality, but these effects would differ by compost type and rate of application. Compost amendments increased SI from 50 % in Cupar. Higher rates of AC treatments increased soil respiration. Although compost amendments increased yield in 2013 in Sugarsnax 54, most compost amendments decreased yield in 2012. The variable responses relative to compost rate, source and time suggest that the effect of

compost based amendments on the soil food web structure and the ecosystem services it provides point away from a one-size-fits-all approach.

In the second experiment, the effect of mixtures of urea and PC at 3:1, 1:1 and 1:3 ratios on soil food web enrichment index (EI), SI, biological activity level, and carrot quality and yield relative to single applications of either product was evaluated. Amendments were applied to supply 135 kg N per ha. Urea alone and non-amended check were included as controls. The hypothesis was that mixtures with higher rates of PC would enhance enrichment index (EI) and SI, soil biological and physicochemical properties, and increase carrot yield and quality. Lower rates of urea mixed with higher rate of PC increased soil biological activity. However, there was no difference among the treatments in carrot yield. In addition, no changes in EI due to treatments were detected.

In a third experiment, how compost works in sterilized soil was used to simulate biologically degraded soil under glasshouse conditions over three months; however, it appeared that a longer time is needed for compost to be effective.

As part of understanding variable responses and integrated amendment use efficiency, a weighted nematode guild abundance concept was introduce to integrate the fertilizer use efficiency (FUE) and soil food web models for better resolution of agroecological analysis relative to soil health. Integrating weighted nematode guild abundance and agronomic data into the FUE model showed that most of the compost treatments were significantly greater than the control. Collectively, the findings help build a foundation up on which soil health-related industry priorities can be addressed through understanding the biological and physicochemical basis of the changes and designing potential solutions that fit variable soil conditions.

To Abnet and Bethel

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KEY TO SYMBOLS OR ABBREVIATIONS

AC	Animal compost
a. i.	Active ingredient
AM	Amendment
BI	Basal index
C: N	Carbon-to-nitrogen
CI	Channel index
DAP	Days after planting
Dim 1	Dimension 1
Dim 2	Dimension 2
EI	Enrichment index
FUE	Fertilizer Use Efficiency
H’	Shannon-Weaver diversity index
MI	Maturity index
PC	Plant compost
PPI	Plant-parasitic index
SI	Structural index

T	Time
TR	Treatment

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

Michigan is one of the main producers of fresh market and processing carrot (*Daucus carota* L.) varieties in the USA (Hausbeck, 2008). Herbivore nematodes cause carrot root damage and reduce marketable yield (Belair, 1992; Berney and Bird, 1992; Wesemael and Moens, 2008). Northern root-knot (*Meloidogyne hapla* Chitwood, 1949), carrot cyst (*Heterodera carotae* Jones, 1950), root lesion (*Pratylenchus penetrans* Cobb, 1917) and pin (*Paratylenchus* spp. Micoletzky 1922) nematodes were identified as major problems in Michigan carrot production systems. Northern root-knot, carrot cyst and lesion nematodes are highly problematic in muck soils. *Paratylenchus projectus* and *P. hamatus* exist mainly in mineral and muck soils, respectively (Hausbeck, 2008). Northern root-knot and carrot cyst nematodes are considered as the most damaging nematodes under Michigan conditions (Berney and Bird, 1992; Melakeberhan et al., 2007; Hausbeck, 2008).

In the face of Food Quality Protection Act-driven restrictions on broad spectrum nematicides and no commercially available nematode resistant carrot cultivars, multi-purpose aspects of organic soil amendments have the potential to be sustainable alternatives for managing nematodes and soil health (Abawi and Widmer, 2000; Melakeberhan et al., 2007, Zasada et al., 2008; Mennan et al., 2010). Organic soil amendments encompassing green manure, cover crops, animal manure and compost are among the promising alternatives to conventional soil fertility management practices. In addition, they suppress diseases and pests, and improved carrot yield and quality (Bulluck III et al., 2002a; Wang et al., 2004; Nahar et al., 2006; Briar et al., 2007).

Organic soil amendments are also known to improve soil conditions and ecosystem services provided by soil food web (Bardgett and Cook, 1998; Ferris et al., 2001). Managing soil food web functions is important to utilizing essential ecosystem services such as nutrient cycling, and pest suppression that require the activities of appropriate functional guilds (Ingham et al., 1985; Ferris et al., 1998; Sánchez-Moreno and Ferris, 2007; Ferris et al., 2012). This can be maintained through consistent supply of organic amendments to the soil (Ferris et al., 2004; Ferris and Bongers, 2006; Ferris, 2010). Apart from sustaining the soil food web, soil organic amendments are known to improve retention of essential nutrients for plant growth and soil water holding capacity (Pimentel et al., 2005; Zasada et al., 2008; Glover et al., 2010; Mennan et al., 2010).

Repeated and excess applications of inorganic fertilizers, which can cause damage to the environment, are required in order to attain the expected crops yield in conventional agriculture (Tilman et al., 2002; Stewart et al., 2005). These losses pose deleterious effects to the environment and human health (Tilman et al., 2002). The sole use of inorganic fertilizers is also causing deterioration in soil physical, chemical and biological properties that reduce cropland productivity (Eche et al., 2013; Odunze et al., 2012; Singh et al., 2013). As a soil organic amendment, compost could be one of the alternatives to improve soil organic matter, soil fertility, soil physical properties, pest suppression potentials, and microbial biomass (Briar et al., 2007; Forge and Kempler, 2009; Ferris et al., 2012).

Besides increasing crop yield, maintaining environmental quality is a major component of sustainable agricultural production (Doran, 2002; Evanylo et al., 2008). Although compost amendments is one of the potential strategies for sustainable agriculture, use of compost amendments alone is usually not sufficient to maintain the expected productivity level as that of chemical fertilizers in the short-term (Parr et al., 1992; Diacono and Montemurro, 2010; Herencia et al., 2008; Pimentel et al., 2005). Hence, designing amendment strategies that exploit the positive impacts of compost amendments and inorganic fertilizers could reduce environmental damage and satisfy yield expectations. One of the strategies to achieve the expected yield and reduce the deleterious environmental impact of inorganic fertilizers is to integrate plant nutrient-management system characterized by reduced input of chemical fertilizers with organic amendments (Gunapala and Scow, 1998; Kaur et al., 2005; Oberson et al., 1996). Integrating compost with inorganic fertilizers in one example (Sikora and Enkiri, 2001; Whalen and Chang, 2007; Sánchez and Richard, 2009).

Implementation of integrated applications of compost amendments and inrooganic fertilizers could be best achieved if their effects on soil food webs are quantified. The soil food web consists of very diverse soil dwelling organisms which depend on plants or external inputs such as organic amendments for their energy and carbon sources (Ferris and Bongers, 2006). Assessing soil health through complete analysis of such a diverse group of organisms may require several extraction techniques and sophisticated equipment, which is technically challenging (Ritz and Trudgill, 1999). However, indicator organisms (bioindicators) that reflect the structure and function of soil ecosystems and those that respond to soil conditions can be used (Neher, 2001).

Nematodes have several attributes to be considered as bioindicators of soil ecosystem change (Bongers and Bongers, 1998). They are the most abundant multicellular organisms and occur across multiple trophic levels in the soil food web (Bongers and Ferris, 1999). Their function in the soil is easily inferred from their mouth structure (Yeates et al., 1993). They can generally be categorized in to five trophic groups: herbivores, bacterivores, fungivores, omnivores and predators (Yeates et al., 1993). There are nematode extraction procedures (Ritz and Trudgill, 1999) that can capture diverse nematode species and yield high intrinsic information from a given soil sample (Bongers and Bongers, 1998; Bongers and Ferris, 1999).

Nematodes have also diverse life history characteristics ranging from r-strategists (colonizers) with c-p 1 (colonizer-persister) characterized by short generation time, high fecundity, and high tolerance to disturbances to k-strategists (persisters) with c-p 5 characterized by long generation time, low fecundity, and greater sensitivy to disturbance. These characteristics make nematodes useful bioindicators (Bongers, 1990; Bongers and Bongers, 1998). There are a number of nematode-based indices that assess the structure and function of soil ecosystems. Diversity indices such as Shannon diversity index (H') (Shannon and Weaver, 1949), and Hill's N1 and Hill's N0 (Hill, 1973) can be used to study the effects of management practices on the diversity and richness of nematodes. The Maturity Index (MI) provides information on the condition of an ecosystem based on the composition of the nematode community (Bongers, 1990; Neher et al., 2005). The value of the MI varies from less than 2 in disturbed conditions to 4 in undisturbed conditions (Bongers and Bongers, 1998).

Weighted nematode guild based soil food web indices have been developed to assess soil ecosystem health (Ferris et al., 2001; Berkelmans et al., 2003; Ferris and Matute, 2003, Sánchez-Moreno and Ferris, 2007; Knight et al., 2013). These include structure (SI), Enrichment (EI), basal (BI) and channel (CI) indices. SI uses functional guilds to assess the soil food web conditions as affected by stress or by disturbance. Presence of functional guilds with c-p values 3-5 indicates structured soil ecosystem with greater trophic links while c-p values 1-2 indicates degraded conditions with fewer trophic links. EI is a measure of turnover of opportunistic bacterivore and fungivore nematodes and whether the soil environment is nitrogen enriched or depleted (Ferris et al., 2001). BI is a measure of general opportunistic bacterivore and fungivore nematodes and describes if the soil food web is diminished due to stress either from nutrient depletion or disturbances.

CI measures opportunistic grazers feeding on fungi and bacteria to determine a predominant decomposition pathway. The nematode trophic ratios (fungivores-to-bacterivores, and fungivores plus bacterivores-to-herbivores) have also been used to compare predominant decomposition pathways of the soil food web in previous studies (Freckman and Ettema, 1993; Wasilewska, 1994).

Melakeberhan (2006) emphasized cross-disciplinary and integrated decision making approach and developed the Fertilizer Use Efficiency (FUE) model. The FUE separates the relationships among plant growth, herbivore nematode parasitism, nutrient deficiency and toxicity. The model describes treatment outcome as a percent of control (untreated check) and graphically expresses data in four quadrants from best to worst case scenarios. Later, the FUE model was modified to include assessment of beneficial nematodes and agronomic parameters (Melakeberhan and Anvendaño, 2008). This modification helps to explain soil ecosystem change when assessing efficiency of soil amendments that simultaneously suppress herbivore nematodes and promote the beneficial nematodes (Melakeberhan, 2010).

While there is a substantial knowledge base on compost's agronomic benefits, little information is available on the impact of specific compost types and rates of applications on nematode trophic diversity, soil food web structure, overall soil health, and carrot yield and quality. The impacts of integrated applications of compost and inorganic fertilizers on nematode trophic diversity, soil food web structure, overall soil health, and carrot yield and quality are also less studied. Soil health is defined as the capacity of a soil to function within ecosystem and land use boundaries, to sustain plant and animal productivity, maintain environmental quality, and promote plant and animal health (Doran and Zeiss, 2000). In this study, nematodes were used as an indicator of soil health.

Hence, the main goal of this research was to develop compost amendment strategies for nutrient, nematode and soil health management to improved carrot yield and quality. The working hypotheses were: i- compost amendments would suppress herbivores, improve nematode community structure, enhance SI, soil respiration and physicochemical properties, and increase carrot yield and quality, but these effects would differ by compost type and rate of application; ii- lower rates of urea integrated with higher rates of PC would improve nematode community structure, EI and SI, soil biological and physicochemical properties, and increase carrot yield and quality; iii- compost amendments would enhance recolonization of biologically degraded soil; iv- integrating the concepts of FUE and nematode-based soil food web models will improve the power of FUE model for integrated analysis of soil health and agronomic parameters. The respective hypotheses were tested in the chapters described below.

In Chapter 3, the objective was to compare the effects of AC and PC composts and rates on herbivore and non-herbivore nematodes, soil food web conditions, soil biological and physicochemical properties, and yield and quality of a processing 'Cupar' and fresh market 'Sugarsnax 54' carrot cultivars in sandy clay loam soil. In Chapter 4, I compared the effects of integrated application of different levels of PC and urea on nematode community structure, soil food web conditions, soil biological and physicochemical properties, and yield and quality of Cupar in a sandy loam soil. In Chapter 5, the effects of different rates of AC and PC on herbivore and non-herbivore nematodes, soil food web conditions, soil biological and physicochemical properties, and growth of Sugarsnax 54 were assessed on sterilized and non-sterilized soils under glasshouse conditions. The study was extended to integrate the concepts of FUE and the food web models described in Chapter 6.

CHAPTER 2

GENERAL MATERIALS AND METHODS

Plot establishment and maintenance

Field experiments were established at the Michigan State University (MSU) Horticulture Teaching and Research Center in Holt, Michigan. Each plot was 3.72 meter square (3.05 m x 1.22 m) separated by 1.83 m wide guard rows between their length and 1.52 m between their widths. The field had been used for mixed vegetables and soybean production in 2010 and 2011 growing season, respectively. The field soil had above optimum phosphorus (P) and potassium (K) levels and did not receive P and K fertilizers. The field was tilled to the depth of 30 cm and amendment treatments were uniformly applied, spread to each plot by hand and mixed to 10 cm soil depth using an RTR2548 rototiller (Land Pride, Assaria, KS, USA) before planting. Seeds were planted using MasterMacc planter (Market Farm Implement, Friedens, PA, USA) with 4 rows set 25 cm apart at a rate of 1 seed every 5 cm and every 2.5 cm in-row spacing for Cupar and Sugarsnax 54, respectively. The seeding rate was equivalent to 640,000 and 1,200,000 seeds/ha for Cupar and Sugarsnax 54, respectively. Throughout the duration of the experiment, weed control measures were done per recommended standard herbicides for carrots and hand weeding (Zandstra, 2011). Herbicides consisted of preemergenc application of linuron (0.56 kg a.i/ha) 1 to 2 weeks after carrot planting, and postemergence application of linuron (0.56 kg a.i/ha) and clethodim (0.1 kg a.i/ha) applied at 4 to 6 weeks after carrot planting. Plots were irrigated with sprinkler irrigation system set for an hour every day until the carrots emerged and for 4 hours as required after carrot emergence. Experiments on Cupar, the processing variety, were completed 132 DAP in 2012 growing season (Chapter 3 and 4), and 133 DAP in 2013 and

2014 growing seasons. The experiments on Sugarsnax 54, the fresh market variety, were completed 78 DAP in 2012, and 79 DAP in 2013.

Soil sampling

In 2012, 2013 and 2014, six soil cores per plot were collected at 0-25 cm soil depth of root zone in the center two rows using a sampling cone (AMES companies, Inc., Camp Hill, PA, USA) at 0 (0), 32 (30), 62 (62) and 78 (79) DAP for Sugarsnax 54 and at 0 (0), 32 (30), 62 (62), 96 (94) and 132 (133) DAP for Cupar. Numbers before the brackets are soil sampling dates in 2012 and numbers in the brackets are soil sampling dates in 2013 and 2014 growing seasons. After soil sampling, the holes were gently closed by returning the soil to the sampling spots to avoid further soil disturbance. The soil from the six cores was thoroughly mixed to form a composite of approximately 1,000 cc, transported to the laboratory and stored in a cold room at temperature of 5 ^{0}C.

Nematode extraction, identification and abundance

Nematodes were extracted from 100 cc of soil within 3-5 days of soil sampling using a semi-automatic elutriator as described earlier (Avendaño et al., 2003) and fixed in double TAF solution (14 ml 40% formalin: 4 ml tri-ethanolamine: 91 ml distilled water) (Hooper, 1986). All nematodes in each sample were counted using an inverted microscope (Accu-scope Inc, Commack, NY, USA) at 400X magnification and identified at genus level following diagnostic keys by Bongers (1994) and the University of Nebraska Lincoln nematode identification website (http:nematode.unl.edu/konzlistbutt.htm). Each identified genus was assigned to a herbivore, bacterivore, fungivore, omnivore or predator trophic group (Yeates et al., 1993; Okada and Kadota, 2003) and to a colonizer-persister (c-p) groups ranging from r-strategists (colonizers) with c-p 1 as short generation time, high fecundity, tolerant to disturbances to k-strategists (persisters) with c-p 5 as long generation time, low fecundity, sensitive to disturbance, also make them an extremely useful indicator organisms (Bongers, 1990; Bongers and Bongers, 1998). Permanent slides of voucher specimens were prepared following methods described by De Grisse (1969) and photographed. The permananent mounts and digital pictures are stored in the Agricultural Nematology Labaoratory, Department of Hoticulture, at Michigan State University (Tables C-1 and C-2).

Nematode community indices

MI of c-p 1 to 5 nematodes and MI of c-p 2 to 5 of free-living nematodes (MI25) were calculated to measure soil ecosystem disturbance levels. Separate plant-parasitic index (PPI) was calculated by including c-p 2 to c-p 5 plant-parasitic nematode genera. MI, MI25 and PPI were calculated as weighted mean frequency, mathematically expressed as $\Sigma\ (vi\ \times fi)/n$ where vi = *c-p* value assigned to family i, fi = frequency of family i in the sample, and n = total number of individuals in sample (Bongers, 1990).

Nematode community diversity was calculated using Shannon diversity index [H′= -$\Sigma pi(ln\ Pi)$], where Pi is the proportion of taxa in the total population (Shannon and Weaver, 1949), Hill's diversity N1 [exp(H′)] and N0 (genera richness = number of all genera in the same community) (Hill, 1973). H′ was used to compare nematode diversity within the community and N1 was used to compare number of abundant genera within the community, respectively.

Soil food web condition, trophic ratios and fertility index

The effect of treatments on soil food web indices was measured as described by Ferris et al. (2001). BI, CI, EI and SI were calculated based on the weighted abundance of nematodes guilds representing structure ($s = \Sigma k_s n_s$), enrichment ($e = \Sigma k_e n_e$) and basal ($b = \Sigma k_b n_b$) where k is the specific weight of each guild and n is the relative frequency of each nematode functional guild in the soil sample using the following formulae: BI = 100[b/(e+s+b)], SI = 100[s/(s + b)] and EI = 100[e/(e + b)]. CI = 100[0.8(c-p 2 fungivores)/ (3.2(c-p 1 bacterivores) + 0.8(c-p 2 fungivores))], was calculated based on the ratio of fungivores of *c-p* 2 with the decomposer guilds (fungivores of *c-p* 2 and bacterivores of *c-p* 1). The soil food web structure and function was graphically described as function of EI (measure of opportunistic bacterivores and fungivores in the community) and SI (indicator of food web status affected by stress or disturbance) as described by Ferris et al. (2001). In addition to CI, fungivores-to-bacterivores (fungivores/bacterivores) (Freckman and Ettema, 1993), and fungivores and bacterivores-to-herbivores ((fungivores + bacterivores)/herbivores) (Wasilewska, 1994) ratios were used to compare predominant nutrient mineralization pathways. Fertility index (FI = PPI/MI) was calculated as a measure of changes in the functioning of the soil in response to treatments (Bongers et al., 1997).

Soil respiration and physicochemical properties

The rate of CO_2 emission from the soil samples was used as an indicator of relative soil respiration and of level of biological activity (Ettema et al., 1998; Ferris and Matute, 2003; Treonis et al., 2010). Fifteen grams of fresh soil sample per plot was incubated in 237 ml glass jars at 22^0C for 7 days at field soil moisture content during sampling (Treonis et al., 2010). The CO_2 concentration of a 0.5 ml headspace gas sample was withdrawn from the jar through a rubber stopper using 1 ml syringe. The concentration was determined after 7 days of incubation using an infrared gas analyzer (LI-820, LI-COR, Inc., Lincoln, NE, USA; Zibilske, 1994) and expressed as µg CO_2-C per gram of soil per day. Soil chemical properties such as pH, phosphorus, potassium, calcium, magnesium, soil organic matter, nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N) and cation exchange capacity were determined at MSU Soil and

Plant Nutrient Laboratory using standard procedures (Huffman and Barbarick, 1981; Nelson, 1983).

Soil moisture content at sampling time, soil bulk density and chemical properties were measured to determine the effects of treatments on soil properties. Soil moisture content in each sample was determined by weight loss after oven drying the soil samples 104 ^{0}C for 24 h. Bulk density was measured on pre-plant, and harvest soil samples by drying core soils (3 cm height and 5 cm diameter) at 104 ^{0}C for 24 hours (Blake and Hartge, 1986).

Carrot yield and quality

All carrots from the center two rows were harvested using spading fork (True Temper, AMES companies, Inc., Camp Hill, PA, USA). The roots with tops still attached were washed with a garden hose, counted and graded (Anon, 1965). Carrots were categorized as marketable when the length was greater than or equal to 13 cm and the diameter at the shoulder was greater than 2 cm for Sugarsnax 54 and 2.5 cm for Cupar cultivars and without defects. Carrots were graded as unmarketable when carrots were stunted (length $\leq$ 13 cm and diameter at the shoulder $\leq$ 2 cm for Sugarsnax 54 and 2.5 cm for Cupar) or had defects such as cracks, forking and rotting (Anon, 1965). Five marketable quality carrots were randomly selected from each plot, and roots and shoots were placed in separate paper bags for fresh and dry weight determination. Dry weight was determined after the roots and shoots had been dried at 66 ^{0}C for 12 days (Hochmuth et al., 2006).

Multiple factor analysis

Multiple factor analysis (Escofier and Pagès, 1994) was performed using R v. 3.1.0 to describe the relationships among abundance of nematode trophic groups and soil physicochemical properties. The relationship among soil physicochemical properties, and soil food web indices, trophic ratios and yield parameters were also analyzed. Multiple factor analysis allows obtaining the best linear combinations of the original variables where Dimension 1 and 2 represent the first and second best summary of variability of the information, respectively. Variables closest to the horizontal axis and the unit circle are best correlated with Dimension 1 (Dim 1) and those closer to vertical axis and unit circle are best correlated with Dimension 2 (Dim 2). The variables closer to -1 on each axis are negatively correlated and *vice versa*.

CHAPTER 3

EFFECTS OF PLANT AND ANIMAL WASTE-BASED COMPOST AMENDMENTS ON NEMATODES, SOIL PROPERTIES, AND YIELD AND QUALITY OF FRESH MARKET AND PROCESSING CARROT CULTIVARS

Abstract

This study tested a hypothesis that compost amendment would improve SI, soil biological and physicochemical properties, and increase carrot yield and quality, but these effects would differ by compost type and rate of application. PC and AC were applied at 1, 1.5 and 2 times the standard N rate (135 kg/ha) for a processing carrot cultivar ‘Cupar’ and fresh market cultivar ‘Sugarsnax 54’. Urea and non-amended check were included as controls. Nematode community was analyzed from soil samples collected at approximately 4-week intervals up to 133 DAP. Soil respiration and physicochemical properties were determined from soils collected at planting and at harvest. For Cupar, compost amendments increased SI compared with 50 % (median of the food web structure), but such effects were not observed in urea. As expected, AC amendments increased soil pH, phosphorus, potassium, and organic matter compared with the controls after two years. Except for PC at 168 kg N/ha and AC at 112 kg N/ha, compost treatments decreased Sugarsnax 54 marketable yield compared with urea in 2012. However, all compost amendment treatments increased marketable and total carrot yield of Sugarsnax 54 compared with the controls in 2013. SI was positively correlated with soil respiration, calcium, magnesium, cation exchange capacity, organic matter and soil pH, but negatively correlated with total unmarketable carrot yield, and fertility and basal indices. Overall, the findings support the working hypothesis that compost amendment would improve SI, soil biological and chemical properties and suggest that the compost related increase in soil food web structure may lead to increasing ecosystem services provided by the soil food web.

Introduction

Organic soil amendments improve soil food web structure and function and ecosystem services (Bardgett and Cook, 1998; Ferris et al., 2001; Hooper et al., 2005). The stewardship of the functions of soil food web is fundamental to optimizing essential ecosystem services such as nutrient mineralization and pest regulations (Ingham et al., 1985; Ferris et al., 1998; Sánchez-Moreno and Ferris, 2007; Ferris et al., 2012). Sufficient biomass and activity of appropriate functional guilds in the soil food web are required to provide adequate levels of various ecosystem services (Ferris et al., 2001). This can be achieved through a consistent supply of new organic material such as compost to the soil (Ferris et al., 2004; Ferris and Bongers, 2006; Ferris, 2010). Moreover, increased organic matter is usually associated with higher soil moisture content, greater retention of essential minerals and improved soil health (Pimentel et al., 2005; Zasada et al., 2008; Glover et al., 2010; Mennan and Melakeberhan, 2010).

Compost is one of the most commonly used organic amendments, and has been shown to increase soil organic matter, nutrient content and microbial biomass, suppresses pests and improve overall soil health (Bulluck et al., 2002a; Briar et al., 2007; Forge and Kempler, 2009; Ferris et al., 2012). For example, addition of compost increased soil organic matter, total nitrogen, available phosphorus, exchangeable potassium, available water content and porosity of the soil (Pinamonti, 1998). Nahar et al. (2006) also reported compost amendment significantly increased particulate organic matter. However, little is known about the effects of different sources and rates of composts on organisms that drive the soil ecosystem functions (Pinamonti, 1998; Briar et al., 2007; Forge and Kempler, 2009).

As the most abundant metazoan in terrestrial ecosystems, nematodes are considered as an important component of the soil biotic community and an indicator of soil ecosystem change

(Bongers and Bongers, 1998; Porazinska et al., 1999). Nematodes have a central position in the soil food web and they respond to nutrient enrichment, environmental perturbation, and recovery from disturbance (Bongers and Bongers, 1998). They also play a key role in decomposition and nutrient mineralization (Ingham et al., 1985; Ferris and Matute, 2003; Wang et al., 2004; Neher et al., 2012). Presence of a range of life strategy characteristics also makes nematodes useful indicator organism (Bongers, 1990; Bongers and Bongers, 1998). Trophic group (herbivores, bacterivores, fungivores, omnivores and predators) abundances, non-herbivores and total nematodes abundances, diversity indices such as H' (Shannon and Weaver, 1949), Hill's N1 and Hill's N0 (Hill, 1973), and maturity indices such as MI, MI25 and PPI (Bonger, 1990) act as useful indicators of ecosystem productivity and change (Nahar et al., 2006; Wang et al., 2006; Cheng and Grewal, 2009; Knight et al., 2013). The MI, a measure of soil disturbance level, has values usually lower than 2 in agroecosystems with frequent farm operations and agrochemical inputs, and up to 4 in natural and undisturbed ecosystems (Bongers and Bongers, 1998).

Furthermore, a range of soil food web indices based on the nematode community have been developed to assess soil ecosystem health (Ferris et al., 2001; Berkelmans et al., 2003; Ferris and Matute, 2003, Sanchez-Moreno and Ferris, 2007; Knight et al., 2013). These include SI indicator of lack of, or recovery from, environmental stress and/or resource depletion which contribute to abundance of predators and omnivores. Sanchez-Moreno et al. (2009) found that highest SI in plots treated with compost and cover crops compared with conventionally treated plots. SI values are usually low in agroecosystems because of physical and agrochemical distrubances (Fiscus and Neher, 2002; Berkelmans et al., 2003; Tenuta and Ferris, 2004; Ferris, 2010; Briar et al., 2011). EI reflects the resource availability of the soil food web. BI is an indicator of soil food webs that are diminished due to stress. CI indicates the percentage of opportunistic grazers feeding on fungi or bacteria, and the predominant decomposition pathway (Ferris et al., 2001). In addition to CI, fungivores-to-bacterivores (Freckman and Ettema, 1993), and fungivores and bacterivores-to-herbivores (Wasilewska, 1994) ratios can be used to compare predominant nutrient mineralization pathways.

Herbivore nematodes are among the soil-borne pests that reduce quality and yield of carrot worldwide (Belair, 1992; Berney and Bird, 1992; Wesemael and Moens, 2008). Currently, there are no commercially available nematode resistant cultivars (Melakeberhan and Wang, 2013) and few sustainable alternatives to the broad spectrum nematicides banned due to Food Quality Protection Act restrictions (Abawi and Widmer, 2000). Compost amendments are among the promising alternatives to conventional soil fertility management practices, which can provide additional benefits such as suppression of diseases and pests, and improved carrot yield and quality (Bulluck III et al., 2002a; Wang et al., 2004; Nahar et al., 2006; Briar et al., 2007). Bulluck et al. (2002a) reported that cotton-gin trash compost application increased bacterivore nematodes in a field cultivated with tomatoes. The abundance of bacterivore, fungivore, omnivore and predator nematodes were increased while herbivore nematodes decreased in composted dairy manure treated plots (Nahar et al., 2006). Similarly, horse manure compost application increased the abundance of total nematodes and the relative abundance of bacterivores, but decreased the relative abundance of herbivores (Lie et al., 2010). However, Ferris et al. (2012) found that abundance of bacterivores and fungivores were not affected by green-waste compost application. While there is a substantial knowledge base on compost's agronomic benefits, the effect of compost on nematode community has been less studied. Moreover, little information is available on the impact of specific compost types and rates of application on nematode trophic diversity, soil food web structure, overall soil health, and carrot yield and quality.

Therefore, the objectives of the study reported in this chapter were to compare the effects of AC and PC and rates on soil food web conditions, soil biological and physicochemical properties, and carrot yield and quality of Cupar and Sugarsnax 54 in sandy clay loam soil. I hypothesized that compost amendment would improve SI, soil biological and physicochemical properties, and increase carrot yield and quality, but these effects would differ by compost type and rate of application.

Materials and methods

Experimental design and treatments

A repeated field experiment was conducted at Michigan State University (MSU) Horticulture Teaching and Research Center in Holt, Michigan (N $43^0$24.040’, W $085^0$56.559’, 854 m elevated) in a Colwood-Brookston sandy clay loam (fine-loamy, mixed, mesic Type, Haplaquolls-Argiaquolls, Anon, 1977) with 54 % sand, 25 % silt and 21 % clay. PC from leaves left to decompose for more than ten years and AC from cow manure-based compost (“Dairy Doo”, Sears, MI, USA) were used as organic amendments. PC was obtained from MSU Student Organic Farm, Holt, MI, USA and AC purchased from Morgan Composting, Inc., Sears, MI, USA (Table 3.1). Urea was the standard inorganic source.

Compost was applied on dry matter basis and reported as average of three years (Table 3.1). Treatments for Cupar were 12.0 Mg/ha (1X), 18.0 Mg/ ha (1.5X) and 24.0 Mg/ha (2X) of PC and 9.6 Mg/ha (1X), 14.4 Mg/ha (1.5X) and 19.2 Mg/ha (2X) of AC where 1X was estimated to supply 135 kg N/ha which is a recommended N for processing carrot cultivars. It is assumed that between 10 % and 50 % of N is available in the first season after application (Sanchez and

Richard, 2009). A total of 293 kg urea (46-0-0) /ha (135 kg N/ha) was applied in three split applications (30 kg N/ha, 45 kg N/ha and 45 kg N/ha) when carrot petiole nitrate content was below thresholds established by Warncke (1997). Treatments for Sugarsnax 54 were 12.0 Mg/ha (X), 18.0 Mg/ha (1.5X) and 24.0 Mg/ha (2X) of PC and 8.7 Mg/ha (X), 13.0 Mg/ha (1.5X) and 17.4 Mg/ha (2X) of AC where X was adjusted at a rate of 112 kg N/ha which is a recommended N for fresh market carrot varieties (0.112 N Mg/ha) and urea (46-0-0) was applied as 0.243 Mg (0.112 Mg N/ha) per plot before planting. The experiment was randomized complete block design with four replications.

The contents of macronutrients (nitrogen, phosphorus, potassium, sodium, and sulfur) and micronutrients (Iron, Zinc, Copper) were significantly higher in AC than in PC (Table 3.1). On the other hand, calcium and aluminum were significantly higher in PC than in AC. However, there were no statistical differences in percentage of organic matter, total carbon and carbon-to-nitrogen ratio (C: N) between AC and PC. Methods pertaining to soil sampling, nematode extraction, identification and nematode community, ecosystem disturbance and soil food web indices, were described in the General Materials and Methods Section (Chapter 2). Similarly, methods used to measure soil respiration, soil physicochemical properties, and carrot yield and quality were stated in Chapter 2.

Table 3.1. Average soil pH, macro (%) and micro nutrient contents (ppm) of animal (AC) andplant compost (PC) and rates at which they were applied (kg/ha) in sandy clay loam soil and planted with Cupar and Sugarsnax 54 carrot cultivars in 2012-2014.

pH and nutrients	Cupar				Sugarsnax 54			
	Content		Rate (kg/ha)		Content		Rate (kg/ha)	
	AC	PC	AC	PC	AC	PC	AC	PC
pH	8.4 a[e]	7.8 a	na[a]	na	9.2[b] a	7.9[b] b	na	na
Macronutrients (%)								
Nitrogen	1.5 a	1.1 b	135.0	135.0	1.3 a	1.0 b	112.0	112.0
Phosphorus	0.6 a	0.1 b	57.0	12.0	0.6 a	0.1 b	52.0	12.0
Potassium	1.5 a	0.3 b	135.0	36.0	1.5 a	0.3 b	130.0	36.0
Calcium	3.0 b	3.8 a	287.0	457.0	2.9 b	4.0 a	252.0	478.0
Magnesium	0.7 a	0.8 a	67.0	96.0	0.7 b	0.9 a	61.0	11.0
Sodium	0.2 a	0.02 b	19.0	2.0	0.2 a	0.02 b	17.0	2.0
Sulfur	0.4 a	0.2 b	38.0	24.0	0.4 a	0.2 b	35.0	24.0
OM [c]	29.2 a	25.2 a	27740.0	3005.0	27 a	23 a	2348.0	2750.0
Carbon	16.9 a	14.6 a	1530.0	1755.0	16 a	14 a	1391.0	1674.0
C: N[d]	11.3 a	13.3 a	na	na	12 a	14 a	na	na
Micronutrients (ppm)								
Iron	6306.8 a	5248.1 b	57.0	60.0	6052.3 a	5307.0 b	52.0	60.0
Zinc	188.4 a	77.6 b	2.0	1.0	188.3 a	82.6 b	2.0	1.0
Manganese	348.2 a	324.2 a	3.0	4.0	344.8 a	329.6 a	3.0	4.0
Copper	102.1 a	28.8 b	1.0	0.4	101.5 a	30.6 b	1.0	0.3
Boron	23.9 a	27.3 a	0.2	0.4	24.4 a	27.1 a	0.2.0	0.3
Aluminum	1896.2b	2663.2 a	19.0	36.0	1936.1 b	2843.5 a	17.0	36.0

[a]Rate was not available because pH and C/N ratio cannot be expressed as a rate of application.
[b]pH value obtained only from 2013.
[c]percent of organic matter.
[d]carbon-to- nitrogen ratio.
[e]Means with different letters in rows within each carrot variety indicate statistical difference at $P \leq 0.05$.

Data analysis

Nematode taxa and trophic group abundances were expressed on an absolute basis (number of nematodes in a taxon *i* per 100 cc of fresh soil). Nematode population abundance data were transformed as ln (x+1) prior to statistical analysis to normalize the variance in the data. Untransformed arithmetic means are presented here in. Treatments were compared for nematode trophic groups, community indices, soil food web indices, trophic group ratios, fertility index, soil physicochemical and yield variables. Statistical analysis was conducted using the PROC MIXED procedure of SAS. The statistical model consisted of fixed effects of amendments and time and the interaction between them and random effects of blocks and block by amendment interaction. The interaction between blocks and amendments was used as an error term to test the effect of amendments. The effect of time was addressed using the repeated measures approach with REPEATED statement of the PROC MIXED. Aikaike information criterion was used to select the optimal variance-covariance structure for the repeated measures analysis. Data were tested separately for 2014 to validate the positive results observed in 2013 in Cupar plots using same repeated measure procedures.

Yield data were compared using one-way analysis of variance (PROC MIXED, SAS ver 9.3, SAS Institute, 2012, Cary, NC, USA). The statistical model consisted of fixed effect of amendments and a random effect of block. F-values were obtained using appropriate error term in the model. Two types of statistical analysis were conducted for SI. First, the SI values were compared following a standard ANOVA and mean separations (Table 3.6). Second, SI values were plotted to the food web model (Fig. 3.1). Then, SI values were tested for statistical difference from 50 % (cut off point for structured soil food web) using one-tail t-test at $\alpha = 0.05$. The means of the treatments with statistical difference from 50 % are noted by asterisks (*).

Comparison among the amendment sources (AC, PC, urea and non-amended check) was done using contrasts in SAS by comparing values before soil amendments in 2012 (0 DAP) and at the end of the two years experiment in 2013 (133 DAP). The nutrient sources were also compared at the beginning of the experiment and the end of the 2014 experiment. Data were analyzed for each carrot variety separately due to differences in amount of amendments applied and 133 DAP for Cupar and about 79 DAP for Sugarsnax 54 length of growing season. When the interaction effect of treatments and sampling time was significant, the result was presented. Otherwise, I presented only significant main effects of the treatments. The probability level $P \leq 0.05$ was regarded as significant.

Results

Composition and abundance of nematode trophic groups

A total of 15 herbivores, 16 bacterivores, 5 fungivores, 7 omnivores and 6 predator genera were detected in all of the soil samples collected from Sugarsnax 54 and Cupar plots over the three-year period (Table 3.2). *Panagrolaimus, Rhabditis, Acrobeloides, Eucephalobus, Heterocephalobus* and *Plectus* from bacterivores, *Aphelenchus, Filenchus* and *Aphelenchoides* from fungivores, and *Basiria* and *Tylenchus* from herbivores were among the most frequently encountered nematode genera. *Acrobeles, Pristionchus, Prodorylaimus, Tripyla, Hemicyclophora, Hoplolaimus, Helicotylenchus,* and *Xiphinema* occurred less frequently. *Rhabditis*, *Panagrolaimus*, *Acrobeloides*, *Eucephalobus*, *Heterocephalobus* and *Plectus* were the most abundant bacterivores, and *Aphelenchoides*, *Aphelenchus*, and *Filenchus* were the most abundant fungivores nematode genera. Among herbivores, *Tylenchus* was the most abundant genus. Omnivores and predators were less abundant in both cultivars except in Cupar at 133 DAP in 2013 and 2014. The average number of herbivores, bacterivores, fungivores, omnivores, and predators per 100 cc of soil was 19, 8, 14, 0.4 and 0.1, and 17, 18, 21, 0.4 and 0.3 in Sugarsnax 54 and Cupar plots, respectively (Table A-1)..

Table 3.2. List of nematode genera detected in AC and PC compost, urea and non-amended check plots in sandy clay loam soil in 2012-2014 growing seasons. Numbers within brackets represent c-p vales following Bongers and Bongers (1998).

Herbivores	Bacterivores	Fungivores	Omnivores	Predators
Basiria (2)	*Eumonhystera (1)*	*Aphelenchoides (2)*	*Eudorylaimus (4)*	*Trypila (3)*
Boleodorus (2)	*Mesorhabditis (1)*	*Aphelenchus (2)*	*Mesodorylaimus (4)*	*Clarkus (4)*
Cephalenchus (2)	*Panagrolaimus (1)*	*Ditylenchus (2)*	*Microdorylaimus (4)*	*Mononchus (4)*
Malenchus (2)	*Pellioditis (1)*	*Filenchus (2)*	*Pungentus (4)*	*Mylonchulus (4)*
Paratylenchus (2)	*Pristionchus (1)*	*Tylencholaimellus (4)*	*Thonus (4)*	*Prionchulus (4)*
Psilenchus (2)	*Rhabditis (1)*		*Aporcelaimellus (5)*	*Nygolaimus (5)*
Tylenchus (2)	*Acrobeles (2)*		*Prodorylaimus (5)*	
Dolichorynchus (3)	*Acrobeloides (2)*			
Helicotylenchus (3)	*Cephalobus (2)*			
Hemicycliophora (3)	*Cervidellus (2)*			
Heterodera (J2) (3)	*Eucephalobus (2)*			
Hoplolaimus (3)	*Heterocephalobus (2)*			
Pratylenchus (3)	*Plectus (2)*			
Tylenchorhynchus (3)	*Microlaimus (3)*			
Xiphinema (5)	*Prismatolaimus (3)*			
	Alaimus (4)			

Table 3.3. Probability values (Pr > F) of treatment (TR), time (T), and interaction of treatment and time (TR*T) effects for nematode trophic abundances, non-herbivore and total nematodes, nematode community and soil food web indices, trophic group ratios and soil physicochemical properties for field plots amended with AC and PC, and standard urea application and non-amended check in sandy clay loam soil planted with Cupar and Sugarsnax 54 cultivars in 2012-2013.

	Probability > F					
	Cupar			Sugarsnax 54		
Variables	Treatment	Time	Treatment x time	Treatment	Time	Treatment x time
Trophic groups						
Herbivores	0.51	<0.0001	0.56	0.44	<0.0001	0.96
Bacterivores	0.014	<0.0001	0.39	0.78	<0.0001	0.76
Fungivores	0.031	<0.0001	0.18	0.76	<0.0001	0.08
Omnivores	0.001	<0.0001	0.04	0.6	<0.0001	0.003
Predators	0.32	<0.0001	0.98	0.43	0.004	0.73
Non-herbivores	0.02	<0.0001	0.11	0.72	<0.0001	0.66
Total nematodes	0.02	<0.0001	0.15	0.93	<0.0001	0.69
Diversity indices						
H'[a]	0.02	<0.0001	0.41	0.014	<0.0001	0.39
Hill's N1	0.061	<0.0001	0.4	0.004	<0.0001	0.48
Hill's N0	0.21	<0.0001	0.46	0.38	<0.0001	0.78
Maturity indices						
PPI	0.25	<0.0001	0.84	0.43	<0.0001	0.0074
MI	0.03	<0.0001	0.41	0.11	<0.0001	0.71
MI25	0.36	<0.0001	0.28	0.47	<0.0001	0.17
Food web indices						
EI	0.73	<0.0001	0.89	0.78	<0.0001	0.24
SI	0.41	<0.0001	0.02	0.49	0.1	0.65
BI	0.7	<0.0001	0.84	0.43	<0.0001	0.24
CI	0.06	<0.0001	0.8	0.21	<0.0001	0.33
Trophic group ratio						
FV/BV[b]	0.15	<0.0001	0.24	0.82	<0.0001	0.5
(FV+BV)/HV[c]	0.46	<0.0001	0.28	0.03	<0.0004	0.31
SR[d]	0.11	<0.0001	0.78	0.04	<0.0001	0.027

Table 3.3 (cont'd)

	Probability > F					
	Cupar			Sugarsnax 54		
Variables	Treatment	Time	Treatment x time	Treatment	Time	Treatment x time
Soil physicochemical properties						
Bulk density	0.99	<0.0001	0.89	0.49	<0.0001	0.91
Porosity	0.99	<0.0001	0.89	0.97	<0.0001	0.74
Moisture	0.51	<0.0001	0.76	0.7	<0.0001	0.74
Soil pH	0.73	<0.0001	0.014	0.27	<0.0001	0.01
Phosphorus	0.12	<0.0001	0.042	0.36	<0.0001	0.01
Potassium	0.57	<0.0001	0.16	0.04	<0.0001	<0.0001
Calcium	0.4	<0.0001	0.71	0.69	<0.0001	0.54
Magnesium	0.17	<0.0001	0.64	0.8	<0.0001	0.9
Organic matter	0.75	<0.0001	0.53	0.28	<0.0001	0.0004
NO_3-N	<0.0001	0.23	<0.0001	0.0017	<0.0001	0.03
NH_4-N	0.54	<0.0001	0.37	0.08	<0.0001	0.67
CEC	0.28	<0.0001	0.89	0.73	<0.0001	0.88

[a]Shannon-Weaver diversity index (Shannon & Weaver, 1949).
[b]Fungivores-to-bacterivores ratio (Freckman and Ettema, 1993)..
[c]Fungivores plus bacterivores-to-herbivores ratio (Wasilewska, 1994).
[d]Rate of soil respiration.

Abundances of omnivores were significantly affected by the interaction of treatment and time in Sugarsnax 54 and in Cupar plots in 2012 and 2013 (Table 3.3). However, the interaction was not significant in Cupar in 2014. In Cupar, omnivores were significantly higher in non-amended check compared with the rest of the treatments at 0 DAP in 2012 (Table A-2). However, omnivores were significantly lower in PC at 270 kg N/ha and urea plots. In 2012 at 132 DAP, PC at 270 kg N/ha, and AC at 135 and 270 kg N/ha significantly increased omnivores compared with PC at 135 kg N/ha, AC at 203 kg N/ha, urea and non-amended check. All compost treatments significantly increased omnivores compared with urea and non-amended check at 133 DAP in 2013. Treatments with highest rate of PC and AC (270 kg N/ha) significantly increased omnivores compared with treatments with lower rates of composts (135 and 203 kg N/ha) at 133 DAP in 2013. In Sugarsnax 54, there was no significant difference in omnivores among the treatments in 2012 sampling dates, but PC at 168 kg N/ha significantly increased omnivores compared with urea in 2013 (Table A-3).

There was no interaction effect of treatment and time on herbivores, bacterivores, fungivores and predators in both cultivars (Table 3.3). However, there was significant treatment effect on bacterivores, fungivores, total non-herbivores and total nematodes abundance in Cupar plots (Table 3.4). Overall, AC at 270 kg N/ha significantly increased bacterivores compared with all of the treatments, except PC at 203 kg N/ha and urea. PC at 203 kg N/ha, AC at 135 and 270 kg N/ha, urea and non-amended check significantly increased fungivores compared with PC at 135 kg N/ha and AC at 203 kg N/ha. There was no significant difference in the abundance of herbivore and predator nematodes among the soil amendment treatments. PC at 203 kg N/ha and AC at 270 kg N/ha significantly increased non-herbivores compared with the rest of the treatments. PC at 203 kg N/ha, AC at 135 and 270 kg N/ha, and non-amended check significantly increased total nematodes compared with PC at 135 and 270 kg N/ha.

Time had significant effect on the abundance of all trophic groups in both cultivars ($p \leq 0.05$) (Table 3.3). Abundance of all trophic groups except omnivores in Cupar, non-herbivores and total nematodes tended to decrease with time. The nematode community was dominated by c-p 2 herbivore and non-herbivores nematode at all sampling dates in both cultivars. In Cupar, the proportions of c-p 4 nematodes increased in compost amended plots compared with urea amended plots at 133 DAP in 2013. The proportion of persister nematodes (c-p 3 to c-p 5) increased over time in compost amended more than in urea amended plots in 2014.

Table 3.4. Means abundance of herbivores (HV), bacterivores (BV), fungivores (FV) and predators (PR) nematode trophic groups, non-herbivore (NHV) and total nematodes (TL) per 100 cc of soils at the studied treatments in Cupar plots across 2012 and 2013 growing seasons.

Amendments	Rate (kg N/ha)	HV	BV	FV	PR	NHV	TL
PC	135	15 a[a]	14 b	18 b	0.4 a	26 c	40 b
	203	18 a	19 ab	25 a	0.4 a	44 a	62 a
	270	16 a	15 b	16 b	0.1 a	30 c	45 b
AC	135	18 a	18 b	24 a	0.4 a	39 bc	56 a
	203	19 a	13 b	18 b	0.3 a	32 bc	51 ab
	270	15 a	24 a	21 a	0.5 a	45 a	61 a
Urea	135	15 a	20 ab	21 a	0.3 a	40 bc	56 ab
Check	0	19 a	18 b	23 a	0.3 a	39 bc	59 a

[a]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$ using Fisher's LSD .

The abundance of omnivores at 0 DAP in 2012 was significantly higher in non-amended check than in PC and urea in Cupar plots. However, PC and AC significantly increased omnivores compared with urea and non-amended check at 133 DAP in 2013. Both PC and AC also significantly increased omnivores at 133 DAP in 2013 compared with 0 DAP in 2012 and the same effect was observed in 2014. AC significantly increased non-herbivores and total nematodes compared with non-amended check at 133 DAP in 2013. There was no significant difference in the trophic groups among the amendment sources in Sugarsnax 54.

Nematode community indices

PPI was significantly affected by the interaction of treatment and time in Sugarsnax 54. PPI was significantly lower in 2013 than in 2012 sampling times in all of the treatments. AC at 135 kg N/ha significantly increased PPI compared with the rest of the treatments in 2014 (Table A-4).

There was no significant treatment and time interaction effect on diversity indices (H', Hill's N1, Hill's N0) and disturbance indices (MI, MI25) in Cupar and Sugarsnax 54 (Table 3.3).

However, there was significant effect of time in all the above indices in both cultivars (Table 3.3). Urea significantly decreased MI compared with the rest of the treatments in Cupar (Table 3.5). PC at 203 kg N/ha, and AC at 135 and 203 kg N/ha significantly increased MI compared with PC at 135 and 270 kg N/ha, and AC at 270 kg N/ha in Cupar (Table 3.5). In Sugarsnax 54, PC at 112 kg N/ha and urea significantly increased H' compared with PC at 168 and 224 kg N/ha, AC at 224 kg N/ha and non-amended check. Similarly, PC at 112 kg N/ha and urea significantly increased Hill's N1 compared with the rest of the treatments except AC at 168 kg N/ha and non-amended check.

In Cupar plots, PC, AC and non-amended check had higher MI at 133 DAP in 2013 compared with 0 DAP in 2012. Similarly, PC and AC significantly increased MI25 at 133 DAP compared with 0 DAP in 2012. In Sugarsnax 54, PC significantly decreased H' and Hill's N1 at 133 DAP in 2013 compared with 0 DAP in 2012. In Cupar, PC, AC and non-amended check had significantly lower PPI at 133 DAP in 2013 compared with 0 DAP in 2012. AC significantly increased MI (1.69 vs 1.94) at 133 DAP in 2013 compared with 0 DAP in 2012 in Cupar plots. In 2014, PC, AC and non-amended check significantly increased MI and MI25 at 133 DAP compared with 0 DAP. Non-amended check significantly increased MI compared to urea at 133 DAP.

Table 3.5. Means across all sampling time points of the Shannon-Weaver (H') and Hill's N1 diversity indices, and maturity index (MI) at the studied treatments in Cupar and Sugarsnax 54 cultivars across 2012 and 2013 growing seasons.

	Carrot cultivar				
	Sugarsnax 54			Cupar	
Amendments	Rate (Kg N/ha)	H'	Hill's N1	Rate (Kg N/ha)	MI
PC	112	2.17 a[a]	8.94 a	135	1.98 b
	168	2.02 b	7.78 b	203	2.09 a
	224	1.99 b	7.81 b	270	2.02 b
AC	112	2.03 b	7.84 b	235	2.05 a
	168	2.08 ab	8.30 ab	203	2.07 a
	224	2.02 b	7.89 b	270	2.00 b
Urea	112	2.16 a	8.83 a	135	1.91 c
Check	0	1.96 b	7.45 b	0	1.99 b

[a]Means within columns followed by same letter (s) are not significantly different at $P \leq 0.05$ using Fisher's LSD.

Soil food web condition, trophic ratios and fertility index

Fertility index, fungivores-to-bacterivores and decomposers-to-herbivores ratios, EI, BI and CI were not affected by the interaction of treatment and time in both varieties (Table 3.3). There was no significant difference in EI, BI and CI among the treatments. SI was significantly affected by the interaction of treatment and time in Cupar, but such effect was not observed in Sugarsnax 54. At 0 DAP in 2013, SI was significantly higher in AC at 270 kg N/ha, but significantly lower in PC at 203 and 270 kg N/ha compared with the rest of the treatments. In Cupar, all compost treatments except AC at 203 kg N/ha significantly increased SI at 132 DAP compared with 0 DAP in 2012, but this effect was not observed in urea and non-amended check (Tables 3.6 and A-5). All the treatments including urea and non-amended check had higher SI at 133 DAP compared with 0 DAP in 2013. SI was significantly greater than 50 % in all compost amendments except AC at 203 kg N/ha at 132 DAP in 2013, but such effect was not observed in urea and non-amended check. Similarly, all of the compost amendments except AC 270 kg N/ha and non-amended check were greater than 50 % SI at 133 DAP in 2014 (Fig. 3.1). In 2014, PC and AC significantly increased SI and significantly decreased BI at harvest compared to pre-plant samples.

At most of the sampling dates, the food web was enriched (EI > 50) in all of the treatments (Fig. 3.1). Faunal profile analysis revealed that compost amended plots showed greater food web structure over time, but such effect was not observed in Sugarsnax 54 (Fig. 3.1A & B). Although there was slight progression at the end of 2012 growing season, soil food web became more structured in all compost treatments except AC at 203 kg N/ha and PC at 270 kg N/ha at the end of 2013 and 2014 growing seasons, respectively.

Table 3.6. Soil food web structure index (SI) from plots amended with plant (PC) and animal (AC) composts and standard urea application, and non-amended check in Cupar plots in sandy clay loam soil at 0, and132 and 133 DAP in 2012 and 2013 growing seasons, respectively.

		SI			
		2012		2013	
Amendments	Rate (kg N/ha)	0	132	0	133
PC	135	7.5 aC[a]	24.5 aB	6.8 bC	72.8 aA
	203	7.6 aC	32.4 aB	2.1 cC	82.6 aA
	270	4.0 aB	29.9 aA	0 cB	74.2 aA
AC	135	11.9 aC	31.6 aB	2.2 bC	80.6 aA
	203	8.6 aC	35.3aC	3.5bC	68.4 aA
	270	8.1 aC	23.4 aB	10.4 aB	78.7 aA
Urea	135	17.0 aB	9.1 aB	5.5 bB	51.4 aA
Check	0	21.2 aBC	6.3 aBC	3.3 bC	59.6 aA

[a]Means with different lower case letters within columns and different upper case letters across rows indicate significant difference at $P \leq 0.05$ using Fisher's LSD.

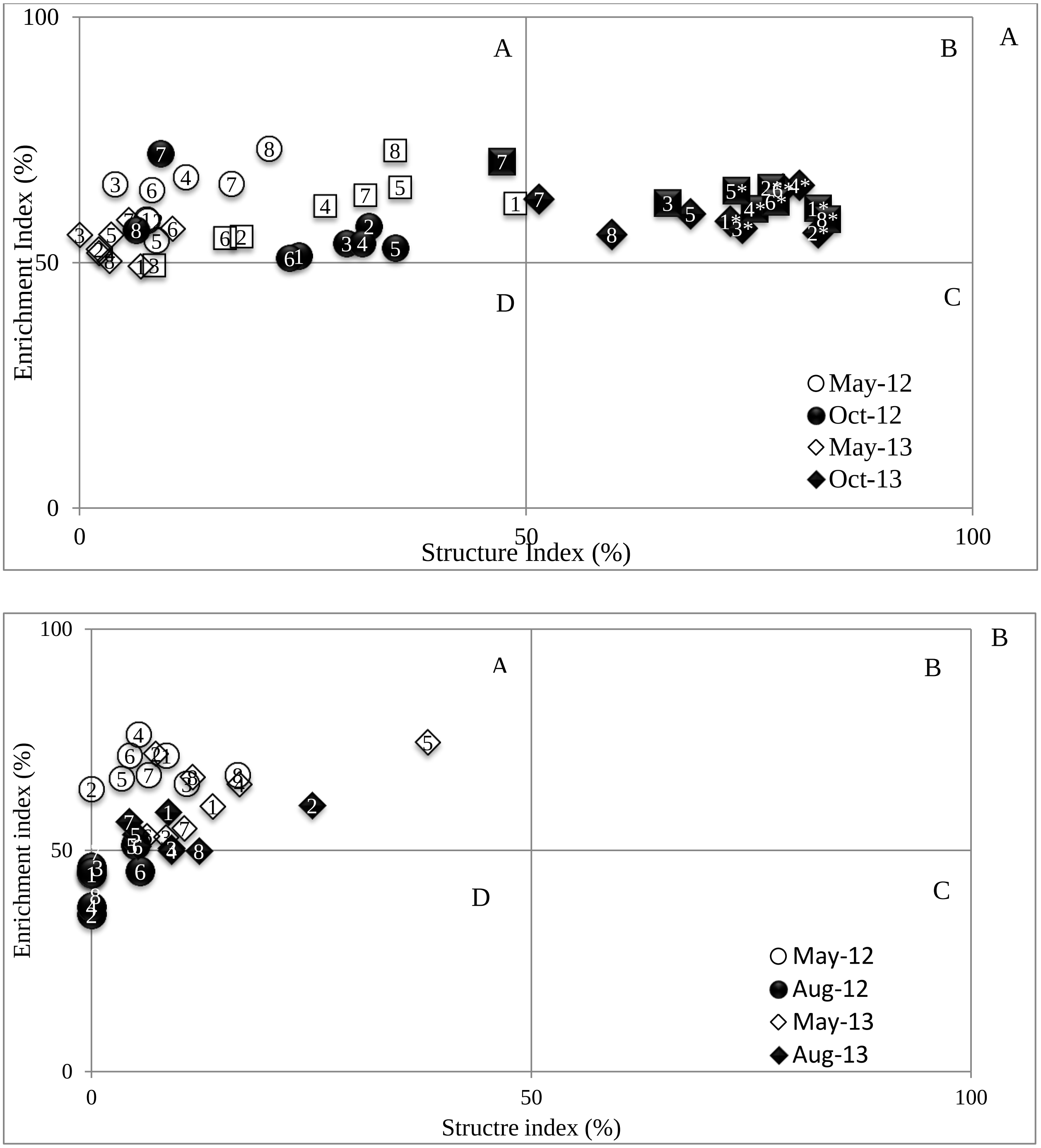


Figure 3.1. Soil food web condition in plots planted with Cupar (A) and Sugarsnax 54 (B) and amended with plant (PC) and animal (AC) compost, standard urea and non-amended check in sandy clay loam soil at planting (May, June) and harvest (August, October) in 2012 -2014 and 2012-2013 growing seasons for Cupar and Sugarsnax 54, respectively. In Cupar plots, numbers 1-3 refer PC at a rate of 135, 203 and 270 kg N/ha, respectively and 4-6 refer AC at a rate 135, 203 and 270 kg N/ha, respectively, 7 and 8 refer urea and check, respectively. In Sugarsnax 54

Figure 3.1. (cont'd)
plots, numbers 1-3 refer PC at a rate of 112, 168 and 224 kg N/ha, respectively and 4-6 refer AC at a rate 112, 168 and 224 kg N/ha, respectively, 7 and 8 refer urea and check, respectively.

*Treatments significantly increased SI from 50 % using one-tail t-test at $\alpha = 0.05$ for Cupar plots in 2013 and 2014 growing seasons.

Soil respiration and physicochemical properties

There were no significant effects of interaction effects of treatment and time, and treatment on soil respiration in Cupar, but treatment and interaction effects were significant in Sugarsnax 54 (Table 3.3). Soil respiration was significantly higher in AC at 168 and 224 kg N/ha plots at harvest in 2013 compared with all the other treatments. Soil respiration rate was also significantly higher at harvest in 2013 compared with at planting and at harvest in 2012 and at planting in 2013 (Table 3.7). Phosphorus, soil pH and NO_3-N, and organic matter and potassium were significantly affected by the interaction of treatment and time in both cultivars and Sugarsnax 54, respectively (Table 3.3). Phosphorus content of the soil was significantly higher in all of the AC treatments than in urea, non-amended check and PC treatments at 2013 harvest in both cultivars (Tables 3.8 and 3.9). Compost treatments significantly increased soil pH while urea decreased it in both cultivars at harvest in 2013 compared with the previous sampling dates. Soil pH was also significantly lower in urea compared with compost treatments and non-amended check at the end of 2013 growing season in both cultivars (Tables 3.8 and 3.9).

Table 3.7. Rate of soil respirations (μg CO_2-C g^{-1} day^{-1}) from plots amended with animal (AC) and plant (PC) composts and standard urea application and non-amended check in sandy clay loam soil at planting (0) and at 132 and 133 days after planting (DAP) in Cupar, and at 78 and 79 DAP in Sugarsnax 54 in 2012 and 2013 growing seasons.

			Nutrient sources and rate of applications							
			PC			AC			Urea	Check
Cultivar	Year	DAP	135[a]	203	270	135	203	270	135	0
Cupar	2012	0	3.2 aA[b]	3.3 aA	3.9 aA	4.7 aA	4.3 aA	3.1 aA	4.7 aA	2.7 aA
		132	6.4 aA	5.2 aA	5.1 aA	5.9 aA	6.2 aA	3.9 aA	6.0 aA	5.2 aA
	2013	0	2.7 aA	2.9 aA	3.6 aA	2.6 aA	2.7 aA	2.5 aA	2.8 aA	2.3 aA
		133	2.9 aA	3.6 aA	5.0 aA	3.8 aA	4.6 aA	6.5 aA	3.5 aA	3.7 aA
			112	168	224	112	168	224	112	0
Sugarsnax 54	2012	0	3.3 aA	3.5 aA	3.3 aA	3.5 aA	3.1 bA	3.3 bA	3.5 aA	3.0 aA
		78	2.8 aA	2.4 aA	3.6 aA	3.4 aA	4.0 bA	3.4 bA	3.9 aA	2.8 aA
	2013	0	2.9 aA	2.8 aA	3.2 aA	3.0 aA	3.0 bA	3.1 bA	2.6 aA	2.8 aA
		79	4.2 aB	3.4 aB	3.7 aB	4.5 aB	6.8 aA	7.9 aA	2.6 aB	2.9 aB

[a]Nitrogen rate (kg N/ha) applied from each treatments.
[b]Means with different lower case letters in columns within each cultivar and different upper case letters across rows indicate significant difference at $P \leq 0.05$ using Fisher's LSD.

In Sugarsnax 54, AC treatments significantly increased potassium compared with PC treatments, urea and non-amended check at harvest in 2013. Urea significantly increased NO_3-N compared with the rest of the treatments at harvest in 2012 and in 2013 in Cupar, but such effect was observed only in 2013 at harvest in Sugarsnax 54. Similarly, urea significantly increased NO_3-N at harvest in 2012 and in 2013 compared with at planting time in Cupar (Table 3.8). However, urea significantly increased NO_3-N only at harvest in 2013 compared with at harvest in 2012 and planting time in 2013 in Sugarsnax 54. PC at 168 kg N/ha, and AC at 112 and 224 kg N/ha significantly increased organic matter compared with urea and non-amended check at harvest in 2013 in Sugarsnax 54.

Table 3.8. Soil pH, and phosphorus (P) and nitrate-nitrogen (NO_3-N) contents (ppm) in Cupar plots amended with animal (AC) and plant (PC) composts, standard urea application and non-amended check in sandy clay loam soil at planting (0) and at 132 and 133 days after planting (DAP) in 2012-2013 growing seasons.

			Nutrient sources and rate of applications							
			PC			AC			Urea	Check
Variables	Year	DAP	135[a]	203	270	135	203	270	135	0
pH		0	7.2 bA[b]	7.2 bA	7.2bA	7.1bA	7.2bA	7.2bA	7.3aA	7.1bA
	2012	132	7.3 bAB	7.1 bAB	7.5abA	7.2bAB	7.2bAB	7.2bAB	6.8cB	7.2aAB
		0	7.5 bA	7.4 bA	7.5abA	7.4bA	7.5bA	7.5bA	7.4abA	7.4aA
	2013	133	7.7 aA	7.7 aA	7.7aA	7.7aA	7.7aA	7.7aA	7.2bB	7.6aA
P		0	53.5 bA	57.5 bA	55.0 aA	46.5 bA	55.5 bA	49.8 cA	57.8aA	57.3aA
	2012	132	57.0 aA	65.3 aA	55.3 aA	54.8 aA	64.0 aA	57.5 bA	59.8aA	54.3abA
		0	43.0 cB	51.7 bA	46.7 bAB	41.7 cB	54.0 bA	50.0 cAB	49bAB	45.7bAB
	2013	133	47.0 abB	52.0 abB	50.3 abB	49.8 abB	81.0 aA	84.7 aA	48.3bB	44.7bB
NO_3-N		0	6.6 aAB	9.2 aAB	5.5 aAB	4.8 aB	5.0 aAB	7.4 aAB	8.4 bA	7.0 aAB
	2012	132	1.6 aB	2.0 aB	2.3 aB	1.3 aB	2.0 aB	1.6 aB	31.7 aA	1.6 aB
		0	4.3 aAB	6.2 aAB	4.0 aB	4.3 aAB	5.0 aAB	4.1 aAB	7.2 bA	4.3 aAB
	2013	133	0.7 aB	1.5 aB	0.8 aB	1.0 aB	1.8 aB	3.3 aB	29.4 aA	1.1 aB

[a]Nitrogen rate (kg N/ha) applied from each treatments.
[b]Means with different lower case letters in columns within each soil variable and different upper case letters across rows indicate significant difference at $P \leq 0.05$ using Fisher's LSD .

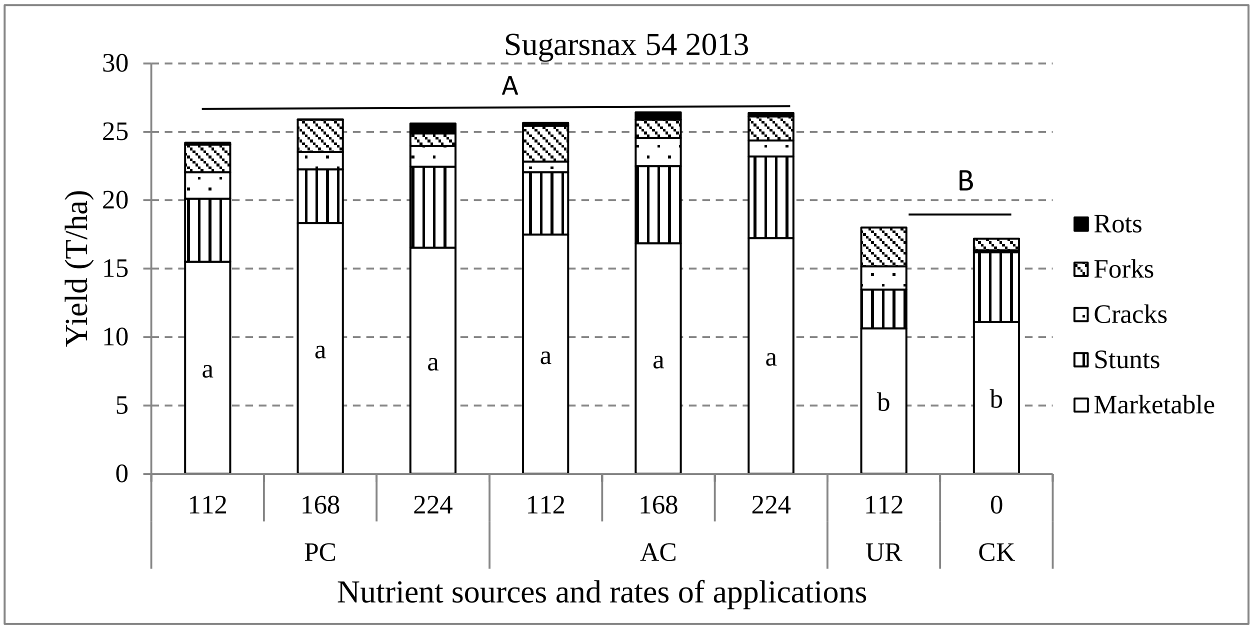
Table 3.9. Soil pH, phosphorus (P), potassium (K) and nitrate-nitrogen (NO_3-N) contents (ppm) and soil organic matter (% OM) in Sugarsnax 54 plots amended with animal (AC) and plant (PC) composts, standard urea application and non-amended check in sandy clay loam soil at planting (0) and at 78 and 79 days after planting (DAP) in 2012-2013 growing seasons.

			Nutrient sources and rate of applications							
			PC			AC			Urea	Check
Variables	Year	DAP	112[a]	168	224	112	168	224	112	0
pH		0	7.3 bAB[b]	7.3 bAB	7.2 bAB	7.4 aA	7.4 bAB	7.3 bAB	7.2 aB	7.3 bAB
	2012	78	7.3 bA	7.3 bA	7.3 abA	7.3 bA	7.4 bA	7.4 bA	7.2 aA	7.3 bA
		0	7.3 bA	7.3 bA	7.3 abA	7.3 bA	7.3 bA	7.2 bA	7.2 aA	7.3 bA
	2013	79	7.5 aA	7.6 aA	7.4 aA	7.6 aA	7.6 aA	7.5 aA	7.0 bB	7.5 aA
P		0	80.0 bA	82.8 bA	80.5 aA	80.0 bA	76.0 bA	74.8 cA	82.0 abA	83.5 bA
	2012	78	89.5 aA	94.3 aA	89.3 aA	101.0 aA	101 aA	90.5 bA	89.5 aA	92.0 aA
		0	78.0 bA	76.3 bA	75.0 aA	80.7 bA	81.0 bA	79.3 cA	74.3 bA	71.7 bA
	2013	79	73.3 bB	76.3 bB	75.3 aB	103.7 aA	109.7 aA	121.3 aA	70.7 bB	75.3 bB
K		0	154.0 aA	162.0 aA	156.3 aA	149.0 bA	148.0 cA	145.3 bA	165.5 aA	163.8 aA
	2012	78	143.5 aB	157.5 abAB	146.3 bB	160.3 bAB	163.5 bA	164.3 bA	152.3 aAB	147.3 bAB
		0	124.3 aA	115.0 cA	114.0 bA	114.3 cA	130.0 cA	121.7 cA	124.7 bA	114.7 cA
	2013	79	125.0 aB	137.3 bB	117.0 bB	204.3 aA	218.7 aA	224.3 aA	125.3 bB	116.7 cB
% OM		0	3.1 aB	3.2 aA	3.0 aB	3.2 aA	3.1 aB	3.0 aB	3.1 aB	3.1 aB
	2012	78	2.3 cA	2.4 cA	2.3 cA	2.4 cA	2.3 cA	2.3 cA	2.2 cA	2.2dA
		0	2.8 bA	2.7 bA	2.7 bA	2.8 bA	2.8 bA	2.7 bA	2.6 bA	2.8 bA
	2013	79	2.7 bAB	2.9 abA	2.8 abAB	3.0 abA	2.9 abA	3.1 aA	2.5 bB	2.6 cB
NO_3-N		0	6.2 aB	9.0 aA	6.0 aB	7.7 aB	6.4 aB	7.7 aB	9.1 aA	9.4 aA
	2012	78	2.8 bAB	2.9 cAB	2.2 bAB	3.5 bA	2.1 bB	2.7 bAB	4.0 cA	2.9 cAB
		0	5.9 aAB	7.5 aAB	4.9 aB	5.6 abAB	8.3 aA	6.0 aAB	5.2 bAB	5.1 bAB
	2013	79	1.4 bB	1.6 dB	0.9 cB	3.7 bB	3.1 bB	3.8 abB	20.1 aA	1.2 cB

[a]Nitrogen rate (kg N/ha) applied from each treatments.
[b]Means with different lower case letters in columns with in each soil variable and different upper case letters across rows indicate significant difference at $P \leq 0.05$ using Fisher's LSD.

Carrot yield and quality

There were no significant differences in carrot yield and quality among the treatments and nutrient sources in Cupar in the three growing seasons (Fig. A-1), but significant difference was observed in Sugarsnax 54 in 2012 and in 2013. PC at 168 kg N/ha and AC at 112 kg N/ha showed comparable marketable carrot yield to urea in 2012, but all other compost treatments had lower yield than the urea control. In 2013, compost amendments significantly increased both marketable and total carrot yields compared with urea and non-amended check (Fig. 3.2). The number of stunted carrots was significantly lower in urea compared with the rest of the treatments in Cupar in 2013. In 2012, PC at 168 kg N/ha and urea significantly increased the number of marketable carrots compared with the rest of the treatments in Sugarsnax 54. In Sugarsnax 54, the total number of unmarketable carrots in 2012 was the highest in PC at 112 kg N/ha.



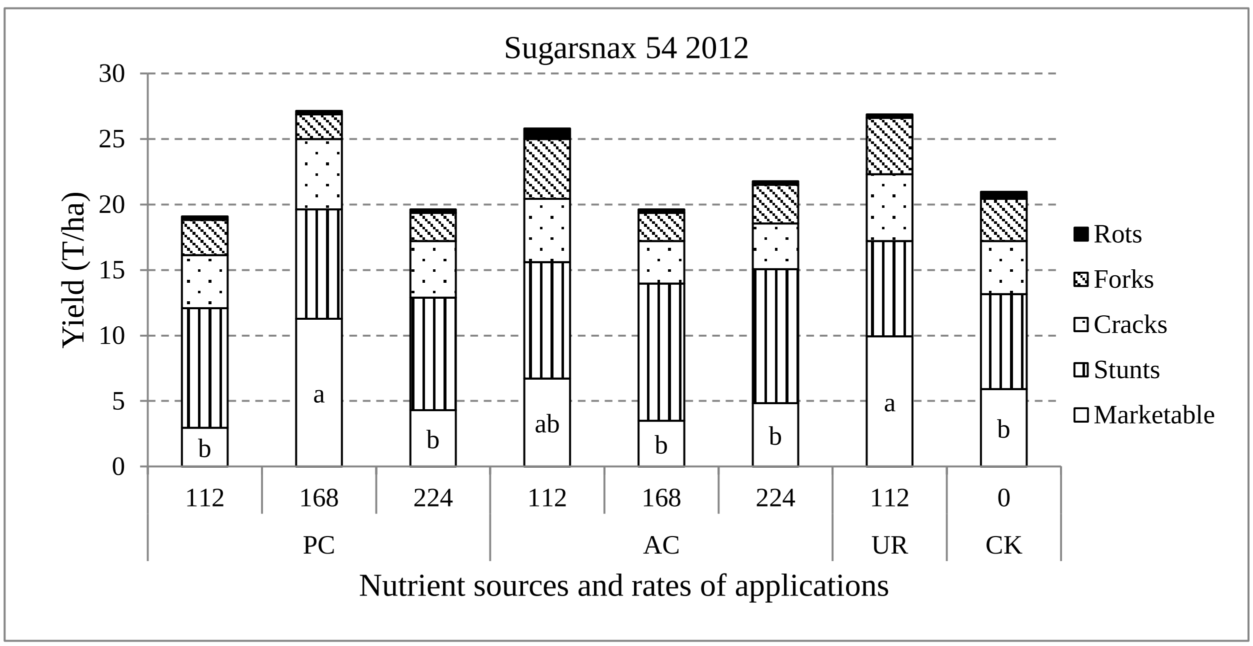


Figure 3.2. Effect of plant (PC) and animal (AC) compost containing 112, 168 and 224 kg N/ha for Sugarsnax 54, standard urea (UR) (243 kg/ha) to supply 112 kg N/ha and non-amended check (CK) on carrot yield and quality in sandy clay loam soil in 2012-2013 growing seasons. Means with different lower case letters within the same quality category are significantly different. Effect of treatments on total carrot yield is indicated by capital letters.

Multifactor analyses of nematode, soil and yield variables showed correlation patterns. In Cupar plots, calcium, cation exchange capacity and soil pH were negatively correlated while fungivores, bacterivores, c-p 1 bacterivores, c-p 2 bacterivores non-herbivores and total nematodes were positively correlated with Dimension 1 (Fig. 3.3A). Porosity was negatively correlated while bulk density and soil moisture content were positively correlated with Dimension 2 (Fig. 3.3A). Cation exchange capacity, calcium, magnesium and omnivores were positively correlated to each other while negatively correlated with c-p 2 herbivores, sum of c-p 3 to c-p 5 herbivores and total herbivores. Soil pH was negatively correlated with c-p 1 bacterivores, c-p 2 bacterivores, total bacterivores, non-herbivores, and total nematodes. As illustrated in Fig. 3.3B, calcium, cation exchange capacity, organic matter, SI, stunt carrots and soil pH were negatively correlated while fertility index, ammonium-nitrogen, bulk density, and cracked, rotten, forked, unmarketable and total carrots were positively correlated with Dimension 1. CI was negatively correlated while EI was positively correlated with Dimension 2. Cation exchange capacity, calcium, organic matter, stuntedness, SI and soil pH were positively correlated to each other while negatively correlated with fertility index, and cracked, rotten, forked, unmarketable and total carrots. CI was negatively correlated with EI and NO_3-N. BI and fungivores-to-bacterivores ratios were negatively correlated with marketable carrots and magnesium, and NO_3-N.

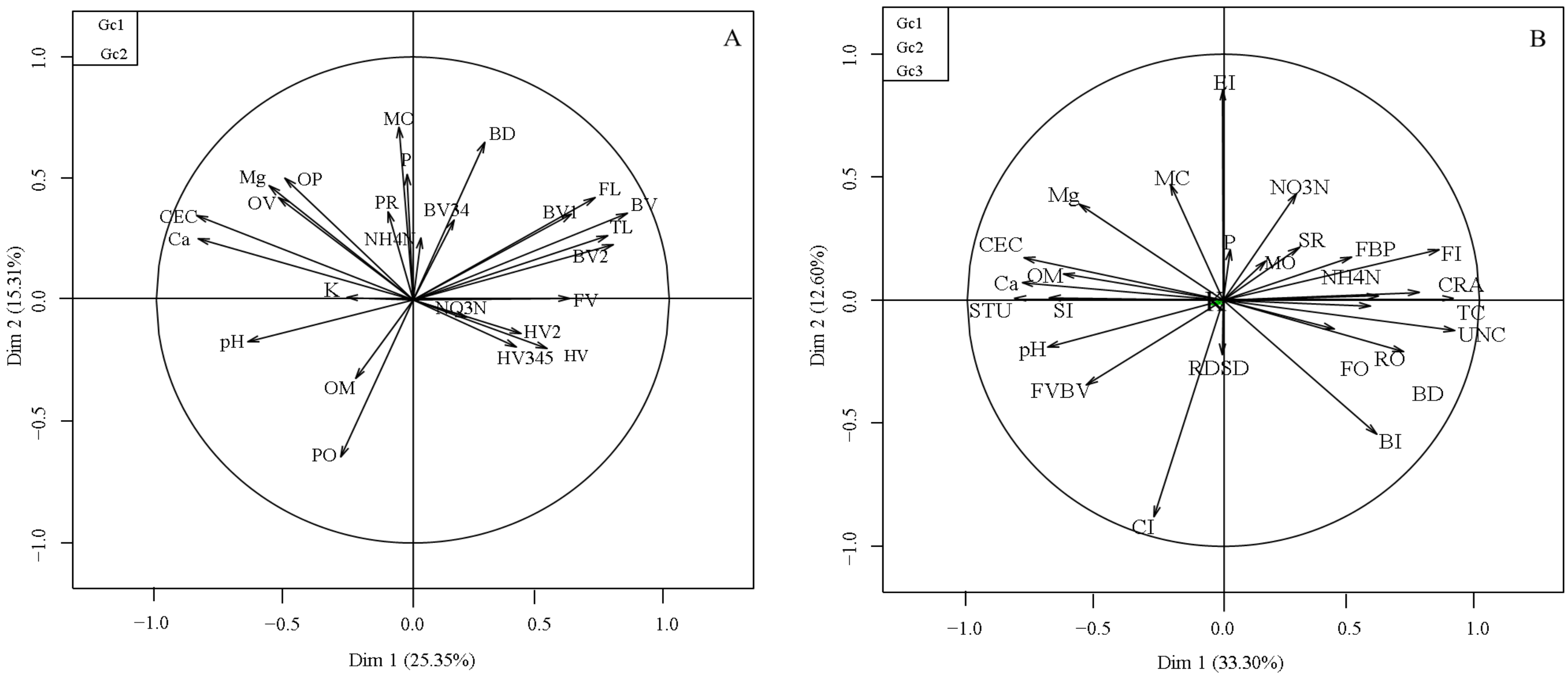


Figure 3.3. Multiple factor analysis of the variables where Dimension 1 (Dim 1) and Dimension 2 (Dim 2) represent the first and second best summary of variability of the information, respectively. (A) The relationships between abundance of nematode trophic groups (Gc) (bacterivores (BV), fungivores (FV), omnivores (OV), predators (PR), sum of omnivores and predators (OP), herbivores (HV) (Yeats et al., 1993)) and non-herbivore (FL) and total (TL) nematodes, and nematode guilds c-p 1 bacterivores (BV1), c-p 2 bacterivores (BV2), sum of c-p 3 and c-p 4 (BV34), c-p 2 herbivores (HV2) and sum of c-p 3 to c-p 5 herbivores (HV345) (Bongers, 1990; Bongers and Bongers, 1998) and soil properties (Gc2) (soil pH (pH) , organic matter percentage (OM), nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N),calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), moisture percent (MO), bulk density (BD), cation exchange capacity (CEC) and porosity (PO). (B) The relationship among soil food web indices and trophic group ratios (Gc1) ((FV/BV)=FV) and ((FV + BV)/HV=FBP), soil physicochemical properties (Gc2) and carrot yield and quality (Gc3) (stunt (STU), forks (FO), rots (RO), cracks (CRA), marketable (MC), total unmarketable carrots (UNC) and root dry-to-shoot dry weight ratio (RDSD)) from treatments with plant (PC) and animal (AC) compost, standard urea (UR) and non-amended check (CK) in Cupar plots in 2012 and 2013 growing seasons.

In Sugarsnax 54 (Fig. 3.4A), c-p 1 bacterivores, c-p 2 bacterivores, bacterivores, fungivores, c-p herbivores, herbivores, non-herbivores and total nematodes were positively correlated with Dimension 1. Calcium, magnesium, cation exchange capacity and soil pH were positively correlated with Dimension 2. Among the soil variables, bulk density and NH_4-N were positively correlated to each other but negatively correlated with porosity, organic matter, nitrate-nitrogen, c-p 2 bacterivores, and sum of c-p 3 to c-p 5 herbivores. As illustrated in Fig. 3.4B, fertility index, bulk density, ammonium-nitrogen, unmarketable carrots and soil moisture content were negatively correlated while marketable carrots, organic matter, and stunt and rotten carrots were positively correlated with Dimension 1. Calcium, cation exchange capacity and CI were positively correlated with Dimension 2. Soil moisture content, unmarketable carrots, bulk density, ammonium-nitrogen and fertility index were positively correlated to each other, but negatively correlated with rotting, stunting and marketable carrots, and organic matter. Magnesium, BI and CI were positively correlated to each other but negatively correlated to EI, soil respiration and SI. Soil pH and cracked carrots were positively correlated to each other, but negatively correlated with forked carrots.

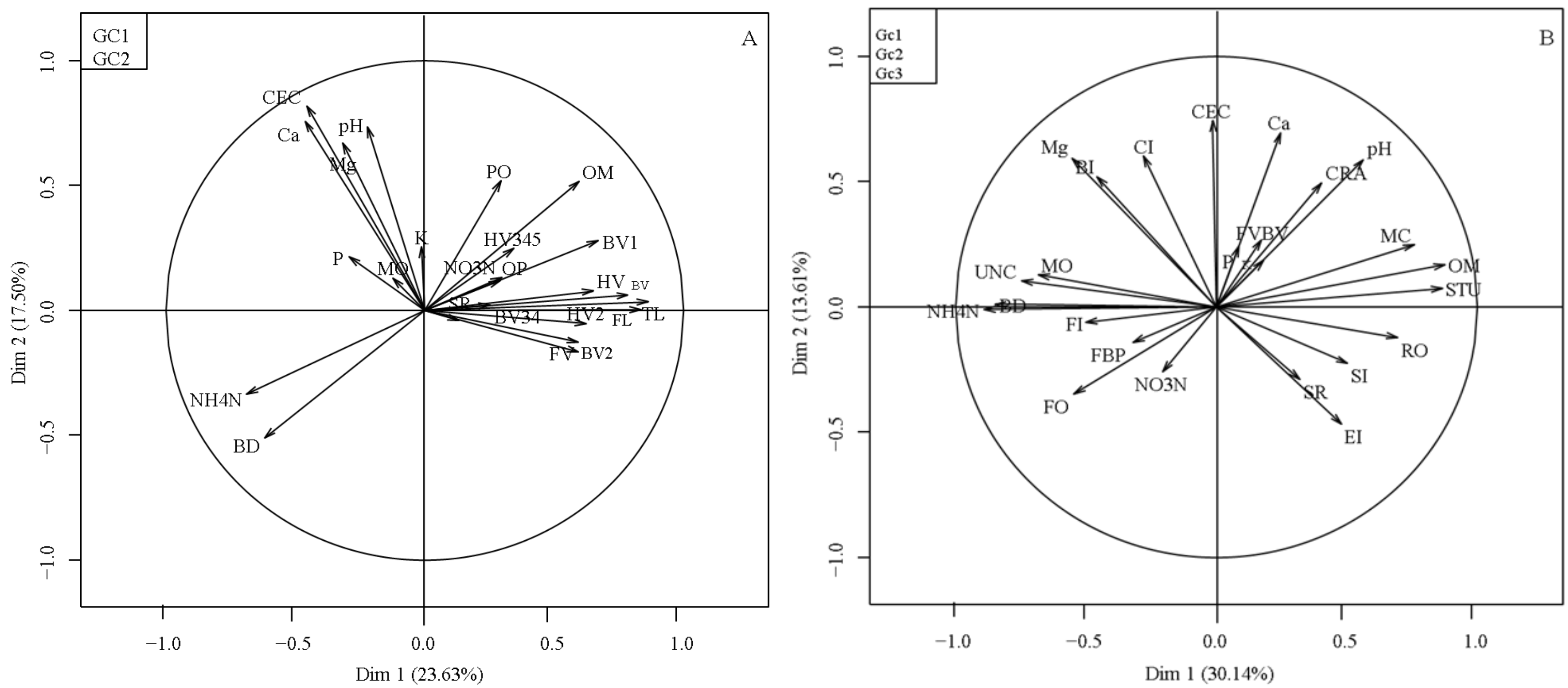


Figure 3.4. Multiple factor analysis of the variables where Dimension 1 (Dim 1) and Dimension 2 (Dim 2) represent the first and second best summary of variability of the information, respectively. (A) The relationships between abundance of nematode trophic groups (Gc1)(bacterivores (BV), fungivores (FV), omnivores (OV), predators (PR), sum of omnivores and predators (OP), herbivores (HV) (Yeats et al., 1993)) and non-herbivore (FL) and total (TL) nematodes, and nematode guilds c-p 1 bacterivores (BV1), c-p 2 bacterivores (BV2), sum of c-p 3 and c-p 4 (BV34), c-p 2 herbivores (HV2) and sum of c-p 3 to c-p 5 herbivores (HV345) (Bongers, 1990; Bongers and Bongers, 1998) and soil properties (Gc2) (soil pH (pH) , organic matter percentage (OM), nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N),calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), moisture percent (MO), bulk density (BD), cation exchange capacity (CEC) and porosity (PO). (B) The relationship among soil food web indices and trophic group ratios (Gc1)((FV/BV)=FV) and ((FV + BV)/HV=FBP), soil physicochemical properties (Gc2) and carrot yield and quality (Gc3)(stunt (STU), forks (FO), rots (RO), cracks (CRA), marketable (MC), total unmarketable carrots (UNC) and root dry-to-shoot dry weight ratio (RDSD)) from treatments with plant (PC) and animal (AC) compost, standard urea (UR) and non-amended check (CK) in Sugarsnax 54 plots in 2012 and 2014 growing seasons.

Discussion

The outcomes of this study were partially in line with the hypothesis that compost amendment treatments increased omnivores compared with urea and non-amended check at the end of the growing seasons. As expected, higher compost rates significantly increased omnivores compared with lower rates of PC and AC at 133 DAP in 2013. However, compost type had no effect on omnivores. The more structured soil food web condition compared with 50 % in compost amendments shows the positive effect of compost (Fig. 3.1). Supporting the hypothesis, AC amendment treatments increased soil chemical proprieties as AC contained greater concentration of nutrients such as phosphorus and soil respiration. PC at 168 kg N/ha and AC at 112 kg N/ha produced yield as high as the urea in 2012, but most of compost treatments decreased marketable carrot yield. In contrast to this, Sugarsnax 54 marketable carrot yield was higher in all compost amendment treatments than in urea and non-amended check in 2013.

Number of omnivores was significantly different at the end of the growing seasons among the treatments in both cultivars. Their increase in abundance showed that reduced soil disturbance level (Bongers, 1990; Bongers and Bongers, 1998). This is consistent with other studies (Nahar et al., 2006; Lie et al., 2010), where compost amendment increased omnivores over time. Similar trend was observed in both cultivars, but the trends in Sugarsnax 54 were not as strong as those in Cupar. This could be due to the short growing season (79 DAP) as omnivores nematodes normally require 95 to 130 days to complete a life cycle (McSorley, 2012). Throughout this study, omnivores nematodes were low in urea plots perhaps due to the toxic effect of nitrogenous compounds (e.g. NH_3) that urea is known to release (Nahar et al., 2006; Ferris, 2010; Ferris et al., 2012). Increase in omnivores can be explained by either compost favoring omnivores or lack of toxicity associated with mineral fertilizer application (Fiscus and Neher, 2002; Ferris et al., 2012).

There was no significant difference in bacterivores, fungivores, predators and herbivores trophic groups, and non-herbivores and total nematode abundance through time in both cultivars. However, significant treatment effects were observed on bacterivores, fungivores, non-herbivores and total nematodes in Cupar, but with no clear difference among compost amendments and the controls. Exceptions were that AC at 270 kg N/ha showed significant increase in bacterivores compared with non-amended check, and PC at 203 kg N/ha and AC at 270 kg N/ha significantly increased non-herbivores nematodes compared with urea and non-amended check. Consistent with the present results, Ferris et al. (2012) reported that compost amendment alone did not increase c-p 1 and c-p 2 nematodes. In contrast, addition of compost with low C:N ratio (< 20:1) at least temporarily increased bacterivores (Bulluck III et al., 2002a; Ferris and Matute, 2003; Briar et al., 2011). Lack of significant increase in bacterivores and fungivores following compost addition in this study could have been due to inadequate sampling intervals to detect possible short term peaks in nematode abundance with short generation time. Bacterivore generation time is usually around ten days (Sánchez-Moreno et al., 2011). Another possibility could be that soil factors such as soil pH suppressed bacterivores and fungivores directly or indirectly suppressing their microbial food base. The negative correlation between some of the soil physicochemical properties and nematode trophic groups supported the later explanation (Fig. 3.3A). The increase in non-herbivore nematodes in PC at 168 and AC 270 kg N/ha can be explained by the relatively higher number of bacterivores and fungivores in those treatments. Low abundance of bacterivores and fungivores may reflect diminished potential of nutrient mineralization (Ferris et al., 2001; Ferris et al., 2004).

In this study, there was no significant effect of treatments on HV. Organic amendments may release chemicals detrimental to herbivores (Akhatar and Malik, 2000; Zasada et al., 2008; Lie et al., 2010; Renčo et al., 2011). Similarly, Melakeberhan et al. (2007) and Mennan and Melakeberhan, (2010) found that application of recycled municipal biosolid had suppressive effect on *Meloidogyne hapla*. Differential effect of compost that favored the abundance of c-p 2 herbivores, especially *Tylenchus* and *Filenchus*, while suppressing c-p 3 plant-parasitic nematode *Pratylenchus spp*. was reported previously (Briar et al., 2011). Other field and glasshouse experiments have also revealed that the effect of compost is dependent on the species of herbivores, amendment type and/or other environmental factors (McSorley & Gallaher, 1997; Kimpinski et al., 2003; Renčo et al., 2011). To my knowledge, there are only a few studies available to explain the impact of soil mineral contents (e.g. calcium, magnesium, potassium) on herbivores. Soil calcium and magnesium content had negative correlation with soybean cyst nematode (Avendaño et al., 2004) and the impact of mineral fertilizer applications on herbivore nematode suppression highlighted elsewhere (Coyne et al., 2004). Hence, multiple factor analysis result suggests that the inconsistent effects of both compost and inorganic fertilizer applications on nematode trophic groups could be due to variations in soil conditions in previous studies.

SI was greater than 50 % in compost amended plots compared with urea at the end the growing seasons in 2013 and in 2014. There was no significant differential effect of compost types and rates of applications on SI in this study. All of the treatments increased SI over time. Similarly, there was also no significant effect of compost amendments, compost types and rate of applications on EI, BI and CI.

Soil nematode faunal profile showed that compost amendments improved soil food web structure over time and led to a balanced bacterial-fungal decomposition channel (Quadrant B) at the end of 2013-2014 growing seasons (Fig.3.1). However, the same trend was observed for the urea and untreated controls. The significant increase of SI from 50 % in compost amendments in the nematode faunal profile of the present study suggests that compost amendments improved soil food web structure with greater trophic links. A high degree of connectivity reflects a result ofant functional redundancy in the regulatory process and functional resilience to perturbation (Ferris et al., 2012).

The results of the present study showed that the higher rates of AC (AC at 168 and 224 kg N/ha) increased soil respiration compared with all of the other treatments at 79 DAP in 2013 growing season and at 0 and 78 DAP in 2012, and 0 DAP in 2013 in Sugarsnax 54 (Table 3.7). This suggests increased soil biological activity. In related studies, organic soil amendment increased rate of soil respiration compared with non-amended controls (Gunapala et al., 1998; Treonis et al., 2010). However, increased soil respiration was observed in treatments containing compost blended with wheat straw, but not from treatments with inorganic fertilizer and compost alone (Ferris and Matute, 2003). Improved soil respiration observed here might be attributed to increased labile organic matter associated to AC (Table 3.1).

Higher phosphorus and potassium in AC than in PC, urea and non-amended check treatments is likely to be due high contents of these elements in the AC source (Table 3.1). Contrary to expectation, compost rate had no detectable impact on soil moisture content and bulk density (Nahar et al., 2006). Compost amendments increased soil pH compared with urea in 2013 growing season. Similarly, all AC treatments and PC at 168 kg N/ha increased organic matter compared with urea and non-amended check after two years in Sugarsnax 54 plots while urea increased NO_3-N compared with all compost amendments and non-amended check in both cultivars (Tables 3.8 and 3.9). Other studies have shown that addition of compost increased soil organic matter and soil nutrients compared with synthetic fertilizers (Bulluck III et al., 2002b; Briar et al., 2007). In contrast, Nahar et al. (2006) reported that compost amendment did not increase organic matter compared with non-amended check after two years. Continuous annual applications of compost are required to cause significant improvement in soil properties (Shiralipour et al., 1992). Thus, it is not surprising that these changes were not observed in all compost treatments in my study.

Urea increased end-of-season soil NO_3-N and reduced soil pH compared with compost amendments and non-amended check in both cultivars. Consistent with these findings, Briar et al. (2007) found higher soil NO_3-N in conventional system receiving chemical fertilizers. Urea hydrolysis and subsequent nitrification result in release of hydrogen ion (H^+) may lead to decline in soil pH in urea plots. Previous studies have shown that urea decreased while compost amendment increased soil pH (Bulluck III et al., 2002b; Li et al., 2010). Compost additions raised the pH of acid soils by forming aluminum complex and increasing base saturation (Shiralipour et al., 1992; Van den Berghe and Hue, 1999). Decline in soil pH induced by synthetic fertilizer application is known to reduce soil biodiversity and promote some pathogens, reduce yield and affect overall soil health (Singh et al., 2013). Although urea decreased soil pH compared with the compost treatments, which supports the established adverse effects of urea on soil environments, the soil pH in my experimental field was above optimum for carrots (Swiader and Ware, 2002).

The expectation was that compost treatments would have greater quality of carrots compared with urea and non-amended check treatments because of the positive effect of compost amendments on nutrient availability, physical properties, and pest suppression (Abawi and Widmer, 2000; Akhtar and Malik, 2000). In the present study, there was no difference in total yield and carrot quality among compost amendments, urea and non-amended check in Cupar in all years (Fig. 3.2). However, all compost treatments other than PC at 168 kg N/ha and AC at 112 kg N/ha had lower marketable yield compared with the urea control in 2012 growing season in Sugarsnax 54. In contrast to this, urea and non-amended check was significantly low in marketable and total carrots in 2013. Lower yield in 2012 in some compost treatments may have been due to lower available N relative to the urea control (Table 3.8). However, more frequent soil N sampling would have been required to test this hypothesis. In contrast, higher yields in compost amended plots compared to urea controls in 2013 were unlikely due to higher levels of N, and more likely due to either changes in other chemical characteristics (higher pH or higher K), improvements in (undetected) soil physical properties, or reductions in pest abundance. With respect to herbivore nematodes, their abundance was low (less than 20 individuals/ 100 cc of soil, Table 3.4) and there was no significant difference in their abundance among compost treatments and urea. Apart from their low abundance, the herbivore nematodes population was dominated by root hair feeders that can cause less carrot damage. Hence, the difference observed in carrot yield is unlikely due to herbivore nematodes.

Although short-term yield increases associated with chemical content of nutrients can be dramatic when compared to unfertilized controls, detection of yield increases due to physical properties in fields amended with compost usually requires three to five years of continuous application (Parr et al., 1992; Pimentel et al., 2005; Herencia et al., 2008; Diacono and Montemurro, 2010). Compost treatments increased total carrot yield and decreased unmarketable carrots (e.g. forking, stunting) and some of the weed species compared to non-composted fields in Michigan, USA (Brainard and Noyes, 2012). Besides, compost's positive impact on yield, lower negative environmental impact and better soil biological health and activity (Bulluck III et al., 2002b, Briar et al., 2007; Briar et al., 2011) may enhance the importance of compost amendment as a soil health management practice in agroecosystems.

Results from multiple factor analysis revealed some key correlations between soil food web indices and carrot yield and quality. SI was positively correlated with soil pH, organic matter, calcium, cation exchange capacity while negatively correlated with almost all of the unmarketable carrot parameters (e.g., rotting, forking and cracking), bulk density and fertility index in Cupar plots (Fig. 3.3B). High soil organic matter improves microbial activity, increase nutrient reserves and soil aggregates and water holding capacity (Pimentel et al., 2005; Forge and Kempler, 2009). This leads to improved carrot yield and quality. Similarly, cation exchange capacity improves nutrient retention capacity of soil, enabling a more steady release of nutrients which improve plant growth. Knight et al. (2013) reported that soil parameters such as clay and soil organic matter as soil heath indicators and lettuce productivity though SI was not correlated with these parameters.

In Sugarsnax 54, SI was positively correlated with soil respiration (indicator of soil biological activity level) and EI (a measure of nutrient availability), and negatively correlated with BI (indicators of stressed soil condition) and CI (slow decomposition pathway). SI increase is linked to improved soil biological activities and nutrient availability while SI decrease is linked to stressed soil conditions and slow mineralization process (Fig. 3.4B; Ferris et al. 2001; Ferris and Matute, 2003). EI was negatively correlated with CI in Cupar plots, and positively correlated with SI, soil respiration, but negatively correlated with BI and CI in Sugarsnax 54. Berkelmans et al. (2003) suggested that SI and BI may be more suitable as general indicators for the soil health status. High BI would indicate poor ecosystem health while a high SI would indicate a well-regulated, healthy ecosystem. In a related study, EI was proposed to be used as an indicator of soil heath and plant productivity because of its predictive value of high nutrient availability to plants (Knight et al., 2013).

In conclusion, this research provided an opportunity to compare the effect of compost amendments on nematode community structure, soil food web, soil physicochemical and biological properties, and carrot yield and quality. The analyses indicated that compost amendments increased soil food web structure compared with 50 % over time. Moreover, higher rate of AC improve soil biological activities. Compost treatment generally increased soil mineral contents and soil pH which could have positive impact on soil fertility. In the contrary, urea decreased soil pH and increase NO_3-N. Multiple factor result revealed the importance of soil food web indices in describing soil health status and carrot yield and quality, suggesting SI, EI, BI and CI in combination can be used to describe the soil health conditions under different management practices. Overall, the results partially support the tested hypothesis and suggest that the compost based improvements in soil food web structure may lead to increases in ecosystem services provided by the soil food web.

CHAPTER 4

EFFECTS OF INTEGRATED APPLICATION OF PLANT-BASED COMPOST AND UREA ON SOIL FOOD WEB, SOIL PROPERTIES, AND YIELD AND QUALITY OF A PROCESSING CARROT CULTIVAR

Abstract

A hypothesis that lower rates of urea mixed with with higher rates of PC would improve nematode community structure, enhance EI and SI, improve soil biological and physicochemical properties, and increase carrot yield and quality was tested during the 2012-2014 growing seasons. Urea and PC were each applied at 135 kg N/ha alone or at 3:1, 1:1 and 1:3 ratios. A non-amended check served as a control. Nematode community was analyzed from soil samples collected five times at approximately 4-week intervals from planting to 133 days after planting. Soil respiration, as a measure of soil biological activity, and soil physicochemical properties were determined from soils collected at planting and at harvest in 2012 and 2013. Results showed that urea decreased Shannon-Weaver diversity index in 2014 (2.2 to 1.7) compared with 2012, but such difference was not observed in 2013. Overall, treatments with urea alone, urea and PC at 3:1 ratio and PC alone increased SI. However, PC alone, and urea and PC at 1:1 ratio resulted in an SI value above 50 % at harvest in 2014. Urea significantly decreased end-of-season soil pH, but increased NO_3-N compared with the other treatments. Mixtures with higher rates of PC increased soil respiration. Urea alone and mixtures with lower rate of PC decreased soil pH and phosphorus content. *Malenchus* and *Helicotylencus* abundance were negatively correlated with carrot fresh weight of most categories such as forking and cracking. Overall, results suggest that integrating lower rates of urea and higher rates of PC are likely to increase soil biological activity, pH and phosphorus content.

Introduction

Maintaining soil and water quality, and obtaining optimum crop yields are major components of sustainable agriculture (Doran, 2002; Evanylo et al., 2008). Excessive amount of inorganic fertilizers, N in particular, are applied and replenished in every growing season in order to achieve a high crop yield (Stewart et al., 2005). These fertilizers are rapidly lost and pose deleterious effects to the environment and human health (Tilman et al., 2002). The sole use of inorganic fertilizers is also causing deterioration in soil physical, chemical and biological properties (Odunze et al., 2012; Eche et al., 2013; Singh et al., 2013).

In contrast, compost amendments increase availability of nutrients, improve soil structure leading to better moisture retention and soil microbial activity and reduce fertilizer loses to the environment (Bulluck III et al., 2002a; Evanylo et al., 2008; Mylavarapu and Zinati, 2009). Such positive traits increase agricultural productivity with minimum damage to the environment (Oquist et al., 2007; Forge and Kemper, 2009; Glover et al., 2010). However, use of compost amendments alone is usually not sufficient to maintain the expected productivity level as that of synthetic fertilizers in the short-term (Pimentel et al., 2005; Herencia et al., 2008; Diacono and Montemurro, 2010). Integrated plant nutrient-management system characterized by reduced input of inorganic fertilizers integrated with organic amendments is one of the alternatives to achieve the expected yield while reducing the deleterious environmental impact of synthetic fertilizers (Oberson et al., 1996; Gunapala and Scow, 1998; Kaur et al., 2005; Pimentel et al., 2005).

Combination of readily available inorganic fertilizers can solve soil nutrient deficits while mineralization of the organic component improves soil biological and physicochemical properties, and enhance yield over time (Noor, 2007; Odunze et al., 2012; Eche et al., 2013).

Moreover, integrated application of nitrogen fertilizers with compost improved nitrogen utilization efficiency of plants (Keeling et al., 2003; Ahmad et al., 2006). Thus, integrated application of inorganic fertilizers and compost that utilizes residues at lower than fertilizers rates and reduces the amount of inorganic fertilizers applied to soil and the accumulation of non-nutrient constituents such as heavy metals is an appealing strategy (Sikora and Enkiri, 2001). Implementation of such an alternative could be best achieved if its effects on soil food web, which drives nutrient transformations and productivity, are studied.

As the most abundant organisms in the terrestrial ecosystems and occurring at multiple levels of the soil food web, nematodes are key drivers of the soil food web (Yeates et al., 1993) and provide insights of the soil conditions (Bongers and Bongers, 1998; Ferris et al., 2001). Nematodes are also considered as a powerful indictor of soil ecosystem change (Freckman and Ettema, 1993; Wasilewska, 1994; Ferris and Matute, 2003; Ferris et al., 2004; Cheng and Grewal, 2009; Knight et al., 2013). Ferris et al. (2001) developed a faunal profile analysis that relates soil nematode community to soil food web structure and function. This model uses a graphic representation of the relationship between the nematode EI (a measure of opportunistic bacterivore and fungivore nematodes) and SI (indicator of food web state affected by stress or disturbanc*e*) to describe the soil community profile in four quadrants.

While there are several studies on the impact of organic amendments and inorganic fertilizer effects on nematode community, soil fertility and plant productivity (Bulluck III et al., 2002a; Briar et al., 2007), the impact of mixed compost-fertilizer applications on soil nematodes community structure and overall soil food web health has been less studied. The objectives of this study were to compare the effects of mixed application of different levels of PC and urea on nematode community structure soil food web health, soil biological and physicochemical properties, and yield and quality of a processing carrot cultivar Cupar in a sandy loam soil. The central hypothesis of this study was that lower rates of urea mixed with higher rates of PC would improve nematode community structure, enhance EI and SI, soil biological and physicochemical properties, and increase carrot yield and quality relative to single applications of either product.

Materials and Methods

Experimental design and treatments

A field experiment was conducted at Michigan State University (MSU) Horticulture Teaching and Research Center in Holt, Michigan (N $42^{0}40.326'$, W $084^{0}28.922'$, 847 m elevated) in a Marlette fine sandy loam (fine-loamy, mixed, mesic Glossoboric Hapludalfs, Anon, 1977) during 2012-2014 growing seasons. Carrots were grown in the field and amended with composted manure in 2010 and 2011 growing seasons. The study was designed to test the effects of mixed applications of different ratios of urea and leaf compost (PC) applied at 3:1, 1:1 and 1:3 ratios, along with urea, and PC alone and non-amended check as controls (Table 4.1). The standard urea rate for a processing carrot is 135 kg N/ha. PC was obtained from MSU Student Organic Farm, Holt, MI, USA. PC levels were applied on dry matter basis and reported as average of the 2012-2014 growing seasons (Table 4.2). Standard urea (135 kg N/ha) and non-amended check were included as controls. The experiment was randomized complete block design with four replications.

Table 4.1. Integrated application of urea and plant compost (PC) at varying ratios to supply the recommended nitrogen (N) for processing carrot cultivars. Treatments are different combinations of N levels coming from urea and PC to provide the recommended nitrogen amount.

		Amount of N (kg/ha)		Actual rate (Mg/ha)	
Treatment	Ratio[a]	Urea	PC	Urea	PC
1	1:0	135	0	0.29	0
2	3:1	101	34	0.22	3
3	1:1	67.5	67.5	0.15	6
4	1:3	34	101	0.07	9
5	0:1	0	135	0	12
6	Check	0	0	0	0

[a]The portion of N source applied as urea and PC ratio to provide a total of 135 kg N/ha.

Methods pertaining to soil sampling, nematode extraction, identification and nematode community, ecosystem disturbance and soil food web indices, were described in the General Materials and Methods Section (Chapter 2). Similarly, methods used to measure soil respiration, soil physicochemical properties, and carrot yield and quality were stated in Chapter 2.

Data analysis

Nematode taxa and trophic group abundances were expressed on an absolute basis (number of nematodes in a taxon i per 100 cc of fresh soil). Nematode abundance data were transformed as ln (x+1) prior to statistical analysis to normalize variance, but untransformed arithmetic means are presented here in. Treatments were compared for nematode trophic groups, community indices, soil food web indices, trophic group ratios, fertility index, soil and yield variables. Statistical analysis was conducted using the PROC MIXED procedure of SAS. The statistical model consisted of fixed effects of amendments and time and the interaction between them and random effects of blocks and block by amendment interaction. The interaction between blocks and amendments was used as an error term to test the effect of amendments. The effect of time was addressed using the repeated measures approach with REPEATED statement of the

PROC MIXED. Aikaike information criterion was used to select the optimal variance-covariance structure for the repeated measures analysis.

Two types of statistical analysis were conducted for SI. First, the SI values were compared following a standard ANOVA and mean separations (Table 4.6). Second, SI values were plotted to the food web model (Fig. 4.1). Then, SI values were tested for statistical difference from 50 % (cut off point of the soil food web structure) using one-tail t-test at α = 0.05. The means of the treatments with statistical difference from 50 % are noted by asterisks (*).

Table 4.2. Average soil pH, macro (%) and micro nutrients (ppm) of plant compost (PC) and rates at which they were applied (kg/ha) in sandy loam soil and planted with a processing carrot cultivar "Cupar" in 2012-2014 growing seasons.

pH and nutrients	Content	Rate (kg/ha)
pH	7.8	na[a]
Macronutrients (%)		
Nitrogen	1.1	135
Phosphorus	0.1	12
Potassium	0.3	36
Calcium	3.8	457
Magnesium	0.8	96
Sodium	0.02	2
Sulfur	0.2	24
OM [b]	25.2	3005
Carbon	14.6	1755
C:N[c]	13.3	na
Micronutrients (ppm)		
Iron	5248.1	60
Zinc	77.6	1
Manganese	324.2	4
Copper	28.8	0.4
Boron	27.3	0.4
Aluminum	2663.2	36

[a]Rates was not available because pH and C/N ratio cannot be expressed as a rate of application.
[b]Percent of organic matter.
[c]Carbon-to-nitrogen ratio.

Treatments were compared for yield parameters using one-way analysis of variance (PROC MIXED, SAS ver 9.3, SAS Institute, 2012, Cary, NC, USA). The statistical model consisted of fixed effect of amendments and a random effect of block and block by amendment. The interaction between blocks and amendments was used as an error term to test the effect of amendments. First, the data was analyzed by the interaction of treatment and sampling time. When the effect of the interaction was not significant, the data were analyzed by the interaction of treatment and year, and presented. Interactive effects of amendment and time are presented in results only when significant. Otherwise, I have presented only significant interaction effects of treatment and year and main effects of treatment. The probability level $P \leq 0.05$ was regarded as significant.

Results

Composition and abundance of nematode trophic groups

A total of 51 nematode genera were identified in the plots throughout the study period (Table 4.3). The number of genera identified as herbivores, bacterivores, fungivores, omnivores and predators were 17, 16, 6, 7 and 5, respectively. On average, 23, 27, 21, 1.4 and 0.4 per 100 cc of soil individuals of herbivore, bacterivore, fungivore, omnivore and predator trophic groups, respectively, were obtained in the three-year period. Among herbivore nematodes, *Malenchus, Pratylenchus, Helicotylenchus* and *Tylenchus* were the most abundant genera and represented 11, 11, 24 and 36 %, respectively. *Mesorhabditis, Microlaimus*, *Acrobeloides* and *Rhabditis* represented 10, 10, 21 and 22 % of the bacterivores, respectively. *Filenchus and Aphelenchus* represented 33 and 46 % of fungivores, respectively. The abundances of omnivores and predators were generally low representing less than 3 % of the total nematode community.

Table 4.3. List of nematode genera detected in plots amended with integrated application of urea and PC at different levels to supply 135 kg N/ha recommended for processing carrot varieties, standard urea, and non-amended check plots in sandy loam soil in 2012-2014 growing seasons. Numbers within brackets represent c-p values following Bongers and Bongers (1998).

Herbivores	Bacterivores	Fungivores	Omnivores	Predators
Basiria (2)	*Eumonhystera (1)*	*Aphelenchoides (2)*	*Eudorylaimus (4)*	*Tripyla (3)*
Boleodorus (2)	*Mesorhabditis (1)*	*Aphelenchus (2)*	*Mesodorylaimus (4)*	*Clarkus (4)*
Cephalenchus (2)	*Panagrellus (1)*	*Ditylenchus (2)*	*Microdorylaimus (4)*	*Mylonchulus (4)*
Malenchus (2)	*Panagrolaimus (1)*	*Filenchus (2)*	*Pungentus (4)*	*Prionchulus (4)*
Paratylenchus (2)	*Pellioditis (1)*	*Diphtherophora (3)*	*Thonus (4)*	*Nygolaimus (5)*
Psilenchus (2)	*Pristionchus (1)*	*Tylencholaimellus (4)*	*Aporcelaimellus (5)*	
Tylenchus (2)	*Rhabditis (1)*		*Prodorylaimus (5)*	
Dolichorynchus (3)	*Acrobeloides (2)*			
Helicotylenchus (3)	*Cephalobus (2)*			
Hemicycliophora (3)	*Cervidellus (2)*			
Heterodera (J2) (3)	*Eucephalobus (2)*			
Pratylenchus (3)	*Heterocephalobus (2)*			
Rotylenchus (3)	*Plectus (2)*			
Tylenchorhynchus (3)	*Microlaimus (3)*			
Trichodorus(4)	*Prismatolaimus (3)*			
Longidorus (5)	*Alaimus (4)*			
Xiphinema (5)				

Nematode trophic group abundance was not affected by the interaction of treatment and time, and treatment, but significantly affected by time (Table 4.4). However, herbivores, bacterivores and predators were significantly affected by interaction effect of treatment and year (Table 4.5). All of the treatments, except urea and PC at 1:3 ratio, significantly increased herbivores in 2014 compared with 2012. However, it should be noted that the lack of increase in herbivores in urea and PC at 1:3 treatment was associated with higher initial abundance of herbivore nematodes in that treatment, rather than lower final herbivore abundance. All of the treatments, except urea alone application, significantly decreased bacterivores in 2014 compared with 2012. Urea significantly increased predator nematodes compared with the rest of the treatments in 2012 while PC alone significantly increased them compared with the rest of the treatments in 2013. Urea alone, and urea and PC at 3:1 ratio significantly increased predators compared with urea and PC at 1:1 ratio and non-amended check treatments in 2014. All of the treatments, except urea, significantly decreased non-herbivores nematodes in 2013 than 2012. Only urea and PC at 1:1 ratio significantly decreased non-herbivores in 2014 than in 2012. However, there was no significant difference in abundance of non-herbivores among the treatments between 2013 and 2014. Urea and PC at 1:3 ratio significantly decreased total nematode abundance in 2013 compared with 2012.

Table 4.4. Probability values (Pr > F) of treatment (TR), time (T), and interaction of treatment and time (TR*T) effects for nematode trophic group abundances, non-herbivore and total nematodes, nematode community and soil food web indices, trophic group ratios, soil respiration and soil physicochemical properties for field plots amended with integrated application of urea and PC at different levels to supply 135 kg N/ha and standard urea application and non-amended check in sandy loam soil in 2012-2014.

Variables	Probability >F		
	TR	T	TR*T
Trophic groups			
Herbivores	0.95	<0.0001	0.60
Bacterivores	0.95	<0.0001	0.67
Fungivores	0.93	<0.0001	0.77
Omnivores	0.86	<0.0001	0.35
Predators	0.48	<0.0001	0.82
Non-herbivores	0.98	<0.0001	0.62
Total nematodes	0.97	<0.0001	0.89
Diversity indices			
H'[a]	0.99	<0.0001	0.2
Hill's N1	0.97	<0.0001	0.29
Hill's N0	0.99	<0.0001	0.44
Ecological disturbance indices			
PPI	0.91	<0.0001	0.43
MI	0.67	<0.0001	0.48
MI25	0.13	<0.0001	0.64
FI[b]	0.91	<0.0001	0.15
Food web indices			
FI	0.63	0.0012	0.49
SI	0.041	<0.0001	0.48
BI	0.623	<0.0001	0.61
CI	0.94	<0.0001	0.48
Trophic group ratios			
FV/BV[c]	0.86	<0.0001	0.64
(FV+BV)/HV[d]	0.85	<0.0001	0.03
Soil respiration	0.02	<0.0001	0.53

Table 4.4 (Cont'd)

Variables	Probability >F		
	TR	T	TR*T
Soil physicochemical properties			
Bulk density	0.45	<0.0001	0.98
Porosity	0.26	<0.0001	0.98
Moisture	0.28	<0.0001	0.73
Soil pH	0.18	<0.0001	0.01
Phosphorus	0.02	0.005	0.74
Potassium	0.69	<0.0001	0.42
Calcium	0.48	<0.0001	0.03
Magnesium	0.74	<0.0001	0.55
Organic matter	0.23	<0.0001	0.54
Nitrate-nitrogen	0.02	<0.0001	<0.0001
Ammonium-nitrogen	0.43	<0.0001	0.99
Cation exchange capacity	0.62	<0.0001	0.55

[a]Shannon-Weaver diversity index (Shannon and Weaver, 1949).
[b]Fertility index (PPI/MI) (Bongers et al., 1997).
[c]Fungivores-to-bacterivores ratio (Freckman and Ettema, 1993).
[d]Decomposers-to-herbivores ratio (Wasilewska, 1994).

Table 4.5. Interaction effects of different levels of urea and PC combined to supply 135 kg N/ha, standard urea and growing seasons (2012, 2013 and 2014) on the abundance of nematode trophic groups (herbivores, bacterivores, fungivores, omnivores and predators) per 100 cc soils. Treatments show the proportion of nitrogen coming from urea and PC to supply 135 kg N/ha recommended for Cupar.

TR[a]	Herbivores			Bacterivores			Fungivores		
	2012	2013	2014	2012	2013	2014	2012	2013	2014
1:0	11 aB[b]	15 aB	43 aA	41 aA	17 aB	21 aAB	31 aA	13 aA	16 aA
3:1	10 aB	15 aB	32 aA	45 aA	12 aB	19 aB	37 aA	14 aA	13 aA
1:1	17 aB	24 aAB	32 aA	47 aA	14 aB	17 aB	36 aA	15 aA	16 aA
1:3	18 aA	15 aA	32 aA	45 aA	17 aB	29 aB	40 aA	13 aB	14 aAB
0:1	13 aB	17 aAB	42 aA	41 aA	16 aB	19 aB	36 aA	14 aA	16 aA
Check	9 aB	22 aB	39 aA	49 aA	17 aB	17 aB	32 aA	12 aA	15 aA

Table 4.5 (Cont'd)

TR[a]	Omnivores			Predators		
	2012	2013	2014	2012	2013	2014
1:0	1 aA	1 aA	1 aA	1 aA	0 bB	1 aA
3:1	1 aA	1 aA	1 aA	0 bB	0.1 bB	1 aA
1:1	1 aA	1 aA	2 aA	0.1 bA	0.3 bA	0.5 bA
1:3	1 aA	1 aA	2 aA	0.2 bB	0.3 bB	0.8 abA
0:1	2 aA	1 aA	2 aA	0.3 bB	0.6 aA	0.9 abA
Check	1 aA	1 aA	3 aA	0.2 bA	0.5 bA	0.6 bA

[a]Treatments that showed the portion of N source applied as urea and PC ratio to provide a total of 135 kg N/ha.
[b]Means with different lower case letters within columns and different upper case letters across rows within trophic groups indicate the significant difference at $P \leq 0.05$ using Fisher's LSD.

Nematode community indices

Nematode maturity (MI, MI25 and PPI) and diversity (H', Hill's N0 and N1) indices were not affected by the interaction of treatment and time or by treatment effect, but they were affected by time (Table 4.4). MI, MI25 and H' were significantly affected by the interaction of treatment and year. MI was significantly higher in non-amended check, and urea and PC at 1:1 ratio in 2014 compared with 2012. However, all of the treatments significantly increased MI25 in 2014 compared with 2012. There was no significant difference in PPI and fertility index among the treatments in all years. Urea significantly decreased H' in 2014 (2.2 to 1.7) compared with 2012, but no significant difference was observed among the treatments in Hill's N0 and N1 indices.

Soil food web condition, trophic ratios and fertility index

Soil food web indices (BI, EI, SI and CI) and fertility index were not affected by the interaction of treatment and time, but sum of fungivores and bacterivores-to-herbivores ratio were affected. All of the soil food web indices except SI, the trophic group ratios and fertility index were not affected by treatment. However, all the soil food web indices, trophic ratios and fertility index were affected by time (Table 4.4). All of the treatments significantly decreased fungivores + bacterivores-to-herbivores ratio over time. Overall, urea, urea and PC at 3:1 ratio, and PC significantly increased SI compared with urea and PC 1:1 and 1:3 ratios, and non-amendd check. Urea and PC at 1:3 ratio significantly decreased SI compared with all of the treatments (Table 4.6). EI and SI were significantly affected by the interaction of treatment and year, but such effect was not observed in BI and CI. Urea and PC at 1:3 ratio significantly increased EI in 2014 compared with 2012 and 2013. Urea and PC at 1:3 ratio also significantly increased EI compared with non-amended check in 2014. All of the treatments significantly increased SI in 2014 compared with 2012.

Table 4.6. Means across all sampling time points of the enrichment index (EI), structure index (SI), basal index (BI) and channel index (CI) at the studied treatments across 2012, 2013 and 2014 growing seasons.

Treatments[a]	EI	SI	BI	CI
1:0	70 a[b]	41 a	24 a	28 a
3:1	70 a	39 a	24 a	30 a
1:1	67 a	37 b	27 a	34 a
1:3	68 a	31 c	27 a	30 a
0:1	66 a	41 a	27 a	37 a
Check	68 a	37 b	25 a	28 a

[a]Treatments that showed the portion of N source applied as urea and PC ratio to provide a total of 135 kg N/ha.
[b]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$ using Fisher's LSD.

The results of soil food web analysis from samples collected at planting and at harvest are presented in (Fig. 4.1). Except urea in 2013, all of the treatments resulted in data falling in Quadrant A (poorly structured soil food webs) at planting in all years. Similarly, all of the treatments resulted in data falling in Quadrant A at harvest in 2013. At harvest in 2013, urea and

PC resulted in data falling in Quadrant B, enriched and maturing food web. All of the treatments had maturing and enriched food webs at harvest in 2014, but only PC alone, and urea and PC at 1:1 ratio showed greater than 50 % food web structure (Fig. 4.1).

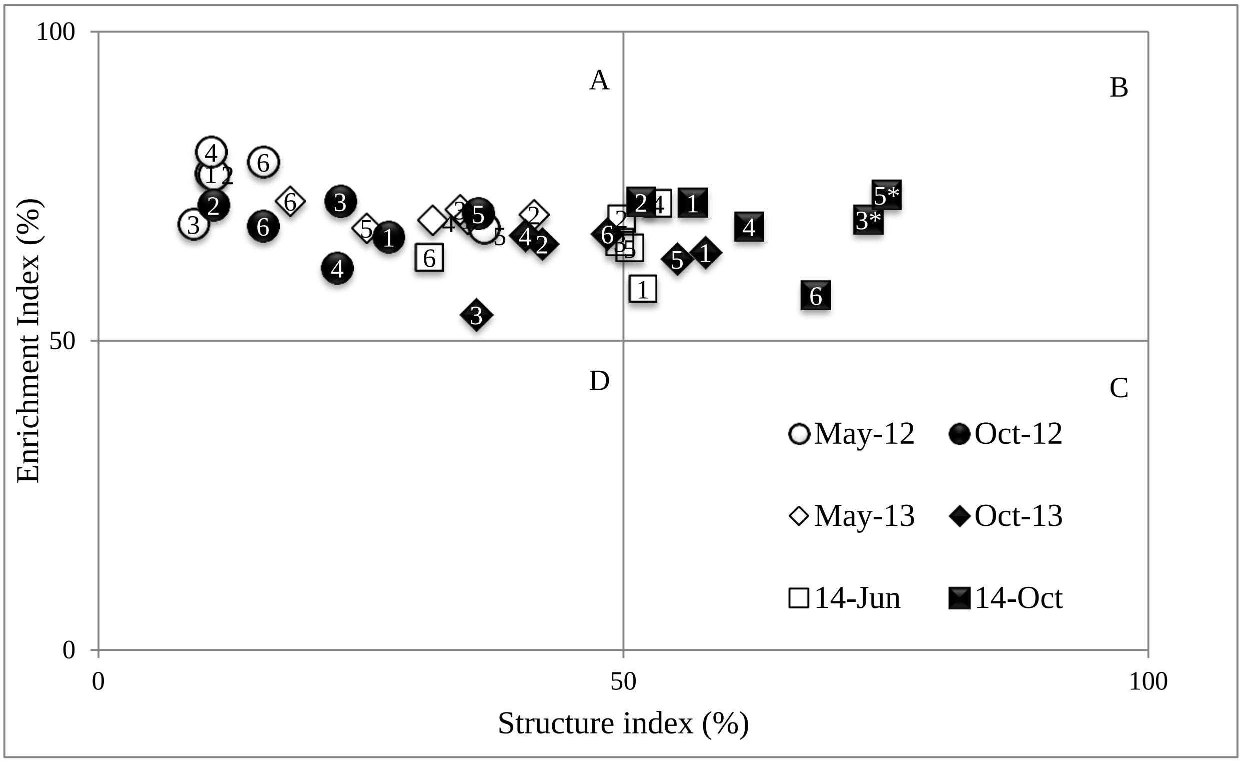


Figure 4.1. Soil food web condition in plots amended with integrated application of urea and PC, standard urea and non-amended check in sandy loam soil at planting (May, June) and harvest (October) in 2012 -2014 growing seasons. Numbers 1-6 represent treatments: 1= Urea alone, 2= 3:1 ratio of urea and PC, 3= 1:1 ratio of urea and PC, 4= 1:3 ratio of urea and PC, 5= PC alone and 6= non-amended check.

*Treatments significantly increased SI from 50 % using one-tail t-test at $\alpha = 0.05$ for 2014 growing season.

Physicochemical properties and soil respiration

Soil pH, calcium and NO_3-N were significantly affected by the interaction of treatment and time while soil respiration and other soil physicochemical properties were not affected

(Tables 4.4 and 4.7). Soil respiration and NO_3-N was significantly affected by treatment while soil respiration and all of the soil physicochemical properties were affected by time.

Table 4.7. Soil pH, nitrate-nitrogen (NO_3-N) and calcium (Ca) contents (ppm) in plots amended with integrated application of urea and PC to supply 135 kg N/ha recommended for Cupar, standard urea application and non-amended check in sandy loam soil at planting (0) and at 132 and 133 days after planting (DAP) in 2012-2013 growing seasons.

			Treatments as a ratio of urea and PC					
Variables	YR	DAP	1:0[a]	3:1	1:1	1:3	0:1	Check
pH	2012	0	6.8 bB[b]	6.8 bB	7.2 bA	7.0 bAB	7.2 bA	7.2 cA
		132	6.4 cB	6.8 bAB	7.4 abA	7.2 bA	7.3 bA	7.3 abcA
	2013	0	6.9 bA	7.0 abA	7.4 abA	7.2 bA	7.3 bA	7.4 bA
		132	6.7 bB	7.1aAB	7.5 aA	7.4 aA	7.6 aA	7.5 abA
NO_3-N	2012	0	1.4 dAB	0.6 cB	0.8 cAB	0.5 cB	0.7 cB	1.5 cA
		132	29.2 aA	2.9 bB	3.0 bB	3.7 abB	4.6 bB	3.0 bB
	2013	0	5.3 cA	5.4 aA	6.0 aA	5.4 aA	6.5 aA	7.2 aA
		132	17.5 bA	2.6 bB	3.4 bB	4.6 aB	3.8 bB	2.7b B
Ca	2012	0	1159.7 b	1120.7 b	1263.3 ab	1139.3 b	1192.7 b	1295.7 b
		132	1057.3 b	1126.7 b	1287.7 ab	1193.7 b	1307.3 ab	1303.7 b
	2013	0	1111.3 b	1108.7 b	1246.7 b	1152.3 b	1345.3 ab	1406.3 a
		132	1243.3 a	1242.3 a	1471.3 a	1388.3a	1423.0 a	1450.3 a

[a]Treatments expressed as urea-to-PC ratio.
[b]Means with different lower case letters within columns and different upper case letters across rows indicate the significant difference at $P \leq 0.05$ using Fisher's LSD.

Urea significantly decreased soil pH at harvest in 2012 compared with at planting in 2012, but such effect was not observed between samples collected at planting and at harvest in 2013. Soil pH was the lowest at harvest in 2012 compared with the rest of the sampling dates in urea treated plots. All of the integrated applications did not significantly increase soil pH at harvest compared with that at planting in 2012. However, urea and PC at 1:3 ratio, and PC significantly increased soil pH at harvest in 2013 compared with at planting and harvest in 2012, and at planting in 2013. Soil pH in urea, and urea and PC at 3:1 ratio treatments was significantly lower compared with all of the other treatments including non-amended check at planting in 2012. However, only urea significantly decreased soil pH at harvest compared with all of the treatments in 2012. There was no significant difference in soil pH among the treatments at planting in 2013, except urea significantly decreased soil pH at harvest compared with all of the other treatments (Table 4.7).

All of the treatments significantly increased soil NO_3-N content at harvest compared with at planting in 2012 (Table 4.7). In 2013, urea significantly increased NO_3-N at harvest compared with at planting. The integrated treatments, except urea and PC at 1:3 ratio, and non-amended check, significantly decreased NO_3-N at harvest than that at planting in 2013. Non-amended check had significantly higher NO_3-N compared with all of the treatments except urea at planting in 2012. Urea significantly increased soil NO_3-N content compared with all of the treatments at harvests in 2012 and 2013.

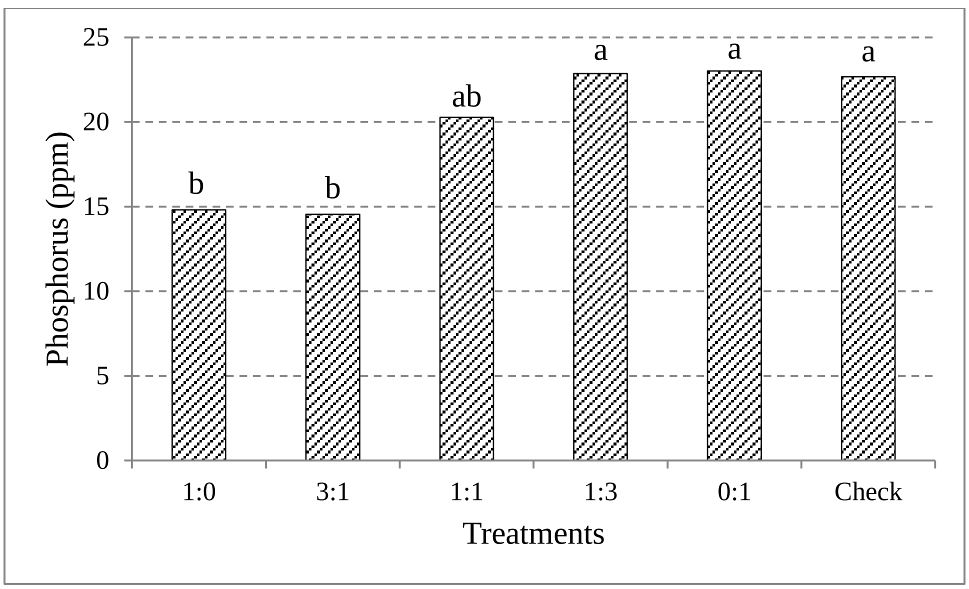


Figure 4.2. Means across all sampling time points of soil phosphorus content at the studied treatments across 2012, 2013 and 2014 growing seasons. Bars with different letters are statistically significant at $P \leq 0.05$ using Fisher's LSD.

There was no treatment effect on soil calcium content at harvest in 2012. All treatments, except PC and non-amended check, significantly increased soil calcium content at harvest in 2013 compared with at planting in 2013. Urea, and urea and PC at 3:1 ratio significantly increased soil calcium content at harvest in 2013 compared with at planting and at harvest in 2012, and at planting in 2013. There was no significant difference in soil calcium content among the treatments in all of the sampling dates. Urea, urea and PC at 3:1 ratio significantly decreased soil phosphorus content compared with all of the treatments (Fig. 4.2). PC, urea and PC at 1:3, and 1:1 ratios significantly increased soil respiration compared with the rest of the treatments (Fig. 4.3).

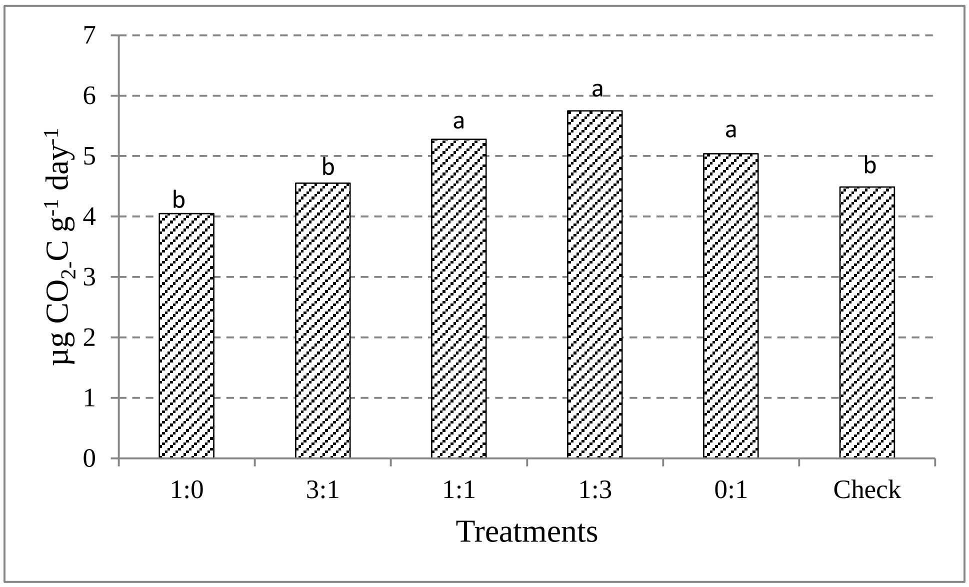


Figure 4.3. Means across all sampling time points of soil respiration at the studied treatments across 2012, 2013 and 2014 growing seasons. Bars with different letters are statistically significant at $P \leq 0.05$ using Fisher's LSD.

Carrot yield and quality

Carrot quantity and quality were not affected by the treatments in any year due to high variability in carrot yield, making it difficult to come to any conclusion about effects on carrot yield.

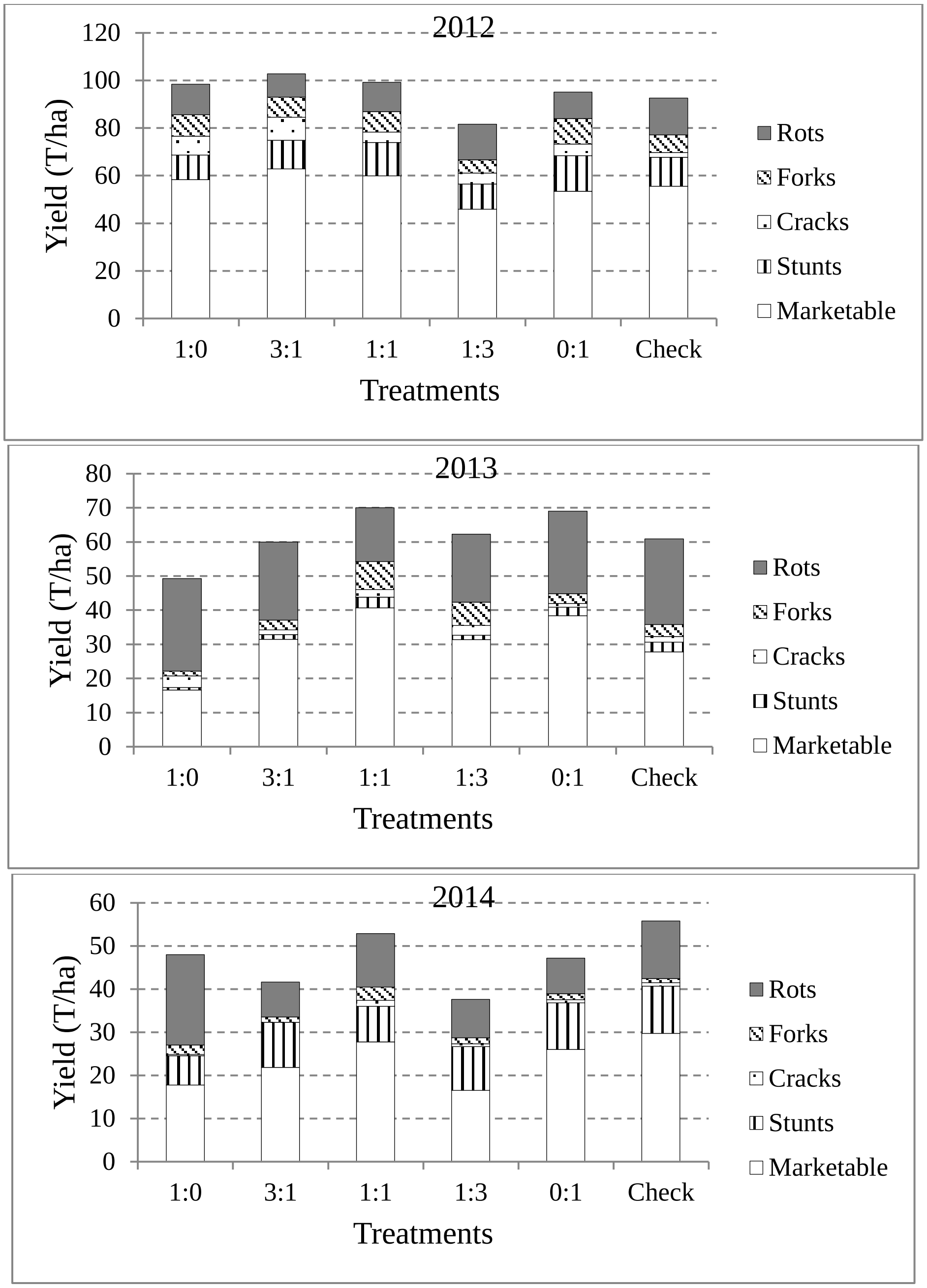


Figure 4.4. Effect of treatments on mean carrot yield by category (marketable, stunts, cracks, forks and rots) in 2012, 2013 and 2014. There was no significant difference in quality category at $P \leq 0.05$ using Fisher's LSD.

Relationships among nematode trophic, soil, and yield variables

Multiple factor analyses of nematodes, soil and yield variables showed correlation patterns. C-p 1 bacterivores and total bacterivores were negatively correlated with Dimension1 while total herbivores, c-p 2 herbivores and sum of c-p 3 to c-p 5 herbivores and soil moisture content were positively correlated with Dimension 2 (Fig. 4.5A). Cation exchange capacity, calcium, magnesium and porosity were positively correlated to each other while negatively correlated with soil moisture content and bulk density. Potassium was negatively correlated with soil pH and sum of c-p 3 to c-p 5 herbivores. C-p 2 bacterivores, total bacterivores, fungivores, non-herbivores and total nematodes were positively correlated with each other. As illustrated in Fig. 4.5B, cation exchange capacity and calcium were positively correlated while stunting was negatively correlated with Dimension 1. CI, fungivores-to-bacterivores ratio and BI were positively while EI, phosphorus, soil organic matter and rotting were negatively correlated with dimension 2. SI, pH and porosity were positively correlated with each other, but negatively correlated with forking, soil moisture content, bulk density, NH_4-N and potassium. Carrot cracking, potassium, NH_4-N, and BI were positively correlated. Magnesium was negatively correlated with sum of fungivores and bacterivores-to-herbivores, fertility index, and unmarketable and total carrots.

Relationships among abundant herbivores and yield

Carrot fresh weight of all categories except stunted and rotten carrots were positively correlated while *Malenchus* and *Helicotylenchus* were negatively correlated with Dimension 1 (Fig. 4.6A). *Pratylenchus* and carrot stunting were positively correlated while rotting was negatively correlated with Dimension 2. As illustrated in (Fig. 4.6B), the number of marketable carrots was positively correlated with Dimension 1. *Malenchus* was negatively correlated with the number of cracked and forked carrots; whereas, *Helicotylenchus* was positively correlated with the number of rotten carrots. *Tylenchus* and *Pratylenchus* were negatively correlated with Dimension 1 and Dimension 2, respectively.

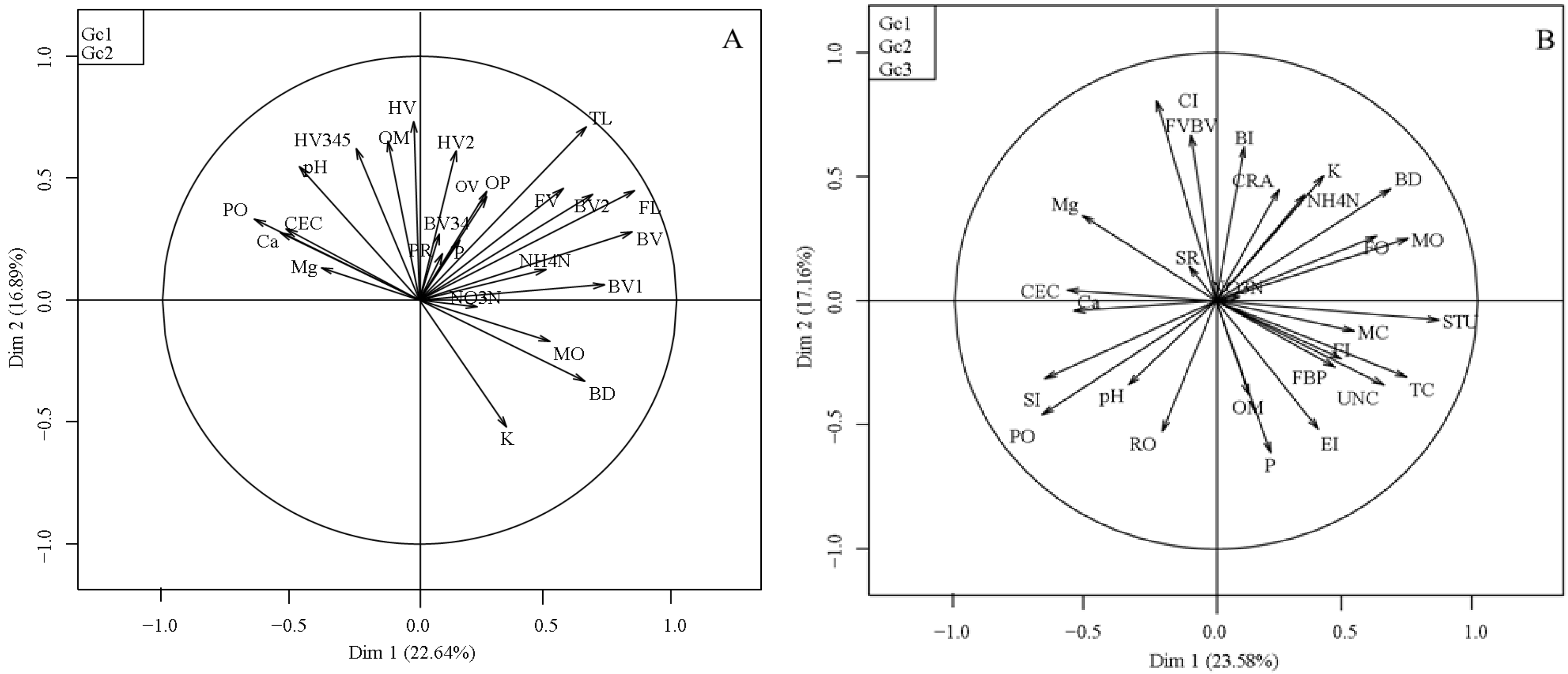


Figure 4.5. Multiple factor analysis of the variables where Dimension 1 (Dim 1) and Dimension 2 (Dim 2) represent the first and second best summary of variability of the information, respectively. (A) Relationships among abundance of nematode trophic groups (Gc1) (bacterivores (BV), fungivores (FV), omnivores (OV), predators (PR), sum of omnivores and predators (OP), herbivores (HV))(Yeats et al., 1993), and non-herbivore (FL) and total (TL) nematodes, and nematode guilds c-p 1 bacterivores (BV1), c-p 2 bacterivores (BV2), sum of c-p 3 and c-p 4 (BV34), c-p 2 herbivores (HV2) and sum of c-p 3 to c-p 5 herbivores (HV345) (Bongers and Bongers, 1998) and soil properties (Gc2) (soil pH (pH) , organic matter percentage (OM), nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N),calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), moisture percent (MO), bulk density (BD), cation exchange capacity (CEC) and porosity (PO). (B) Relationships of soil food web indices and trophic groups (Gc1) ((FV/BV)=FV) and ((FV + BV)/HV=FBP), soil properties (Gc2), and carrot yield and quality (Gc3) (stunt (STU), forks (FO), rots (RO), cracks (CRA), marketable (MC), total unmarketable carrots (UNC) and root dry-to-shoot dry weight ratio (RDSD)) from plots amended with integrated application of urea and plant compost.

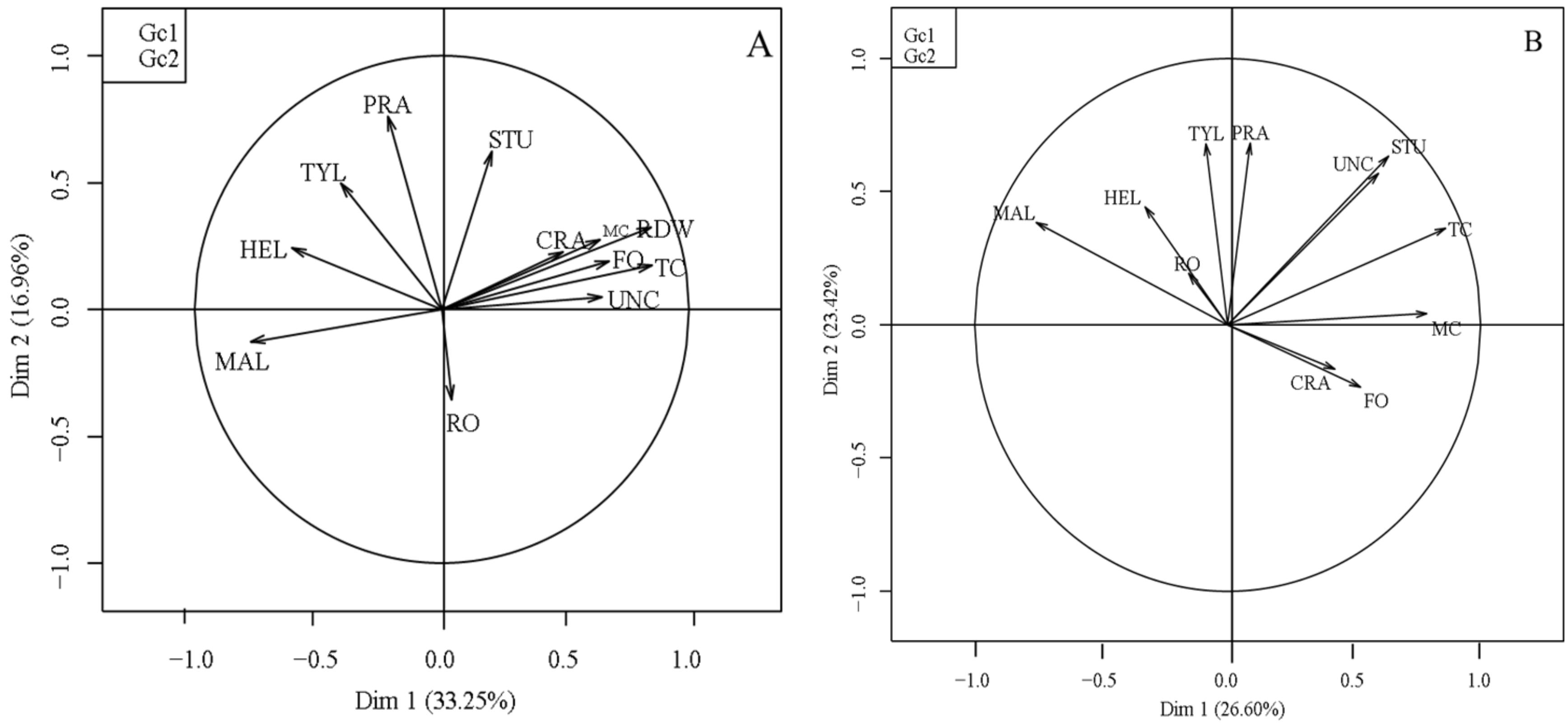


Figure 4.6. Multiple factor analysis of the variables where Dimension 1 (Dim 1) and Dimension 2 (Dim 2) represent the first and second best summary of variability of the information, respectively. (A) Relationships among carrot yield and quality expressed as fresh weight (Gc1) ((stunt (STU), forks (FO), rots (RO), cracks (CRA), marketable (MC), total unmarketable carrots (UNC) and root dry weight (RDW) and abundant herbivores (Gc2) (*Malenchus*, MAL; *Tylenchus*, TYL; *Helicotylenchus*, HEL; *Pratylenchus*, PRA). (B) Relationships among carrot yield and quality (Gc1) expressed as number and abundant herbivores nematodes (Gc2) from plots amended with integrated application of urea and plant compost.

Discussion

The expectation was that lower rates of urea mixed with higher rates of PC would improve nematode community structure, enhance EI and SI, soil biological and physicochemical properties, and increase carrot yield and quality. Wang et al. (2006) have reported that nitrogen fertilizer application increased the percentage of herbivores, but organic amendments are known to reduce herbivores (Melakeberhan et al., 2007; Mennan and Melakeberhan, 2010). Variable experimental conditions make generalization of outcomes of compost and other organic amendments difficult (Akhtar and Malik, 2000; Renčo et al., 2011). All of the treatments, except urea application decreased bacterivores in 2014 compared with 2012 while bacterivores were unchanged in urea plots (Table 4.5). This result was partially consistent with Li et al. (2010), who showed increased bacterivores in nitrogen fertilized treatments. In contrast to this, nitrogen fertilization did not increase bacterivores (Ferris and Matute, 2003). Addition of compost with low C: N ratio, as in the present study, at least temporarily increased opportunistic bacterivores, probably due to high microbial activity (Bulluck III et al., 2002a; Briar et al., 2011). However, other studies showed compost had no effect or decreased non-herbivores (Cheng and Grewal, 2009; Ferris et al., 2012).

Since omnivores and predators are sensitive to agrochemicals (Fiscus and Neher, 2002), their low numbers from urea treatments in the present study were expected. It is assumed that integrated applications reduced the negative effect of inorganic fertilizer application (Gruzedeva et al., 2007; Lie et al., 2010). Moreover, integrated application enhances microbial activities and improves soil physicochemical properties (Lazcano et al., 2013).

MI was higher in non-amended check (2.1 vs 1.8), and urea and PC at 1:1 ratio (2.1 vs 1.7) in 2014 than in 2012. In contrast, urea application reduced MI in previous studies (Bongers et al., 1997; Ferris, 2010). MI offers possibilities to measure changes in the functioning of the soil ecosystem as result of disturbance and subsequent recovery (Bongers and Bongers, 1998). Hence, the improved MI in urea and PC at 1:1 ratio and non-amended check suggests improved soil conditions.

Urea treatment significantly decreased H' (2.2 to 1.7) in 2014 compared with 2012. This suggests decreased nematode diversity over time. In contrast to this, both inorganic and organic amendments did not affect nematode diversity in previous studies (Bulluck III et al., 2002a; Cheng et al., 2008). However, Okada and Harada (2007) observed organic amendments increased nematode diversity due to increase in non-herbivores.

The impact of inorganic fertilization on SI did not conform to expectations. Urea, urea and PC at 3:1 ratio, and PC significantly increased SI compared with all of the treatments while urea and PC at 1:3 ratio significantly decreased SI compared with all of the treatments (Table 4.6). I expected that as urea rate decreases, SI increases due to increase in omnivores and predators (Bongers and Ferris, 1999; Okada and Harada, 2007; Lie et al., 2010). The SI increase in urea and integrated application with higher rate of urea in the present study needs further investigation. However, consistent with my finding that compost amendment increased SI in Sanchez-Moreno et al. (2009) (Table 4.6). This may be due to increase in food base for omnivores and predators driven by compost amendment.

Analyses of the soil conditions revealed that the soil food web structure progressed overtime (Fig. 4.1). All treatments including the controls had maturing and enriched food webs at harvest in 2014, where treatments with PC alone, and urea and PC at 1:1 ratio significantly increased SI from 50 %. EI represents availability of nutrients in the soil to support the opportunistic nematodes as observed in this study (Ferris et al., 2001). SI values are usually low in agroecosystems because of physical and/or chemical disturbance of the soil (Fiscus and Neher, 2002; Berkelmans et al., 2003; Briar et al., 2011). The relatively more structured soil food web in PC, and urea and PC at 1:1 ratio may show reduced soil disturbance.

Urea treatment significantly decreased soil pH, but the other treatments increased soil pH overtime. After two years of the experiment, soil pH was low in urea plots compared with the other treatments except urea and PC at 3:1 ratio. Consistent to my findings, other studies showed that urea decreased soil pH while compost amendment increased it (Bulluck III et al., 2002b; Li et al., 2010). Compost additions raise the pH of acid soils by forming aluminum complex and increasing base saturation (Shiralipour et al., 1992; Van den Berghe and Hue, 1999). Inorganic nitrogen fertilizers lower soil pH that, in turn, adversely affect soil biodiversity, overall soil health and crop yield (Singh et al., 2013). However, increase in soil pH due to integrated application with higher rates of PC and PC alone is desirable, especially in acidic soils (Singh et al., 2013).

Urea application increased residual soil NO_3-N at the end of the season compared with the rest of the treatments in cluding non-amended control. Consistent with my findings, Briar et al. (2007) found higher soil NO_3-N in conventional system receiving inorganic fertilizers. In 2012, urea application resulted in significantly higher NO_3-N at harvest, suggesting that NO_3-N loses to the environment. Surprisingly, most of the integrated applications had higher NO_3-N at planting in 2013 compared with at planting and at harvest in 2012. This indicates residual effect of PC that makes nitrate available to the subsequent growing seasons through decomposition (Sánchez and Richard, 2009).

Urea, urea and PC at 3:1 ratio decreased soil phosphorus content compared with the rest of the treatments except urea and PC at 1:1 ratio (Fig. 4.2). This suggests that integrated applications supplies other plant nutrients that inorganic fertilizers may not. In addition to delivering nutrients present in commercial fertilizers, compost includes nutrients that are sometimes not applied in adequate quantities by farmers (e.g. manganese, zinc, and sulfur). Compost can serve as insurance against potential yield limiting nutrients **(**Bulluck III et al., 2002b). Moreover, the integrated application reduces the non-nutrient components of compost compared with compost alone treatments that alleviate unintended consequences (Sikora and Enkiri, 2001).

This study revealed that PC, and urea and PC at 1:3 and 1:1 ratios significantly increased soil respiration compared with the rest of the treatments, indicating improved soil biological activity as I expected (Fig. 4.3). Ferris and Matute (2003) found improved soil respiration in treatments containing compost blended with wheat straw, but not from treatments with inorganic fertilizer and compost alone. Consistent with my results, organic soil amendment increased rates of soil respiration compared with non-amended check (Gunapala et al., 1998; Treonis et al., 2010).

I expected greater quality of carrots from plots treated with integrated application due to reduced nitrogen fertilizer that support early growth, and improvement in soil physicochemical properties and pest suppression from PC (Abawi and Widmer, 2000; Lazcano et al., 2013; Aluko et al., 2014). In my study, yield response was highly variable. In previous studies, integrated application increased plant growth, yield, quality and soil fertility (Ahmed et al., 2006; Mahmoud et al., 2009). Keeling et al. (2003) also reported integrated application of nitrogen fertilizer with compost improved nitrogen utilization efficiency. Although I did not see yield increase in integrated application in this study, the benefits of enhanced biological activities and the anticipated reduction of negative environmental damage provide basis for further studies to test impact of integrated application on carrot yield and quality.

Sum of c-p 3 to 5 herbivores were negatively correlated with potassium and positively correlated with soil pH. Total herbivore nematode abundance was also positively correlated with soil organic matter (Fig. 4.5A). Increase organic matter resulted in increased nutrient status and enhanced biological activity which promotes plant growth, and subsequently increases in herbivores (Bonger et al., 1990; Pimentel et al., 2005; Forge and Kempler, 2009). Negative correlation of potassium with herbivores suggests suppressive effect on herbivore nematodes (Coyne et al., 2004). Previous studies also showed the combination of SI, EI, CI and BI could be use to describe the soil health status and plant productivity (Berkelmans et al., 2003; Knight et al., 2013).

The multiple factor analysis between the most abundant nematodes and carrot yield parameters showed correlation patterns. *Malenchus* and *Helicotylencus* were negatively correlated with carrot fresh weight of all categories except carrot stunting and rotting while *Helicotylenchus* was positively correlated with rotting (Fig. 4.6A and 4.6B). However, considering that *Malenchus* is a root hair feeder (Yeates et al., 1993; Bongers and Bongers, 1998), its negative correlation with carrot yield suggests the need for further investigation to avoid carrot damage from underestimated herbivore nematodes.

In conclusion, the positive impact of urea and PC at 1:1 ratio on MI, SI and herbivores, the increasing trend of omnivore nematodes as PC rate increases, and negative impact of urea on H' suggested the potential positive impact of integrated applications on nematode community structure and soil food web conditions. PC and integrated application mixed with higher rates of PC, increased soil pH, nutrient content and soil biological activity levels while urea decreased soil pH and increased NO_3-N. The negative correlation between *Malenchus* with carrot yield indicates the need for further investigation to prevent potential yield loses from underestimated nematode groups. Although I did not see yield increase in integrated application in this study, the benefits of enhanced biological activities, and increase in soil pH and nutrient contents together with the anticipated reduction in negative environmental damage would encourage further studies. One of the areas of the research could be mixing different compost types with inorganic fertilizers to exploit integrated application in carrot production systems.

CHAPTER 5

EFFECTS OF PLANT- AND ANIMAL WASTE-BASED COMPOST AMENDMENTS, AND SOIL STERILIZATION ON NEMATODES, SOIL PROPERTIES, AND YIELD OF A FRESH MARKET CARROT CULTIVAR UNDER GLASSHOUSE CONDITIONS

Abstract

A comparative study was conducted using sterilized and non-sterilized soils to test the effects of plant and animal compost amendments on nematode community structure, soil food web conditions, soil properties and growth of fresh market carrot cultivar 'Sugarsnax 54'. The overarching question here was to know how compost amendments work under severe biological degradation. The study was conducted using 1 liter plastic pots in a glasshouse in 2012 and 2013. PC and AC were applied at 112, 168 and 224 kg N/ha. Urea (112 kg/ha) and non-amended check were included as controls. Nematode community and soil properties were analyzed from soil samples collected at planting and at harvest. Carrots were uprooted at 86 days after planting and root and shoot fresh and dry weight determined. No nematodes were recovered in the sterilized soil in both years, suggesting delayed recolonization by nematodes from the environment. Nematode community in the non-sterilized soil was dominated by c-p 2 groups, reflecting stressed nematode community. Generally soil sterilization increased most of the measured soil nutrients and CO_2 evolution while decreasing soil pH, suggesting heating during soil sterilization enhances decomposition of organic matter. Carrot growth was stunted. Overall, results did not support the initial hypothesis that compost amendments will improve nematode community structure, soil food web condition, soil properties, and carrot yield in degraded soil compared with urea and non-amended check. Perhaps, reinoculating the sterilized soil with a small amount of control soil could have made a difference.

Introduction

Herbivore nematodes are among the soil-borne pests that reduce quality and yield of carrot (Belair, 1992; Berney and Bird, 1992; Wesemael and Moens, 2008). Currently there are no commercially available nematode resistant cultivars in temperate vegetables (Melakeberhan and Wang, 2013) and few sustainable alternatives to the broad spectrum nematicides banned due to Food Quality Protection Act restrictions (Abawi and Widmer, 2000). Developing soil amendment-based alternatives for suppressing herbivores, other pests and diseases while improving soil quality are highly desired by conventional and organic carrot and other vegetable production systems. These include organic soil amendments such as green manure, cover crops, animal manure and compost (Abawi and Widmer, 2000; Wang et al., 2004; Briar et al., 2007) and a range of soil sterilization methods (Malowany and Newton, 1947; McNamara et al., 2003; Piśkiewicz et al., 2007; Berns et al., 2008).

Compost is one of the most commonly used organic amendments for increasing soil organic matter, nutrient content and microbial biomass, suppresses pest species, and improves overall soil health (Forge and Kempler, 2009; Ferris et al., 2012). As part of a project initiated to develop appropriate compost amendment strategy for nutrient, nematode and soil health management that will lead to improved carrot yield and quality, I tested the effects of PC and AC at different rate of applications on nematode community, soil food web structure, soil physicochemical changes, and carrot yield and quality under field condition (Chapter 3). As the most abundant metazoan in terrestrial ecosystems, nematodes are considered as an important component of the soil biotic community and an important indicator of soil ecosystem services (Bongers and Bongers, 1998; Porazinska et al., 1999; Ferris et al., 2001; Wang et al., 2006; Sánchez-Moreno and Ferris, 2007; Cheng and Grewal, 2009; Knight et al., 2013).

In order to address the overarching priorities of suppressing herbivore nematodes and other pests and diseases while improving soil quality using compost in conventional and organic production systems, there is a need to consider the production practices. For example, carrot productions naturally has high disturbance on soils for creating the fine seedbed and to reduce weeds and pests (Brainard et al., 2012) and frequent application of broad range of agricultural inputs often add to soil biological degradation (Eche et al., 2013; Odunze et al., 2012; Singh et al., 2013). Under these circumstances, it is necessary to know if compost application will reverse biologically degraded soils.

Therefore, the objective of the study was to (1) compare the performance of PC and AC sources in improving nematode community structure, soil food web structure, soil properties, and growth of Sugarsnax 54 under sterilized and non-sterilized conditions. I hypothesized that the compost amendment would enhance recolonization of biologically degraded soil.

Materials and methods

Soil samples

Soil for this experiment was collected from Michigan State University (MSU) Horticulture Teaching and Research center, Holt, Michigan (N 43^{0}24.040', W 085^{0}56.559', 854 m elevated) in September 2012 and October 2013. The soil is characterized as a Colwood-Brookston sandy clay loam (fine-loamy, mixed, mesic Type, Haplaquolls-Argiaquolls, Anon, 1977) with 54 % sand, 25 % silt and 21 % clay. This was the same field where the experiments in Chapter 3 were conducted. Approximately 64 liters of bulk soil sample was shoveled from the top15 to 20 cm depth (Melakeberhan et al., 2007) from 10 randomly selected spots from the guard rows each year (Fig. A-2), homogenized, filled in containers and transported to Agricultural Nematology Laboratory cold room set at 5 ^{0}C. In order to eliminate preexisting organisms, half of it was sterilized using an autoclave (AMSCO, ERIE, Pennsylvania, USA) at 120 ^{0}C and 22 psi for 16 hr in MSU Department of Plant Biology soil sterilization facility (De la peña et al, 2013).

Experimental design and treatments

The experiment was conducted from December 21, 2012 to March 15, 2013 and repeated from October 18, 2013 to January 15, 2014 in MSU Plant Science glasshouse facility. Composts used for these experiments were the same with that were used in 2012 and 2013 field experiments for Sugarsnax 54 carrot cultivar. PC and AC (Dairy Doo, Sears, MI, USA) were used as organic amendments. PC was obtained from MSU Student Organic Farm, Holt, MI, USA and AC purchased from Morgan Composting, Inc., Sears, MI, USA (Table 5.1). Standard urea equivalent to 243 kg/ha which is recommended for Sugarsnax 54 carrot cultivar and non-amended check were included as controls.

Treatment adjustment was made using the 'Hectare furrow slice' techniques that assumes a hectare contains 2, 600,000 kg of soil used in many laboratories for nutrient recommendations. This technique was used to match the recommended amount of soil amendments used in my field experiment (Burden and Sims, 1999). A total of 64 experimental units (8 treatments x 2 soils x 4 replications) were used. Each pot received 960 g of either sterilized or non-soil sterilized soils before applying the amendments to each pot. Compost with nutrient composition reported in Table 5.1 was applied on dry matter basis. In 2012 experiment, the treatments were:

Table 5.1. Average soil pH, macro (%) and micro nutrient contents (ppm) of animal (AC) and plant compost (PC) and rates of application (kg/ha) in 2012 and 2013.

pH and nutrients	Compost nutrient composition and rate			
	Content		Rate (kg/ha)	
	AC	PC	AC	PC
pH	9.2[a] a	7.9[a] b	na[b]	na
Macronutrients (%)				
Nitrogen	1.3 a	1.0 b	112	112
Phosphorus	0.6 a	0.1 b	52	12
Potassium	1.5 a	0.3 b	130	36
Calcium	2.9 b	4.0 a	252	478
Magnesium	0.7 b	0.9 a	61	11
Sodium	0.2 a	0.02 b	17	2
Sulfur	0.4 a	0.2 b	35	24
OM [c]	27 a	23 a	2348	2750
Carbon	16 a	14 a	1391	1674
C: N[d]	12a	14 a	na	na
Micronutrients (ppm)				
Iron	6052.3 a	5307.0 b	52	60
Zinc	188.3 a	82.6 b	2	1
Manganese	344.8 a	329.6 a	3	4
Copper	101.5 a	30.6 b	1	0.3
Boron	24.4 a	27.1 a	0.2.0	0.3
Aluminum	1936.1 b	2843.5 a	17	36

[a]pH value obtained only from 2013.
[b]Rate was not available because pH and C/N ratio cannot be expressed as a rate of application.
[c]percent of organic matter.
[d]carbon-to- nitrogen ratio.
[e]Means with different letters across rows indicate statistical difference at $P \leq 0.05$.

6 g (X), 9 g (1.5X) and 12 g (2X) of PC and 4 g (X), 6 g (1.5X) and 8 g (2X) of AC where X was adjusted at a rate of 112 kg N/ha which is a recommended N for fresh market carrot varieties and urea (46-0-0) was applied as 0.1 g per pot which is equivalent to 112 kg N/ha. The 2013 treatments were: 4 g (X), 7 g (1.5X) and 9 g (2X) of PC and 4 g (X), 6 g (1.5X) and 8 g (2X) of AC and urea (46-0-0) was applied as 0.1 g per pot. The treatments were applied to each pot and

mixed to the soil. Each pot was water to saturation 1 hour prior transplanting two-week old carrot seedlings (Melakeberhan et al., 2007). Pots were monitored every day and watered as needed throughout the experiment. Treatments were arranged in randomized complete block design (RCBD) with four replications on glasshouse bench. The experiments were terminated 86 DAP.

Nematode extraction, identification and abundance

In order to establish base line information, nematodes were extracted from four soil samples each from sterilized and non-sterilized bulk soils before planting carrots using a semi-automatic elutriator as described earlier (Avendaño et al., 2003). Methods pertaining to soil sampling, nematode extraction, identification and nematode community, ecosystem disturbance and soil food web indices, were described in the General Materials and Methods section (Chapter 2). Similarly, methods used to measure soil respiration, soil physicochemical properties, and carrot yield and quality were stated in Chapter 2.

Carrot yield

After 86 days, carrots were uprooted from each pot. The root and shoot were weighted separately for fresh weight and placed in a separate paper bags for dry weight determination. The dry weight determinations were made after the roots and shoots had been dried to constant weight at 66 ^{0}C (Hochmuth et al., 2006).

Data analysis

Treatments were compared for nematode trophic groups, community indices, soil food web indices, trophic group ratios, fertility index (PPI/MI), soil and yield variables. Statistical analysis was conducted using the PROC MIXED procedure of SAS. The statistical model consisted of fixed effects of amendments and soil (sterilized and non-sterilized) and the interaction between them, and random effects of block. Comparisons were performed by using two-way analysis of variance for soil and yield parameters accounting soil sterilization and treatments as factors of the experiment.

Treatments were compared using one-way analysis of variance (Proc Mixed, SAS ver 9.3, SAS Institute, 2012, Cary, NC, USA) for nematode data because nematodes were not extracted from sterilized soil. F-values were obtained using appropriate error term in the models. Multiple comparisons were adjusted to Tukey-Kramer when F is not significant to perform the preplanned comparisons. Prior to analysis; nematode population abundance was transformed to ln (x+1) to meet the assumptions of normality and equal variances, but untransformed arithmetic means are presented. The probability level $P \leq 0.05$ was regarded as significant.

Results

Nematode composition and abundance

A total of 29 nematode genera were detected from soil samples in 2012 and 2013 (Table 5.2). The nematode genera detected from herbivore, bacterivore, fungivore, predator and omnivore trophic groups were 8, 13, 4, 1 and 3, respectively. *Eudorylaimus*, *Cephalobus* and *Cervidellus* were detected only in 2012, and *Basiria*, *Acrobeles*, *Alaimus* and *Mononchus* were detected only in 2013 soil samples. *Tylenchus, Acrobeloides*, and *Aphelenchus* and *Filenchus* were the most abundant herbivore, bacterivore and fungivore genera, respectively. Overall, the abundance of omnivores and predators were low, and nematode abundance was higher in 2012 compared with 2013 samples. Nematodes were not detected in sterilized soil in both 2012 and 2013 soil samples.

Herbivores were significantly higher at planting compared with AC at 168 kg N/ha, urea and check at harvest in 2012 (Table 5.3). Similarly, bacterivores were significantly higher at planting compared with all the treatments at harvest in 2012. Fungivores were significantly higher at planting and AC at 112 and 224 kg N/ha at harvest in 2012 compared with the rest of the treatments. In 2013, herbivores and Fungivores were significantly higher at planting compared with all of the treatments at harvest. In both years, there was no significant difference in omnivores and predators among the treatments.

Nematode community indices

Shannon-Weaver diversity index was significantly higher at planting and AC at 112 and 224 kg N/ha, urea and non-amended check at harvest compared with the rest of the treatments in 2012 (Table 5.4). Hill's N1 was significantly higher at planting compared with PC at 168 and 224 kg N/ha, and AC at 168 kg N/ha at harvest in 2012. Hill's N1 was significantly higher in AC at 112 kg N/ha, AC at 224 kg N/ha, urea and non-amended check compared with AC at 168 kg N/ha in 2012. Hill's N0 was significantly higher in PC at 112kg N/ha, and AC at 112 and AC at 224 kg N/ha compared with AC at 168 kg N/ha at harvest in 2012. In 2013, Hill's N0 was significantly higher at planting compared with all of the treatments at harvest. There were no significant differences in MI and MI25 at planting and harvest samples, and among the treatments in 2012 and 2013 (Table 5.5). There was also no significant difference in PPI at planting and harvest, and among the treatments in 2012. PPI was significantly higher at planting compared with the rest of the treatments at harvest in 2013.

Table 5.2. List of nematode genera detected in AC and PC amendments, standard urea and non-amended check in pots filled with 960 g non-sterilized sandy clay loam soil planted with Sugarsnax 54 at planting and 86 days later at harvest in 2012 and 2013 glasshouse experiments. Numbers within brackets represent c-p vales following Bongers and Bongers (1998).

Herbivores	Bacterivores	Fungivores	Predators	Omnivores
Basiria[a] *(2)*	*Mesorhabditis (1)*	*Ditylenchus (2)*	*Mononchus*[a] *(4)*	*Eudorylaimus (4)*[b]
Cephalenchus (2)	*Panagrolaimus (1)*	*Aphelenchoides (2)*		*Thonus (4)*
Malenchus (2)	*Pelliodititis*[c] *(1)*	*Aphelenchus (2)*		*Aprocelaimellus(5)*
Paratylenchus (2)	*Pristionchus*[a] *(1)*	*Filenchus (2)*		
Psilenchus (2)	*Rhabditis (1)*			
Tylenchus (2)	*Acrobeles*[a] *(2)*			
Heterodera (3)	*Acrobeloides (2)*			
Pratylenchus (3)	*Cephalobus*[c] *(2)*			
	Cervidellus[c] *(2)*			
	Eucephalobus (2)			
	Heterocephalobus (2)			
	Plectus (2)			
	Alaimus[a] *(4)*			

[a]Detected only in 2013.
[b]Detected only at harvest in 2012 experiment.
[c]Detected only in 2012.

Table 5.3. Mean numbers of herbivores, bacterivores, fungivores, predators and omnivores nematode trophic groups abundances in 100 cc of soil amended with animal (AC) and plant (PC) composts, standard urea and non-amended check in pots filled with 960 g of non-sterilized sandy clay loam soil planted with Sugarsnax 54 at planting[b] and at harvest[c] (86 DAP) across 2012 and 2013 glasshouse experiments.

AM[a]	Rate (kg N/ha)	HV	BV	FV	PR	OV
		[b]10 a[d]	52 a	42 a	0	1
PC	112	[c]3 b	14 b	25 b	0	1
	168	4 b	12 bc	22 b	0	0
	224	3 b	6 bc	14 b	0	1
AC	112	3 b	15 b	19 b	0	0
	168	1 b	5 c	3 c	0	0
	224	4 b	13 b	21 b	0	0
Urea	112	2 b	14 b	15 b	0	0
Check	0	2 b	15 b	14 b	0	0

[a]Amendments.
[b]Planting samples
[c]Harvest samples
[d]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$ using Fisher's LSD.

Table 5.4. The effect of animal (AC) and plant (PC) composts at different rates, standard urea and non-amended check on Shannon-Weaver (H'), Hill's N1 (N1) and Hill's N0 (N0) in pots filled with 960 g of non-sterilized sandy clay loam soil planted with Sugarsnax 54 at planting[b] and at harvest[c] (86 DAP) in 2012 and 2013 glasshouse experiments.

AM[a]	Rate (Kg N/ha)	H'	N1	N0	H'	N1	N0
		2012			2013		
		[b]2.49 a[d]	12.12 a	15 a	1.50 a	5.40 a	8 a
PC	112	[c]1.88 ab	7.88 abc	10 ab	0.97 a	3.41 a	3 b
	168	1.86 ab	6.47 bc	9 abc	0.87 a	3.34 a	3 b
	224	2.00 ab	7.40 bc	8 bc	0.91 a	2.82 a	2 b
AC	112	2.13 a	8.50 ab	10 ab	1.26 a	3.75 a	3 b
	168	1.12 b	4.17 c	4 c	0.86 a	2.74 a	2 b
	224	2.21 a	9.22 ab	11 ab	1.40 a	4.54 a	4 b
Urea	112	2.13 a	8.40 ab	9 abc	1.17 a	3.95 a	3 b
Check	0	2.08 a	8.19 ab	8 bc	1.14 a	3.81 a	3 b

[a]Amendments.
[b]Planting samples.
[c]Harvest samples.
[d]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$ using Fisher's LSD.

Table 5.5. The effect of animal (AC) and plant (PC) composts at different rates, standard urea and non-amended check on maturity indices (PPI, MI and MI25) in pots filled with 960 g of non-sterilized sandy clay loam soil planted with Sugarsnax 54 at planting[b] and at harvest[c] (86 DAP) in 2012 and 2013 experiments.

	Rate (Kg N/ha)	PPI	MI	MI25	PPI	MI	MI25
		2012			2013		
AM[a]		[b]2.13 a[d]	1.75 a	2.02 a	2.00 a	1.80 a	2.00 a
PC	112	[c]2.08 a	1.95 a	2.00 a	0.00 b	1.89 a	2.00 a
	168	2.26 a	1.81 a	2.00 a	0.00 b	1.56 a	2.00 a
	224	2.25 a	1.97 a	2.00 a	0.00 b	1.92 a	2.00 a
AC	112	2.10 a	1.92 a	2.00 a	0.00 b	2.00 a	2.00 a
	168	2.00 a	1.92 a	2.00 a	0.00 b	2.44 a	2.50 a
	224	2.05 a	1.94 a	2.00 a	0.50 b	1.84 a	2.00 a
Urea	112	2.17 a	1.87 a	2.00 a	0.00 b	1.94 a	2.00 a
Check	0	2.04 a	1.87 a	2.00 a	0.00 b	1.20 a	2.00 a

[a]Amendments.
[b]Planting samples.
[c]Harvest samples.
[d]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$ using Fisher's LSD.

Soil food web indices, trophic ratios and fertility index

There were no significant differences in soil food web indices between at planting and at harvest samples in 2012. However, PC at 168 kg N/ha and non-amended check were significantly higher in EI compared with PC at 112 and 224 kg N/ha, and AC at 112 kg N/ha in 2013 (Table 5.6). This result was supported by the faunal profile analysis where only a few data points fell in Quadrant A, but most data points fell in Quadrant D (Fig. 5.1). Similarly, there was no significant difference in fungivores-to-bacterivores and fungivores plus bacterivores-to-herbivores ratios and fertility index between planting and harvest samples, and among the treatments in 2012 and 2013 (Table 5.7).

Table 5.6. The effect of animal (AC) and plant (PC) composts at different rates, standard urea and non-amended check on food web enrichment (EI) and structure (SI), basal index (BI), and channel index (CI) in pots filled with 960 g of non-sterilized sandy clay loam soil planted with Sugarsnax 54 at planting[b] and at harvest[c] (86 DAP) in 2012 and 2013 experiments.

AM[a]	Rate (kg N/ha)	EI	SI	BI	CI	EI	SI	BI	CI
		2012				2013			
		[b]67 a[d]	4 a	32 a	29 a	65 ab	5 a	27 a	42 a
PC	112	[c]52 a	3 a	47 a	75 a	30 c	0 a	52 a	60 a
	168	59 a	1 a	40 a	63 a	75 a	0 a	25 a	36 a
	224	51 a	11 a	47 a	72 a	33 c	0 a	67 a	78 a
AC	112	50 a	3 a	49 a	61 a	39 bc	0 a	61 a	100 a
	168	44 a	0 a	56 a	51 a	47 abc	25 a	40 a	78 a
	224	47 a	0 a	53 a	72 a	58 abc	0 a	42 a	66 a
Urea	112	53 a	0 a	47 a	62 a	46 abc	0 a	54 a	82 a
Check	0	53 a	2 a	46 a	54 a	75 a	0 a	24 a	21 a

[a]Amendments.
[b]Planting samples.
[c]Harvest samples.
[d]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$ using Fisher's LSD.

Table 5.7. The effect of animal (AC) and plant (PC) composts at different rates, standard urea and non-amended check on fungivores-to-bacterivores ratio (FV/BV), sum of bacterivores and fungivores-to-herbivores ((BV + FV)/HV) and fertility index (FI= PPI/MI) in pots filled with 960 g of non-sterilized sandy clay loam soil planted with Sugarsnax 54 at planting[b] and at harvest[c] (86 DAP) in 2012 and 2013 experiments.

AM[a]	Rate (Kg N/ha)	FV/BV	(BV+FV)/HV	FI	FV/BV	(BV+FV)/HV	FI
		2012			2013		
		[b]0.75 a[d]	13.24 a	1.22 a	1.40 a	1.10 a	3.36 a
PC	112	[c]2.02 a	11.70 a	1.07 a	0.28 a	0.21 a	0.00 a
	168	2.43 a	19.97 a	1.33 a	0.53 a	0.40 a	0.00 a
	224	2.32 a	5.14 a	1.15 a	0.96 a	0.96 a	0.00 a
AC	112	1.22 a	12.98 a	1.09 a	1.56 a	1.17 a	0.00 a
	168	1.83 a	3.75 a	1.04 a	0.75 a	0.38 a	0.00 a
	224	1.68 a	12.73 a	1.06 a	1.67 a	1.25 a	0.63 a
Urea	112	1.33 a	23.25 a	1.16 a	0.47 a	0.23 a	0.00 a
Check	0	1.14 a	14.10 a	1.09 a	0.72 a	0.54 a	0.00 a

[a]Amendments.
[b]Planting samples.
[c]Harvest samples. [d]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$ using Fisher's LSD.

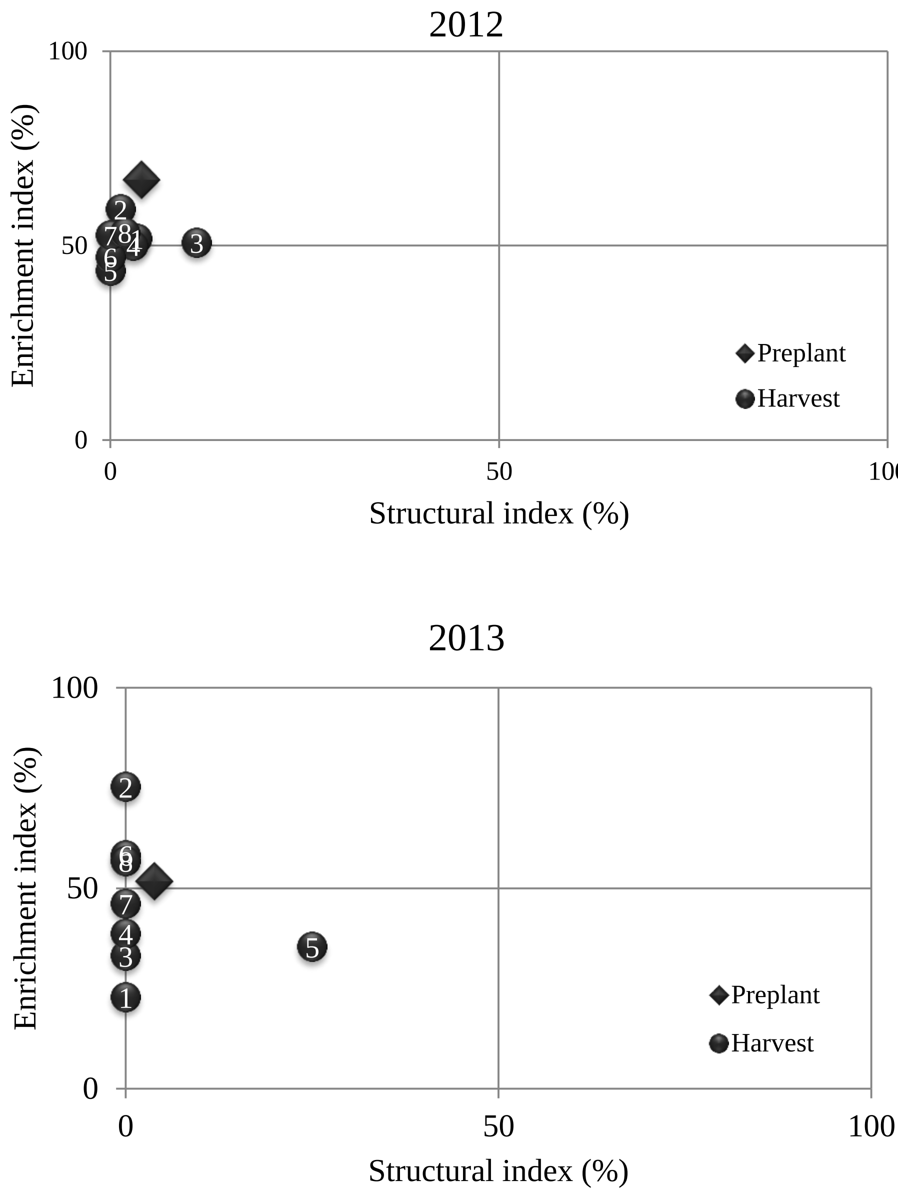


Figure 5.1. Faunal profiles representing the structure (SI) and enrichment (EI) conditions of the soil food web in pots filled with non-sterilized sandy clay loam soil planted with Sugarsnax 54 cultivar in 2012 and 2013 glasshouse experiments. Pots were amended with animal compost (AC) and plant compost (PC) at different rates, standard urea and non-amended check. Numbers represent: 1-3= PC adjusted at 112, 168 and 224 kg N/ha, respectively; 4-6= AC adjusted to supply 112, 168 and 224 kg N/ha, respectively, 7= urea and 8= non-amended check.

Soil properties and soil respiration

All of the AC treatments significantly increased soil pH on sterilized soil at harvest compared with at planting in 2012. In 2013, all of the treatments significantly increased soil pH on sterilized soil at harvest compared with at planting. In non-sterilized soil, however, only AC at 224 kg N/ha significantly increased soil pH compared with AC at 168 kg N/ha and urea in 2013. AC at 224 kg N/ha significantly increased soil pH at harvest compared with at planting in 2013. Generally, soil sterilization decreased soil pH in these experiments except in AC at 168 kg N /ha and urea (Tables 5.8 and 5.9). All of the treatments increased soil phosphorus content on non-sterilized soil at harvest compared with that at planting in 2013, but only AC at 224 kg N/ha had such effect in 2012. All of the AC treatments increased phosphorus compared with urea. In 2012, soil phosphorus was generally higher at harvest than at planting in all treatments including urea and non-amended check on sterilized soil. However, PC at 224 kg N/ha and all of the AC treatments increased soil phosphorus content on sterilized soil in 2013.

Table.5.8. Soil pH, moisture content (% MO) and phosphorus (P), potassium (K), calcium (Ca), Magnesium (Mg) contents (ppm), cation exchange capacity (CEC) (100 me/100g), organic matter (% OM), nitrate-nitrogen (NO_3-N) (ppm), ammonium-nitrogen (NH_4-N) (ppm) and soil respiration (SR) (μ CO_2-C per gram per day) in animal (AC) and plant (PC) composts amendments at different rates, standard urea and non-amended check in pots filled with 960 g of sterilized (S) and non-sterilized (NS) sandy clay loam soil planted with Sugarsnax 54 at planting[b] and at harvest[c] (86 DAP) in 2012 glasshouse experiments.

	Rate	pH		% MO		P		K	
	(kg	S	NS	S	NS	S	NS	S	NS
AM[a]	N/ha)	[b]7.3 bB[d]	7.5 dA	8.4 a	10.6 a	72.8 c	71.6 b	135.8 a	136.6 a
	112	[c]7.4 abB	7.7 abcA	7.0 aB	10.3 aA	77.0 bcA	68.7 bB	115.3 de	119.3 b
PC	168	7.5 abB	7.8 abcA	8.0 a	9.3 ab	79.0 bcA	68.0 bB	112.7 de	115.0 b
	224	7.4 abB	7.8 abA	8.5 a	7.3 b	83.0 abA	73.3 abB	120.0 bcde	123.0 ab
	112	7.6 a	7.7 abc	6.4 aB	9.4 abA	82.0 abA	72.0 abB	129.7 ab	121.3 b
AC	168	7.5 a	7.6 dc	7.2 a	9.1 ab	82.0 abA	72.7 abB	129.0 abc	126.3 a
	224	7.5 aB	7.8 aA	7.5 a	6.6 b	85.7 aA	76.3 aB	125.7 abcd	136.3 a
Urea	112	7.4 ab	7.6 bcd	6.3 a	8.6 ab	79.3 bA	69.3 bB	109.7 e	113.0 b
Check	0	7.4 abB	7.7 abcA	8.7 a	8.2 ab	82.0 abA	70.7 abB	111.7 e	112.3 b

Table 5.8 (cont'd)

AM[a]	Rate (kg N/ha)	Ca		Mg		CEC	
		S	NS	S	NS	S	NS
		1332 b	1317.4 b	274.8 aB	336.8 aA	9.3 b	9.72 b
PC	112	1348.3 b	1385.7 ab	263.3 ab	287.0 b	9.2 b	9.60 b
	168	1366.3 b	1360.0 b	253.0 ab	261.3 b	9.2 b	9.30 b
	224	1349.0 b	1507.7 a	262.7 ab	316.3 b	9.2 bB	10.5 aA
AC	112	1391.3 ab	1368.0 b	258.0 ab	287.0 b	9.4 b	9.50 b
	168	1419.7 ab	1369.7 b	250.7 ab	293.0 b	9.5 b	9.60 b
	224	1350.0 b	1404.0 ab	239.7 b	276.7 b	9.1 b	9.70 b
Urea	112	1353.3 b	1342.7 b	240.0 b	275.0 b	9.0 b	9.30 b
Check	0	1371.3 b	1354.0 b	243.7 b	263.7 b	9.2 b	9.30 b

AM[a]	Rate (kg N/ha)	% OM		NO_3-N		NH_4-N		SR	
		S	NS	S	NS	S	NS	S	NS
		[b]2.02 a[d]	2.10 b	20.18 c	21.50 b	20.36 aA	1.64 aB	6.00 aA	3.10 aB
PC	112	[c]2.10 a	2.10 b	44.20 abA	28.20 bB	5.70 b	2.40 a	4.90 a	3.10 a
	168	2.00 a	2.10 b	45.80 abA	21.00 bB	5.70 b	2.80 a	4.70 abA	2.30 aB
	224	2.00 aB	2.20 aA	40.30 bA	26.70 bB	5.10 b	2.70 a	4.20 ab	3.20 a
AC	112	2.10 a	2.20 a	44.20 abA	25.40 bB	7.30 bA	2.60 aB	4.00 ab	3.20 a
	168	2.00 a	2.10 b	47.10 abA	25.00 bB	8.80 bA	2.50 aB	3.90 ab	3.00 a
	224	2.00 a	2.10 ab	39.50 b	30.60 b	7.40 bA	2.70 aB	4.70 ab	2.90 a
Urea	112	2.00 a	2.00 b	52.70 a	69.30 a	8.20 bA	2.60 aB	3.60 abA	1.70 aB
Check	0	2.00 a	2.10 ab	40.90 b	31.60 b	5.30 b	2.70 a	2.90 b	2.60 a

[a]Amendments. [b]Planting samples. [c]Harvest samples.
[d]Means with different lower case letters within columns and different upper case letters between soil conditions (S vs. NS) within each variable indicate the significant difference at $P \leq 0.05$ using Fisher's LSD.

All of the PC treatments, urea and non-amended check decreased soil potassium content at harvest compared with at planting in 2012. However, there was no significant difference among all of the AC treatments at harvest compared with planting in 2012. In 2013, all of the treatments except PC at 168 kg N/ha and urea increased soil potassium content on sterilized soil at harvest compared with at planting (Tables 5.8 and 5.9). On non-sterilized soil, only AC at 168 and 224 kg N/ha increased soil potassium content at harvest compared with at planting in 2012. However, only AC at 224 kg N/ha increased potassium at harvest on non-sterilized soil in 2013. There was no difference in calcium content on sterilized soil in both years.

PC at 224 kg N/ha increased soil calcium content at harvest in 2012 compared with that at planting, but calcium content decreased in all of the treatments at harvest compared with at planting in 2013. Magnesium was lower in AC at 224 kg N/ha, urea and non-amended check at harvest than at planting in 2012 (Table 5.8). All of the treatments increased magnesium content at harvest in 2013 (Table 5.9). Similarly, magnesium content was low in non-sterilized soil in all the treatments at harvest compared with at planting in 2012. However, only PC and AC at 224 kg N/ha, and non-amended check were low in magnesium at harvest than at planting in 2013.

Table 5.9. Soil pH, moisture (% MO) and phosphorus (P), potassium (K), calcium (Ca), Magnesium (Mg) contents (ppm), and cation exchange capacity (CEC) (100 me/100g), organic matter (% OM), nitrate-nitrogen (NO_3-N) (ppm), ammonium-nitrogen (NH_4-N) (ppm) and soil respiration (SR) (µ CO_2-C per gram per day) in animal (AC) and plant (PC) composts amendments at different rates, standard urea and non-amended check in pots filled with 960 g of sterilized (S) and non-sterilized (NS) sandy clay loam soil planted with Sugarsnax 54 at planting[b] and at harvest[c] (86 DAP) in 2013 glasshouse experiments.

	Rate	pH		% MO		P		K	
	(kg	S	NS	S	NS	S	NS	S	NS
AM[a]	N/ha)	[b]7.10 bB[d]	7.80 aA	13.20 a	10.20 b	52.70 b	45.30 d	101.00 b	119.33 b
	112	[c]7.60 aB	7.90 aA	13.10 a	14.50 a	85.70 a	79.70 abc	127.00 a	128.30 ab
PC	168	7.50 aB	7.90 aA	13.40 a	13.90 a	83.30 a	75.30 bc	120.30 ab	127.00 ab
	224	7.60 a	7.70 a	14.40 a	14.00 a	86.70 a	83.70 abc	129.00 a	133.70 ab
	112	7.70 aB	8.00 aA	13.90 a	13.40 a	85.00 a	87.00 a	135.00 a	132.30 ab
AC	168	7.70 a	7.90 ab	13.10 a	13.40 a	84.70 a	86.70 a	133.70 a	133.70 ab
	224	7.60 a	7.70 a	13.90 a	13.50 a	91.00 a	84.30 ab	134.00 a	143.70 a
Urea	112	7.60 a	7.80 a	13.20 a	14.00 a	87.30 aA	74.30 cB	119.70 ab	130.00 ab
Check	0	7.60 a	7.80 a	13.70 a	13.20 a	83.30 a	79.30 abc	128.00 a	129.30 ab

Table 5.9 (cont'd)

AM[a]	Rate (kg N/ha)	Ca		Mg		CEC	
		S	NS	S	NS	S	NS
		1520.70 aB	1720.70 aA	246.00 bB	378.67 aA	9.90 aB	12.10 aA
PC	112	1496.70 a	1491.00 b	337.70 a	355.30 ab	10.60 a	10.70 b
	168	1468.00 a	1524.70 b	321.30 a	348.30 ab	10.30 a	10.90 b
	224	1430.00 a	1475.70 b	325.30 a	333.00 b	10.20 a	10.50 b
AC	112	1492.00 a	1487.70 b	341.30 a	348.70 ab	10.70 a	10.70 b
	168	1408.00 a	1451.30 b	320.30 a	343.70 ab	10.10 a	10.50 b
	224	1411.30 a	1520.00 b	317.30 a	338.70 b	10.00 a	10.80 b
Urea	112	1446.00 a	1563.70 b	312.30 aB	355.00 abA	10.10 aB	11.10 bA
Check	0	1455.00 a	1489.70 b	309.00 a	322.70 b	10.20 a	10.50 b

AM[a]	Rate (kg N/ha)	% OM		NO_3-N		NH_4-N		SR	
		S	NS	S	NS	S	NS	S	NS
		[b]1.60 b[d]	1.60 b	2.40 c	3.30 c	15.70 aA	1.90 bB	10.59 aA	1.97 cB
PC	112	[c]2.50 a	2.70 a	66.70 aA	31.20 abB	2.80 b	1.40 b	1.98 b	6.32 b
	168	2.60 a	2.70 a	57.10 abA	29.00 abB	2.80 b	1.20 b	2.12 b	1.94 c
	224	2.60 a	2.70 a	54.50 ab	45.40 ab	2.80 b	7.70 a	4.25 b	4.04 bc
AC	112	2.50 a	2.60 a	46.30 b	26.60 bc	4.40 b	1.30 b	2.58 b	2.01 c
	168	2.60 a	2.70 a	38.20 b	42.80 ab	3.00 b	1.20 b	3.81 b	2.03 c
	224	2.70 a	2.60 a	49.70 ab	45.70 ab	4.30 b	1.30 b	3.48 b	3.26 bc
Urea	112	2.40 aB	2.70 aA	67.70 a	55.80 a	5.50 b	1.10 b	2.12 b	2.12 c
Check	0	2.40 a	2.50 a	53.00 ab	36.60 ab	5.00 b	3.90 ab	1.76 b	2.56 c

[a]Amendments. [b]Planting samples. [c]Harvest samples. [d]Means with different lower case letters within columns and different upper case letters between soil conditions (S vs. NS) within each variable indicate the significant difference at $P \leq 0.05$ using Fisher's LSD.

In sterilized soil, there was no difference in cation exchange capacity between planting and harvest samples and among the treatments at harvest in both years (Tables 5.8 and 5.9). There was also no difference in soil organic matter between planting and harvest samples, and among the treatments at harvest soil in 2012, but all of the treatments increased soil organic matter at harvest compared with at planting in 2013. Soil sterilization decreased soil cation exchange capacity and organic matter in PC at 224 kg N/ha and urea in 2012 and 2013, respectively.

In non-sterilized soil, PC at 224 kg N/ha increased cation exchange capacity at harvest than at planting in 2012. However, all of the treatments were low in cation exchange capacity at harvest than at planting in 2013. PC at 224 and AC at 112 kg N/ha increased soil organic matter at harvest than at planting in 2012. Similarly, PC at 224 kg N/ha and AC at 112 kg N/ha increased soil organic matter at harvest compared with PC at 112 and 168 kg N/ha, AC at 168 kg N/ha, and urea in 2012. However, all the treatments increased soil organic matter at harvest than at planting in 2013.

All of the treatments increased soil NO_3-N content on sterilized soil at harvest compared with that at planting in 2012 and 2013 (Tables 5.8 and 5.9). Among the treatments, PC at 224 kg N/ha and AC at 112 kg N/ha significantly increased NO_3N compared with PC at 112 and 168 kg N/ha, and non-amended control on sterilized soil at harvest in 2012. In contrast to this, PC at 112 kg N/ha and urea significantly increased NO_3-N compared with PC at 224 kg N/ha and AC at 112 kg N/ha in 2013. Soil sterilization increased NO_3-N content in all of PC treatments, AC at 112 and 168 kg N/ha in 2012. On non-sterilized soil, only urea significantly increased NO_3-N compared with the rest of the treatments in 2012. Similar to this, urea increased NO_3-M compared with AC at 112 kg N/ha in 2013. In 2013, the effect of soil sterilization was observed only in PC at 112 and 168 kg N/ha.

In sterilized soil, NH_4-N decreased in all treatments at harvest compared with at planting, but there were no differences among the treatments at harvest in 2012 and 2013. Soil sterilization significantly increased NH_4-N at planting, in all of the AC treatments and urea in 2012, but such effect was observed only at planting in 2013. On non-sterilized soil, there was no significant difference in NH_4-N between planting and harvest soil samples in 2012. Similarly, there was no significant difference among the treatments at harvest in 2012. However, PC at 224 kg N/ha significantly increased NH_4-N compared with all of the treatments except non-amended check in 2013.

Soil respiration was significantly higher at planting compared with non-amended check, and all of the treatments on sterilized soil at harvest in 2012 and 2013, respectively. On non-sterilized soil, there was no significant difference between planting and harvest samples, and among the treatments in 2012. In 2013, PC at 112 kg N/ha significantly increased soil respiration in non-sterilized soil compared with at planting, and all of the treatments except PC and AC at 224 kg N/ha. Soil sterilization increased soil respiration in PC at 168 kg N/ha, and urea in 2013, but there was no such effect in 2012.

Carrot yield

There were no treatment and soil sterilization effects on root fresh and dry weight in 2012 (Table 5.10). However, AC at 224 kg N/ha, significantly increased shoot fresh weight on sterilized soil compared with non-amended check in 2012. In non-sterilized soil, PC at 224 kg N/ha and AC at 112 and 224 kg N/ha significantly increased shoot fresh weight compared with urea and non-amended check. PC at 112 kg N/ha and AC at 224 kg N/ha significantly increased shoot dry weight on sterilized soil compared with non-amended check. However, all the treatments except urea significantly increased shoot dry weight on non-sterilized soil compared with non-amended check in 2012. PC at 168 kg N/ha and AC at 168 kg N/ha significantly increased root-to-shoot dry weight ratio on sterilized soil compared with non-amended control in 2012. However, AC at 224 kg N/ha significantly increased root-to-shoot dry weight ratio compared with all of the treatments in 2012. Soil sterilization significantly increased shoot fresh weight in urea treatment in 2012, but no effect of soil sterilization observed in shoot dry weight and root-to-shoot dry weight ratio.

In 2013 on sterilized soil, PC at 224 kg N/ha significantly increased root fresh weight compared with all of the treatment except AC at 112 and 224 kg N/ha (Table 5.11). Soil sterilization significantly increased root dry weight in AC at 112 and 224 kg N/ha. However, soil sterilization decreased root dry weight in urea and increased root fresh weight in PC and AC at 224 kg N/ha and urea. In 2013 in non-sterilized soil, AC at 224 kg N/ha significantly increased root fresh weight compared with AC at 168 kg N/ha, urea and non-amended check (Table 5.11). All of the treatments significantly increased root fresh weight compared with non-amended check in 2013. However, there were no significant differences among the treatments including the cobtrols in root dry weight.

In 2013 in sterilized soil, AC at 112 and 224 kg N/ha, and PC at 224 kg N/ha significantly increased shoot fresh weight compared with AC at 168 kg N/ha, urea and non-amended check (Table 5.11). PC at 112 kg N/ha also significantly increased shoot fresh weight compared with urea and non-amended check. Soil sterilization significantly increased shoot fresh weight in PC at 112 and 224 kg N/ha and AC 112 kg N/ha. However, soil sterilization had no significant effect on shoot dry weight and root-to-shoot dry weight ratio. There was no significant difference in shoot fresh weight among the treatments on non-sterilized soil in 2013.

Table 5.10. The effect of animal (AC) and plant (PC) compost amendment at different rates, standard urea and non-amended check on carrot root fresh weight (RFW), root dry weight (RDW), shoot fresh weight (SFW), shoot dry weight (SDW) and root -to-shoot dry weight ratio (RD/SD) in pots filled with 960 g of sterilized (S) and non-sterilized (NS) sandy clay loam soil planted with Sugarsnax 54 after 86 days in 2012 experiments.

		RFW		RDW		SFW		SDW		RD/SD	
AM[a]	TR	S	NS	S	NS	S	NS	S	NS	S	NS
PC	112	[b]0.60 a[c]	0.81 a	0.22 a	0.28 a	0.65ab	0.49 ab	0.47 a	0.39 a	0.44 ab	0.79 b
	168	0.91 a	0.61 a	0.34 a	0.23 a	0.56 ab	0.59 ab	0.35 ab	0.53 a	0.95 a	0.45 b
	224	0.46 a	0.92 a	0.21 a	0.34 a	0.58 ab	0.87 a	0.41 ab	0.49 a	0.48 ab	0.70 b
AC	112	0.61 a	1.02 a	0.28 a	0.36 a	0.51 ab	0.65 a	0.35 ab	0.54 a	0.93 ab	0.75 b
	168	0.85 a	1.13 a	0.33 a	0.42 a	0.51 ab	0.59 ab	0.37 ab	0.45 a	0.98 a	0.93 b
	224	0.63 a	0.83 a	0.33 a	0.34 a	0.69 a	0.69 a	0.51a	0.44 a	0.68 ab	1.17 a
Urea	112	0.17 a	0.23 a	0.09 a	0.11 a	0.61 abA	0.27 bB	0.43 abA	0.17 abB	0.27 ab	0.51 b
Check	0	0.25 a	0.14 a	0.11 a	0.09 a	0.34b	0.27 b	0.21 b	0.14 b	0.21 b	0.36 b

[a]Amendments.
[b]values expressed in gram (g).
[c]Means with different lower case letters within columns and different upper case letters between soil conditions (S vs. NS) with each variable indicate the significant difference at $P \leq 0.05$ using Fisher's LSD.

Table 5.11. The effect of animal (AC) and plant (PC) compost amendment at different rates, standard urea and non-amended check on carrot root fresh weight (RFW), root dry weight (RDW), shoot fresh weight (SFW), shoot dry weight (SDW) and root -to-shoot dry weight ratio (RD/SD) in pots filled with 960 g of sterilized (S) and non-sterilized (NS) sandy clay loam soil planted with Sugarsnax 54 after 86 days in 2013 experiments.

AM[a]	Rate (kg N/ha)	RFW		RDW		SFW		SDW		RD/SD	
		S	NS	S	NS	S	NS	S	NS	S	NS
PC	112	[b]6.73 bc[c]	4.87 ab	1.78 abc	1.52 a	3.59 abA	2.63 aB	0.66 a	0.54 a	2.84 a	2.82 a
	168	6.90 bc	4.74 ab	1.56 bcd	1.14 a	3.07 abc	2.45 a	0.52 a	0.43 a	3.03 a	2.77 a
	224	10.17 aA	4.69 abB	1.73 abcd	1.51 a	3.77 aA	2.82 aB	0.68 a	0.59 a	2.83 a	2.65 a
AC	112	7.55 abc	4.55 ab	2.42 aA	1.14 aB	4.02 aA	2.88 aB	0.77 a	0.58 a	3.24 a	1.99 a
	168	4.89 dc	5.29 ab	1.19 cd	1.6 a	2.77 bc	2.86 a	0.69 a	0.49 a	1.95 a	3.36 a
	224	8.66 abA	4.83 abB	2.13 abA	1.23 aB	3.77 a	2.87 a	0.63 a	0.46 a	3.29 a	2.81 a
Urea	112	3.61 dB	7.37 aA	0.99 dB	1.91 aA	2.45 c	3.15 a	0.45 a	0.68 a	2.48 a	3.07 a
Check	0	4.94 cd	4.28b	1.72 abcd	1.24 a	2.48 c	2.28 a	0.69 a	0.42 a	3.23 a	3.15 a

[a]Amendments.

[b]values expressed in gram (g).

[c]Means with different lower case letters within columns and different upper case letters between soil conditions (S vs.NS) within each variable indicate the significant difference at $P \leq 0.05$ using Fisher's LSD.

Relationships between nematodes and soil properties

The multifactor analysis results revealed correlation pattern in nematode trophic groups, nematode community and food web indices, soil and yield parameters in 2012 and 2013. In 2012, bacterivores, fungivores, and herbivores were positively while NH_4-N negatively correlated with Dimension 1 (Fig. 5.2A). CEC was positively correlated with Dimension 2. Calcium and soil pH were positively correlated each other while negatively correlated with soil moisture content. Herbivores, fungivores, omnivores and bacterivores positively correlated with each other while negatively correlated with NH_4-N. As illustrated in Fig. 5.2B, there was also a correlation pattern in soil food web indices, soil properties and yield parameters. Soil calcium, potassium and magnesium contents, and cation exchange capacity were positively correlated with each other and Dimension 1 (Fig. 5.2B). Most of the yield parameters positively correlated to each other while negatively correlated with soil nitrate-nitrogen and Dimension 2 (Fig. 5.2B). BI, CI and NH_4-N were negatively correlated with EI and decomposers-to-herbivores ration.

In 2013, soil magnesium and calcium contents, cation exchange capacity, bacterivores, and fungivores were positively correlated while nitrate-nitrogen, soil moisture, phosphorus and organic matter contents negatively correlated with Dimension 1 (Fig. 5.3A). Omnivores and predators positively correlated with Dimension 2 while negatively correlated to soil pH. Calcium and magnesium contents and cation exchange capacity were positively correlated while soil phosphorus, nitrate-nitrogen, moisture and organic matter contents negatively correlated with Dimension 1 (Fig. 5.3B). BI and CI positively correlated to each other, but negatively correlated with SI and EI. Root fresh and shoot fresh weights, and shoot dry weight was positively correlated each other while negatively correlated with soil phosphorus, nitrate-nitrogen, moisture and organic matter contents (Fig. 5.3B).

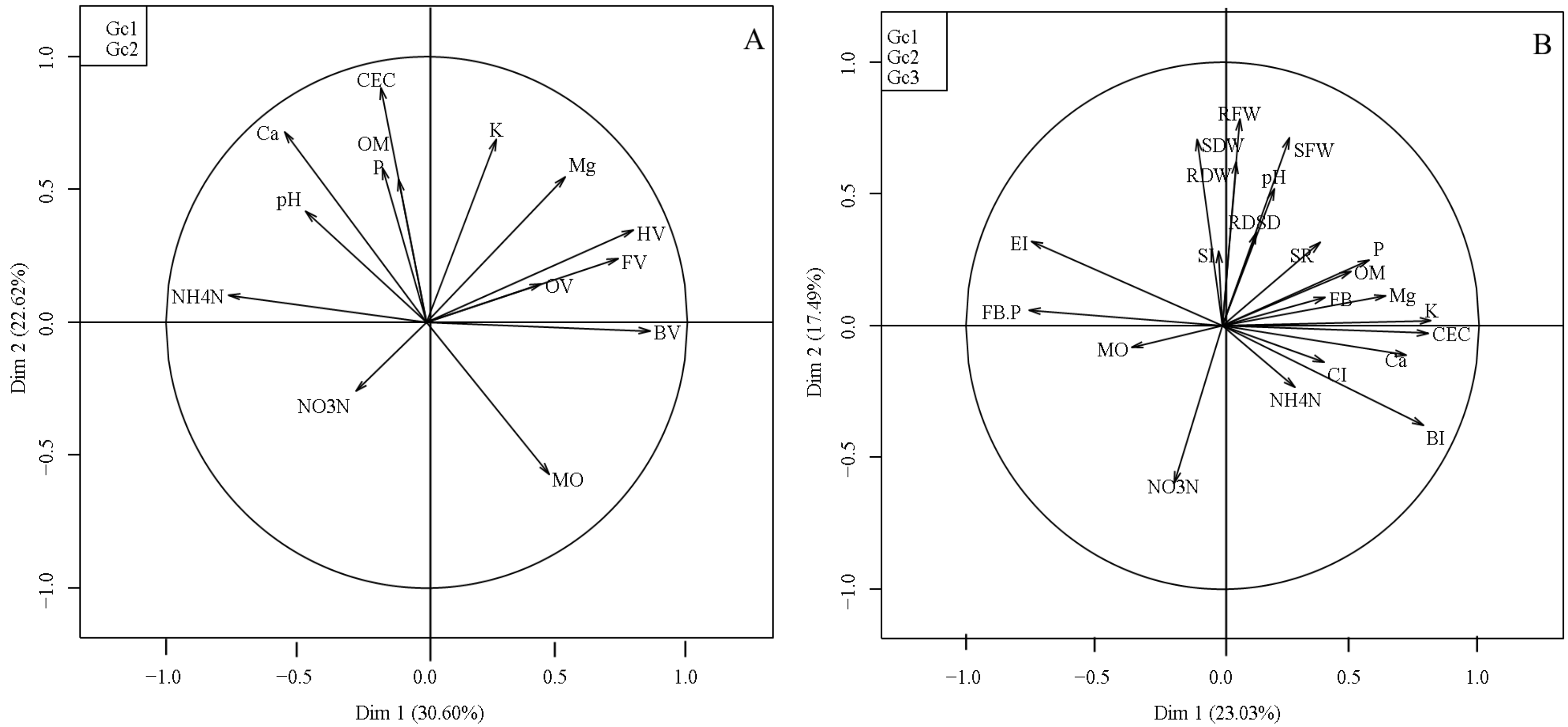


Figure 5.2. Multiple factor analysis of the variables where Dimension 1 (Dim 1) and Dimension 2 (Dim 2) represent the first and second best summary of variability of the information, respectively. (A) The relationship among abundance of nematode trophic groups (Gc1) (bacterivores (BV), fungivores (FV), omnivores (OV), predators (PR) and herbivores (HV) (Yeats et al., 1993)) and soil properties (Gc2) (soil pH (pH) , organic matter percentage (OM), nitrate-nitrogen (NO3N), ammonium-nitrogen (NH4N),calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), moisture percent (MO) and cation exchange capacity (CEC) in 2012. (B) The relationship among soil food web indices, trophic group ratios ((FV/BV)=FB) and ((FV + BV)/HV=FB.P) (Gc1), soil properties (Gc), and carrot yield (Gc3) (root fresh weight (RFW), root dry weight (RDW), shoot fresh weight (SFW), shoot dry weight (SDW) and root dry-to-shoot dry weight ratios (RDSD)) in 2012 from glasshouse experiment.

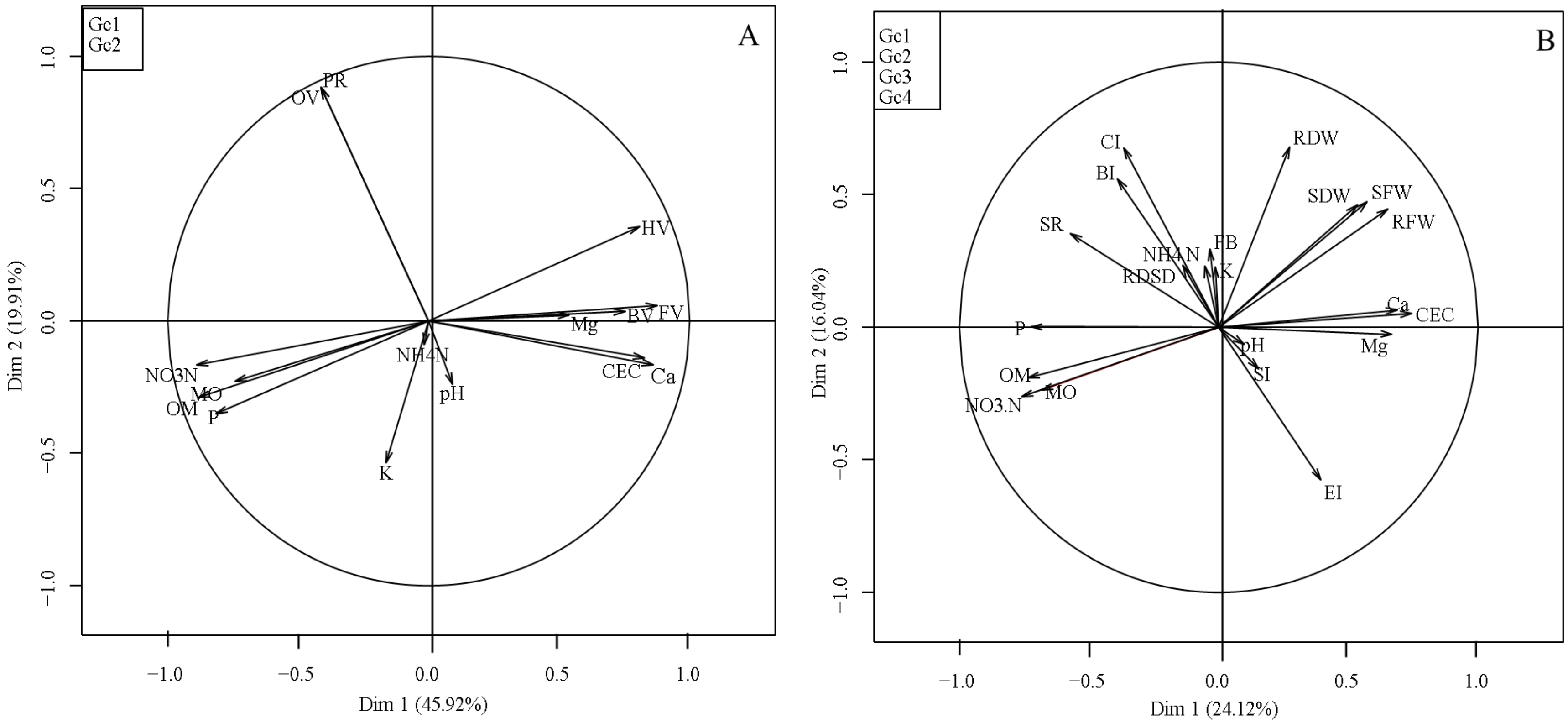


Figure 5.3. Multiple factor analysis of the variables where Dimension 1 (Dim 1) and Dimension 2 (Dim 2) represent the first and second best summary of variability of the information, respectively. (A) The relationship among abundance of nematode trophic groups (bacterivores (BV), fungivores (FV), omnivores (OV), predators (PR) and herbivores (HV) (Yeats et al., 1993)) and soil properties (soil pH (pH) , organic matter percentage (OM), nitrate-nitrogen (NO3N), ammonium-nitrogen (NH4N),calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), moisture percent (MO) and cation exchange capacity (CEC) in 2013. (B) The relationship among soil food web indices and, trophic group ratios (Gc1) ((FV/BV)=FB) and ((FV + BV)/HV=FB.P), soil properties (Gc), and carrot yield (Gc3) (root fresh weight (RFW), root dry weight (RDW), shoot fresh weight (SFW), shoot dry weight (SDW) and root dry-to-shoot dry weight ratios (RDSD)) in 2013 from glasshouse experiment.

Discussion

Tylenchus, Acrobeloides, and *Aphelenchus* and *Filenchus* were the most abundant herbivore, bacterivore and fungivore genera, respectively. These nematode genera were also among the most abundant nematodes extracted in the field experiment data collected from same treatments reported in Chapter 3. All of these genera belong to c-p 2 nematodes, which have stress tolerance ability (Bongers and Bongers, 1998). Overall, the abundance of omnivores and predators were low, may be due to unfavorable soil condition in the pots or short experimental period (86 days) as these nematodes normally require up to 130 days to reproduce (McSorley, 2012). The multiple factor analysis result supports the former argument that NH_4-N and NO_3-N were negatively correlated with the nematode trophic groups (Fig. 5.2A and 5.3A). Nematode abundance was higher in 2012 compared with 2013 samples at harvest. Nematodes were not detected in sterilized soil in both 2012 and 2013 soil samples because of either lack of recolonization from the air and tap water or they are below detection level requiring longer period of time depending of the area of recovery (Yeates et al., 1991; Yeates and van der Meulen, 1996). The alternative explanation could be soil sterilization alters the soil chemistry in ways that inhibit fast colonization by the nematodes (Trevors, 1996; Shaw et al., 1999; Ferris, 2010). Indeed, soil sterilization increased soil NO_3-N and NH_4-N and both of which were negatively correlated with nematodes.

Herbivores, bacterivores and fungivores were higher at planting before the treatments were applied in non-sterilized soil. Similarly, H’ and Hill’s N1 diversity indices were higher at planting compared with some of the treatments at harvest. In 2013, Hill’s N0 was also higher at planting. However, there were no differences in MI, MI25, EI, SI, BI, CI, fungivores-to-bacterivores and fungivores plus bacterivores-to-herbivores ratios and fertility index among the treatments in both years except PPI was higher at planting in 2013. The food web was basal in most of the data points, suggesting stressed soil condition with where fungal feeders dominated decomposition pathway and degraded soil food web (Ferris et al., 2001).

The result of the present study showed that generally compost amendments increased soil pH in sterilized and non-sterilized soils, and soil sterilization generally decreased soil pH. This is contrary to some of the previous studies that showed increase in soil pH due accumulation of ammonium as a result of decomposition of dead microorganisms and the loss of ammonium oxidizing bacteria (Tanaka et al., 2003). However, the results are partially in line with my field experiments that compost amendments increased soil pH (Chapter 3). However, Skipper and Westermann (1973) and Shaw et al. (1999) reported that decreased in soil pH due to release of organic acids from organic matter. The variable effects of soil sterilization could be due to differences in soil characteristics (Williams-Linera and Ewel, 1984; Shaw et al., 1999).

AC had greater effect in increasing soil phosphorus content than urea. This supported the result of the field experiment from the same treatments (Chapter 3). Soil sterilization also increased soil phosphorus content may be either due to break down of organic phosphorus or increase in solubility of organic phosphorus that will be broken down later (Malowany and Newton, 1947). Treatments had variable effects on soil potassium content though these treatments increased potassium in the field experiment (Chapter 3). Soil sterilization had no effect on soil potassium content. Previous reports were also inconsistent on the effect of soil sterilization on potassium content (Salonius et al., 1967; Skipper and Westermann, 1973).

Similar to previous studies, soil sterilization had no effect on soil calcium content (Skipper and Westermann, 1973; Williams-Linera and Ewel, 1984). Treatment effect was variable on soil magnesium content though these treatments had no effect on soil magnesium content in the field (Chapter 3). Similarly, effect of sterilization was not consistent on magnesium content in other studies (Salonius et al., 1967; Williams-Linera and Ewel, 1984). The results showed that only PC at 224 kg N/ha increased cation exchange capacity on non-sterilized soil in 2012. Eno and Popenoe (1964) reported that soil sterilization had no effect on cation exchange capacity as observed in the present study. Similarly, all of these treatments did not increase or decrease cation exchange capacity in 2 years field data (Chapter 3). The increase in cation exchange capacity in PC at 224 kg N/ha in the glasshouse may be attributed to high calcium content of PC that increased with the rate of application (Table 5.1).

Effects of soil amendments were not consistent on soil organic matter that showed increase only in 2013. However, compost amendments increased soil organic matter after 2 years of the experiment (Chapter 3). Over all soil sterilization did not decrease soil organic matter though studies showed organic matter decreased due to decomposition as a result of heating during soil sterilization (Malowany and Newton, 1947; Skipper and Westermann, 1973). Different studies have shown that soil sterilization increased NO_3-N gradually as I found here (Malowany and Newton, 1947; Salonius et al., 1967). The results in non-sterilized soil were consistent with my field data that only urea significantly increased NO_3-N compared with plant and animal compost amendments (Chapter 3). Consistent to the result of the field experiment, compost amendments did not increase NH_4-N in the glasshouse (Chapter 3). However, soil sterilization increased soil NH_4-N. Previous reports showed that soil sterilization increased NH_4-N compare with non-sterilized soil because of the decomposition of organic matter (Malowany and Newton, 1947; Salonius et al., 1967; Trevors, 1996).

The significant increase in soil respiration in sterilized soil at planting in the present study may be due to initial release of CO_2 due to decarboxylation of organic matter (McNamara et al., 2003). Otherwise, substrate induced respiration rates generally reduced relative to the control due to decreased microbial activity (Ramsay and Bawden, 1983). Compost amendments and urea increased shoot fresh and dry weight compared with non-amended check on both sterilized and non-sterilized soils in 2012. However, compost amendments generally increased root fresh and dry weight, and shoot fresh weight compared with urea and non-amended check on sterilized soil, but such effect was not observed on non-sterilized soil.

In conclusion, the nematode genera dominated by c-p 2 herbivores and non-herbivores in non-sterilized soil in both years. Omnivores and predators almost non-existent on non-sterilized soil may be because of unfavorable soil condition in the pots that affect their reproduction or short experiment time that was no long enough for these nematodes to complete their life cycle. The soil food web analysis also revealed that the food web was basal in most of the data points, suggesting stressed soil condition with fungal dominated decomposition pathway and degraded soil food web. Nematodes were not detected in sterilized soil at planting and harvest in both years because of either lack of recolonization from the air and tap water or they are below detection level which requires longer period of time depending on recovery conditions. It could also be because of the effect of soil sterilization on the soil chemical and physical properties that inhibit the fast colonization by nematodes. Soil sterilization, generally, increased the contents of measured nutrients. Soil sterilization decreased soil pH may be due to release of organic acids from soil organic matter. I also found soil sterilization increased CO_2 evolution in sterilized soil. Carrot fresh and dry weights were small due to the stunt carrot growth. These results generally suggest that the effect of compost amendments may not be observed in severe biologically degraded soil in the short-term.

CHAPTER 6

SECOND MODIFICATION OF THE FERTILIZER USE EFFICIENCY (FUE) MODEL INTEGRATING WEIGHTED NEMATODE GUILDS FOR BROADER USE IN SOIL HEALTH MANAGEMENT

Abstract

The objective in this chapter was to integrate the concepts of FUE and soil food web models and test FUE model resolution power on integrated cross-disciplinary decision-making. To accomplish this, I used data from field experiments conducted in 2012-2014 and 2012-2013 where the effects of different rates of PC and AC compost on nematode community, soil properties, and yield and quality of 'Cupar' and 'Sugarsnax 54', respectively, were tested. Most of the data points of compost amendments fell in Quadrant B (best case scenario) for organic matter, soil pH and marketable yield while data points of urea fell in Quadrant A (poor soil health) and Quadrant C (poor soil health and agronomic traits). Statistical comparisons between treatments data points and 100 % (the control) showed that most of the compost amendments were significantly greater than 100 % for organic matter after two years. PC at 135 and 203 kg N/ha also showed greater marketable yield and lower unmarketable yield. Except PC at 270 kg N/ha and AC at 203 kg N/ha, weighted nematode guilds abundance was significantly greater than 100 % in compost amendments. These results supported findings on nematode-based soil food web model reported in Chapter 3. The overall analysis showed not only an improvement of the FUE model for soil health analysis in this study, but also integrates it with soil food web model. This is a step towards broader and cross-disciplinary efficiency analyses of management practices across ecosystems.

Introduction

As the most abundant metazoan on the planet, nematodes are excellent indicators of changes in soil ecosystem (Bongers and Bongers, 1998). Nematodes are also central players in the soil food web and nutrient cycling processes (Ingham et al., 1985; Ferris et al., 2001). The latter point is particularly significant in the development of integrated and sustainable soil nutrient and agroecosystem management practices (Ferris et al., 2001; Yeates et al., 2009). In order to exploit nematodes' best attributes, however, we need to understanding how agronomic, pest and disease as well as soil nutrient management practices in the prevailing agroecosystems influence nematodes (Bulluck III et al., 2002a; Wang et al., 2006; Neher, 2010; Melakeberhan et al., 2015). For example, most nematode management in agricultural practices are focused on suppressing herbivore nematodes. Moreover, most pest and disease management, and increasing crop yield by modifying the plant and/or the soil (Melakeberhan, 1997; Baligar et al., 2001; Good et al., 2004) and do not factor beneficial nematodes and their role in nutrient cycling (Ingham et al., 1985; Neher et al., 2012).

In order to utilize the best attributes of nematodes, it is necessary to consider the current soil and nutrient management practices designed to improve crop yield and/or suppress nematodes and other pests and diseases (Melakeberhan, 2006). For the most part, they are applied to manage one factor or another and do not consider integrated outcomes (Melakeberhan and Avendaño, 2008). In other words, they test the hypothesis that either crop yield will increase and/or pest will be suppressed as opposed to testing whether there are quantifiable relationships that will lead to assessing integrated efficiency. Such an approaches need to account for ecosystem functions and processes where agrobiological, physicochemical, economic and environmental efficiencies can be separated (Melakeberhan, 2010). This can be achieved using the Fertilizer Use Efficiency (FUE) model (Melakeberhan, 2006).

The FUE model, which separates the relationships among plant growth, herbivore nematode parasitism, nutrient deficiency and toxicity, allows cross-disciplinary and integrated decision-making (Melakeberhan, 2006). It calculates treatment outcome as a percent of control (untreated check) and graphically expresses data in four quadrants from best (Quadrant A) to worst case (Quadrant D) scenarios (Fig. 6.1a). The FUE model was modified to include assessment of beneficial nematodes and soil physicochemical properties (Fig. 6.1b, Melakeberhan and Anvendaño, 2008). Such integrated analysis links nematology and cross-disciplinary gaps in testing agriculturally and ecologically sustainable management practices (Melakeberhan and Avendaño, 2008; Melakeberhan, 2010).

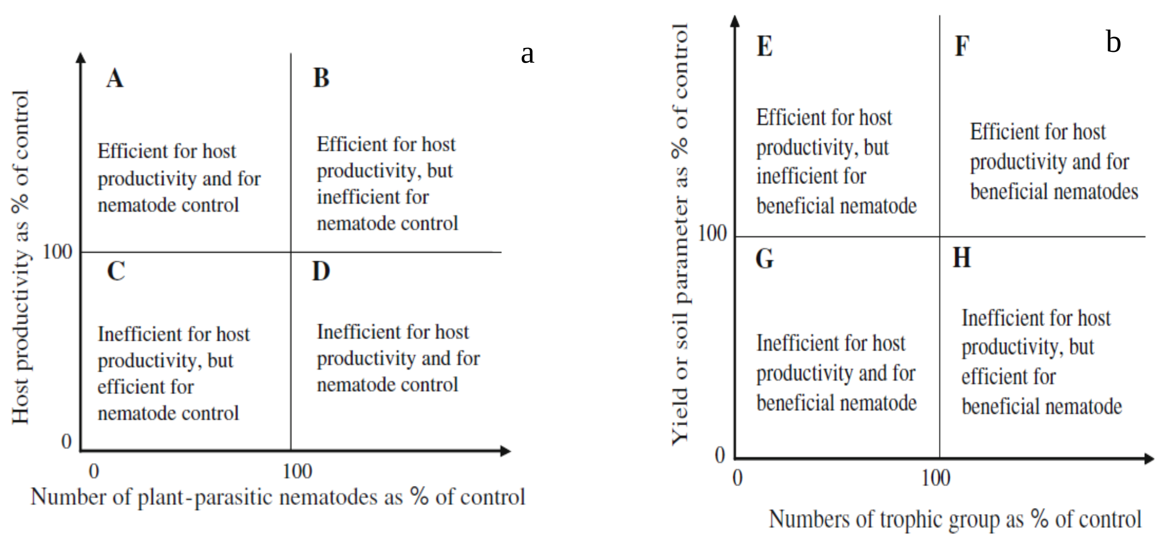


Figure 6.1. Fertilizer use efficiency (FUE) model and its modification. (a) Four hypothetical categories of FUE derived from host productivity/nematode/nutrient interactions (Melakeberhan, 2006) with permission from Brill and (b) modified FUE model applied to assess the effect of soil amendment on the relationships between nematode trophic groups (excluding plant-parasitic) and yield or soil parameters (Melakeberhan and Avendaño, 2008) with permission Springer.

The nematode-based Ferris et al. (2001) soil food web model describes soil conditions from best (Quadrant B) to worst (Quadrant D) case scenarios for agroecosystem suitability and nutrient cycling potential (Fig. 6.2). It uses a graphic representation of the relationship between the nematode EI (a measure of opportunistic bacterivore and fungivore nematodes) and SI (indicator of food web state affected by stress or disturbance) to describe the soil community profile in four quadrants.

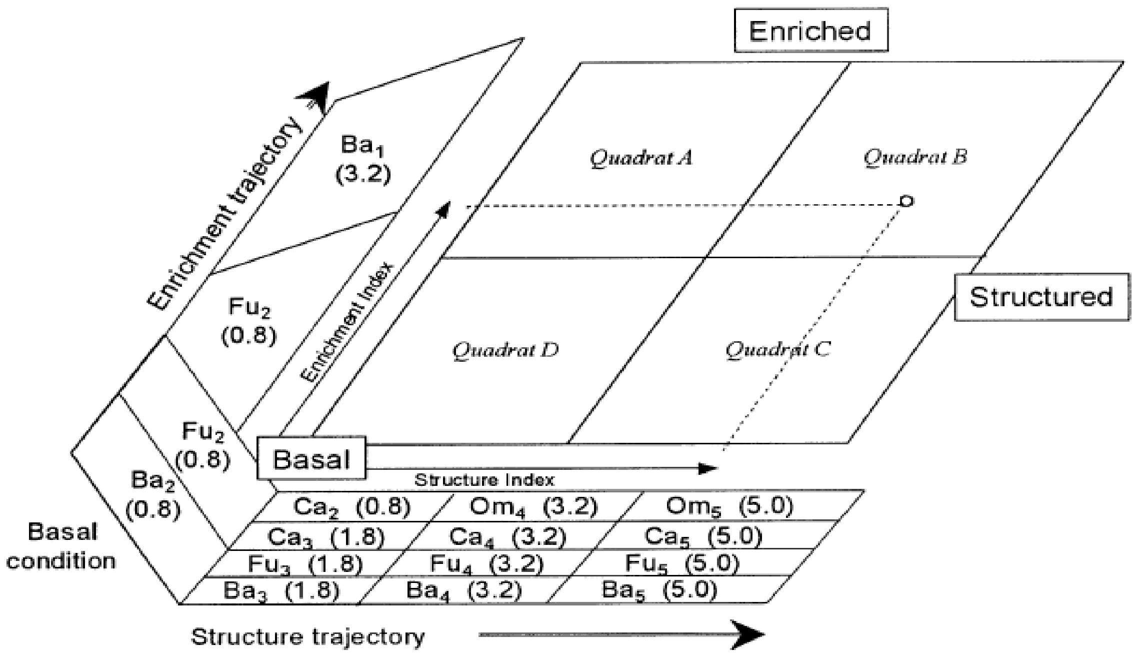


Figure 6.2. Functional guilds of soil nematodes characterized by feeding habit and by life history characteristics expressed along a colonizer-persister (c-p) scale (After Bongers & Bongers, 1998). Indicator guilds of soil food web conditions (basal, structured and enriched) are designated and weightings of the guilds along the structure and enrichment trajectories are provided for determination of the enrichment index (EI) and structure index (SI) of the food web (Source: Ferris et al., 2001) with permission from Elsevier.

Apart from the possibility for cross-disciplinary and integrated analysis, the graphical presentation of FUE model creates an opportunity to demonstrate changes not apparent in the calculation of nematode indices. However, the FUE model and its modification are based on numbers of nematodes, but not functional guilds. On the other hand, soil food web model lacks integrated efficiency analysis on the impact of management practices.Therefore, the objective of the study was to integrate the concepts of FUE and soil food web models and test FUE model resolution power on integrated agroecological analysis.

Materials and methods

Experimental design and treatments

A field study was conducted to investigate the effects of PC and AC on nematode community structure, herbivores suppression and soil properties, and yield and quality of Cupar and Sugarsnax 54 in 2012- 2014 growing seasons. AC was purchased from Morgan Composting, Inc., Sears, MI, USA, and PC was obtained from MSU Student Organic Farm, Holt, MI, USA. The characteristics of the composts are presented in Chapter 3 (Table 3.1). The experiment was conducted at Michigan State University (MSU) Horticulture Teaching and Research Center in Holt, Michigan (N 43^{0}24.040', W 085^{0}56.559', 854 m elevated) in a Colwood-Brookston sandy clay loam (fine-loamy, mixed, mesic Type, Haplaquolls-Argiaquolls, Anon, 1977) with 54 % sand, 25 % silt and 21 % clay.

Compost treatments were adjusted to supply 135, 203 and 270 kg N/ha, and 112, 168 and 224 kg N/ha for Cupar and Sugarsnax 54, respectively. Standard urea (135 and 112 kg N/ha for Cupar and Sugarsnax 54', respectively) and non-amended check were included as controls. Treatments were arranged in randomized complete block design with four replications.

Each plot was 3.72 meter square. Treatments were applied, distributed uniformly by hand and mixed to a depth of 30 cm using an RTR2548 rototiller (Land Pride, Assaria, KS, USA) before planting. Carrot seeds were planted at the rates of 640,000 and 1, 200,000 seeds/ha for Cupar and Sugarsnax 54, respectively, using MasterMacc planter (Market Farm Implement, Friedens, PA, USA). Throughout the duration of the experiment, weed control measures were taken as per recommended standard herbicides for carrots and hand weeding. Herbicides consisted of preemergenc application of linuron (0.56 kg a.i/ha) 1 to 2 weeks after carrot planting, and postemergence application of linuron (0.56 kg a.i/ha) and clethodim (0.1 kg a.i/ha) applied at 4 to 6 weeks after carrot planting. Plots were irrigated with sprinkler irrigation system set for an hour every day until the carrots emerged and for 4 hours as required after carrot emergence. Experiments for Cupar were completed 132 and 133 DAP in 2012, and 2013 and 2014 growing seasons, respectively, and Experiment for Sugarsnax 54 were completed 78 and 79 DAP in 2012 and 2013 growing seasons, respectively.

Soil sampling, and nematode extraction, identification and enumeration

In 2012, 2013 and 2014, six soil cores per plot were collected at 0-25 cm soil depth of root zone from the center two rows using a sampling cone (AMES companies, Inc., Camp Hill, PA, USA) at planting (May, June) and at harvest (October). After soil sampling, the holes were gently closed by returning soil to the sampling spots to avoid further soil disturbance. The soil from the six cores was thoroughly mixed to form a composite of approximately 1,000 cc, transported to the laboratory and stored in a cold room at temperature of 5 ^{0}C. Nematodes were extracted from 100 cc of soil using the standard lab procedures (Avendaño et al., 2003) and fixed according to Hooper (1986). Nematodes were identified under inverted microscope (Accu-scope Inc, Commack, NY, USA) at 400X magnification at genus level following diagnostic keys by Bongers (1994) and the University of Nebraska Lincoln nematode identification website (http:nematode.unl.edu/konzlistbutt.htm). Each identified nematode was assigned to a colonizer-presister (c-p) scale according to Bongers & Bongers (1998).

Soil pH, organic matter and carrot yield

Soil organic matter and soil pH, and marketable and unmarketable carrot yield were selected as a measure of integrated efficiency of the treatments. Soil pH and organic matter were determined from 2012 and 2013 samples by the MSU Soil and Plant Nutrient Laboratory using standard procedures (Huffman & Barbarick, 1981; Nelson, 1983). Carrots were harvested from the center two rows using spading fork (True Temper, AMES companies, Inc., Camp Hill, PA, USA) and washed with a garden hose. Carrots were categorized and counted as marketable and unmarketable following USDA standards (Anon, 1965).

Integrating FUE and soil food web models concepts

The original FUE model is centered on managing the impact of herbivore nematodes (Melakeberhan, 2006). It was modified to integrate beneficial nematodes trophic groups with links to agronomic, economic and soil health parameters (Melakeberhan and Avendaño, 2008). In order to expand the FUE model's use, it needs integration of nematode guilds concept (Ferris et al., 2001). The Ferris et al. (2001) model evaluates the soil food web and soil conditions by identifying three food web conditions as basal, enriched and structured. Soil food web model is potentially important for soil resource managers, both for diagnostic purposes and as a basis for management decisions (Ferris et al., 2012).

The second modification of the FUE model (Fig. 6.3), proposed herein, integrates nematode guilds concept of Bongers & Bongers (1998) and weightings of nematode guilds (Ferris et al., 2001). Nematode guild concept refers the assemblage of nematode species with similar biological attributes and response to environmental conditions as described by Ferris et al. (2001). As described in Ferris et al. (2001) weighting system integrates nutrient transfer during the life course, organism longevity, food web complexity, individual biomass and disruption-sensitivity of functional guilds.

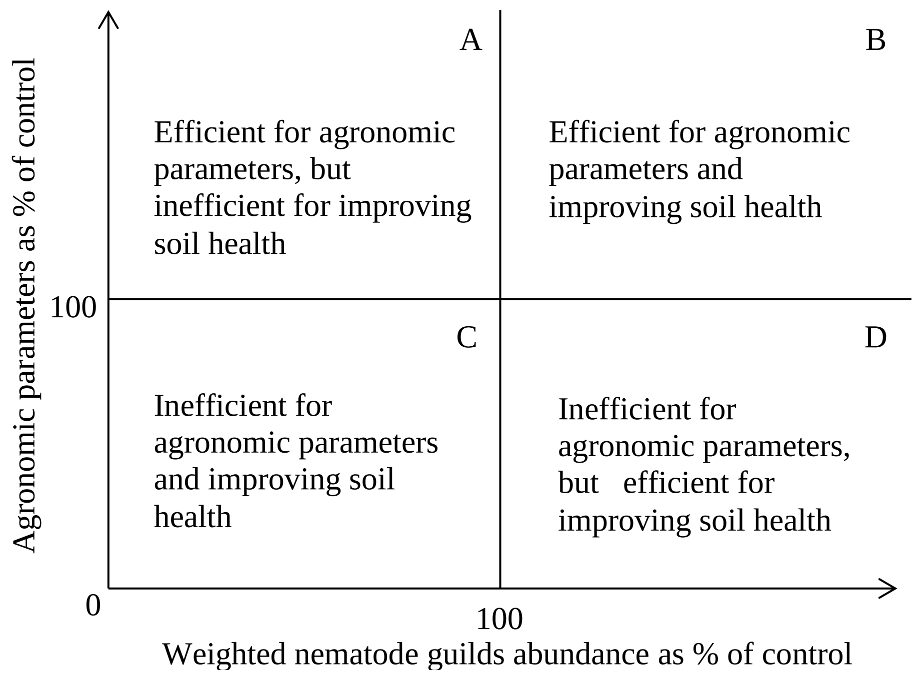


Figure 6.3. The second modification of FUE model that integrated concepts of modified FUE and soil food web models to assess the effect of soil amendment on the relationships between nematode functional guilds as indicator of soil health and other agronomic parameters. Data points that fall above the controls (100 %) will show an increase/improvement in tested agronomic parameters (A and B) and soil health status (B and D). Data points in Quadrant B would be best-case scenario, in Quadrant C would be worst-case scenario, and those Quadrant A and D provide a choice of improving soil health or yield, respectively (After Melakeberhan and Avendaño, 2008) with permission from Springer.

Unlike the soil food web model, the enrichment and structure components of the food web are not treated separately in the second modification of FUE model. The total nematode assemblage is treated in the concept of trophic connectance in food web of increasing complexity as the system matures or becomes progressively simple as the system degrades. The assumption is that the food web in healthy soils will contain all the nematode functional groups including c-p 1 nematodes which are present in all habitats from disturbed to the most stable tropical forest, fruits and carcasses (Bongers and Bongers, 1998). This explains food webs of higher complexity contain representatives of food webs of lower complexity (Bongers and Bongers, 1998). As Ferris et al. (2012) stated, a healthy soil food web should sustain nematodes of different life strategies. These include those with feeding behaviors ranging from fast-growing and fast-breeding bacteria-feeding nematodes at the bottom of the food chain, to those slow growing, long generation and low fecundity predaceous nematodes at the top.

Second modification of the FUE model

Weighted nematode guilds abundance that includes all nematode guilds in the calculations was proposed (Fig. 6.3). Ferris et al. (2001) weighting systems for c-p 2 up to c-p 5 nematodes were adopted and introduced a new weight for c-p 1 nematodes. The Ferris et al. (2001) weightings of nematode guilds in structure trajectory reflect the postulated degree of trophic connectance in food webs of increasing complexity as the system matures or progressive food web simplicity as the system degrades. They assumed that trophic links (l) increase as a constant fraction of square of the number of species (s) and is calculated as αs^2 where α is a constant and s is the number of species. Based on the available data, they established the formula for weightings of c-p values which is $0.8*(0.5*(n+1))^2$ where n is the c-p value and "0.5" is a fraction of increase in food web complexity with each increment in c-p class. Using this concept and formula, a new weight was introduced for the c-p1 nematodes different from the weight given by Ferris et al. (2001).

C-p 1 nematode received weight $(0.8*(0.5*(0+1))^2 = 0.2)$ based on their indicator role in the structured food web though Ferris et al. (2001) assigned the weight (3.2) to c-p 1nematodes based on their responsiveness to nutrient enrichment. Their weight (0.2) is reasonable to weight their presence and abundance in structured food web and undisturbed soil. In the calculations, weighted nematode guilds abundance received the following weights based on their presence and abundance in healthy soil assumed to have structured soil food web. The weights will be c-p 1= 0.2, c-p 2 = 0.8, c-p 3 = 1.8, c-p 4 = 3.2 and c-p 5 = 5. Weights of nematode guild for each treatment were calculated as:

Weighted nematode guilds abundance

= (0.2*total no. cp1) + (0.8*total no. cp2) + (1.8*total no. of cp3) + (3.2*total no. cp4) + (5*total no. cp5) [1]

Fitting the data to the second modification of the FUE model

Before plotting the data, values will be standardized as percent of control as follows:

Weighted nematode guilds abundance as % of control

$$= 100 * \left(\frac{\text{average weighted nematode guids for each treatment}}{\text{average weghted nematode guilds for the control}}\right) \qquad [2]$$

Agronomic or soil parameter of interest as % of control

$$= 100 * \left(\frac{\text{average organic matter \% in each treatment}}{\text{average organic matter \% in control}}\right) \qquad [3]$$

After calculating weighted nematode guild abundance and other agronomic parameters as a percent of control, they are plotted on x-axis (weighted nematode guild abundance) and y-axis (agronomic parameters and other parameters) for analysis of integrated efficiency (Fig. 6.3). Best case scenario would be if data points fell in Quadrant B, where the agronomic parameters and soil health condition are improved. Worst case scenario would be if data points fell in Quadrant C, where agronomic parameters and soil health status are not improved. Data points that fall in Quadrants A and D are half efficient and will require complementary intervention to improve soil health status or other agronomic parameters, respectively. The second modification not only improves the power of the FUE model for soil health analysis, but also integrates it with the soil food web model. This, in turn, will lead to much broader and cross-disciplinary analyses on management practices than currently exist.

Statistical analysis of data fitted to the second modification of the FUE model

Two types of statistical analyses were conducted. First, data used in this study were analyzed following the standard ANOVA and mean separations (Tables 6.1 and 6.2). Second, the weighted nematode guilds abundance (x-axis) and agronomic parameters (y-axis) data points were expressed on a percent of control basis and fitted to the FUE model (Figs. 6.4 – 6.7). The data fitted to the FUE model were then tested for statistical difference from the control (100 %) using one-tail t-test at $\alpha = 0.05$. The means of the treatments with statistical difference from 100 % are noted by asterisks (*).

Results

The previous data analysis (Chapter 3) showed that compost treatments significantly increased soil pH in Cupar at harvest in 2013 compared with at planting in 2012 (Table 6.1). However, urea decreased soil pH at harvest in 2013 compared with at planting in 2012. Urea also significantly decreased soil pH at harvest in 2012 and 2013 compared with all of the compost treatments. There was no significant difference in soil organic matter, marketable and unmarketable carrots among the treatments.

In Sugarsnax 54, all of the compost amendments significantly increased soil pH at harvest 2013 compared with at planting in 2012 (Table 6.1). Urea significantly decreased soil pH at harvest in 2013 compared with at planting in 2012. PC at 168 kg N/ha, and AC at 112 and 224 kg N/ha significantly increased organic matter compared with urea and non-amended check in Sugarsnax 54 at harvest in 2013. PC at 168 kg N/ha and AC at 112 kg N/ha showed comparable marketable carrot yield to urea in 2012. In 2013, compost amendments significantly increased marketable carrot yields compared with urea and non-amended check (Table 6.2).

In 2012, almost all of the soil samples were generally lower in organic matter relative to non-amended check before the treatments were applied in Cupar (Fig. 6.4). At the same time, weighted nematode guilds abundance was lower in all of the compost treatments except PC at 135 N/ha and AC at 135 and 270 kg N/ha relative to non-amended check in Cupar (Fig. 6.4). However, all compost amendments except PC and AC at 135 kg N/ha increased organic matter at harvest 2013. Comparing these data points with the control (100 %) showed that all of the AC treatments and PC at 270 kg N/ha were significantly greater than 100 % at harvest (October) in 2013 (Fig. 6.4). Similarly, all of the compost amendments increased weighted nematode guilds abundance except PC at 135 kg N/ha and AC at 203 kg N/ha at harvest in 2012. Weighted nematode guilds abundance in all of the treatments was not different from 100 % at harvest in 2012. At harvest in 2013, PC at 203 kg N/ha and AC at 270 kg N/ha were significantly greater than 100 %. Similarly, weighted nematode guilds abundance at harvest in 2014 as significantly greater than 100 % in all of the compost amendments except PC at 270 kg N/ha and AC at 203 kg N/ha. Such effect was not observed in urea (Fig. 6.4 and 6.5). Organic matter and weighted nematode guilds abundance in all compost amendments were greater than in the check at harvest in 2013 (Fig. 6.4). Moreover, the effects of AC amendments on both organic matter and weighted nematode guilds were greater compared with the PC amendments except PC at 270 kg N/ha. Although urea increased organic matter in 2012 relative to the check, it decreased in 2013. Furthermore, urea decreased or did not affect weighted nematode guilds abundance compared with non-amended check in 2012 and 2013.

At planting in 2012, soil pH was higher in all compost treatments compared with non-amended check in Cupar. However, all of the compost treatments except AC at 135 kg N /ha had lower weighted nematode guilds abundance compared with the non-amended check at planting in 2012 (Fig. 6.4). However, all compost amendments except PC at 203 kg N/ha, had higher or same level of soil pH compared with non-amended check at harvest in 2012. The t-test comparison showed that PC and AC at 270 kg N/ha plots and urea had significantly higher soil pH than 100 % at the beginning. However, PC at 135 kg N/ha and AC at 270 kg N/ha, significantly increased soil pH while urea significantly decreased it at harvest in 2013 (Fig. 6. 4). All compost increased soil pH at harvest in 2013. However, urea decreased soil pH compared with the non-amended check in 2012 and 2013. All compost amendments, except PC at 135 and 270 kg N/ha in 2012 and PC at 270 kg N/ha, increased marketable carrots relative to non-amended check (Fig. 6.5). However, the comparison showed that none of the treatments were significantly greater than 100 % in marketable and unmarketable carrot in 2012. PC at 203 kg N/ha was greater than 100 % in marketable carrots in 2013. In 2014, PC at 135 and 203 kg N/ha were greater than 100 % in 2014 (Fig. 6.5). Overall, all of compost treatments except PC at 203 and AC at 203 kg N/ha reduced unmarketable carrots relative to non-amended check in all years. However, urea increased unmarketable yield relative to the check in 2013 and 2014. The comparison with 100 % showed that PC at 135 and 270 kg N/ha, and AC at 135 kg N/ha significantly decreased unmarketable carrots in 2013. Such significant decrease in unmarketable carrots was observed in PC at 135 kg N/ha while urea increased it (Fig. 6.5). All of compost amendments, except PC at 135 kg N/ha in 2012 and PC at 270 kg N/ha, in 2014 increased weighted nematode guilds abundance relative to non-amended check. However, urea decreased weighted nematode guilds abundance in all years relative to non-amended check.

Table 6.1. Soil organic matter (% OM), soil pH, and marketable and unmarketable carrots (T/ha) in Cupar plots amended with animal (AC) and plant (PC) composts at different rates (kg N/ha), standard urea application and non-amended check in sandy clay loam soil at planting (0) and at 132 and 133 days after planting (DAP) in 2012-2013 growing season for % OM and pH, and in 2012-2014 growing seasons for carrot yield (T/ha).

		% OM				pH				Marketable			Unmarketable		
		2012		2013		2012		2013		2012	2013	2014	2012	2013	2014
	Rate (Kg	DAP				DAP				DAP					
AM[a]	N/ha)	0	132	0	133	0	132	0	133	132	133	132	133	132	133
PC	135	1.6	1.8	2.4	2.1	7.2 bA[b]	7.3 bAB	7.5 bA	7.7 aA	35	56	35	46	14	13
	203	1.7	1.9	2.3	2.0	7.2 bA	7.1 bAB	7.4 bA	7.7 aA	59	64	34	46	23	16
	270	1.7	2.0	2.4	2.2	7.2bA	7.5bA	7.5 bA	7.7 aA	30	58	19	51	14	18
AC	135	1.7	1.9	2.3	2.1	7.1bA	7.2bAB	7.4 bA	7.7 aA	59	56	24	43	15	20
	203	1.7	2.0	2.4	2.2	7.2bA	7.2bAB	7.5 bA	7.7 aA	44	54	26	52	17	22
	270	1.6	2.0	2.3	2.2	7.2bA	7.2bAB	7.5 bA	7.7 aA	44	52	31	52	15	21
Urea	135	1.7	2.0	2.4	1.9	7.3aA	6.8cB	7.4 abA	7.2 bB	56	54	26	47	23	26
Check	0	1.8	1.9	2.4	1.9	7.1bA	7.2bAB	7.4 aA	7.6 aA	44	52	23	51	19	21

[a]Amendments.

[b]Means with different lower case letters in rows within each variable and different upper case letters within columns indicate significant difference at $P \leq 0.05$ using Fisher's LSD.

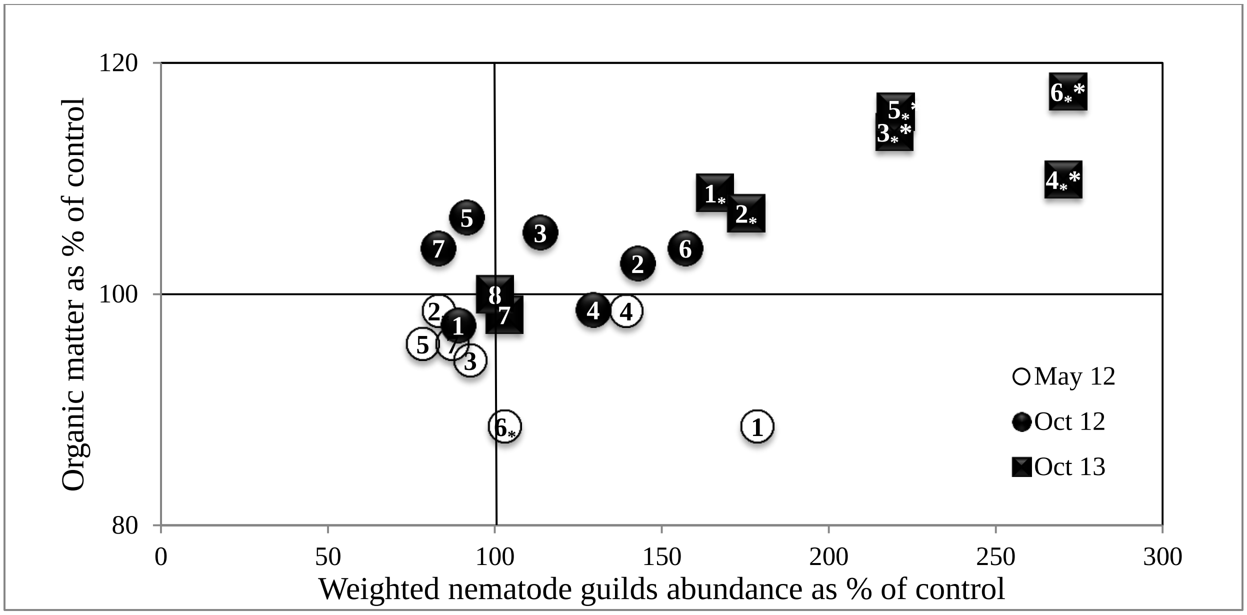
Table 6.2. Soil organic matter (% OM), Soil pH, and marketable and unmarketable carrots (T/ha) in Sugarsnax 54 plots amended with animal (AC) and plant (PC) composts at different rates (kg N/ha), standard urea application and non-amended check in sandy clay loam soil at planting (0) and at 78 and 79 days after planting (DAP) in 2012-2013 growing seasons.

		% OM				pH				Marketable		Unmarketable	
		2012		2013		2012		2013		2012	2013	2012	2013
	Rate (Kg	DAP		DAP		DAP		DAP		DAP		DAP	
AM[a]	N/ha)	0	78	0	79	0	78	0	79	78	79	0	79
PC	135	3.1 aB[b]	2.3 cA	2.8 bA	2.7 bAB	7.3 bAB	7.3 bA	7.3 bA	7.5 aA	3 b	16 a	16	9
	203	3.2 aA	2.4 cA	2.7 bA	2.9 abA	7.3 bAB	7.3 bA	7.3 bA	7.6 aA	11 a	18 a	16	8
	270	3.0 aB	2.3 cA	2.7 bA	2.8 abAB	7.2 bAB	7.3 abA	7.3 abA	7.4 aA	4 b	17 a	16	9
AC	135	3.2 aA	2.4 cA	2.8 bA	3.0 abA	7.4 aA	7.3 bA	7.3 bA	7.6 aA	7 ab	17 a	19	8
	203	3.1 aB	2.3 cA	2.8 bA	2.9 abA	7.4 bAB	7.4 bA	7.3 bA	7.6 aA	3 b	17 a	16	10
	270	3.0 aB	2.3 cA	2.7 bA	3.1 aA	7.3 bAB	7.4 bA	7.2 bA	7.5 aA	5 b	17 a	17	9
Urea	135	3.1 aB	2.2 cA	2.6 bA	2.5 bB	7.2 aB	7.2 aA	7.2 aA	7.0 bB	10 a	11 b	17	7
Check	0	3.1 aB	2.2dA	2.8 bA	2.6 cB	7.3 bAB	7.3 bA	7.3 bA	7.5 aA	6 b	11 b	15	6

[a]Amendments.
[b]Means with different lower case letters in rows within each variable and different upper case letters within columns indicate significant difference at $P \leq 0.05$ using Fisher's LSD.

In Sugarsnax 54, all compost treatments increased organic matter at harvest while urea decreased it relative to non-amended check at harvest in 2012 and 2013 (Fig. 6.6). There was no significant difference from 100 % in soil organic matter at the beginning of 2012 and at the end of 2012 growing season. However, all compost amendments were greater than 100 % at harvest in 2013, but such effect was not observed in urea (Fig. 6.6). All compost amendments except PC at 168 and 224 kg N/ha, increased weighted nematode guilds abundance at harvest in 2012 and 2013. At harvest in 2012, weighted nematode guilds abundance in PC at 168 and 224 kg N/ha was significantly lower than 100%. At harvest in 2013, weighted nematode guild abundance was significantly greater in AC at 224 kg N/ha than 100 % (Fig. 6.6). Soil pH in compost amendments was not different from 100 %, but urea was significantly lower than 100 %.

With regard to Sugarsnax 54 carrot yield, PC at 112 and 224 kg N/ha, and AC at 112, 168 and 224 kg N/ha, decreased marketable carrots relative to non-amended check in 2012. However, all compost amendments increased marketable carrots relative to non-amended check in 2013 (Fig. 6.7). Contrary to this, all the compost treatments increased total unmarketable carrots relative to non-amended check in 2012 and 2013 (Fig. 6.7). Marketable carrots in 2012 in PC at 112 kg N/ha was significantly lower than 100 % while higher in PC at 168 kg N/ha and in urea treatments. In 2013, marketable carrot in all of the compost amendments was greater than 100 %, but urea did not show such result (Fig. 6.7). Unmarketable carrots was greater than 100 % in AC at 112 kg N/ha in 2012. However, all of the compost treatments, except PC at 168 kg N/ha and AC at 112 kg N/ha, increased unmarketable carrot in 2013 (Fig. 6.7).



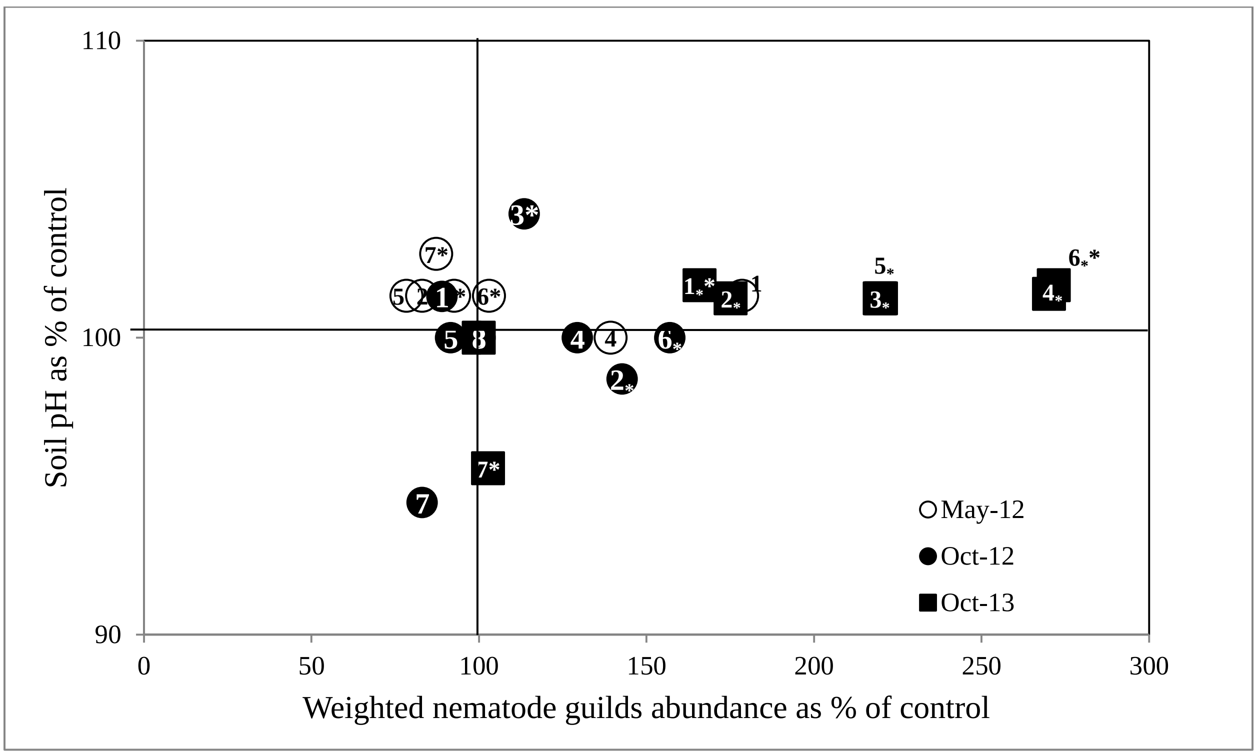
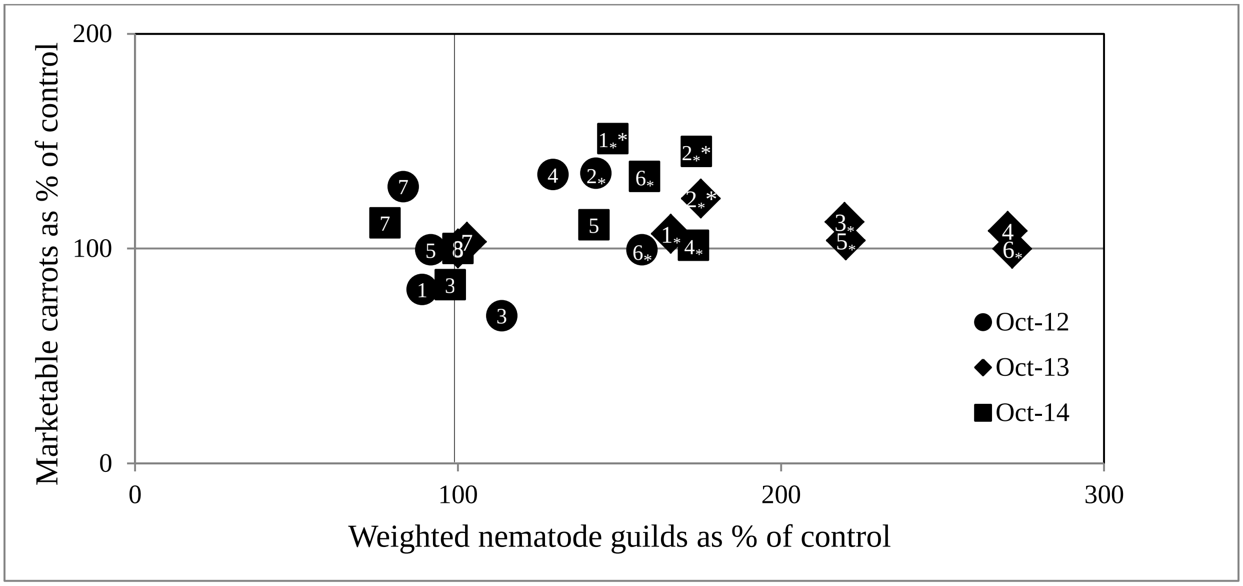


Figure 6.4. Effects of compost types and rate of application data plotted on the modified-modified FUE model for Cupar carrot cultivar at planting in May 2012, and harvest in October 2012 and 2013 growing seasons for organic matter and soil pH. Weighted nematode guilds abundance (x-axis) as indicator of soil health condition and agronomic parameters (y-axis) (organic matter and soil pH) as measures of efficiency of compost amendments on agronomic parameters. Numbers 1-3 refer PC at a rate of 135, 203 and 270 kg N/ha, respectively and 4-6

Figure 6.4. (cont'd)
refer AC at a rate 135, 203 and 270 kg N/ha, respectively, 7 and 8 refer urea and non-amended check, respectively.

*Treatments with subscripts and superscripts asterisks (*) indicate significantly different form 100 % for weighted nematode guilds abundance, and soil organic matter and soil pH, respectively, using one-tailed t-test at α = 0.05.



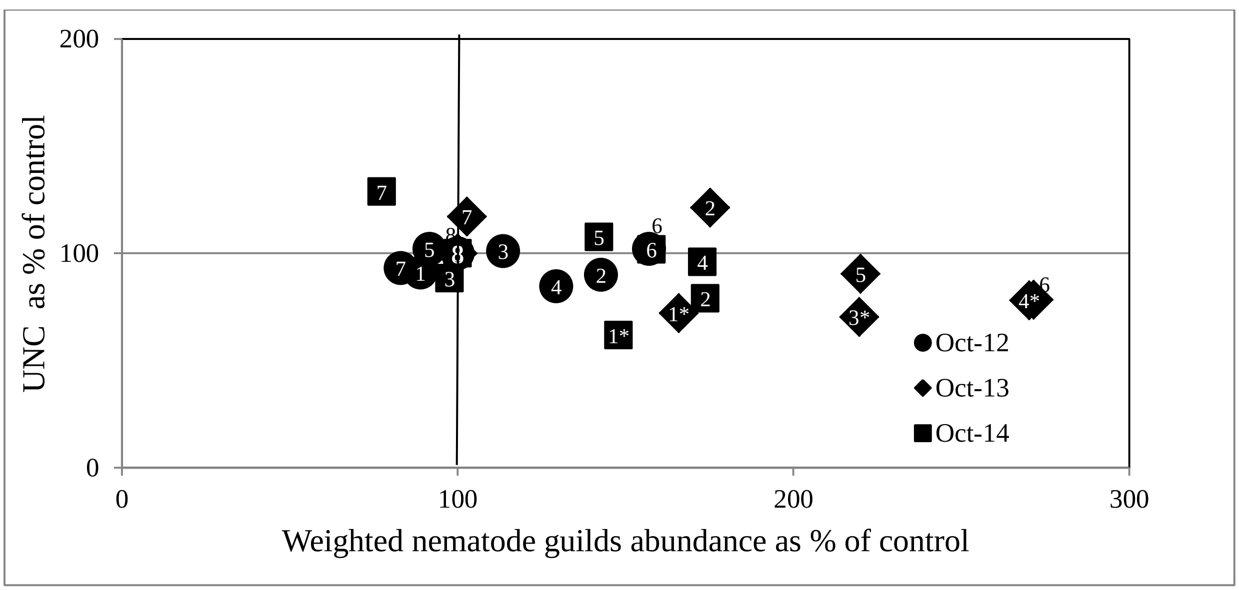
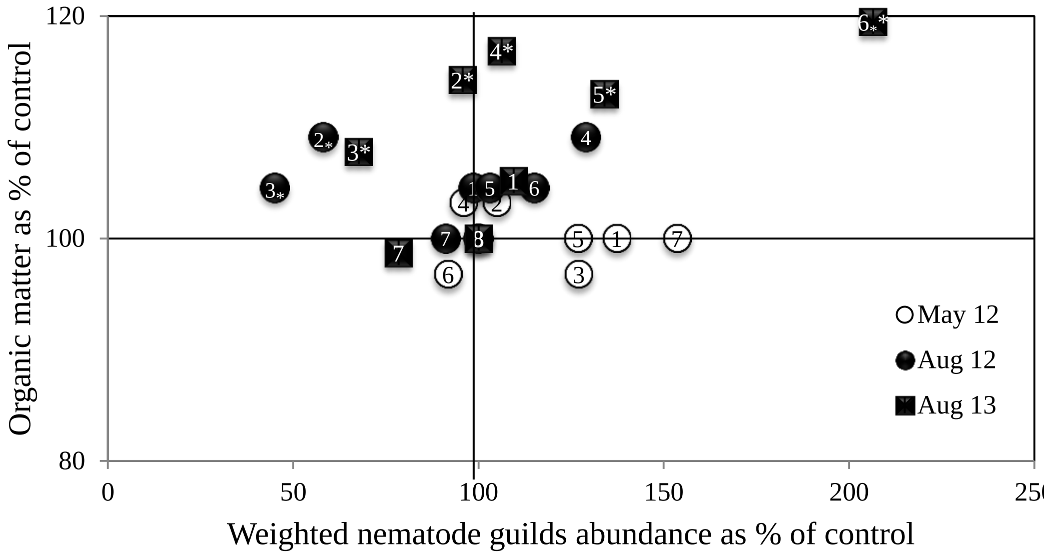


Figure 6.5. Effects of compost types and rate of application data plotted on the modified-modified FUE model for Cupar carrot cultivar for marketable and unmarketable (UNC) carrots at harvest in October 2012, 2013 and 2014 growing seasons. Weighted nematode guilds abundance (x-axis) as indicator of soil health condition and agronomic parameters (y-axis) (marketable and UNC carrots) as measures of efficiency of compost amendments on agronomic parameters.

Figure 6.5. (cont'd)
Numbers 1-3 refer PC at a rate of 135, 203 and 270 kg N/ha, respectively and 4-6 refer AC at a rate 135, 203 and 270 kg N/ha, respectively, 7 and 8 refer urea and non-amended check, respectively.

*Treatments with subscripts and superscripts asterisks (*) indicate significantly different form 100 % for weighted nematode guilds abundance, and marketable and UNC carrots, respectively, using one-tailed t-test at α = 0.05.



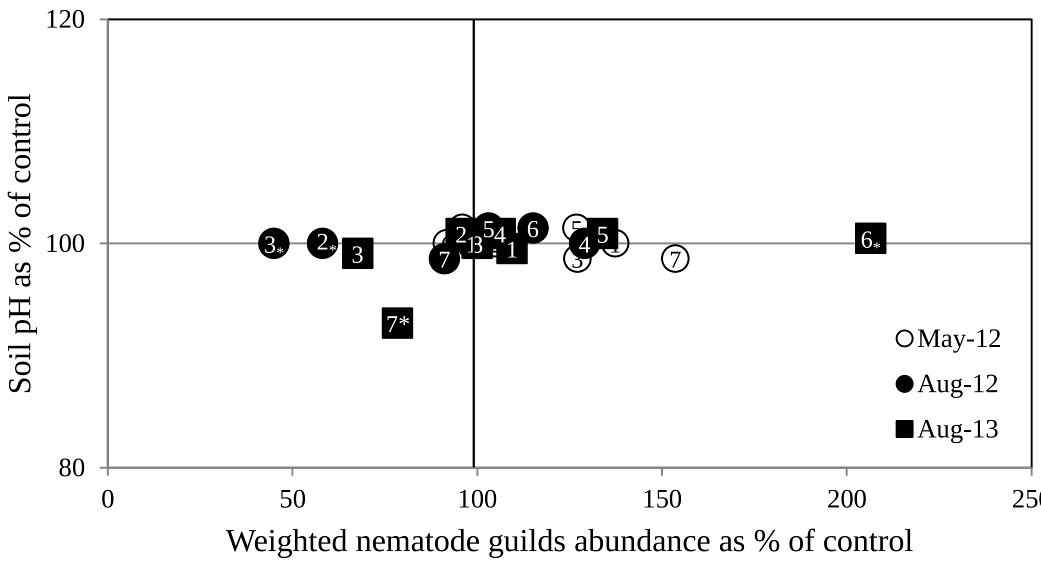
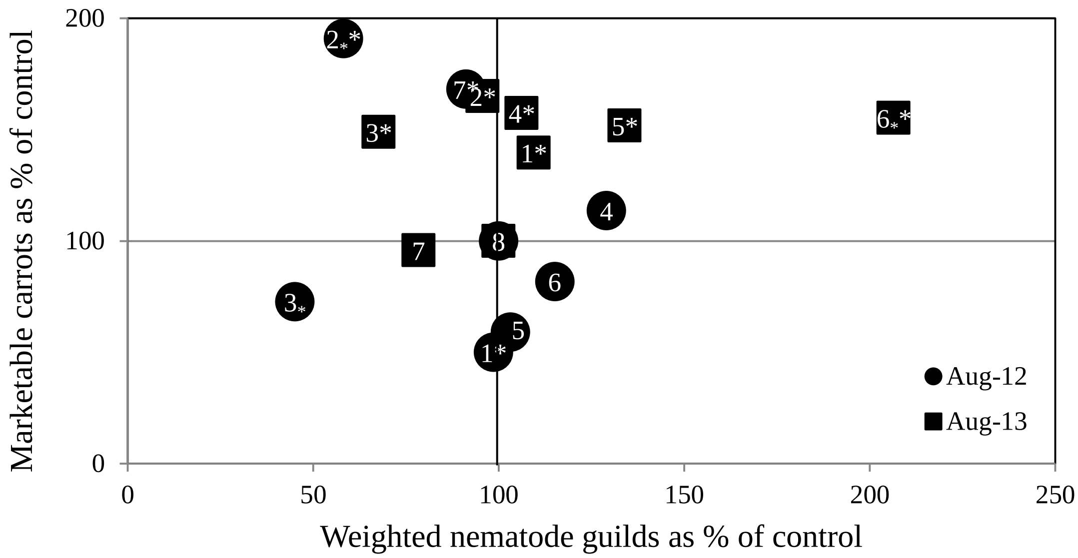


Figure 6.6. Effects of compost types and rate of application data plotted on the modified-modified FUE model for Sugarsnax 54 carrot cultivar at planting in May 2012, and harvest in August 2012 and 2013 growing seasons for organic matter and soil pH. Weighted nematode guilds abundance (x-axis) as indicator of soil health condition and agronomic parameters (y-axis) (organic matter and soil pH) as measures of efficiency of compost amendments on agronomic

Figure 6.6 (cont'd)
parameters. Numbers 1-3 refer PC at a rate of 112, 168 and 224 kg N/ha, respectively and 4-6 refer AC at a rate 112, 168 and 224 kg N/ha, respectively, 7 and 8 refer urea and non-amended check, respectively.

*Treatments with subscripts and superscripts asterisks (*) indicate significantly different form 100 % for weighted nematode guilds abundance, and soil organic matter and soil pH, respectively, using one-tailed t-test at α = 0.05.



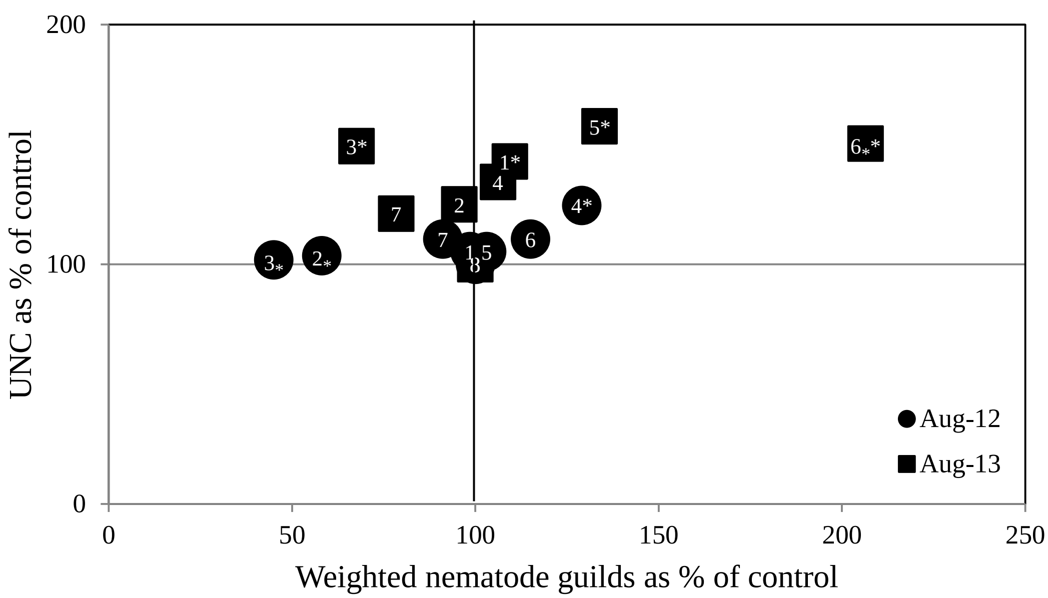


Figure 6.7. Effects of compost types and rate of application data plotted on the modified-modified FUE model for Sugarsnax 54 carrot cultivar for marketable and unmarketable (UNC) carrots at harvest in August 2012 and 2013 growing seasons. Weighted nematode guilds abundance (x-axis) as indicator of soil health condition and agronomic parameters (y-axis)

Figure 6.7 (cont'd)
(marketable and UNC carrots) as measures of efficiency of compost amendments on agronomic parameters. Numbers 1-3 refer PC at a rate of 112, 168 and 224 kg N/ha, respectively and 4-6 refer AC at a rate 112, 168 and 224 kg N/ha, respectively, 7 and 8 refer urea and non-amended check, respectively.

*Treatments with subscripts and superscripts asterisks (*) indicate significantly different form 100 % for weighted nematode guilds abundance, and marketable and UNC carrots, respectively, using one-tailed t-test at $\alpha = 0.05$.

Discussion

The second modification of the FUE model introduces weighted nematode guilds to describe the integrated efficiency of compost amendment use outcomes in four possible categories. Best case scenario would be if the weighted nematode guilds data points fell in Quadrant B, indicating that the agronomic parameters and soil health conditions of the prescribed treatments are desirable. Worst case scenario would be if data points fell in Quadrant C, indicating that the compost amendment treatments have resulted in an undesirable outcome for soil health and crop yield expectations. Data that fall in Quadrants A and D would indicate the need for complementary intervention to improve soil health and agronomic parameters, respectively.

Fitting the weighted nematode guilds data to the second modification of the FUE model showed that organic matter, soil pH and marketable carrot data points of compost amendment treatments fell in Quadrant B while data points of urea treatments fell in either in Quadrant A or Quadrant C in Cupar. Most unmarketable carrots data points from the compost amendment treatments fell in Quadrant D while data points from the urea treatments fell in Quadrant A. These results show that compost amendments are efficient in increasing organic matter, soil pH and marketable carrot yield, and improving soil health. These results were not only in line with soil health condition diagnosed in the soil food web evaluation using Ferris et al. (2001) model, but also allow integrated analysis of agronomic parameters.

In Sugarsnax 54, organic matter and soil pH data points from compost amended treatments fell in either Quadrant A or Quadrant B while data points from urea treatments fell in Quadrant C. Unlike in Cupar, data points of PC at 168 and 224 kg N/ha amendments fell in Quadrant A. Thus, suggesting that the compost amendments were efficient in improving soil organic matter and soil pH. Such conclusions would not have been possible without the integrated analysis the modifications introduced into the FUE model. All of the compost amendment treatments increased unmarketable carrots relative to non-amended check in 2012 and 2013. While this suggests the need for intervention to improve marketable carrots yield, it is necessary to consider how factors such as soil compaction, coarse texture, undecomposed organic debris or fluctuations in nutrient and moisture content may be contributing to producing unmarketable carrot (Guteziet, 2001; Walker, 2004).

In Cupar, statistical analysis of the effect of compost amendments, urea and non-amended check on organic matter, marketable and unmarketable carrots showed no significant differences (Table 6.1). However, plotting the data on FUE model showed differences that were not explained in the statistical analysis. This allowed seeing difference between compost types which was not apparent in the means through statistical analysis. Moreover, comparison of the data points with 100 % revealed most of the data points were greater than 100 % for most of compost amendments at the end of the growing seasons. I found consistent results with my previous statistical analysis that those significant differences in organic matter and marketable carrots among the treatments in Sugarsnax 54 are clearly seen on FUE model (Table 6.2 and Fig. 6.6). In 2012, PC at 168 kg N/ha and urea were significantly higher in marketable carrots compared with the rest of the treatments in Sugarsnax 54. Also, urea and non-amended check were significantly decreased marketable carrot yield compared with compost amendments in 2013, these results are clearly apparent on second modification of the FUE model. Therefore, FUE model is powerful in separating both significant and non-significant, but meaningful differences in both agronomic parameters and soil health condition.

Weighted nematode guild analysis was also in line with the result of faunal profile analysis obtained from this data set (Chapter 3). Data points of compost amendments fell in Quadrant B while those of urea fell in Quadrant A and B (Fig. 6.6A). The interpretation of the data in the second modification of the FUE model here is the best case scenario that showed compost amendments were efficient in agronomic parameters and soil health condition. Similar interpretation as the best case scenario following Ferris et al. (2001) that the soil food web was enriched and maturing in compost treatments in Cupar. Although data from Sugarsnax 54 did not overlap with the faunal profile analysis, the second modification of the FUE model further separates the data points that show slight differences among compost treatments, and between compost treatments and urea (Fig. 6.6B). These show that the second modification of the FUE model not only describing the effect of management practices on soil health, but also allow integration of other agronomic parameters for cross-disciplinary decision making. The model helps to identify and monitor changes in soil conditions, thereby creating the necessary bridges to disciplinary gaps (Melakeberhan and Avendaño, 2008).

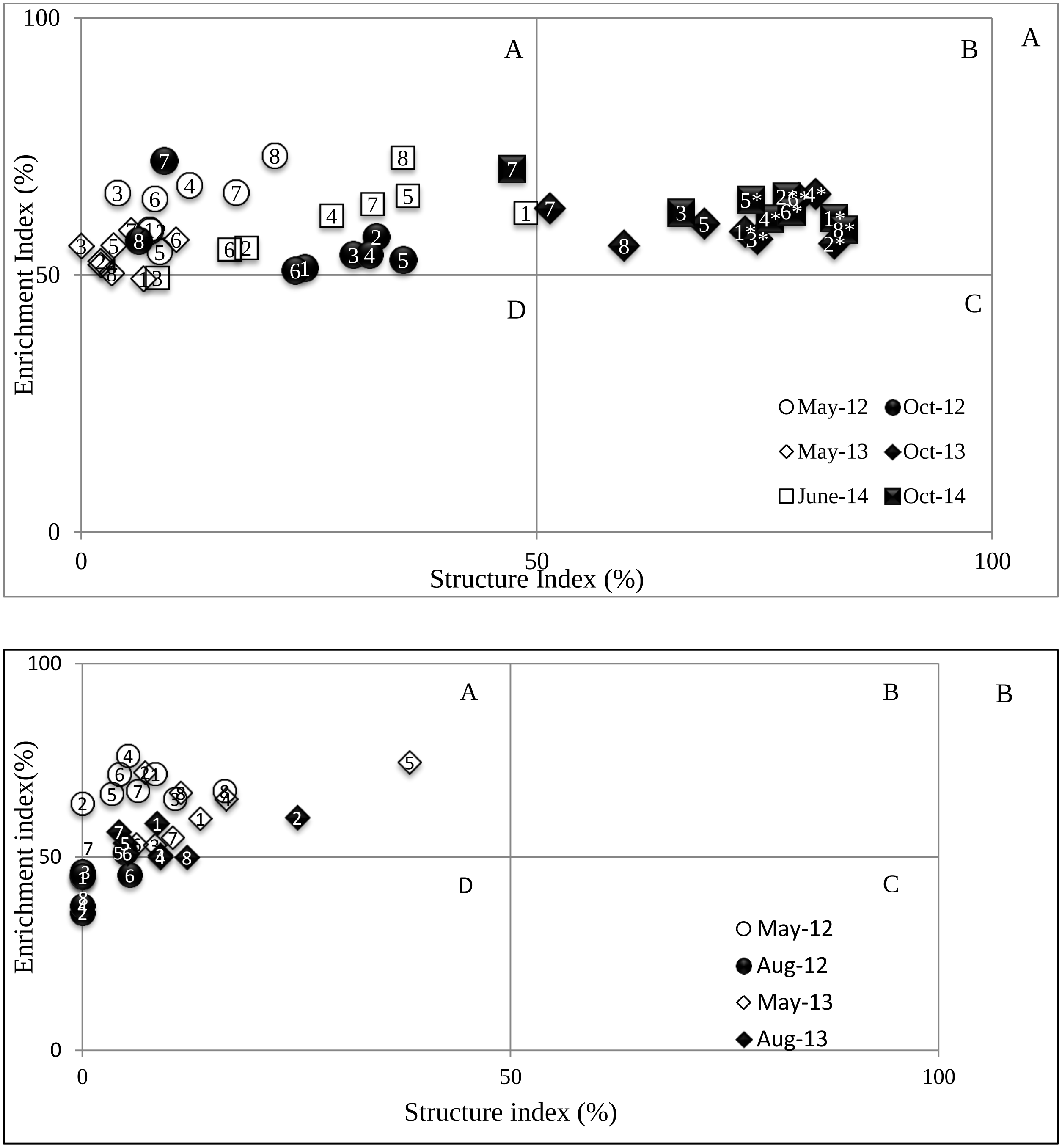


Figure 6.8. Soil food web condition in plots planted with Cupar (A) and Sugarsnax 54 (B) and amended with plant (PC) and animal (AC) compost, standard urea and non-amended check in sandy clay loam soil at planting (May, June) and harvest (August, October) in 2012 -2014 and 2012-2013 growing seasons for Cupar and Sugarsnax 54, respectively. In Cupar plots, numbers 1-3 refer PC at a rate of 135, 203 and 270 kg N/ha, respectively and 4-6 refer AC at a rate 135, 203 and 270 kg N/ha, respectively, 7 and 8 refer urea and check, respectively. In Sugarsnax 54 plots, numbers 1-3 refer PC at a rate of 112, 168 and 224 kg N/ha, respectively and 4-6 refer AC

Figure 6.8. (cont'd)
at a rate 112, 168 and 224 kg N/ha, respectively, 7 and 8 refer urea and check, respectively (Source: Chapter 3).

*Treatments significantly increased SI from 50 % using one-tail t-test at $\alpha = 0.05$ for Cupar plots in 2013 and 2014 growing seasons.

In conclusion, the second modification of the FUE model integrated the concepts of FUE and soil food web models for enhanced diagnostic power of the impacts of soil amendment management practices. In order to fully assess soil health, the modification needed the power of integrating nematode functions by giving different weights to the presence and abundance of nematode guilds. A new guild weight (0.2) was assigned for c-p 1 nematodes which is proportional to their indicator value in soil health, which is different from the weight given by Ferris et al. (2001). The second modification of the FUE model showed promising and interesting results in explaining soil health condition as in soil food web model and addressing additional agronomic parameters of interest. Generally, the analysis in the present study showed that the new modification improved the explanatory power of the FUE model towards integrated soil health analysis. Thus, second modification of FUE model creates a road map for cross- and multidisciplinary applications of soil amendment-based management practices.

CHAPTER 7

GENERAL DISCUSSION AND CONCLUSIONS

The goal of my Dissertation was to develop integrated compost amendment use strategy for managing soil nutrient, nematodes, soil health, and carrot yield and quality in potentially sustainable ways. Although compost's agronomic benefits such as increasing organic matter, nutrient supply and pest suppression are well known (Pinamonti, 1998; Abawi and Widmer, 2000), variable responses continue to be a major challenge (Akhtar and Malike, 2000; Renčo et al., 2011, McSorley, 2011). Moreover, little information is available on the impact of specific compost types and rates of applications on herbivore nematode suppression, nematode community structure, soil food web conditions, overall soil health, and carrot yield and quality. This is particularly important when considering the growing environmental concerns relative to nematicide/pesticide use that have negative impact on soil organisms, which drive the soil food web and nutrient transformations and for which nematodes are excellent indicators (Ingham et al., 1985; Bongers and Bongers, 1998; Ferris et al., 2001; Ferris et al., 2010). In order to address the multitude of challenges and gaps, it is necessary to recognize the need for generating integrated data sets and developing models that explain variable responses and efficiencies of soil amendment experimental outcomes for better cross-disciplinary applications.

The thrust of my Dissertation has been to understand the relationships among plant- and animal-based organic amendments, harmful and beneficial nematode communities, and changes in soil ecosystem services under fresh market and processing carrot production in mineral soils under field and controlled conditions. Among my significant findings include identifying the a) complexities of the shifts in nematode community structure relative to animal- and plant-based organic amendments and rates of applications; b) interactions of integrated plant-based organic amendment and conventional fertilizer; c) challenges associated with introducing compost in biologically degraded soil; and d) parameters necessary to integrate the soil food web and fertilizer use efficiency models for greater cross-disciplinary applications. I also did a one-time minor survey as part of relating the nematode communities in my experimental field to what may be happening in the carrot production fields (Appendix B).

Compost amendment integrated with inorganic fertilizer used as alternatives to conventional managements in my study improved soil health as reflected in the presence and abundance of omnivores and predators that represent the higher trophic level of the soil food web. Potentially, this will lead to long-term healthy environmental quality and better yield (Fig. 7.1). The presence of higher trophic levels in the soil food web indicates higher biological interactions and trophic links in soils typical of carrot production shows the kinds of biological changes that may occur in such soils. This provides basis for developing better strategic use of compost than currently exist.

On the other hand, urea application in my study negatively affected the soil biology and soil physicochemical properties. The soil food web dominated by bacterivores and fungivores that ultimately lead to ecosystem disservices, which in turn cause poor soil health and environmental quality, and yield reduction. The reduction of the higher trophic level of soil food web, and decline in MI, biological activity levels, soil pH and nutrients observed in my study from urea treated plots may reflect what is happening in conventional carrot production systems (Fig. 7.1).

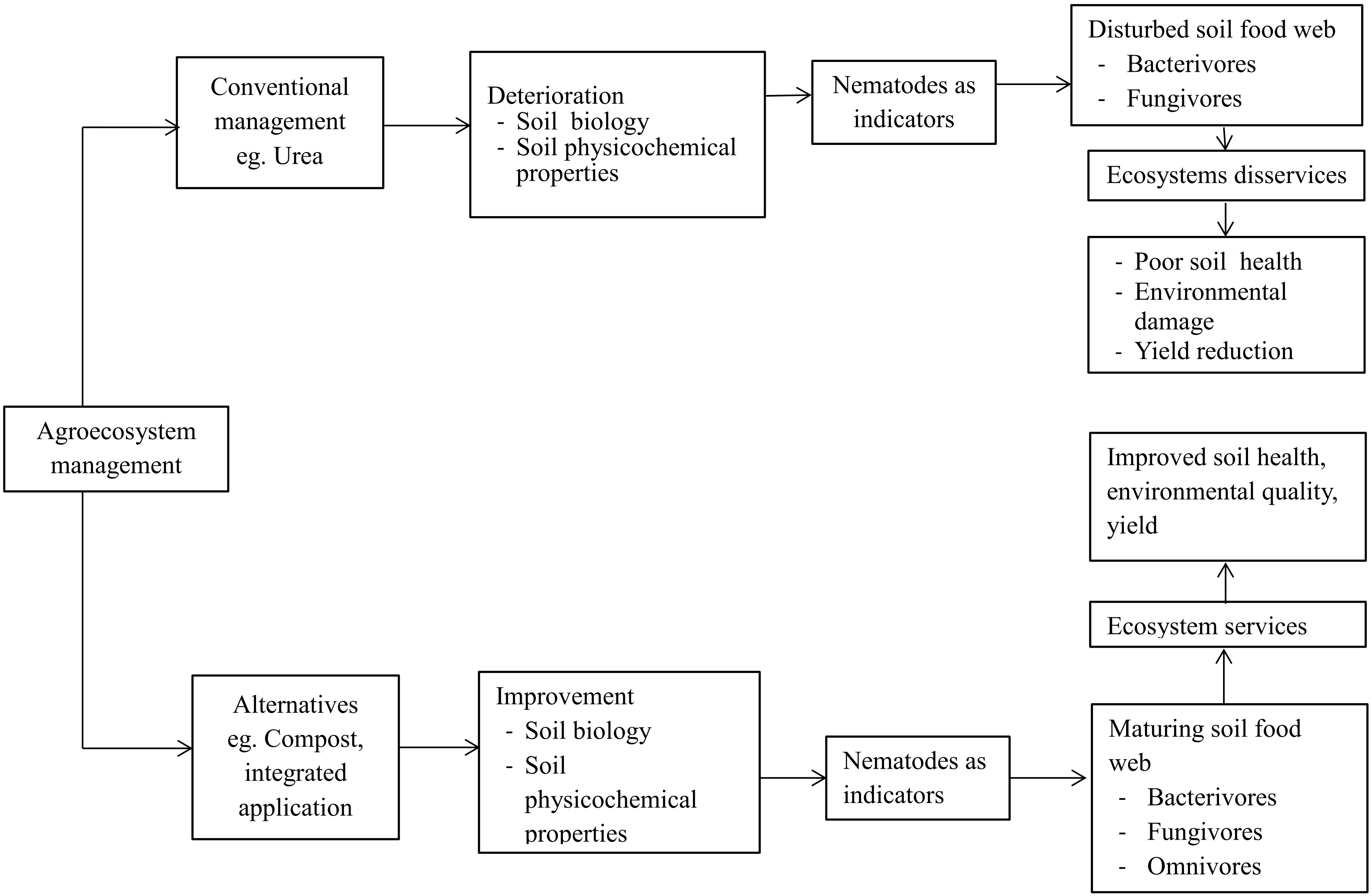


Figure 7.1. The long-term impact of conventional and alternative management practices on soil health, environmental quality and yield

As mentioned earlier, the overall results of this study supported the value of nematodes as indicators of ecosystem change. In Chapter 3, I compared the effect of compost types and rates of applications on soil food web conditions, soil physicochemical and biological properties, and carrot yield and quality. Compost amendments increased omnivore nematodes over time in Cupar, the processing cultivar. This was reflected by the more structured soil food web with greater trophic links with potential pest regulatory ecosystem services. However, the positive impact of compost on soil food web structure was not observed in Sugarsnax 54, the fresh market cultivar. It is likely that the growing season may have been too short for the omnivore nematodes to reproduce (McSorley, 2012). This, in turn, may explain some of the sources of variability when assessing the benefits of compost application relative to cultivar differences.

My findings in Chapter 3 also pointed out variabilities relative to compost rate and time. The increased CO_2 levels after two years under the higher rates of AC suggests improve soil biological activity. Similarly, the general increase in soil mineral contents in AC amendments over time suggests positive impact on soil fertility and chemistry. To the contrary, urea decreased soil pH and increase NO_3-N. The positive impacts on soil food web structure, soil biological activities and soil nutrient contents over time suggest the need for repeated compost application to see the benefits. Moreover, the variable effects of compost rate suggest a rate-dependent response and provide a road map to getting accurate outcomes. The time, nutrient source and compost rate of application described herein explain why the hypothesis that compost amendment would improve nematode community structure, soil biological and physicochemical properties, and increase carrot yield and quality was partially true.

Finding a balance among nutrient supply, N in particular, sources and rates, environmental safety, and crop quality and yield is very challenging. For the most part, Chapter 4 was designed to address the challenge of finding a balance by applying urea and PC mixed at different proportions. As in Chapter 3, the there were variabilities in nematode community structure and soil food web conditions. For example, SI increased in urea alone, and urea and PC at 3:1 ratios, contradicts with previous studies (Fiscus and Neher, 2002; Ferris, 2010). However, MI, a measure of changes in the functioning of the soil ecosystem relative to disturbance (Bongers, 1990; Bongers and Bongers, 1998) and SI, a measure of greater trophic links (Ferris et al., 2001) improved over time when urea and PC were applied at 1:1 ratio compared with urea alone (Fig. 4.1). It is promising that the lower urea rate and integrated with PC enhanced biological activity level, and increased soil pH and nutrients. This is an appealing alternative to inorganic fertilizers only for meeting crop requirements and reducing environmental damages (Sikora and Enkiri, 2001). Promoting the PC and urea mix could be a good alternative to urea alone as urea decreased soil pH and increased NO_3-N, which leaches to the water table and causes environmental damages (Oberson et al., 1996; Gunapala and Scow, 1998; Kaur et al., 2005; Pimentel et al., 2005).

Although yield increase was not observed in the integrated urea and PC application study, the benefits of enhanced biological activities, and increase in soil pH and nutrient contents together with the anticipated reduction of environmental damage point to the need for further studies to understand the linkages among the different interacting factors influencing crop yield. It is known that herbivore nematodes affect plant growth and reduce yield by interfering with water and nutrient uptake (Melakeberhan, 1997). Previous studies have shown that root hair feeders contribute to increase in microbial activity by eliciting leakage of metabolites from roots, but do not seem to cause measurable plant damage (Bardgett et al., 1999; Yeates et al., 1999; Verschoor, 2002; Ferris et al., 2010). Whether or not the negative correlation of the abundance of

Malenchus, a root hair feeder, with carrot yield may be similar to the previous studies is not clear.

The glasshouse study using sterilized and non-sterilized soil was designed to simulate how biologically degraded soils would respond to compost application (Chapter 5). The stunted carrot yield and c-p 2 group dominated nematode community on non-sterilized soil regardless of the treatments indicate other experimental conditions may not have been ideal for determining the effects of the treatments in the glasshouse experiment. The absence of nematodes on sterilized soil may be attributed to the soil physical and chemical property changes due to sterilization, which results in conditions that inhibit or slow recolonization. Perhaps, reinoculating the sterilized soil with a small amount of control soil could have made a difference. One possible reason could be increased concentration of NH_4-N and NO_3-N after soil sterilization that negatively correlated with nematode trophic groups in non-sterilized soil. Soil sterilization increased most of the measured soil nutrients while decrease soil pH.

Designing cross-disciplinary and integrated analyses tools are necessary to promote both agronomic and soil health benefits. As described in Chapter 6, I have developed a weighted guild approach to modify the FUE model and integrate it with the soil food web model. The FUE model separates nutrient deficiency and toxicity from nematode parasitism and agrobiological efficiency. The soil food web model describes soil nutrient cycling relative to availability and agroecosystem suitability using nematode community analyses. Nematodes of different guilds have different biological attributes, respond differently to environmental perturbation (Bongers and Bongers, 1998) and indicate health of the soil (Ferris et al., 2001).

The guild weights reflect increasing complexity as the system matures or progressive simplicity as the system degrades (Ferris et al., 2001). The assumption is that food webs of higher complexity contain representatives of food webs of lower complexity (Bongers and Bongers, 1998; Ferris et al., 2001). My including the guild functions in the modification of the FUE model shows promising and interesting results in explaining the soil health conditions as in soil food web model while addressing additional agronomic parameters of interest. This builds an integrated soil health analysis tool that creates a road map for cross-disciplinary applications of soil amendment-based management practices (Melakeberhan and Avendaño, 2008).

The major highlights of the outcomes of the hypotheses that I tested can be summarized as follows: The first hypothesis was partially true as shown by the improved soil food web in Cupar and soil potassium and phosphorus, and soil respiration in the higher rates of AC. In Sugarsnax 54, although some compost amendments had comparable marketable and total yield compared with that of urea in 2012, all of compost amendments were higher in marketable carrot yield in 2013. The findings pointed out variabilities relative to compost rate, source and time, and suggest compost based improvements in soil food web structure may lead to increase in ecosystem services provided by the soil food web.

The second hypothesis was also partially true as shown by improved soil biological activity and phosphorus content in the lower rates of urea and integrated with higher rates of PC. This is an appealing alternative to inorganic fertilizers for meeting crop requirements and improving soil health. The outcomes of the two hypotheses pointed to variable responses, a major challenge when dealing with soil amendment studies and the soil biological and physicochemical changes they drive and their collective impact on crop yield and quality (McSorley, 2011). My developing the second modification of the FUE model and integrating it with soil food web model adds more power to integrated and cross-disciplinary analysis of variable responses in soil health management. This new model separates data points that reflect efficiencies of compost amendments on soil health, and soil pH, organic matter and carrot yield and quality. Hence, the model serves as an important tool to identify areas of targeted intervention. Moreover, the powers of the new model will be critical to understanding the gaps when dealing with rehabilitating soils with severe biological degradations. Collectively, the information that I have generated is a significant step towards addressing the industry priorities through understanding the biological and physicochemical basis of the changes in soil health and designing potential solutions that fit variable soil conditions.

APPENDICES

APPENDIX A: SUPPORTING DATA

Table A-1. Nematode trophic groups, and non-herbivores and total nematodes abundances in 100 cc of soil amended with AC and PC containing 135, 204 and 270, and 112, 168 and 224 kg N/ha for Cupar and Sugarsnax 54, respectively, and standard urea application[a] and non-amended check in sandy clay loam soil in 2012-2014, and 2012 and2013 growing seasons for Cupar and Sugarsnax 54, respectively.

	Processing variety	Fresh market variety
Trophic groups	Mean	Mean
Herbivores	17.0 (0-69)[b]	19.0 (9-46)
Bacterivores	18.0 (2-120)	8.0 (1-64)
Fungivores	21.0 (0 - 214)	14.0 (1-53)
Omnivores	0.4 (0-10)	0.4 (0 - 4)
Predators	0.3 (0-2)	0.1 (0 – 2)
Non-herbivores	40.0 (1-258)	26.0 (6-105)
Total nematodes	57.0 (2-304)	45.0 (7-142)

[a]293 and 243 kg/ha urea supplying 135 kg N/ha and 112 kg N/ha for Cupar and Sugarsnax 54 cultivars, respectively.
[b]Range of nematodes abundance in 100 cc of soil.

Table A-2. Omnivore nematodes abundance in 100 cc of soil amended with animal (AC) and plant (PC) composts containing 135, 203 and 270 kg N/ha and standard urea application supplying 135 kg N/ha and non-amended check for Cupar in sandy clay loam soil at different days after planting in 2012-2013 growing seasons.

Amendments	Rate (kg N/ha)	Number of omnivores per 100 cc of soil									
		Days after planting									
		2012					2013				
		0	32	62	96	132	0	30	62	94	133
PC	135	1 bB[a]	0 aB	0 bB	1 bB	1 bB	1aB	0 aB	0 bB	1 aB	5 bA
	203	1 bB	0 aB	0 bB	1bB	2 bA	0 aB	0 aB	2 aA	1 aB	5 bA
	270	0 cC	0 aC	1 aB	3 aA	3 aA	0 aC	1 aB	1 bB	1 aB	10 aA
AC	135	1 bC	0 aD	0 bD	2 aBC	3 aB	0 aD	1 aC	1 bC	1 aC	7 bA
	203	1 bB	0 aB	0 bB	1 bB	2 bA	1 aB	0 aB	2aA	0 aB	7 bA
	270	1 bC	0 aC	0 bC	0 bC	3 aB	1 aC	1 aC	1 bC	1 aC	10 aA
Urea	135	0 cB	0 aB	0 bB	1 bA	0 bB	0 aB	0 aB	1 bA	0 aB	2 cA
Check	0	2 aA	0 aB	1 aB	1 bB	1 bB	1 aB	0 aB	1 bB	1 aB	3 cA

[a]Means with different lower case letters within columns and different upper case letters across rows indicate significant difference at $P \leq 0.05$.

Table A-3. Omnivore nematodes abundance in 100 cc of soil amended with animal (AC) and plant (PC) composts containing 112, 168 and 224 kg N/ha and standard urea application supplying 112 kg N/ha and non-amended check for Sugarsnax 54 in sandy clay loam soil at different days after planting in 2012-2013 growing seasons.

Amendments	Rate (kg N/ha)	Number of omnivores per 100 cc of soil							
		Days after planting							
		2012				2013			
		0	32	62	78	0	30	62	79
PC	112	0.5 aB[a]	0.0 aB	0.3 aB	0.0 aB	0.0 bB	0.8 abB	1.8 aA	0.3 abB
	168	0.0 aB	0.0 aB	0.0 aB	0.0 aB	0.5 abAB	0.0 bB	0.5 bAB	1.0 aA
	224	0.3 aB	0.0 aB	0.3 aB	0.0 aB	0.5 abB	0.3 bB	2.0 aA	0.3 abB
AC	112	0.3 aB	0.0 aB	0.0 aB	0.0 aB	0.8 abAB	0.3 bB	1.3 aA	0.5 abAB
	168	0.3 aB	0.0 aB	0.0 aB	0.0 aB	1.3 aA	0.8 abAB	0.0 bB	0.3 abB
	224	0.0 aA	0.0 aA	0.0 aA	0.3 aA	0.5 abA	0.8 abA	0.3 bA	0.5 abA
Urea	112	1.0 aA	0.0 aA	0.0 aA	0.0 aA	0.5 abA	0.5 abA	0.0 bA	0.0 bA
Check	0	0.8 aAB	0.0 aB	0.0 aB	0.0 aB	0.3 bB	1.3 aA	0.0 bB	0.3 abB

[a]Means with different lower case letters within columns and different upper case letters across rows indicate the significant difference at $P \leq 0.05$.

Table A-4. Plant-parasitic index (PPI) values obtained from plots amended with animal (AC) and plant (PC) composts containing 112, 168 and 224 kg N/ha and standard urea application supplying 112 kg N/ha and non-amended check for Sugarsnax 54 in sandy clay loam soil at different days after planting in 2012-2013 growing seasons.

Amendments	Rate (kg N/ha)	Plant-parasitic index[a]							
		Days after planting							
		2012				2013			
		0	32	62	78	0	30	62	79
PC	112	2.7 aA[b]	2.5 abBC	2.4 aB	2.5 aBC	2.4 aB	2.1 aC	2.3 aC	2.2 abC
	168	2.5 aA	2.5 abA	2.6 aB	2.5 aA	2.2 aB	2.2 aB	2.2 abB	2.2 abB
	224	2.3 bA	2.4 bA	2.4 aA	2.1 bB	2.2 aB	2.1 aB	2.1 bB	2.1 bB
AC	112	2.3 bB	2.5 abA	2.6 aA	2.5 aA	2.3 aB	2.3 aB	2.3 aB	2.3 abB
	168	2.4 bB	2.7 aA	2.7 aA	2.3 aAB	2.3 aC	2.3 aC	2.2 abC	2.4 aB
	224	2.6 aA	2.5 abA	2.5 aA	2.4 aA	2.2 aB	2.4 aA	2.2 abB	2.2 abB
Urea	112	2.3 bB	2.6 abA	2.6 aA	2.4 aB	2.3 aB	2.3 aB	2.2 abB	2.2 abB
Check	0	2.5 aA	2.5 abA	2.5 aA	2.4 aA	2.3 aB	2.2 aB	2.1 bB	2.1 bB

[a]Plant-parasitic nematodes index (PPI) which expresses the maturity of plant-parasitic nematodes with c-p 2 to c-p 5 (Bongers, 1990).

[b]Means with different lower case letters within columns and different upper case letters across rows indicate the significant difference at $P \leq 0.05$.

Table A-5. Soil food web structure index (SI) in plots amended with animal (AC) and plant (PC) composts containing 135, 203 and 270 kg N/ha and standard urea application supplying 135 kg N/ha and non-amended check in Cupar plots in sandy clay loam soil at different days after planting in 2012-2013 growing seasons.

		Structure index (SI)									
		Days after planting									
		2012					2013				
AM[a]	Rate (kg N/ha)	0	32	62	96	132	0	30	62	94	133
PC	135	7.5 aC[b]	8.7aB	7.1 aC	8.0 bC	24.5 aB	6.8 bC	30.2 aB	11.0 aB	15.9 aB	72.8 aA
	203	7.6 aC	3.2 aC	0.0 aC	10.6 bC	32.4 aB	2.1cC	9.9 bC	51.6 aB	26.9 aB	82.6 aA
	270	4.0 aB	5.9 aB	17.6 aA	41.6 aA	29.9 aA	0 cB	19.1 abA	39.2 aA	16.9 aB	74.2 aA
AC	135	11.9 aC	3.4 aC	3.7 aC	16.7 abC	31.6 aB	2.2 bC	38.6 aB	38.0 aB	38.8 aB	80.6 aA
	203	8.6 aC	15.2 aC	8.7 aC	20.6 abC	35.3 aC	3.5 bC	36.0 aB	36.9 aB	11.5 aC	68.4 aA
	270	8.1 aC	7.1 aC	2.5 aC	2.6 bC	23.4 aB	10.4 aB	25.4 aB	26.1 aB	20.4 aB	78.7 aA
Urea	135	17.0 aB	8.1 aB	11.3 aB	10.3 abB	9.1 aB	5.5 bB	15.0 abB	11.0 aB	10.3 aB	51.4 aA
Check	0	21.2 aBC	19.0 aBC	9.1 aBC	12.9 abBC	6.3 aBC	3.3 bC	17.0 abBC	32.0 aB	17.9 aBC	59.6 aA

[a]Amendments.

[b]Means with different lower case letters within columns and different upper case letters across rows indicate significant difference at $P \leq 0.05$.

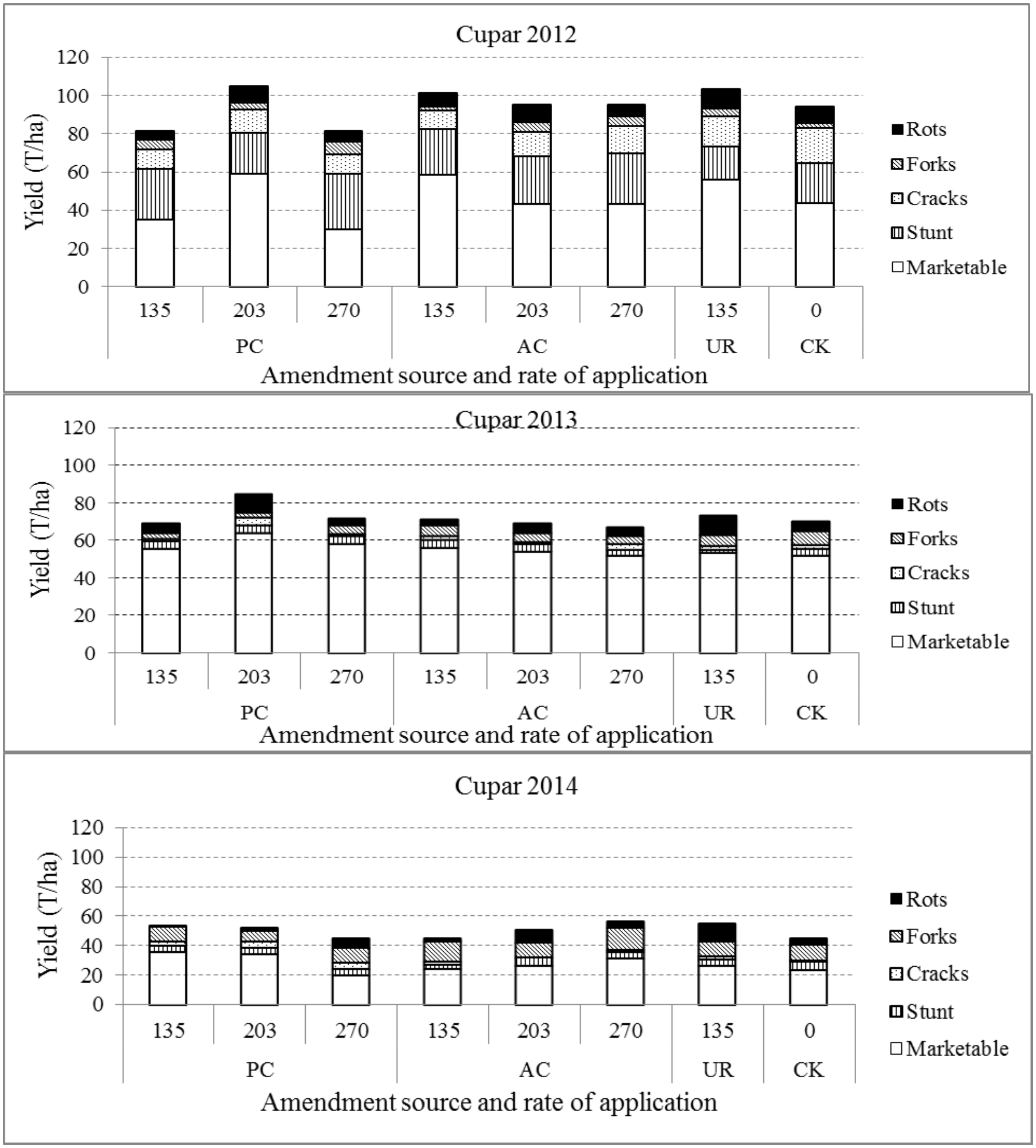


Figure A-1. Effect of plant (PC) and animal (AC) compost containing 135, 203 and 270 kg N/ha for Cupar, standard urea (UR) (293 kg/ ha) to supply 135 kg N/ha and non-amended check (CK) on carrot yield and quality in sandy clay loam soil in 2012-2014 growing seasons.

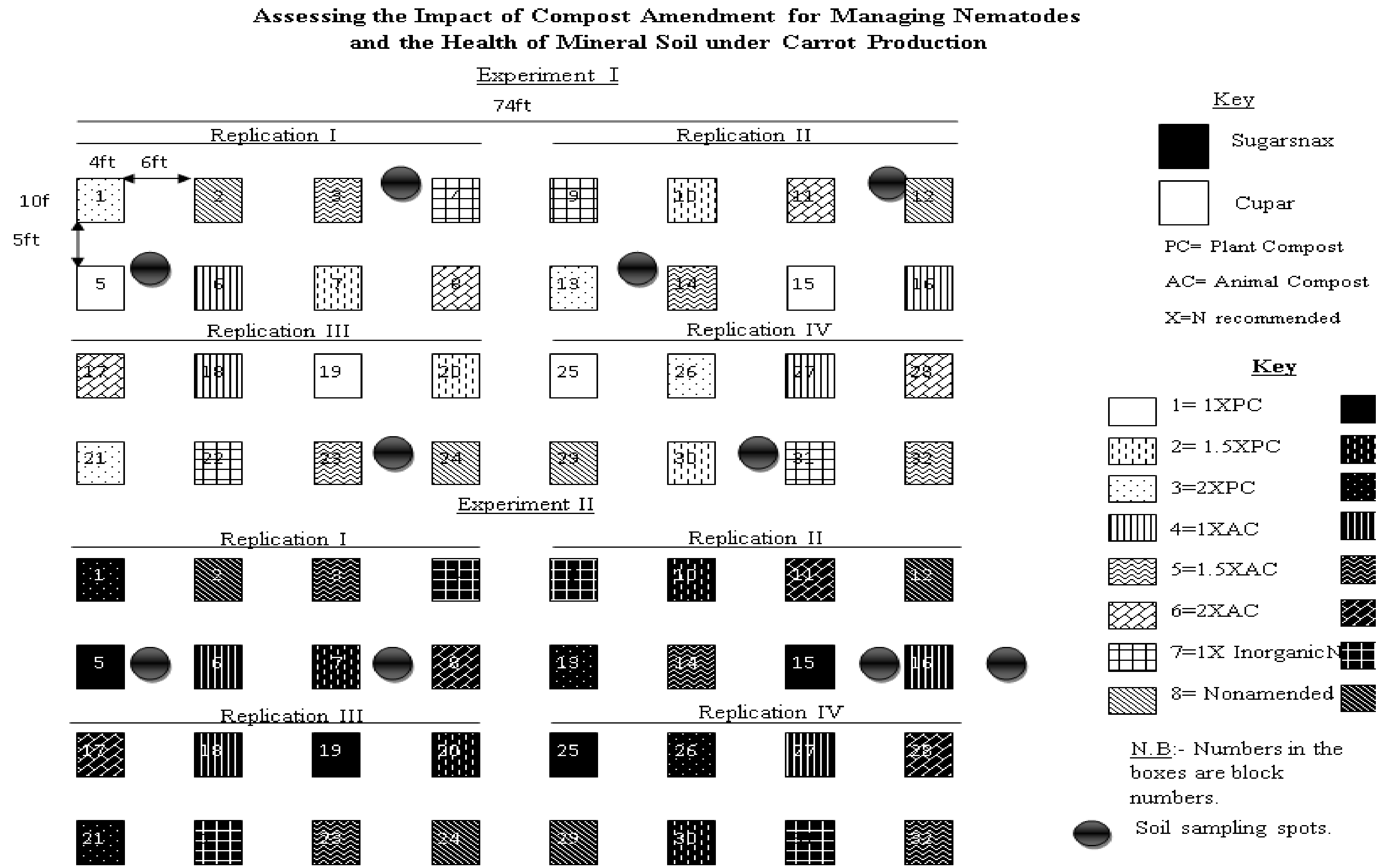


Figure A-2. Ten soil sampling spots for the glasshouse experiment from the field experiment site in 2012 and 2013.

APPENDIX B: CARROT FIELD SURVEY

Abstract

Herbivore nematodes are among the soil-borne pests and diseases that reduce quality and yield of carrot in Michigan. The objective of this preliminary study was to identify economically important herbivore nematodes and associated soil health conditions in selected Michigan carrot production areas. A survey of four fields indicated that the predominant herbivore nematode in all the fields was root lesion nematodes (*Pratylenchus* spp.) and soil health conditions were distrurbed in site 3 and 4, but maturing in site 1 and 2.

Introduction

Michigan is the second and fourth producer of fresh market and processing carrots in the USA, respectively (Hausbeck, 2008). Herbivore nematodes cause carrot root damage such as galls, cracks, forks and stunts that reduce marketable yield (Belair, 1992; Walker, 2004; Wesemael and Moens, 2008). They may also increase secondary infection by other pathogens (LaMondia, 2006).

Herbivore nematodes are common problems in Michigan carrots producing areas though there are a few published works on carrot nematodes (Hausbeck, 2008). Northern root-knot (*Meloidogyne hapla* Chitwood, 1949), carrot cyst (*Heterodera carotae* Jones, 1950), root lesion (*Pratylenchus penetrans* Cobb, 1917) and pin (*Paratylenchus* spp. Micoletzky 1922) nematodes were identified from Michigan carrot fields (Berney and Bird, 1992; Hausbeck, 2008). Northern root-knot and carrot cyst nematodes are considered as the most damaging under Michigan conditions (Berney and Bird, 1992).

The formal survey was back to the 1990's and may not reflect the current carrot field conditions though efficient herbivore management requires identifying predominant herbivore nematodes before taking any management decisions. Knowing the presence and abundance of herbivores helps to understand the impact of management practices on herbivores abundance and their potential threats, and overall soil health condition. Moreover, nematodes management should consider simultaneous suppression of herbivores and promotion of beneficial nematodes represented by bacterivores, fungivores, omnivores and predators.

Keeping the beneficial nematodes in the soil is important because nematodes are the most abundant multicellular organisms on the earth occurring at multiple trophic levels that can represent soil food web and play a key role in nutrient cycling (Bongers and Bongers, 1998;

Ferris et al., 2001; Ferris et al., 2004; Neher et al., 2012). Thus, investigating the association between herbivores, and nematode community and food web indices in on-farm practices could be useful to develop appropriate management strategies. This further enables growers to understand the impact of their management practices on the soil health status. Generating information on the impact of the management practices on herbivores and non-herbivores increase the growers' awareness on soil health condition and enable them to select appropriate nematode management practices.

A total of four carrot fields that have alleged herbivores nematodes problems, but with no formal sampling for nematode identification were selected (Table B-1). One of the fields was located in Mason and the other three were in Oceana counties in Michigan. These Counties are among the major carrot producing regions in the State (Hausbeck, 2008). Generating such data will give insight to growers and county agents on potentially damaging herbivores nematodes. The overall goal of this project was to identify the presence of economically important herbivore nematode genera and their abundance in the selected fields. I also described the soil health status of the fields using nematode community analysis.

Table B-1. Carrot quality of five randomly selected carrots from each 2 hectares portion of the carrot farm sites.

Site	County	Sample #	Forks	Marketable
1		1	2	3
	Mason	2	4	1
		3	1	4
		4	2	3
			2	3
2		1	5	0
	Oceana	2	5	0
		3	5	0
		4	5	0
3		1	2	3
	Oceana	2	0	5
		3	0	5
		4	2	3
4	Oceana	1	1	4
		2	1	4
		3	1	4
		4	1	4
		5	0	5

Materials and Methods

Field selection and soil sampling

The field survey was conducted in four selected carrot fields in September 2014. Soil samples were collected from four carrot fields in Mason and Oceana Counties based on the growers' report of nematode problem, but not sampled before for nematode analysis. The range of the sampled fields was 8 to 10 hectares. Each carrot field was approximately divided into 2 hectares. From each 2 hectares portion of the farm one composite soil sample containing 20 soil cores using zig-zag sampling pattern was collected. Each soil core was collected close to the carrot root to increase chance of getting herbivores. I collected 5, 4, 4 and 5 composite soil samples from site 1, 2, 3 and 4, respectively (Table B-1). I have also randomly collected 5 carrots from each 2 hectare portion and categorized them as stunt, fork, crack or rot carrots following carrot grade standards (Anon, 1965). The composite soil and carrot samples were transported to Agricultural Nematology Laboratory, Department of Horticulture, Michigan State University and stored at 5 ^{0}C.

Nematodes extraction, identification and enumeration

Within 3 days, the nematodes were extracted from 100 cc of soil using a semi-automatic elutriator as described earlier (Avendaño et al., 2003). The nematodes were fixed in double TAFF solution as described by Hooper (1986). Then, they were enumerated and identified at genus level following diagnostic keys by Bongers (1994) and the University of Nebraska Lincoln nematode identification website (http:nematode.unl.edu/konzlistbutt.htm). Nematodes were assigned to a herbivore, bacterivore, fungivore, omnivore or predator trophic group according to Yeates et al. (1993) and Okada and Kadota (2003) and a c-p value was assigned according to Bongers and Bongers (1998).

Nematode community and food web analysis.

Shannon-Weaver diversity (Shannon and Weaver, 1949) and Hill's diversity (Hill, 1973), and maturity indices (MI, MI25 and PPI) (Bongers, 1990) were calculated to study the nematodes diversity and community structure, respectively. EI, SI, BI and CI were calculated and the soil food web condition was graphically described as function of EI and SI as described in Ferris et al. (2001). Nematode trophic group ratios such as fungivores-to-bacterivores (Freckman and Ettema, 1993) and fungivores plus bacterivores-to-herbivores (Wasilewska, 1994) were calculated to know a predominant nutrient mineralization pathway. Fertility index (FI = PPI/MI) was also calculated as a measure of changes in the functioning of the soil ecosystem (Bongers et al., 1997).

Data analysis

Statistical analyses of all data were conducted using SAS ver 9.3 (SAS Institute, 2012, Cary, NC). The general linear Model (Proc GLM) was used to obtain F values for completely randomized design using the appropriate error term in the model. Nematode taxa and trophic group abundances were expressed on an absolute basis (number of nematodes in a taxon i per 100 cc of fresh soil). Dependent variables were the abundance of nematode trophic groups, non-herbivore and total nematodes, percentage of lesion nematode in non-herbivores and total nematodes, nematode community and food web indices, fertility index (PPI/MI), and trophic ratios. Independent variable was the carrot field site. Multiple comparisons were adjusted to Tukey-Kramer when F-value is not significant to perform the preplanned comparisons. Prior to analysis; nematode population abundance was transformed to ln (x+1) to meet the assumptions of normality and equal variances, but untransformed arithmetic means are presented. The probability level $P \leq 0.05$ was regarded as significant.

Result

Carrot quality

The randomly selected carrots from each 2-ha carrot field were categorized based on their quality and grouped into marketable and unmarketable (Table B-1). The percent of unmarketable carrots were 44, 100, 20 and 16 in site 1, 2, 3 and 4, respectively. Visually, rot carrots were very common in site 2 compared with the rest of the study sites. Stunt and cracks were not detected from any of the fields.

Nematode genera and abundance

This survey revealed the presence of 38 nematode genera, 9, 16, 6, 6 and 1 genera from herbivore, bacterivore, fungivore, omnivore and predator trophic group, respectively, from the four study sites (Table B-2). Total nematodes abundance ranges from 35 to 203 individuals per 100 cc of soil. The abundance of herbivores in average was 19, 44, 36 and 45 for site 1, 2, 3 and 4, respectively. Bacterivores abundance was 45, 44, 78 and 110 individuals for site 1, 2, 3 and 4, respectively. The abundance of fungivores was generally low referring 6, 11, 9 and 11 in site 1, 2, 3 and 4, respectively. Abundance of omnivores was 10, 8, 4 and 2 individuals in site 1, 2, 3 and 4, respectively. Among the herbivores, *Basiria, Cephalenchus* and *Psilenchus* were detected only in site 1, 2 and 3. *Malenchus* detected only from site 2 and 4. *Tylenchus* was detected in all sites except site 2. *Xiphinema* and *Tylenchorynchus* were detected in site 2 and 3, respectively. But, root lesion nematode was detected in all of the study sites. The abundance of root lesion nematodes in average was 19, 43, 33, 35 individuals per 100 cc of soil in site 1, 2, 3 and 4, respectively.

Herbivore nematodes, *Basiria, Cepahenchus, Malenchus, Psilenchus* and *Tylenchus* of the epidermal cell and root hair feeders were less than four individuals per 100 cc of soil. Single individual of ectoparasitic herbivore nematodes from *Tylenchorynchus* and *Xiphinema* genera were detected only in a single sample from site 3 and 2, respectively. On average, 4 individuals of ectoparasitic herbivore, *Helicotylenchus* were detected in site 4 in 3 out of five soil samples.

There was significant difference in herbivores nematodes among the study sites (Table B-3). The abundance of herbivores were significantly higher in site 4 compared with the rest of the sites. Similarly, bacterivores abundance was significantly higher in site 4 compared with site 1 and site 2. However, there was no significant difference in fungivores, omnivores, and predators among the study sites though the abundance of omnivores was greater in site 1 and site 2.

Table B-2. List of nematode genera from herbivore, bacterivore, fungivore, omnivore and predator trophic groups detected during the field survey. Numbers within brackets represent c-p values following Bongers and Bongers (1998).

Herbivores	Bacterivores	Fungivores	Omnivores	Predators
Basiria(2)	*Eumonhystera (1)*	*Aphelenchoides (2)*	*Eudorylaimus (4)*	*Prionchulus (4)*
Cephalenchus (2)	*Mesorhabditis (1)*	*Aphelenchus (2)*	*Mesodorylaimus (4)*	
Malenchus(2)	*Panagrolaimus(1)*	*Ditylenchus (2)*	*Microdorylaimus (4)*	
Psilenchus (2)	*Rhabditis (1)*	*Filenchus (2)*	*Thonus (4)*	
Tylenchus (2)	*Acrobeles (2)*	*Diphtherophora (3)*	*Aporcelaimellus (5)*	
Helicotylenchus (3)	*Acrobeloides (2)*	*Tylencholaimellus (4)*		
Pratylenchus (3)	*Cephalobus (2)*			
Tylenchorhynchus (3)	*Cervidellus (2)*			
Xiphinema (5)	*Chiloplacus (2)*			
	Eucephalobus (2)			
	Heterocephalobus (2)			
	Plectus (2)			
	Wilsonema (2)			
	Microlaimus (3)			
	Prismatolaimus (3)			
	Alaimus (4)			

Non-herbivore and total nematodes were significantly higher in site 4 compared with site 1 and site 2 (Table B-3). Total nematodes were significantly higher in site 3 compared with site 1. The most abundant herbivore nematode was root lesion nematodes in all of the study sites representing 98, 99, 92 and 78 % of total herbivore nematodes in site 1, 2, 3 and 4, respectively. This percentage was significantly higher in site 1, 2 and 3 compared with site 4. Root lesion nematodes were also representing 25, 42, 25 and 21 % of the total nematode abundance in site 1, 2, 3 and 4, respectively (Table B-3).

Table B-3. Abundance of herbivores (HV), bacterivores (BV), fungivores (FV), and omnivores (OV), non-herbivores (NHV), and total nematodes per 100 cc soil of the four selected carrot fields. The proportion of root lesion nematodes was expressed as a percent of herbivores (Pr/HV) and as percent of total nematodes (Pr/TL).

Site	HV	BV	FV	OV	NHV	TL	Pr/HV (%)	Pr/TL (%)
1	19 b[a]	45 b	6	10	62 b	82 c	98 a	25
2	44 b	44 b	11	8	62 b	106 bc	99 a	42
3	36 b	78 ab	9	4	91 ab	127 ab	92 a	25
4	45 a	110 a	11	2	123 a	169 a	78 b	21

[a]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$.

Nematode community indices

There was no significant difference in nematode diversity among the study sites though the number of abundant genera (Hill's N1) was relatively lower in site 2 (Table B-4). PPI was significantly higher in site 1 and 2 compared with site 4. MI was significantly higher in site 2 compared with site 3 and 4. MI was also significantly higher in Site 1 compared with site 4. MI25 was significantly higher in site 1 compared with site 3 and 4. Similarly, MI25 was significantly higher in site 2 compared with site 4.

Table B-4. Nematodes diversity expressed by Shannon diversity index (H'), Hill's N1 and Hill's N0, and nematode community maturity expressed as plant-parasitic index (PPI), maturity index for free-living nematodes (MI) and maturity index of free-living nematodes with c-p 2 to 5 values for the carrot fields.

	Diversity indices			Maturity indices		
Site	H'	Hills N1	Hills N0	PPI	MI	MI25
1	2.38	11.60	15.00	2.98 a[a]	2.19 ab	2.59
2	2.23	9.67	16.00	3.00 a	2.23 a	2.50
3	2.43	11.65	16.50	2.93 ab	1.81 bc	2.25
4	2.39	11.23	17.00	2.83 b	1.73 c	2.11

[a]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$.

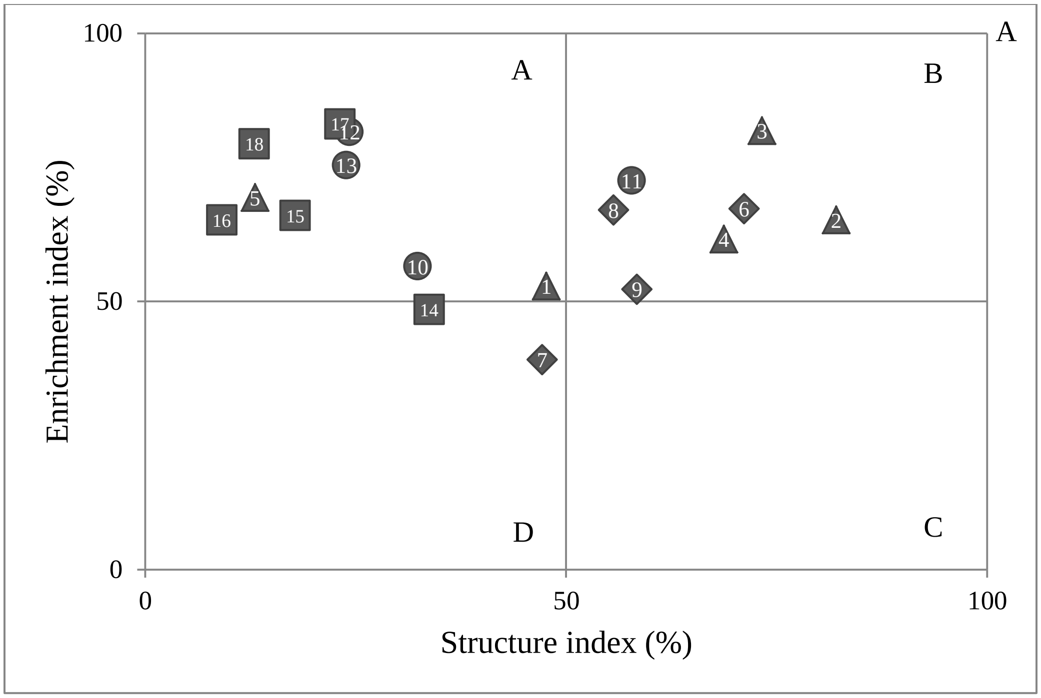
Food web indices, trophic ratios and fertility index

None of soil food web indices were significantly different among the study sites except SI (Table B-5). SI was significantly higher in site 1 and 2 compared with site 4. Overall, CI was low (< 50 %) in all the sites indicating predominant bacterial decomposition pathway. The soil food web analysis indicated that the soil food web was enriched in all of the study sites, but structured only in site 1 and 2. The soil food web condition was maturing (Quadrant B) in site 1 and 2, but disturbed (Quadrant A) in site 3 and 4 (Fig. B-1). There was no significant difference in fungivores-to-bacterivores ratio, but fungivores + bacterivores-to-herbivores ratio was significantly lower in site 2 compared with the rest of the study sites (Table B-5). Fertility index was significantly low in site 1 and 2 compared with site 4, but significantly low in site 2 compared with site 3.

Table B-5. Soil food web enrichment (EI), structure (SI), basal (BI) conditions and channel index (CI) calculated for the carrot fields. Nematode trophic group ratios were expressed as fungivores (FV)-to-bacterivores (BV), and fungivores plus bacterivores-to-herbivores ((FV + BV)/HV), and the fertility index (FI) expressed as PPI/MI of the selected fields.

	Food web indices				Trophic ratios		
Site	BI	CI	EI	SI	FV/BV	(FV+BV)/HV	FI
1	21.73 a[a]	4.86 a	66.16 a	56.95 a	0.13	2.31 a	1.39 bc
2	27.36 a	11.61 a	56.43 a	58.09 a	0.23	1.20 b	1.35 c
3	24.04 a	6.56 a	71.52 a	34.58 ab	0.12	3.05 a	1.64 ab
4	28.45 a	7.19 a	68.42 a	19.35 b	0.10	2.74 a	1.66 a

[a]Means within columns followed by same letter(s) are not significantly different at $P \leq 0.05$.



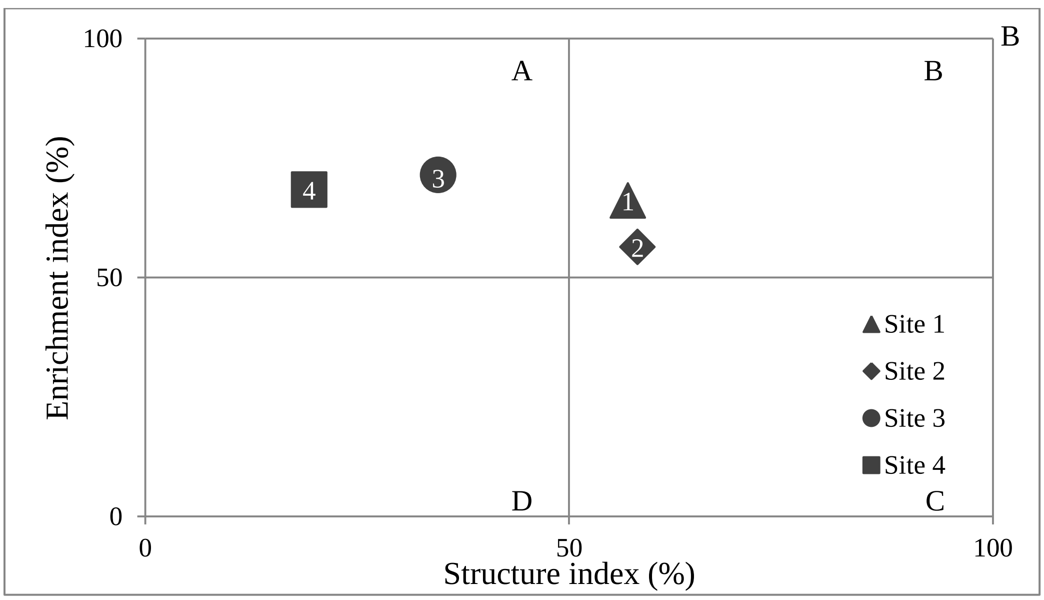


Figure B-1. Soil food web conditions representing the structure (SI) and enrichment (EI) conditions of the soil food web in the selected carrot fields (A) from each experimental unit (2 hectares) and (B) from each (site). The quadrants of nematode faunal profile indicate (A) highly disturbed soil, N-enriched, bacterial decomposition channel, low C/N ratio and disturbed soil food web condition (B) low to moderately disturbed soil, N-enriched, balanced bacterial-fungal decomposition channel, low C/N ratio and maturing soil food web (C) undisturbed, moderately enrichment, fungal decomposition channel, moderate to high C/N ratio and structured food web (D) stressed soil, depleted, fungal decomposition channel, high C/N ratio and degraded soil food web condition (Ferris et al., 2001).

Discussion

The abundance of the herbivore nematodes genera were less than 5 individuals per 100 cc of soil except root lesion nematodes and the numbers in average range between 19 in site 1 and 43 in site 2. Root lesion nematodes were the predominant herbivore genera comprising 98, 99, 92 and 78 % of the herbivores in site 1, 2, 3 and 4, respectively. In previous study *M. hapla*, *P. penetrans*, *H. carotae* and *Paratylenchus* spp. were reported from Michigan carrot fields (Berney and Bird, 1992; Hausbeck, 2008). Root lesion nematodes are known to cause serious damage on vegetables (LaMondia, 2006; Bao and Neher, 2011). The above-ground symptoms such as wilting and patches observed and greater carrot damages (Table B-1) in site 2 possibly associated with root lesion nematodes which represented 99 and 40 % of the herbivores and total nematodes community, respectively.

The abundance of non-herbivores and total nematodes was higher in site 4 compared with site 1 and 2 due to high number of bacterivores (Table B-3), suggesting disturbed soil system. Bacterivores are more abundant in disturbed soils (Bongers, 1990, Bongers and Bongers, 1998). Apart from this, MI, MI25 and SI values were low in site 4 compared with the other sites, suggesting a relatively disturbed soil condition (Bongers, 1990; Ferris et al., 2001). The lower PPI in site 4 and higher in the other sites were because of lower abundance (78 % of herbivores) of root lesion nematodes in site 4. Greater abundance of root-lesion nematodes in site 1 and 2 which are considered as relatively stable could be improved soil condition that can increase carrot growth that supports more root lesion nematodes, or the past management practices favor root lesion nematodes. Some winter cover crops such as winter rye and vetch are good host for root lesion nematodes may increase the nematodes pressure on carrots, and potentially reduce yield as observed in site 2 (Abawi and Ludwig, 1995; Bao and Neher, 2011).

The soil food web analysis indicated that the soil food web was disturbed in site 3 and 4 (Quadrant A), but maturing in site 1 and 2 (Quadrant B) (Fig. B-1), suggesting the soil food web with greater trophic links and potential pest suppression ecosystem services in site 1 and 2 (Ferris et al., 2001; Sánchez-Moreno and Ferris, 2007). The lower fertility index value in site 1 (1.39) and 2 (1.34) compared with site 4 (1.66), suggesting surplus of nutrients with high microbial activity in site 1 and 2, but severely nutrient-enriched in site 4 (Bongers et al., 1997). SI values are usually low in agroecosystems because of soil disturbance as a result of tillage and application of agrochemicals (Berkelmans et al., 2003; Briar et al., 2011; Fiscus and Neher, 2002) while structured in natural undisturbed ecosystems (Ferris et al., 2001). Hence, the nematode community analysis revealed differences in soil health condition among the study sites.

Root lesion nematode is one of the most prevalent herbivores with wide host range (Castillo and Volvas, 2007; Bao and Neher, 2011) and their threshold level may vary with changes in weather conditions, crop cultivars and other environmental factors (Ferris, 1978). In some states, root lesion nematode above 100 individuals per 100 cc of soil is considered as economic threshold level with potential yield reduction (Bao and Neher, 2011). With this standard, the threshold level for root lesion nematode did not reach to economic threshold level in our study that ranges between 7-60 individuals per 100 cc of soil. However, my result suggests the presence of potential damage of carrots from root lesion nematodes and a need for appropriate management strategy to keep root lesion nematodes at lower density to avoid economic damages.

Because of the restrictions on broad spectrum nematicides, alternative nematode management practice is required. Rotation to non-host crops can substantially reduce the nematode population (Belair, 1996; Viaene and Abawi, 1998; LaMonda, 2006) though difficult because of the wide host range of root lesion nematodes that includes weeds (Bao and Neher, 2011). Some of the cover crops used in Michigan vegetable production systems such as winter rye and vetch are good hosts for root lesion nematodes. Therefore, the use of these cover crops in fields infested with these nematodes could increase pressure on subsequent crops and potentially reduce yield.

In contrast, cover crop such as white clover was associated with the reduction of lesion nematode density in Vermont vegetable farms (Bao and Neher, 2011). Using Saia oat, Polynema marigold and sudangrass in rotation or as green manure reduced the number of lesion nematodes (LaMondia, 2006; Hooks et al., 2010). Also, annual ryegrass and wheat were poor hosts for root lesion nematodes (Kimpinski and Sanderson, 2004). This shows that knowing the presence of herbivore nematodes in a particular field and selecting appropriate cover/ rotation crops are important steps in nematode management. Use of cover crops with suppressive effect to more than one herbivore nematodes will have greater impact. For example, using sudangrass and Polynema marigold has suppressive to both root lesion and root-knot nematodes (Viaene and Abawi, 1998; Kimpinski and Sanderson, 2004; LaMondia, 2006).

The other option to control root lesion nematodes could be use of compost amendments. Animal manure reduced the number of root-lesion nematodes (Maharn et al., 2008, 2009; Bao and Neher, 2011). Annual application of spent mushroom compost prior to planting reduced the number of root lesion nematodes (LaMondia et al., 1999; LaMondia, 2006). Organic amendments can also be effective at controlling diseases and nematodes through the release of toxic compounds (Widmer and Abawi, 2000), or by providing more suitable habitable environment for antagonists of nematodes (LaMondia et al., 1999; Kerry, 2000).

In conclusion, in all of the sites, the predominant herbivore nematodes are root lesion nematodes, suggesting appropriate management practices are required to reduce the nematodes densities. This further suggests that lesion nematodes could be predominant in this area accounting the similarities in cropping system, soil type and climatic conditions. However, nematode taxa that were not recovered in these carrot fields do not necessarily mean they do not occur and infest carrots. Site 1 and site 2 have low-to-moderate soil disturbance, balanced bacterial-fungal decomposition pathway and maturing soil food web, suggesting better soil health condition. Site 3 and 4 have highly disturbed soil, bacterial decomposition pathway and disturbed soil food web, suggesting poor soil health status. Overall, the study sites require management practices that can manage both root lesion nematodes and soil health. Overall, my result provides information on the predominant herbivore nematodes and soil health status of the selected carrot fields that may be true for carrot fields of the counties.

APPENDIX C: VOUCHER SPECIMENS

Table C-1. List of voucher specimens[a] of nematode genera identified from the experimental samples and mounted on glass slides. The specimens were from MSU Teaching and Research center, Holt, MI, USA (N 43^{0}24.040’, W 085^{0}56.559’ and N 42^{0}40.326’, W 084^{0}28.922’) from 2012-2014 growing seasons. The samples are stored in the Agricultural Nematology Laboratory, Department of Horticulture at MSU.

Slide No	Nematode genera	Number of individuals	Developmental stage
1	*Acrobeloides*	1	Juvenile
2	*Acrobeloides*	1	Female
3	*Aphelenchus*	1	Juvenile
4	*Aphelenchus*	1	Juvenile
5	*Aphelenchus*	1	Female
6	*Aporcelaimellus*	1	Juvenile
7	*Aporcelaimellus*	1	Juvenile
8	*Aporcelaimellus*	1	Juvenile
9	*Aporcelaimellus*	1	Female
10	*Aporcelaimellus*	1	Female
11	*Cephalobus*	1	Male
12	*Clarkus*	1	Juvenile
13	*Clarkus*	1	Juvenile
14	*Clarkus*	1	Juvenile
15	*Diphtherophpra*	1	Juvenile
16	*Eucephalobus*	1	Female
17	*Filenchus*	1	Juvenile
18	*Helicotylenchus*	1	Female
19	*Helicotylenchus*	1	Juvenile
20	*Heterocephalobus*	1	Female
21	*Heterocephalobus*	1	Juvenile
22	*Mesodorylaimus*	1	Juvenile
23	*Mesodorylaimus*	1	Juvenile
24	*Mesodorylaimus*	1	Juvenile
25	*Mesodorylaimus*	1	Female
26	*Mesodorylaimus*	1	Female
27	*Mesodorylaimus*	1	Female
28	*Microdorylaimus*	1	Juvenile
29	*Nygolaimus*	1	Juvenile

Table C-1 (cont'd)

Slide No	Nematode genera	Number of individuals	Developmental stage
30	*Panagrolaimus*	1	Juvenile
31	*Plectus*	1	Juvenile
32	*Psilenchus*	1	Female
33	*Pungentus*	1	Juvenile
34	*Pungentus*	1	Juvenile
35	*Pungentus*	1	Female
36	*Rhabditis*	1	Juvenile
37	*Rhabditis*	1	Female
38	*Rhabditis*	1	Juvenile
39	*Rhabditis*	1	Female
40	*Thonus*	1	Juvenile
41	*Thonus*	1	Juvenile
42	*Thonus*	1	Male
43	*Thonus*	1	Juvenile
44	*Tylencholaimellus*	1	Female
45	*Tylenchus*	1	Female
46	*Tylenchus*	1	Female
47	*Tylenchus*	1	Female
48	*Tylenchus*	1	Female
49	*Tylenchus*	1	Female
50	*Tylenchus*	1	Female
51	*Tylenchus*	1	Female

[a]Pictures of the voucher specimens were filed in Room 256, Agricultural Nematology Laboratory, Department of Horticulture at MSU.

Table C-2. List of additional photographed and documented nematode genera identified from MSU Teaching Research Center, Holt, MI, USA (N 43^{0}24.040’, W 085^{0}56.559’ and N 42^{0}40.326’, W 084^{0}28.922’) from 2012-2014 growing seasons.

Nematode genera		
Acrobeles	*Heterocephalobus*	*Psilenchus*
Acrobeloides	*Heterodera*	*Pungentus*
Alaimus	*Hoplolaimus*	*Rhabditis*
Aphelenchoides	*Longidorus*	*Thonus*
Aphelenchus	*Malenchus*	*Trichodorus*
Aporcelaimellus	*Mesodorylaimus*	*Trypila*
Basiria	*Mesorhabditis*	*Tylencholaimellus*
Boleodorus	*Microdorylaimus*	*Tylenchorhynchus*
Cephalenchus	*Microlaimus*	*Tylenchus*
Cephalobus	*Mononchus*	*Xiphinema*
Cervidellus	*Mylonchulus*	
Clarkus	*Nygolaimus*	
Diphtherophora	*Panagrolaimus*	
Ditylenchus	*Paratylenchus*	
Dolichorynchus	*Pellioditis*	
Eucephalobus	*Plectus*	
Eudorylaimus	*Prionchulus*	
Eumonhystera	*Prismatolaimus*	
Filenchus	*Pristionchus*	
Helicotylenchus	*Prodorylaimus*	

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