AN ABSTRACT OF THE THESIS OF

Candace R. Banners for the degree of Master of Science in Soil Science presented on July 1, 2005.

Title: Soil Quality Dynamics in an Integrated Reduced-Tillage and Cover-Cropped Vegetable Agroecosystem

Abstract approved: Redacted for privacy

Richard P. Dick

Soil response and function were investigated following the adoption of an integrated reduced-tillage and cover-cropped vegetable system in the Willamette Valley of Western Oregon. The experiment was conducted over three cropping seasons (2002-2004) at the Oregon State University Vegetable Research Farm (Corvallis, OR). The design was a randomized complete-block with four replications of the following three treatments: 1) strip-tillage with winter cover crop; 2) conventional tillage with winter cover crop; and 3) conventional tillage with winter fallow. The objective of this study was to track biological and physical soil properties indicative of soil quality in a silty clay loam during the transition to an integrated vegetable system compared to a conventional system. Additionally, relationships between soil properties and crop yield were assessed, and techniques used to measure earthworm activity were evaluated. The major findings were: 1) biological soil quality indicators responded rapidly to reduced tillage and cover crops, whereas physical soil quality indicators responded differently; 2) crop yield correlated negatively with

biological soil quality indicators and soil bulk density; over time correlations became less negative with biological properties and more negative with bulk density; 4) earthworm activity was affected by tillage and cover crops, and both midden counts and mustard solution extraction could detect these differences to varying degrees.

Soil Quality Dynamics in an Integrated Reduced-Tillage and Cover-Cropped

Vegetable Agroecosystem

by

Candace R. Banners

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented July 1, 2005
Commencement June 2006

Master of Science thesis of Candace R. Banners presented on July 1, 2005.

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Candace R. Banners, Author

ACKNOWLEDGEMENTS

I wish to thank the Sustainable Agriculture Research and Education (SARE) branch of the USDA for funding this project, in addition to the National Science Foundation (NSF) for funding me on a GK-12 Graduate Teaching Fellowship during my final year of this project, and to Dr. Richard Dick for making this project possible. I also wish to thank all of the graduate students in Richard's lab for their help with ideas, their motivation, and sense of humor. Special thanks are extended to the following graduate students, colleagues, undergraduates and friends whose help was invaluable in the field: Russell Wymore, Dan McGrath, Andy Moldenke, Marcelo Fernandes, Lara Fritz, Ben Linzy, Naoyuki Ochiai, Jennifer Washburn, Siré Diedhiou, Ekwe Dossa, Leigh Winowiecki, Wes Bascom, Dirk Richcreek, and Chris Russo. Thanks also to Hank Loescher for help with statistics and always lending an objective ear. The Crop and Soil Science Department deserves warm and heartfelt thanks for all of the help and support during the time I was ill, especially Russ Karow. I would also like to acknowledge the unending assistance and support from Joan Sandeno in the lab, field, and hospital (a.k.a. "Lab Mom"). I cannot express my appreciation enough for her expertise, reliability, and caring personality (not to mention her fabulous cheesecakes!). Jenn Kucera, in addition to help in the lab and field, has provided mentorship and a deep friendship for which I am grateful. And to Chris Russo, my partner in life, who's extraordinary spirit is nurturing, encouraging, and wise—from helping me to understand mounds of data, and making me laugh when I was stressed, to having a delicious meal cooking in the kitchen—thank you.

CONTRIBUTION OF AUTHORS

Dr. Dan McGrath and Dr. Andy Moldenke assisted with the field design. Marcelo Fernandes, Russell Wymore and Joan Sandeno assisted with sample collection.

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I dedicate this thesis to:
My father Del Banners
My mother Florence Banners.

SOIL QUALITY DYNAMICS IN AN INTEGRATED REDUCED-TILLAGE AND COVER-CROPPED VEGETABLE AGROECOSYSTEM

CHAPTER 1

LITERATURE REVIEW

INTRODUCTION

Current demands are increasing for processed vegetable growers in the Pacific Northwest to reduce pesticide applications, improve salmon habitat, and enhance soil quality. Because vegetables are high value crops, any decreases in yields or fruit quality can have significant impacts on economic returns. Therefore, growers are interested in a system that provides a balance between environmental concerns and crop productivity. A production system that integrates reduced tillage and cover crops has the potential to meet these needs. However, commercial vegetable growers in the Willamette Valley have adopted such management strategies with mixed success (D. McGrath, personal communication, 2005). An integrated approach is thought to improve soil quality; nevertheless, some growers have experienced suppressed yields. It seems likely that the key to managing these systems lies in understanding the soil ecosystem.

Although previous research has been conducted in integrated agricultural systems (Griffith et al., 1988; Wilhoit et al., 1990; Dick et al., 1991; Vyn and Raimbault, 1992; Rutledge, 1999), little has been done in the Willamette Valley focusing on high-value vegetable crops. In response to this, a field study integrating reduced tillage and cover crops in vegetable row crops was initiated in 2001 to track changes in soil quality resulting from different management strategies. The objectives of this study were to:

1) Evaluate the use of biological and physical soil quality indicators to monitor the impact of integrated and conventional systems on soil biological and physical properties.

2) Explore soil quality changes to better understand the mechanisms driving soil ecosystem dynamics after the adoption of a strip-tilled/cover-cropped agroecosystem.

3) Assess differences in vegetable yield with integrated and conventional systems and investigate relationships between yield and soil quality measurements.

4) Determine how a reduced-tillage/cover-cropped system would affect earthworm abundance and evaluate several methods to monitor earthworm activity.

5) Specifically assess the role of earthworms as an indicator of soil quality in a reduced-tillage/cover-cropped system by correlating earthworm activity with other soil quality indicators.

We hypothesized that integrated systems incorporating reduced tillage with cover crops would improve soil quality, and this would be evident in several biological and physical soil quality indicators. We also hypothesized that as soil quality increased, a subsequent increase in vegetable crop yield would be observed. Any decreases in yield were thought to be associated with specific soil quality properties that may not improve after the adoption of an integrated system. It was also proposed that reduced tillage, in combination with winter cover crops, would increase earthworm abundance by decreasing soil disturbance and providing a food source. Furthermore, earthworm abundance would positively correlate with other soil biological and physical properties that act as soil quality indicators, suggesting that earthworm abundance can be added to the suite of soil quality indicators.

SOIL QUALITY

The topic of soil quality has recently come to light with the growing awareness of the important role of soil in sustaining life and environmental quality on our planet. Doran and Parkin (1994) created a working definition of soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". In an agroecosystem, the quality of the soil is critical to maintain current and future levels of food production, and is regarded as a primary aspect of sustainable agriculture (Warkentin, 1995).

It is useful for growers to gauge soil quality changes that may reveal the accumulation of long-term benefits of different management strategies, yet the task of measuring soil quality proves challenging, probably due to the multifaceted nature of the concept (Carter, 2002). In a recent effort to measure and monitor soil quality in agroecosystems, soil biological, physical, and chemical properties have been explored (Dick, 1994; Fauci and Dick, 1994; Ndiaye et al., 2000; Carter, 2002; Knight and Dick, 2004). This research has identified the need for soil quality indicators to exhibit the ability to detect changes in a relatively short time period as well as discriminate between the outcomes on the soil resource (Fauci and Dick, 1994). Determining a suite of soil quality indicators that respond quickly to changes in soil management is desirable for agricultural professionals and researchers.

Soil Biological Properties

In the Royal Society of London's Leeuwenhoek Lecture, Quastel (1955) highlighted Antonie van Leeuwenhoek's idea that "a vast world of microorganisms lies in the soil". The diverse and abundant microbial fraction of the soil is apparent when considering that one gram of soil can contain in excess of one hundred million (10^8) individuals of bacteria with as many as 10^4 to 10^6 different species (Wollum, 1999). The extensive microbial fraction of the soil combined with soil fauna such as invertebrates, insects, and burrowing mammals, define soils as biological systems (Quastel, 1955). Interactions between soil biology and soil physical and chemical properties influence plant growth and soil ecosystem dynamics.

Soil biology such as fungi and earthworms influence soil physical properties because aggregates are entrapped in hyphae (Gupta and Germida, 1988; Oades, 1993, Amézketa, 1999), and earthworms excrete stable castings, thus building soil structure (Hopp and Slater, 1948; Oades, 1993). In addition, mycorrhizal fungi help deliver immobile soil nutrients such as phosphorus to plants (Chen, 2005), and earthworms increase organic matter decomposition (Shaw and Pawluk, 1986) and mineralization rates (Satchell, 1967).

Microorganisms also aid in decomposition and nutrient mineralization as they break down organic material (Tate, 2000). Temporary nutrient immobilization occurs as nutrients from the breakdown of organic matter are stored inside the bodies of microorganisms, followed by mineralization via the death and decomposition of microorganisms. It is through this microbially mediated process that microorganisms play a key role in nutrient cycling. The size and activity of the microbial biomass will therefore influence the extent of nutrient turnover (Martens, 1995), which directly relates to the productivity of soil.

Microbial Biomass. Microbial biomass is a measure of the amount of microorganisms found in the soil and has been shown to reflect changes in soil management (Fauci and Dick, 1994). This is due to the fact that carbon and nitrogen in microbial biomass undergo rapid turnover and therefore parallel changes in soil management before it is possible to detect changes in total soil carbon or nitrogen (Fauci and Dick, 1994). Because soil organic matter is often an acceptable index of soil quality (Andrews et al., 2002; Carter, 2002), and soil organic matter is reflected in total organic carbon, microbial biomass measurements are a promising indicator of soil quality (Carter, 1986). Microbial biomass carbon is a useful soil quality indicator in part because it is not influenced by inorganic nitrogen fertilizer often applied in agricultural ecosystems (Fauci and Dick, 1994).

The size of the microbial biomass can be measured by several techniques including substrate-induced respiration, ATP extraction, microscopic plate-counts, chloroform fumigation-extraction, or chloroform fumigation-incubation. The chloroform fumigation-incubation method (CFIM) as described by Jenkinson and Powlson (1976) has been the most widely used and accepted method (Martens, 1995) due primarily to its simplicity and affordability.

Enzyme Activity. Determining the activity of the microbial biomass is achieved by alternate techniques, examples being microbial respiration or enzyme activity. The origin of most soil enzymes are thought to be microbially derived (Ladd, 1978), although plants and animals can contribute. It has been shown that plants influence soil enzymes by excreting extracellular enzymes (Dick and Tabatabai, 1986) thus increasing enzymatic activity in the rhizosphere soil (Castellano and Dick, 1991). However, this was shown to be the case for select soil enzymes and not always a rule. Because it is difficult to differentiate between plant-derived and microbially-derived enzymes, a plausible theory would be that the phenomenon known as the "rhizosphere effect" — where soils directly surrounding plant roots have increased microbial activity (Alexander, 1977) — may play a role in the increased enzyme activity in rhizosphere soils (Dick 1994).

Soil enzymes have been distinguished by Burns (1982) to include biontic and abiontic enzymes, terms coined by Skujinš (1976). Biontic enzymes are those coupled with living cells. Abiontic enzymes are those that are no longer linked to living cells; they have been excreted from cells, attached to cell debris, or leaked into the soil from dead or lysed cells (Dick, 1994). Soil enzymes themselves are proteins that act as catalysts, increasing the rate of chemical reactions within the soil environment. This is achieved by binding the reactants together at an active site on the enzyme allowing the proper stereochemical alignment to initiate and control the chemical reaction (Fuhrmann, 1999).

Enzymes are specific in the reactions they catalyze; therefore, soil enzymes can be studied relative to the processes with which they are associated. Glucosidases, for example, are linked with the carbon cycle (Eivazi and Tabatabai, 1988), specifically β-glucosidase in soils provides energy sources to microorganisms via hydrolysis products of the reaction it catalyzes (Tabatabai, 1994). Measuring β-glucosidase activity involves a relatively simple procedure and the results have been shown to discriminate among soil management effects (Bandick and Dick, 1999), a property indicative of a good soil quality indicator.

Earthworm Abundance. Soil that has passed through the microbially active earthworm gut is excreted as earthworm castings which have been shown to have greater microbial activity compared to undigested soil (Barois and Lavelle, 1986). This increase in microbial activity includes increases in bacteria, fungi, and actinomycetes (Dkhar and Mishra, 1986), which affects nutrient cycling. Nutrient availability (C, N, P, K, Ca) is increased due to this greater microbial activity as organic matter is transformed to more available forms (Satchell, 1967), and earthworms have been found to influence decomposition rates (Shaw and Pawluk, 1986).

Earthworms affect physical properties of soils by ingesting soil and organic material, and by burrowing as a means to gather further debris and for protection. The development of burrows and deposition of castings increases large pores in the soil profile (Edwards and Lofty, 1977). Large amounts of organic material consumed by some earthworm species, combined with their internal secretions, result in the formation of water stable aggregates, which improve soil structure and productivity (Hopp and Slater, 1948). The combination of increased aggregation and porosity from earthworm activity also reduces surface crusting and surface run-off, which in turn increase infiltration and water retention. The subsequent improved soil quality promotes root growth and penetration, and decreases erosion potential.

Earthworms also affect the flow of water by increasing the rate of water infiltration through their burrow systems. However, due to different burrowing habits, the extent to which infiltration is increased varies depending on the earthworm species. Large, vertical channels can rapidly conduct water through macropores and contribute to direct, or preferential flow (Bouma, 1991; Trojan and Linden, 1992; Blair et al., 1995; Trojan and Linden 1998; Lamgmaack et al., 1999). Advantages to this rapid infiltration include increased drainage, which can be beneficial for plants growing in heavy soils. However, this can facilitate preferential movement to groundwater of pollutants such as pesticides and fertilizers.

Soil biological properties impact nutrient cycling, soil structure, root diseases and some insect pests. Microorganisms and soil fauna fuel the transformations of nutrients such as nitrogen, phosphorus, potassium and sulfur. Exudates, fibers, and detritus from soil biology also provide organic glues that aid in the formation of soil aggregates. Additionally, soil fauna affect macroporosity through the action of burrowing.

Soil Physical Properties

The physical properties of soils are pivotal in the function of agroecosystems, and can be related to crop productivity (Vyn and Raimbault, 1992; Abu-Hamdeh, 2003). If soil quality is defined as maintaining ecosystem, plant, and animal health, soils must provide ample spaces for air and liquid to permeate and flow. This is accomplished through the maintenance of soil structure which influences water use efficiency (Boyle et al., 1989; Unger et al., 1998; Shukla et al., 2003), seedling establishment, and plant root growth (Wang and Smith, 2004). Soil structure is defined as the way in which soil particles are arranged in aggregates (Brady and Weil, 1999). Structure is altered by shrinking and swelling, freezing and thawing, tillage, or by physical movement of particles by soil flora and fauna. The amount and type of clay content of the soil determines the extent to which shrinking and swelling affects structure (Oades, 1993). Aggregate formation is based on abiotic features such as parent material, adsorbed cations, climate, and tillage. It is also based on biotic features including plant roots and their exudates, organic matter, fungal hyphae, and extracellular polysaccharides of microbial origin (Hartel, 1999).

The mechanism behind aggregation, as explained by Kemper and Rosenau (1986), begins with the surface tension of the interface between air and water, and the forces of adhesion and cohesion of water surrounding particles in moist soils. As soils dry, the liquid solution retreats into tiny pores where it is held by capillary forces. Compounds soluble in water are concentrated in this liquid solution, such as carbonates, silica, and organic molecules. Particle-to-particle interfaces offer the lowest free energy associated with adsorption, and these are the places where the liquid solution recedes further with increased soil drying. At these interfaces, the soluble compounds eventually precipitate as crystalline or amorphous compounds, acting as binding agents as they glue aggregates together. Soil particles that are drawn together by this process also provide increased opportunities for strong hydrogen bonds to form between oxygen and hydroxyl groups, as well as other bonding which increase the strength of aggregation when soils are dry (Kemper and Rosenau, 1986).

Several physical soil parameters exist that provide insight into soil quality, including percent water stable aggregates (WSA), bulk density, and infiltration rate.

Aggregate stability. Aggregate stability has a bearing on the suitability of soil for plant growth. Binding agents that help form aggregates also determine the extent to which aggregates will resist disruption from environmental forces such as raindrops, or in the case of an irrigated vegetable field, overhead water (Oades, 1993). If aggregates are unstable under such conditions, they disintegrate into smaller aggregates, known as slaking, resulting in the formation of crusts on the soil surface (Kemper and Rosenau, 1986; Lado et al., 2004). Surface crusting hinders infiltration into the soil and can result in surface runoff or overland flow of water and solutes such as fertilizer and pesticides. Slaking below the surface results in the collapse of macropores, and decreasing places where air and water are available to plant roots. Connectivity of pores is also compromised making the path for water infiltration more tortuous and hence slower. This can lead to saturated conditions encouraging root rot diseases and inhibiting the transport of nutrients to deeper roots.

Testing the stability of aggregates can be done both dry and wet. Dry stable aggregates (DSA) are sieved multiple times to determine their resistance to mechanical disruption. On the other hand, WSA are immersed in water and sieved while remaining immersed using a mechanical wet-sieving device that provides even, replicable sieving cycles (Kemper and Rosenau, 1986). This technique is applicable for aggregates from 1-2 mm in size; sand-size particles are subtracted from the percent water stable aggregates at the end of the analysis when a dispersing agent is added to breakdown all aggregates leaving remaining sand-size particles on the sieve.

Bulk Density and Infiltration Rate. The mass of a specific volume of dry soil, including both solid particles and pore space, is described as the bulk density of soil (Brady and Weil, 1999). Water infiltration is a function of bulk density in that the bulk density is used to calculate the percent pore-space of a soil; soil porosity directly impacts infiltration as well as soil aeration and plant root growth. Soil texture (percent sand, silt, and clay) influences the bulk density of a soil as particle sizes relate to the pore spaces in a given volume. Bulk density can be used as a measurement of soil compaction and can determine the location of zones of compaction that may impede plant roots.

Many methods exist to determine bulk density, including the core method, clod method, and radiation method. Both the core and clod methods are destructive and if performed incorrectly, can influence bulk density measurements by artificially compacting soil within the core. Radiation methods transmit gamma radiation into the soil; the way in which the radiated particles travel through the soil is influenced by the bulk density. Radiation density gauges measure this transmission and calculate bulk density in situ.

Infiltration rate is often influenced by soil aggregation and porosity, and can be measured in the field via a falling- or constant-head infiltrometer; in each case, a metal ring is inserted into the soil. Falling-head infiltrometers measure the time it takes for a known volume of water to infiltrate into the soil within the ring, and constant-head infiltrometers measure the volume of water needed to maintain a specific head within the ring.

Soil physical properties impact costs and effectiveness of tillage, seedling establishment, and plant root growth (Wang and Smith, 2004). Stable soil aggregates that are able to withstand disturbances from rain or irrigation preserve porosity between and within them, retaining space for air and water infiltration. Adequate soil structure and density permits roots to easily grow to provide strong structural support, water absorption, and nutrient uptake.

COVER CROPS

Benefits of cover crops are vast, as they reduce soil erosion, improve moisture and nutrient availability, prevent nutrient leaching and runoff, encourage beneficial insects while helping to control pests, suppress weeds and diseases, and diminish off-site effects of pesticides (Bowman et al., 1998). Cover crops suppress weed emergence by blocking light penetration to the soil which decreases the germination of many weed seeds stimulated by sunlight (Teasdale and Mohler, 1993), and by exhibiting allelopathic properties, both of which decrease dependence on herbicides. Furthermore, habitat for beneficial insects and nematodes is created with the use of cover crops (Bowman et al., 1998). Decreased insect pressure was noted by Abdul-Baki and Teasdale (1993) who noticed few Colorado potato beetles on their tomato plants when grown with cover crops compared to those grown without.

Cover crops also add organic matter to the soil, contributing to increased soil aggregation. Roots from cover crops and fungal hyphae associated with increased organic matter have been shown to help stabilize macroaggregates, important in infiltration (Tisdall and Oades, 1982; Gupta and Germida, 1988; Oades, 1993). Aggregation as a result of cover crops was highlighted by Buller (1999) who reported increased mean weight diameters of aggregates in cover-cropped portions of split fields. Humic materials and microbial products resulting from the presence of cover crops have been proposed as binding agents of microaggregates as well; Ball-Coelho et al. (2000) showed an increase in microaggregate stability in the presence of cover crops.

Buller (1999) also found water intake rates improved significantly with only two cover crop treatments in an on-farm research trial. In the same trial, the use of annual ryegrass interseeded with corn increased water stable aggregates during the second year compared to a section of the same field without ryegrass, indicating that cover crop effects on aggregation and infiltration can be observed fairly quickly.

In addition to improving soil physical properties, an increase in organic matter also boosts beneficial microbial populations and nutrient cycling efficiency. Previous research has found disease suppression in soils with increased organic matter from added composts (Hoitink et al., 1997; Stone et al., 2001). Other studies have shown mineralized carbon (Mendes et al., 1999) and nitrogen (Mendes et al., 1999; Schutter and Dick, 2002) levels in soils with cereal-legume cover crops to be greater than in fallow soils. Additionally, soils under cereal and legume cover crops have exhibited greater enzyme activity (Bandick and Dick, 1999; Mendes et al., 1999; Ndiaye, et al., 2000) due to either specific organic material associated with these cover crops, or greater carbon inputs. Microbial respiration (Schutter and Dick, 2002) and biomass (Mendes et al., 1999; Ndiaye et al., 2000) was also found to increase in cover cropped soils compared to fallow soils. Ndiaye et al. (2000) reported the greatest increase in a cereal-legume mix, followed by the cereal alone, emphasizing the importance of cover crop type. This treatment effect was noticeable in the first two years of cover cropping, again illustrating the rapid changes in soil quality that occur with cover crops.

Environmental quality is enhanced with the use of cover crops in that, in addition to improved soil quality, water quality is protected as the cover crops provide conditions that encourage infiltration of water and solutes and improved water intake (Wang and Smith, 2004). Improved water intake and decreased evaporative loss from the soil surface results in greater soil moisture which provides a natural safeguard for vegetables in the event of drought (Munawar et al., 1990; Wilhoit et al., 1990; Teasdale and Mohler, 1993; Johnson and Hoyt, 1999).

Furthermore, cover crops can trap and hold nitrogen, a mobile soil nutrient, to prevent nitrogen leaching into the groundwater, protecting both human and wildlife health (Bowman et al., 1998). Nitrogen is also fixed via bacterial associations with leguminous cover crops which contribute plant available nitrogen to the soil, and decrease synthetic fertilizer costs.

Challenges related with cover crops include delayed fruit maturity due to decreased soil temperature (Abdul-Baki and Teasdale, 1993), and immobilization of nitrogen from cover crops by microbial biomass (Doran, 1987). Timing with respect to microbially mediated nutrient immobilization/mineralization and uptake by plants is essential. In the Pacific Northwest in general, and the Willamette Valley, specifically, autumn and spring weather can be sporadic and unpredictable. Autumn cover crop establishment can be uneven, and spring soil moisture and temperature may not be ideal for early plantings due to cover crop residue.

As soil health is improved, it is thought that crop yields will also improve. However, vegetable crops grown in a cover-cropped management system have been shown to improve over conventional systems (Kelly et al., 1995), equal that of conventional systems (Wilhoit et al., 1990; Abdul-Baki et al., 1997), as well as decline compared to conventional systems (Creamer et al., 1996; Harrison et al., 2004). It appears that soil texture and climate play key roles in the success of vegetable production systems that include cover crops.

REDUCED TILLAGE IN A VEGETABLE SYSTEM

Reduced tillage includes a variety of tillage techniques that deliver minimal disturbance to the soil environment. Types of reduced tillage include strip tillage which uses a rotary and shank/coulter to till a narrow strip where crops are planted leaving the between-row zones tillage-free; and no-till, or direct drill, where seeds are drilled directly into an untilled soil bed. Cover crops are almost always included in a reduced tillage system. In contrast, conventional tillage includes the use of a moldboard plow, ripper, disker, rotovator, or often a combination of these techniques to achieve a relatively deep, evenly tilled seed bed.

The attractive aspects of reduced tillage include the conservation of water, soil (Johnson and Hoyt, 1999), fuel and labor (Doster et al., 1983; Luna and Staben, 2002). Soil organic matter is also conserved in reduced tillage systems as decomposition slows when organic matter is allowed to remain on the soil surface, compared to rapid decomposition of organic matter that has been incorporated by a conventional plow (Blevins et al., 1983; Staley et al., 1988; Carter, 1992).

Water conservation occurs mainly due to cover crops; soil moisture is elevated under cover crop residue which decreases evaporative water loss (Teasdale and Mohler, 1993; Johnson and Hoyt, 1999). Soil conservation can be observed as increased soil aggregate stability with reduced tillage (Emmond, 1971; Carter, 1992; Kandeler and Murer, 1993; Ball-Coelho et al., 2000), and soil surface protection from cover crops resulting in decreased erosion (Coolman and Hoyt, 1993). Passing heavy tillage equipment over fields contributes to fuel and labor expenses, which are diminished in a reduced tillage system as the number of passes required drops significantly. Luna and Staben (2002) report an average savings of \$38.50 hectare^{-1} in tillage costs and an average savings of 0.59 hours hectare^{-1} in labor costs when a rotary strip tillage system was used compared to a conventional tillage system.

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CHAPTER 2

BIOLOGICAL AND PHYSICAL SOIL QUALITY DYNAMICS IN AN INTEGRATED VEGETABLE AGROECOSYSTEM

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Prepared for submission to:

Soil Science Society of America Journal

ABSTRACT

Integrated vegetable cropping systems that include winter cover crops and reduced tillage help to conserve natural resources but growers adopting these systems in Western Oregon have had inconsistent crop yields. These results are likely related to soil response and function. The objective of this study was to track soil biological and physical properties in a silty clay loam during transition to an integrated system in comparison to a conventional vegetable system. The experiment was done over three cropping seasons (2002-2004), and had a randomized complete-block design with the following treatments: 1) strip-tillage with winter cover crop (Strip-CC); 2) conventional tillage with winter cover crop (Till-CC); and 3) conventional tillage with winter fallow (Till-WF). After year one, there was a rapid increase in soil biological properties (microbial biomass-C and β-glucosidase enzyme activity) in the completely integrated Strip-CC treatment that continued over time. Physical soil properties responded differently. Percent water stable aggregates (WSA) were significantly higher for both cover-cropped treatments when compared to Till-WF during all sampling periods. However, WSA did not increase further in completely integrated Strip-CC treatments, suggesting WSA was most sensitive to cover crops. In contrast, the between-row bulk density remained significantly greater ($p < 0.05$) in Strip-CC compared to other treatments. Although reduced tillage and cover cropping caused a rapid response to soil biological properties, there was a corresponding increase in soil compaction under strip tillage which could affect crop productivity. In theory, amelioration of soil compaction via increased soil biological processes is

possible; however, this process did not occur in the first three years after adoption of an integrated system.

INTRODUCTION

Current demands are increasing for processed vegetable growers in the Pacific Northwest to reduce pesticide applications, improve salmon habitat, and enhance soil quality. Because vegetables are high value crops, any decreases in yields or fruit quality can have significant impacts on economic returns (Johnson and Hoyt, 1999). Therefore, growers are interested in a system that provides a balance between environmental concerns and crop productivity. A production system that integrates reduced tillage and cover crops has the potential to meet these needs. In the Willamette Valley, however, such a system has generated mixed results with respect to crop productivity.

Past research has identified important benefits associated with cover crops and reduced tillage. Cover crops add organic matter to the soil, and increase soil aggregation (Buller, 1999). Roots and fungal hyphae, such as those associated with cover crops, have been shown to help stabilize macroaggregates which are important in water infiltration and retention (Tisdall and Oades, 1982). Humic materials and microbial products resulting from the presence of cover crops have been proposed as binding agents of microaggregates, and Ball-Coelho et al. (2000) showed microaggregates to be more stable in the presence of cover crops.

Winter cover crops have been shown to rapidly improve aggregation and infiltration. Water intake rates improved significantly with only two cover crop treatments in an on-farm research trial (Buller, 1999); and Ndiaye et al. (2000) found the greatest increase in a cereal-legume mix, followed by the cereal alone.

An increase in organic matter also boosts beneficial microbial populations as well as the efficiency of nutrient cycling. Studies have shown mineralized carbon (Mendes et al., 1999) and nitrogen (Mendes et al., 1999; Schutter and Dick, 2002) levels in soils with cereal-legume cover crops to be greater than winter fallow soils. Soils under cereal and legume cover crops also have exhibited greater enzyme activity (Bandick and Dick, 1999; Mendes et al., 1999; Ndiaye et al., 2000), microbial respiration, and microbial biomass (Schutter and Dick 2002).

Cover crops and reduced tillage systems could have a synergistic impact towards the development of a more sustainable system. Cover crops prevent light penetration and smother weed seedlings, decreasing weed problems when tillage is reduced (Teasdale and Mohler, 1993). Cover crops improve soil structure by maintaining porosity which is important for soil aeration under reduced tillage.

The attractive aspects of reduced tillage include the conservation of water, soil, fuel and labor. Cover crops associated with reduced tillage systems prevent evaporative loss of soil moisture and can benefit plants during dry periods (Wilhoit et al., 1990). Soil organic matter also is conserved in reduced tillage systems when decomposition slows as organic matter is allowed to remain on the soil surface, as opposed to being incorporated by conventional tillage. Cover crops in a reduced tillage system contribute to the protection of the soil surface from rain and irrigation preventing soil crusting and subsequent surface runoff of fertilizer and pesticides. Lal

(1976) found that in a no-till system, infiltration rates increased when compared to a conventionally tilled system.

Passing heavy tillage equipment over fields contributes to fuel and labor expenses as well, which are diminished in a reduced tillage system as the number of passes required drops significantly. Luna and Staben (2002) report an average savings of \$38.50 ha^{-1} in tillage costs and an average savings of 0.59 hours ha^{-1} in labor costs when a rotary strip tillage system was used compared to a conventional tillage system.

Despite the ecological advantages and likely positive impacts on soil quality, the vegetable growers in Western Oregon have had mixed success relative to yields when integrating cover crops and reduced tillage (D. McGrath, personal communication, 2005). These results are likely related to the soil ecosystem; understanding the soil biological and physical mechanisms in response to a shift towards integrated agriculture may provide insight into the challenges observed in plant productivity.

Doran and Parkin (1994) created a working definition of soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". Soil quality is regarded as a primary aspect of sustainable agriculture (Warkentin, 1995), yet the task of measuring soil quality proves challenging, probably due to the multifaceted nature of the concept (Carter, 2002). An effort to evaluate soil quality in an agroecosystem should focus on indicators of sustainable function that promote the health of the landscape, the crop, and subsequently, those who consume it.

Several soil biological and physical properties can be used as indicators to gauge soil quality and possibly reveal the accumulation of long-term benefits of sustainable agricultural practices. Soil quality indicators should exhibit the ability to detect changes in a relatively short time period as well as discriminate between the outcomes on the soil resource (Fauci and Dick, 1994). To those growing crops, it is useful to be able to measure soil quality and track changes over time as new soil management strategies are implemented.

Microbial biomass-carbon (MB_C) and enzyme activity have the potential to reflect soil quality. These indicators integrate key biological properties and functions of the soil ecosystem. A larger and more active microbial community can improve soils by increasing the large aggregates and their stability (Tisdall and Oades, 1982; Gupta and Germida, 1988; Oades, 1993; Rillig, 2004). Hyphae of branching organisms enmesh soil particles (Tisdall and Oades, 1982; Gupta and Germida, 1988; Oades, 1993) and the general microbial community can produce organic compounds during decomposition including filamentous structures, biopolymers, and extracellular polysaccharides (Tisdall and Oades, 1982; Oades, 1993; Amézketa, 1999; Rillig, 2004) that provide the "glue" that holds and stabilizes soil particles (Gupta and Germida, 1988; Oades, 1993). Furthermore, organic inputs can stimulate microbial activity and biomass and promote disease suppressive soils (Hoitink et al., 1997; Stone et al., 2001; Ochiai, 2004).

Soil physical properties are important to soil quality for processes such as water efficiency (Boyle et al., 1989; Unger et al., 1998; Shukla et al., 2003), seedling establishment, and plant root growth (Wang and Smith, 2004), and can be related to crop productivity (Vyn and Raimbault, 1992; Abu-Hamdeh, 2003). Stable aggregates withstand disturbance and preserve porosity that promotes gas exchange, infiltration, and water retention. Low soil density promotes root growth to gain structural support and improved water and nutrient uptake. Physical soil quality indicators include water stable aggregates, bulk density, and water infiltration.

Previous research in the Pacific Northwest has shown positive effects of integrating cover crops on soil quality (Bandick and Dick, 1999; Buller, 1999; Ndiaye et al., 2000; Schutter and Dick 2002), and generally no reports of adverse effects on yield in the Willamette Valley with reduced tillage practices (Luna and Staben, 2002). Adding reduced tillage to winter cover crop systems would be attractive by reducing disturbance and associated labor and energy costs. However, vegetable growers of Western Oregon who have tried zero- or strip-tillage systems have had inconsistent crop productivity (D. McGrath, personal communication, 2005). There is very little information about the soil mechanisms that may be affected during conversion to an integrated cover crop/reduced tillage system. Therefore, the objectives of this study were to compare a conventional tillage and winter fallow vegetable-based system with a combined winter cover crop and strip-tillage system in relation to key soil biological and physical properties. It was hypothesized that soil quality would improve with the addition of cover crops and a reduction in tillage, and this improvement would be evident in biological and physical soil quality indicators.

MATERIALS & METHODS

Site. Experimental Design, and Soil Sampling

The experimental site is located at the Oregon State University Vegetable Research Farm in Corvallis, Oregon, in the Willamette Valley of Western Oregon. The climate is Mediterranean with warm, dry summers and cool, wet winters. The soils are classified as Chehalis silty clay loam (fine-silty, mixed, superactive, mesic Cumulic Ultic Haploxerolls). The soils are very deep and well drained, formed in mixed alluvium on the flood plain along the Willamette River. The average soil texture at this site is 5.1, 66.5, and 28.4 kg kg^{-1} sand, silt, and clay, respectively. Slight variations exist across the field; however, these variations were accounted for by the randomized complete block field design (Table 2.1).

The design was a completely randomized block experiment with four replications and three treatments: 1) strip tillage with winter cover crop (Strip-CC); 2) conventional tillage with winter cover crop (Till-CC); or 3) conventional tillage left fallow in winter (Till-WF). Each treatment within a block was established in a 10 x 40 m plot.

Table 2.1. Selected soil characteristics among blocks at the Vegetable Research Farm for an integrated vegetable experiment in Western Oregon.

	Vegetable Research Farm Field Blocks			
Soil characteristics	Block 1	Block 2	Block 3	Block 4
Total N (g kg^{-1})	0.25 a*	0.29 b	0.24 a	0.25 a
Total C (g kg^{-1})	1.85 a	1.93 a	1.89 a	1.95 a
pH	6.0 a	5.9 a	5.9 a	5.8 a

*Means followed by the same letter within a row are not significantly different ($p <$ 0.05).

Both Till-CC and Till-WF plots received fall and spring tillage with one pass of a rollover plow, one pass of a disc, and two passes of a rotary tiller plus a roller. Strip-CC plots received fall tillage of one pass with a disc, and two passes with a rotary tiller plus a roller prior to planting the winter cover crop. Winter cover crops were sprayed in early spring with 1.2 L ha^{-1} glyphosate. In late spring, the Strip-CC plots received one pass with a Northwest Strip Tiller (Northwest Tillers, Inc., Yakima, WA), which tills four rows approximately 30 cm apart and 15 to 20 cm deep. The sequence of vegetables and cover crops are shown in Table 2.2. Each vegetable crop was planted with an application of 43.6 kg N ha^{-1}, 45.8 kg P ha^{-1}, 30.2 kg K ha^{-1}, and 29.04 kg S ha^{-1}.

Table 2.2. Crop planting at Vegetable Research Farm during three years of the experiment (2002-2004).

Year of Study	Winter Cover Crop	Summer Vegetable Crop
1	Oat (*Avena sativa* L.), vetch (*Vicia sativa* L.)	Broccoli (*Brassica oleracea* L.; transplanted)
2	Barley (*Hordeum vulgare* L.), field pea (*Pisum sativum* L.)	Snap bean (*Phaseolus vulgaris* L.; seeded)
3	Barley (*Hordeum vulgare* L.), vetch (*Vicia sativa* L.)	Sweet corn (*Zea mays* L.; seeded)

Baseline soil samples were collected in July 2001, followed by the establishment of cover crop or winter fallow treatments in September 2001. Soil samples were then collected twice a year in 2002, 2003 and 2004: once in early spring (approximately the last week of March) prior to cover-crop spraying; and again in summer approximately 30 days after planting of the vegetable crop. In the spring sampling, 10 to 15 10-cm cores were collected, composited and homogenized for three randomly chosen sub-replicate locations within a plot. For Strip-CC plots, the 0-5 cm portion and 5-10 cm portion were divided and collected in separate bags. Summer sampling mirrored spring sampling with the exception that samples were collected perpendicular to the row to proportionally represent soil from within and outside the row.

<u>Biological Measurements (spring and summer sampling)</u>

Microbial biomass-carbon was measured on fresh soils within three days of sampling. The chloroform fumigation-incubation method as outlined by Jenkinson and Powlson (1976) was performed. In brief, soils were exposed to chloroform vapors for 24 hours under vacuum and then incubated at 25°C in the dark for 10 days. Following incubation, a gas chromatograph was used to measure CO_2 produced, and MB_C was calculated without subtracting the control using a k_C value of 0.41 (Voroney and Paul, 1984).

Beta-glucosidase activity levels were measured as described by Tabatabai (1994). Air-dried soils were used, and after a one-hour incubation in the presence of the substrate (*p*-nitrophenyl-β-D-gluco-pyranoside) the product's (*p*-nitrophenol, PNP) color intensity was determined on a spectrophotometer set at a 420 nm wavelength. Two analytical replicates and one control were analyzed for each soil sample, and activity reported as μg PNP g^{-1} soil hr^{1}.

Physical Measurements (summer sampling)

Water stable aggregates were measured according to Kemper and Rosenau (1986) with the following modification. Field moist soil samples were initially passed through a 2 mm sieve and allowed to air-dry for 48 h prior to collection of the 1-mm size fraction. Aggregates were initially sieved in a wet sieving machine at a frequency of 35 cycles min^{-1} in 75 mL of de-ionized water (DI) during which unstable aggregates were collected in the DI water. Following this, any aggregates remaining on the sieves were then wet-sieved in 75 mL of sodium polyphosphate dispersing agent (DS) at a concentration of 2 g L^{-1}. Soils retained in the DI and the DS solutions were oven-dried in the respective containers, allowed to cool for five minutes after removing from the oven, and then weighed. Percent water stable aggregates were calculated as follows:

$$\text{Percent WSA} = \frac{(soil_{DS} - 0.16) * 100}{(soil_{DS} + soil_{DI}) - 0.16}$$

Subtraction of 0.16 g was included to compensate for the mass of the dispersing solution.

Soil bulk density was measured using a Troxler nuclear density gauge (Troxler Electronic Laboratories Inc., Research Triangle Park, NC). Bulk density readings were taken both within and between rows at 5, 10, 20, and 30 cm depths at three sub-replicate locations within each plot.

Water infiltration was measured using a constant-head infiltrometer. Three sub-replicate measurements were taken from each plot on a relatively uniform soil surface. Measurements were taken during active crop growth approximately three weeks prior to harvest date. Metal infiltration rings (30 x 30 cm) were placed between rows, and pushed in to a depth of 15 cm. Soil was pre-moistened by filling each ring with 6 L of tap water which was allowed to infiltrate for 15 to 20 minutes. A mark was then made on the inside of the ring, 5 cm from the bottom of the soil surface, and water was added to form a 5 cm head in the infiltration ring. Marriot suction devices were inserted into the rings and the water flow was adjusted on the 20 L Marriot tube container to maintain the 5 cm head. This procedure was continued for two hours or until the 20 L were drained, whichever occurred first; all times were recorded using a stopwatch. Marks were made on the 20 L container at the commencement and completion of the process. At completion, each 20 L container was backfilled with water in order to determine the amount of water that had infiltrated in the given time, and the infiltration rate was expressed as L h^{-1}.

Chemical measurements

Using a 1:2, soil to water ratio, pH was measured on each soil sample during the summer 2003 sampling period using a pH electrode. Total soil carbon measurements were performed on baseline soil samples and again during the spring and summer 2002 sampling periods. Each air-dried sample was analyzed by dry combustion in a LECO (LECO Corporation, St. Joseph, MI) carbon analyzer using a $CaCO_3$ standard. Baseline samples also were analyzed for total soil nitrogen using a Kjeldahl digestion followed by steam distillation and titration as outlined by Nelson and Sommers (1972).

Statistical analysis

Analysis of variance of the data was done as a randomized block design at each sampling, and a linear mixed model was used to analyze repeated measures. The Fisher LSD was used to separate main effects at a 95% confidence level. Data were analyzed using the statistical software package S-Plus (Insightful Corporation, Seattle, WA).

RESULTS

Biological Responses

Microbial biomass-carbon fluctuated seasonally for all sampling years and treatments except Strip-CC during 2003 (Fig. 2.1). Spring sampling MB_C was consistently higher than summer sampling, and all cover-cropped treatments maintained a significantly higher MB_C ($p < 0.05$) than Till-WF for all sampling periods. Microbial biomass-carbon was significantly higher ($p < 0.05$) for Strip-CC compared to both conventionally tilled treatments during years two and three.

Similar to MB_C, β-glucosidase activity levels after one year showed significant treatment effects (Fig. 2.2). Both cover-cropped treatments had significantly higher levels of enzyme activity ($p < 0.05$) over the winter fallow (Till-WF). In the second year, Strip-CC had even higher levels of enzyme activity, and separated out significantly ($p < 0.05$) from both Till-WF and Till-CC. Unlike MB_C, Strip-CC increased in β-glucosidase activity regardless of season after the second year. However, there was a significant treatment-by-year interaction ($p < 0.05$) with both MB_C and β-glucosidase activity indicating that over time, Strip-CC continued to increase when compared to the other two treatments.

Physical responses

Water stable aggregates were measured as a percent change from the baseline measurements due to significant differences between plots prior to treatment implementation that were not accounted for by blocking. Both cover-cropped treatments remained significantly higher in WSA ($p < 0.05$) than Till-WF at all sampling periods (Fig. 2.3). Water stable aggregates generally decreased over time in all treatments.

Between rows, bulk density was significantly greater ($p < 0.05$) in Strip-CC compared to both conventionally tilled treatments in the upper 10 cm (Fig. 2.4). Although not statistically significant, Till-WF tended to have the lowest between-row bulk density each year.

Water infiltration rate tended to have high variability in 2002 and between years (Fig. 2.5). Till-CC showed the highest infiltration rates in 2002, but the lowest in 2003. In both years, Strip-CC had similar infiltration rates with Till-WF.

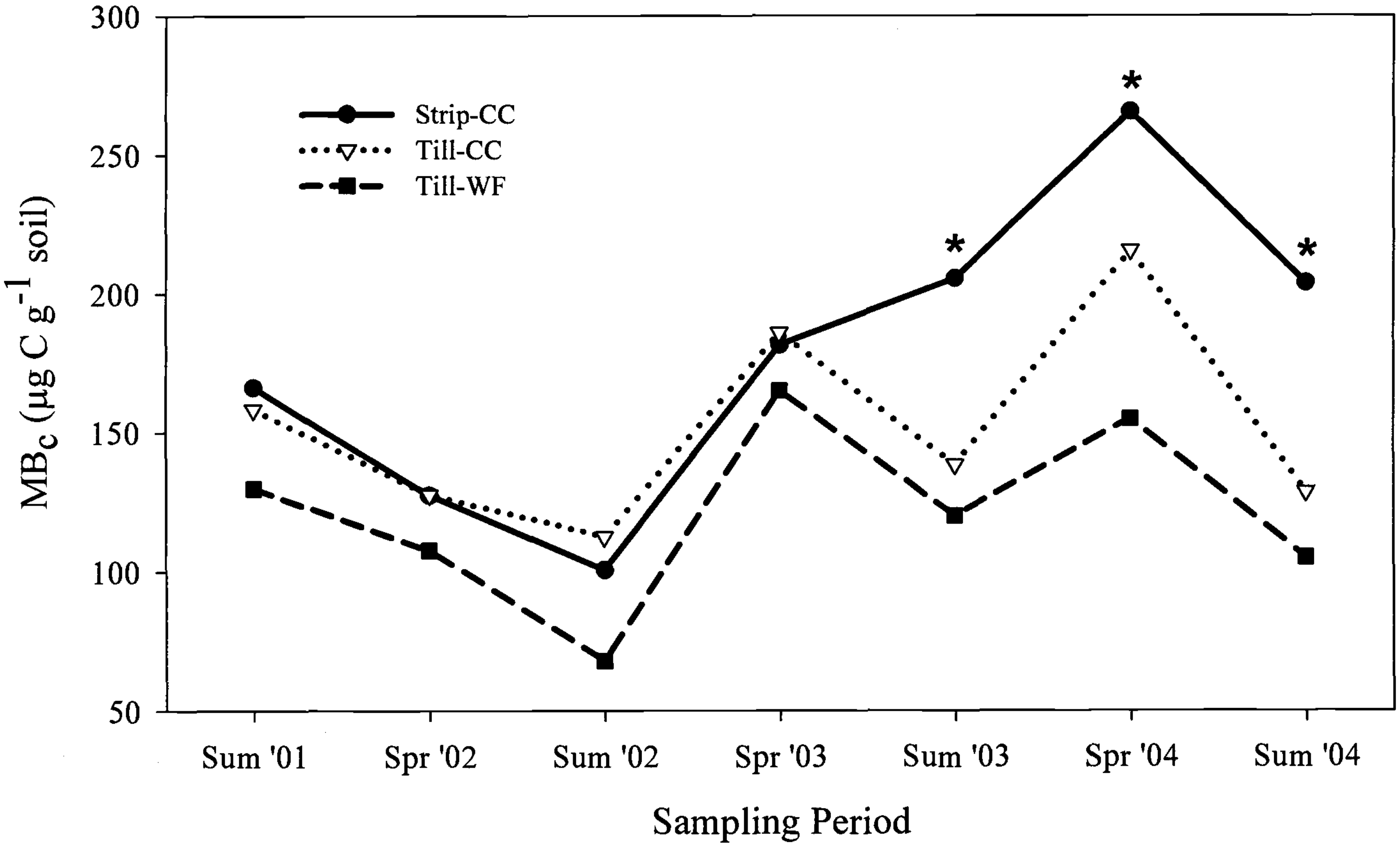

Fig. 2.1. Tillage and cover crop effects on soil microbial biomass-C in an integrated vegetable experiment in Western Oregon (* indicates significant treatment effect at $p < 0.05$).

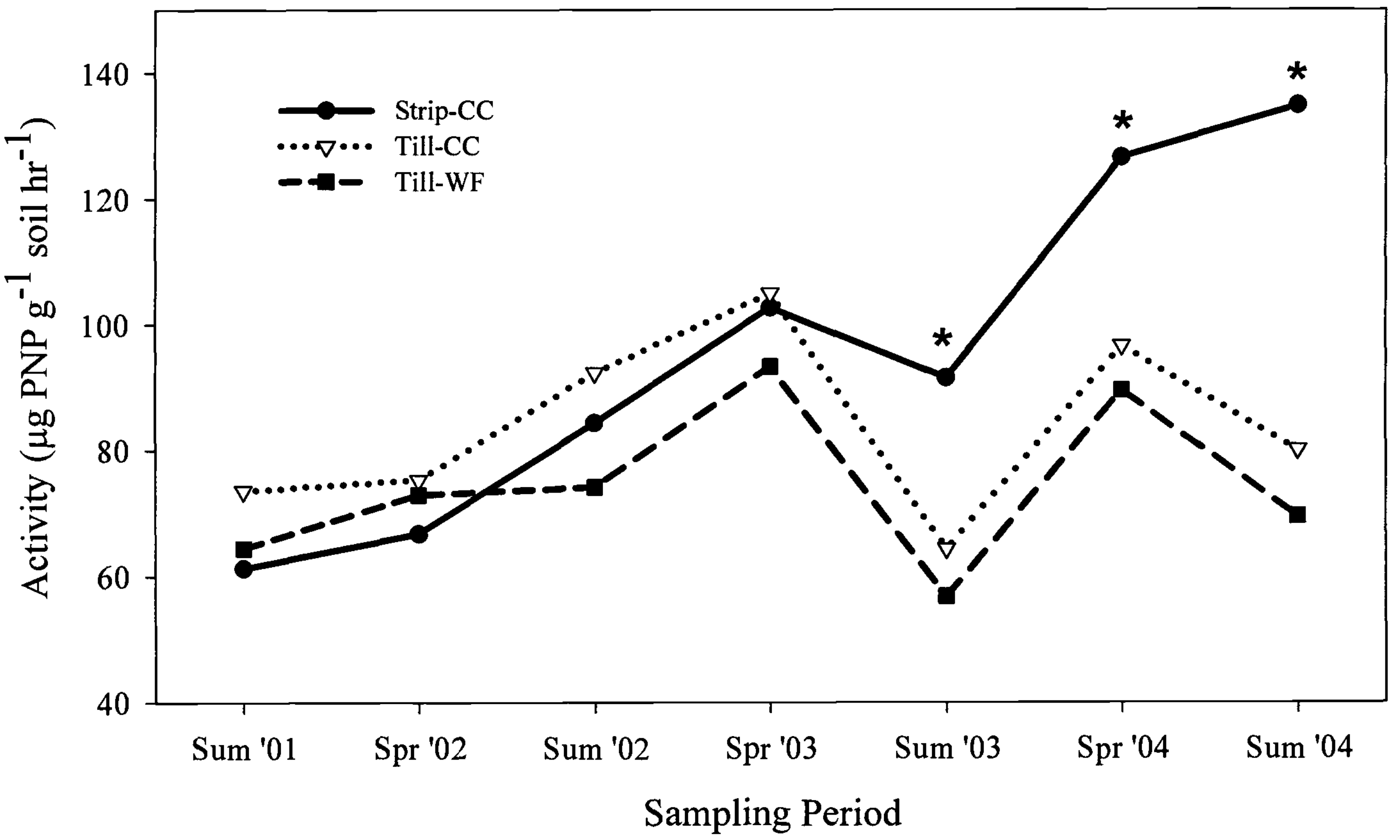

Fig. 2.2. Tillage and cover crop effects on β-glucosidase activity in an integrated vegetable experiment in Western Oregon (* indicates significant treatment effect at $p < 0.05$).

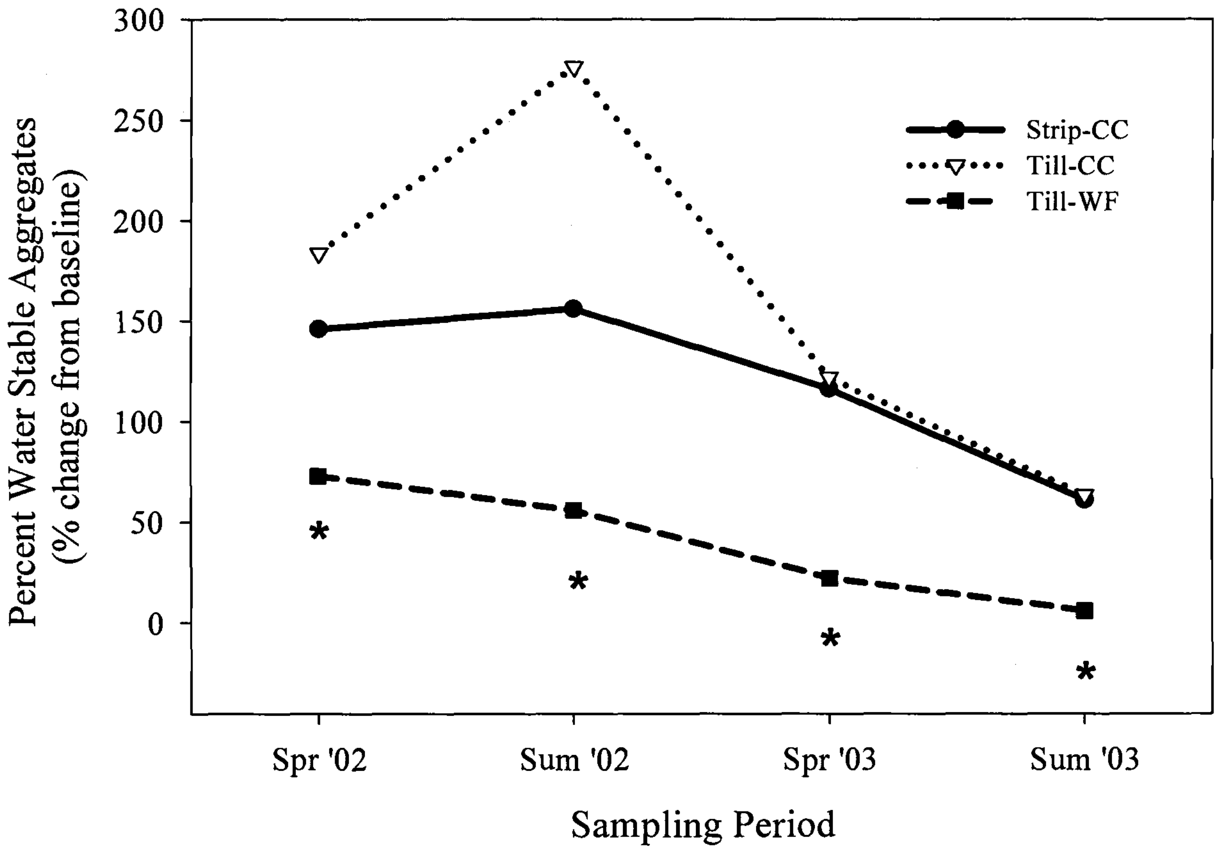
Percent Water Stable Aggregates
(% change from baseline)
300
250
200
150
100
50
0
Strip-CC
Till-CC
Till-WF
*
*
*
*
Spr '02
Sum '02
Spr '03
Sum '03
Sampling Period

Fig. 2.3. Tillage and cover crop effects on percent WSA in an integrated vegetable experiment in Western Oregon (* indicates significant treatment effect at $p < 0.05$).

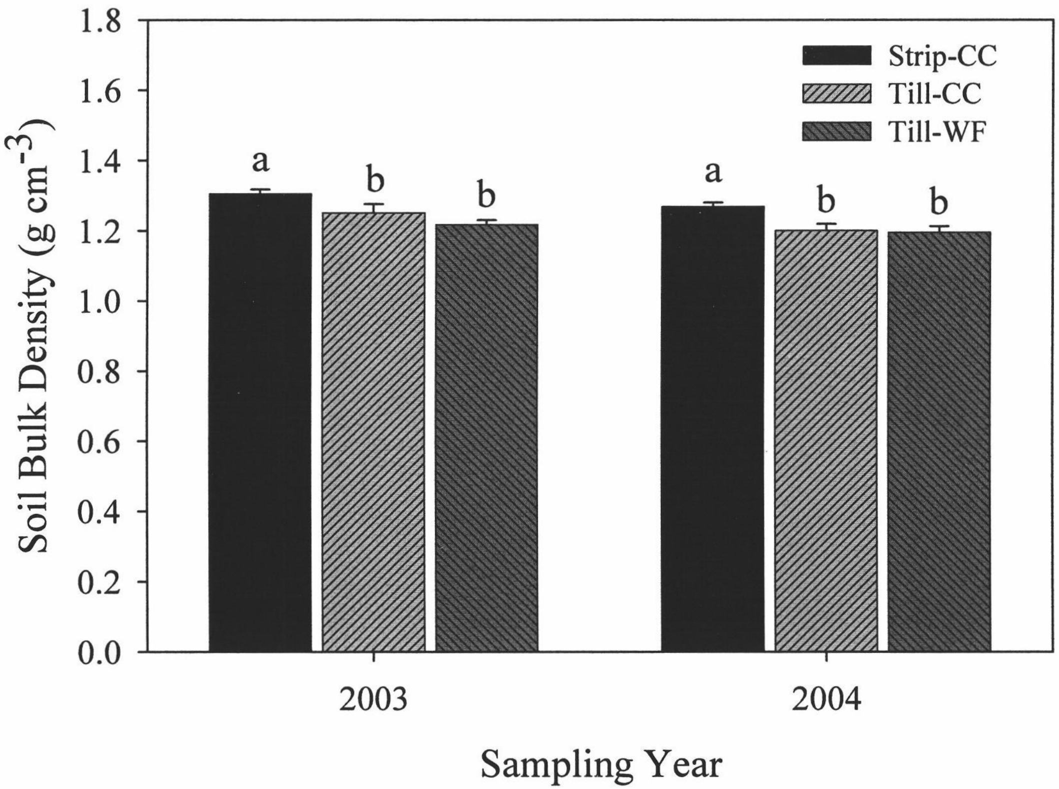

Fig. 2.4. Bulk density between rows in the upper 10 cm of soil for years 2003 and 2004 in an integrated vegetable experiment in Western Oregon (bars within a sampling year with the same lower case letters are not significantly different at $p < 0.05$).

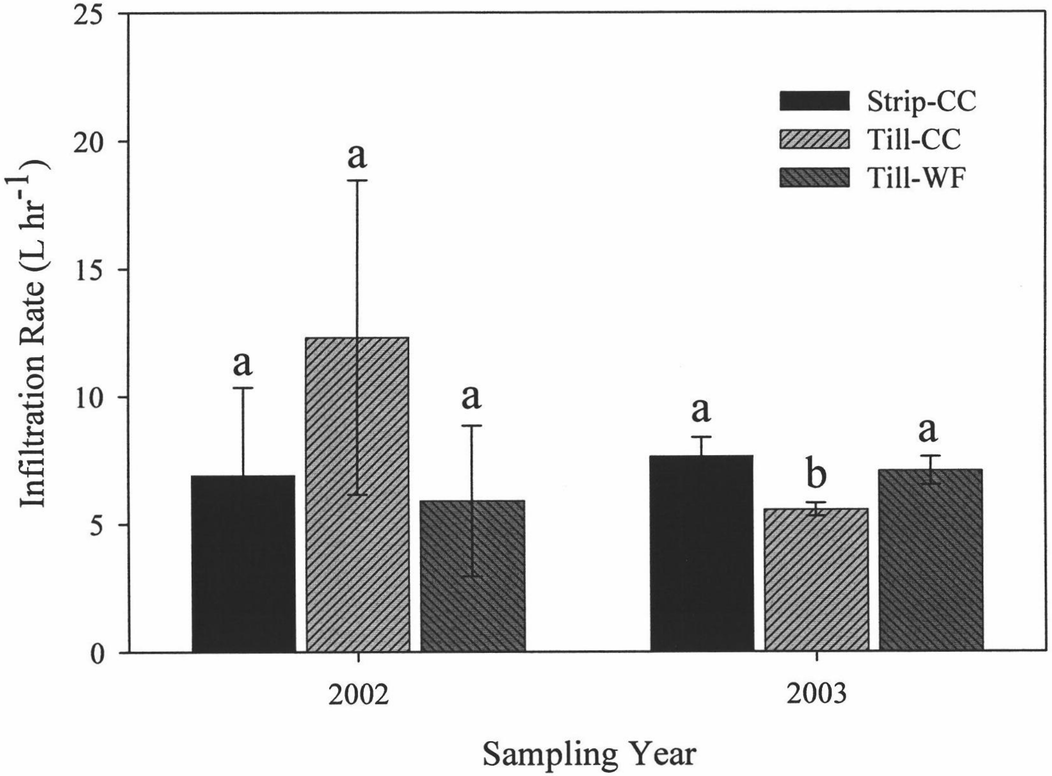

Fig. 2.5. Water infiltration rates for years 2002 and 2003 in an integrated vegetable experiment in Western Oregon (bars within a sampling year with the same lower case letters are not significantly different at $p < 0.05$).

DISCUSSION

Soil Biological Properties

There was a striking seasonal effect on MB_C where levels among all treatments were consistently higher in the spring than in the summer within the same year. If this effect was shown only in cover-crop plots, this could be attributed to a "rhizosphere" effect because of the standing cover-crop plants. However, the winter fallow also had a similar MB_C response, suggesting there was some other factor involved. It seems soil moisture content was not a factor as it remained relatively equal between sampling periods due to irrigation in the summer. Also, temperature was not a factor as soils would be warmer in the summer than in spring. Nonetheless, our findings are consistent with other studies (Granatstein et al., 1987; Van Gestel et al., 1992; Ndiaye, 1999).

Lynch and Panting (1982) suggested this seasonal effect could be due to release of root exudates in the spring season as plant growth and turnover increase. This may well explain the response for cover crop treatments in our experiment, but not for the winter fallow treatment which also had elevated MB_C in the spring. One possible explanation is tillage, which occurred between the spring and summer sampling that would disrupt microbial habitat (Ndiaye, 1999). However, strip-tilled plots had only about 50% of the surface tilled which confounds the tillage explanation for seasonal changes in MB_C. From our suite of treatments it is difficult to explain this seasonal effect. Given that regardless of tillage intensity or presence of cover crop, MB_C always was higher in the spring which suggests there are some natural soil/climate interactions that stimulate MB_C in the spring. It may well be as soils come out of the colder winter and begin warming there is an increase in accessible substrates from soil organic matter that increases MB_C.

A cover-crop treatment effect was seen as increased MB_C and β-glucosidase activity when comparing Till-CC to Till-WF. These differences were significant following the first year of integration, and continued throughout the study. Similar results in other cover crop studies were found on soils of the Willamette Valley (Bandick and Dick, 1999; Ndiaye et al., 2000), and can be attributed to an increase in organic matter inputs from cover crops. The cover-crop residues during decomposition provide substrates that stimulate microbial communities and increase microbial diversity. This was shown by Schutter and Dick (2002) in an incubation study that plant materials had much greater impacts on microbial communities than did pure model plant components such as lignin, cellulose, proteins or even the readily available energy source, glucose. Furthermore, the cover-cropped plots had greater earthworm activity (Chapter 3) and thus cast soil could also stimulate microbial biomass and activity.

The reduction in tillage with strip-till in combination with cover crops further increased MB_C and β-glucosidase activity over tillage with or without cover crops. This was a very immediate response that was shown after the first year for both MB_C and β-glucosidase activity. Corroborating these results are data from several other studies where MB_C increased with a reduction in tillage (Lynch and Panting, 1980; Doran, 1987; Staley et al., 1988; Staley, 1999). This is likely due to less physical destruction of microbial habitat under reduced tillage. For example, branching organisms such as fungi are greatly reduced by regular tillage (Coleman and Hendrix, 1988; Gupta and Germida, 1988). Not only do these surface residues provide substrate for microorganisms, but they encourage earthworm activity as well. Slow incorporation of these remaining residues via earthworm activity could stimulate increased microbial activity. Barois and Lavelle (1986) found microbial activity of the ingested soil of certain earthworm species to be higher than non-ingested soil. Furthermore, microbial populations and enzyme activity are higher for earthworm casts when compared to bulk soil (Dkhar and Mishra, 1986; Tiwari et al., 1989).

Soil Physical Properties

The WSA data suggest cover crops can increase aggregate stability. This is consistent with Kandeler and Murer (1993) who found cover crops stimulated microbial properties and aggregation. Interestingly, they showed that without elevated biological activity aggregate stability would decrease. This would suggest that there must be regular organic inputs to maintain high aggregation that can be easily lost with removal of those organic inputs.

Cover crops also provide root exudates and organic decomposition products can aid aggregation. These substances can act as “glue” to hold clay and silt particles together (Gupta and Germida, 1988). It seems likely for these reasons that WSA increased for cover cropped treatments over the Till-WF treatment.

Another process that may have contributed to stabilizing aggregates with cover cropping is earthworm activity. These treatments did have increased earthworm abundance (Chapter 3). Through burrowing and possibly formation of casts, earthworms can increase aggregation (Vershinin, 1971; Lal and Akinremi, 1983; Oades, 1993).

Strip-till as a reduced tillage system did not increase WSA over the other two tillage treatments even after three years. This is in contrast to the results of Ball-Coelho et al. (2000) who found an increase in WSA with a reduction in tillage. However, this may be due to differences in soil texture; Ball-Coelho et al. (2000) had sandy soils which are inherently unstable, and reducing tillage likely has an immediate positive aggregation response. Conversely, our soil has a relatively high clay content (28 kg kg^{-1}). Soil structure can be formed abiotically as clay particles fill spaces between larger sand particles (Oades, 1993), resulting in increased aggregation with increases in clay content. Because of this, the Chehalis silty clay loam soil in our study may be intrinsically capable of maintaining aggregation even when some tillage is employed. Another consideration is that physical soil properties, such as WSA, may take longer to respond to changes in tillage than do biological properties.

One complicating factor in our experiment was that all plots received a light disking after the growing season, including Strip-CC treatments. If the area between the strips were maintained as "tillage-free zones", perhaps significantly higher WSA would be observed, as predicted by Angers et al. (1993) who proposed that no-till systems are better at preserving aggregates than are tilled systems. This would require direct drilling of cover crop seed in comparison to the broadcast cover planting of our system, which is the typical grower practice and requires minimal tillage for crop establishment.

The WSA decreased in general for all treatments. This may be related to the summer crop species sequence or the cover crop sequence as they may vary in the types of root systems and exudates. Furthermore, cover crop biomass often associated with increased WSA (Buller, 1999) was greatest during year one (Chapter 3) and therefore could have contributed to initially higher levels of WSA.

The absence of tillage in the between-row soil in Strip-CC during the spring and summer months caused increased bulk density over tilled soil. Similar trends have been observed in no-till silt loam soils by Petersen et al. (2002). Although this may be a temporary or artificial lowering in bulk density with full tillage, it may be important and related to why some growers have lower yields when they try strip-till planting.

Differences in the response of physical soil properties to tillage may well be linked to soil texture (Griffith et al., 1988; Dick et al., 1991; Vyn and Raimbault, 1992). The Western Oregon environment has a long winter of steady rain that likely disperses some soil particles and, particularly for silt-size particles, they may fill voids between aggregates. Furthermore, mild winters often lack freeze/thaw cycles that can contribute to soil cracks and macropore formation, with the end result being increased bulk density. Without any spring tillage (Strip-CC) the between-row zones remains compacted; but conventional tillage breaks up this winter compacted soil. In turn, these between-row zones of compaction create an environment less fit for root growth.

Water infiltration rates varied widely between years and within treatments, variability was quite high in year one. This may be due to inexperience in using this method which affected the results of year one. It is unclear why differences exist in Till-CC between years along with similarities between Strip-CC and Till-WF. A possible explanation is that infiltration rings are place-bound and subject to high short-distance spatial variability. In part, this may be due to unknown wheel track compaction zones. It seems likely that increasing the number of replications to decrease variability is needed when doing infiltration measurements in these systems.

Soil quality indicators

This experiment provided an opportunity to determine the ability of several biological and physical properties as early indicators to detect changes in soil management. We chose methods that are relatively simple that could be adopted by commercial soil testing laboratories or agricultural consultants.

The physical measurements have several drawbacks. First, they were less sensitive in showing treatment effects and/or showed high variability. Unlike WSA, where composited soil cores can provide a means for integrating short-term spatial variability, bulk density and water infiltration are place-bound which significantly reduces their potential to capture short-distance spatial variability. Also, water infiltration is labor-intensive and time-consuming. For this study, although useful for research purposes, we would not recommend the physical measurements we used as routine soil quality indicators.

Clearly the biological measures were best at showing treatment effects. This is consistent with recent research in forest soils where biological soil quality indices improved despite soil compaction (Shestak and Busse, 2005). Although MB_C could consistently separate treatment effects within a sampling period, it showed wide variations over the three-year period, making it difficult to calibrate this method compared with other soil tests such as nutrient availability.

In contrast, β-glucosidase activity levels showed a trajectory over time with minimal seasonal shifts. This consistency over time can be explained by the accumulation of enzymes no longer associated with living cells, termed "abiontic" enzymes (Skujinš, 1976). These abiontic enzymes can become stabilized on humic or clay colloids and accumulate in a steady fashion under a consistent soil management regime (Knight and Dick, 2004). Beta-glucosidase, therefore, has more potential to be calibrated for growers' situations where "controls" are not available for comparison.

PERSPECTIVES

We found that a soil management system integrating reduced tillage with cover crops improved soil quality as indicated by biological factors. Microbial biomass-carbon and β-glucosidase activity responded rapidly to changes in tillage and cover crops, however, the consistent activity levels over seasons associated with β-glucosidase suggest this measure is a more useful tool to gauge soil quality when comparative controls are not available. Physical soil quality indicators remained inconsistent in their response to treatments. In part, this is due to difficulties associated with spatial variability when assessing water infiltration rates. However, an actual decrease in physical soil quality after adoption of an integrated system was evidenced by increased bulk density between rows of the reduced tillage treatment. It is possible that this compaction may be related to the fine silty texture of the soil in addition to the Mediterranean climate in the Willamette Valley; mild winters are common, alleviating soil freeze/thaw cycles that could aid in the formation of macropores and ameliorate compaction. The potential for earthworm activity to decrease bulk density between rows remains a possibility, but this process would require the maintenance of tillage-free zones, which were not accomplished in this study.

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CHAPTER 3

AGRONOMIC YIELD VARIATIONS AND ASSOCIATIONS WITH SOIL PROPERTIES FOLLOWING ADOPTION OF AN INTEGRATED VEGETABLE CROPPING SYSTEM

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Prepared for submission to:

Soil Science Society of America Journal

ABSTRACT

The Pacific Northwest processed vegetable industry has been very competitive with an increase in management intensity and continued pesticide dependency. At the same time environmental health, including soil health, must be improved to sustain future vegetable crop production. A shift to an integrated reduced-tillage system with winter cover crops holds potential to maintain profits as well as to improve soil quality; however, such a vegetable system has generated mixed success with respect to yield in the Pacific Northwest. This study assessed vegetable yields over a three-year period in a randomized complete-block design with four replications and three treatments: 1) strip tillage with winter cover crop (Strip-CC); 2) conventional tillage with winter cover crop (Till-CC); and 3) conventional tillage left fallow in winter (Till-WF). Vegetable yields for broccoli (*Brassica oleracea* L.), snap bean (*Phaseolus vulgaris* L.), and sweet corn (*Zea mays* L.) were evaluated and related to several biological and physical indicators of soil quality in order to determine changes in soil health and crop yield with the adoption of an integrated system. Biological soil quality indicators negatively correlated with yield, especially during the first year, but these negative associations became less apparent throughout the remaining two years. Physical soil quality indicators did not significantly correlate with yield; however, an increase in bulk density was found in Strip-CC plots, which may have impacted yield. Cover crop biomass correlated significantly with yield ($p < 0.001$), as did cover crop cereal/legume ratio ($p < 0.001$); it is therefore possible that the type and amount of cover crop residue could have affected yield. Soil moisture also was significantly

lower for Till-WF ($p < 0.05$) during the spring sampling period, although soil moisture was not determined at the time of spring tillage. Of the three soil management strategies, Till-WF had the highest yields over all three years, but this was significant only during year one ($p < 0.05$). The effect of strip tillage appears to initially suppress yields, possibly due to greater soil compaction, but there is potential that yields may improve given more time.

INTRODUCTION

Growers and the public are increasingly interested in agricultural systems that reduce the use of pesticides and conserve natural resources, including soils. However, because vegetable crops tend to be high value crops, any decreases in yields or fruit quality can have significant impacts on economic returns. Consequently, sustainable systems must meet not only the goal of protecting the environment but also provide profitable yields.

An integrated agricultural system incorporating reduced tillage with winter cover crops has the potential to meet both economic and environmental goals. However, Willamette Valley growers have had mixed success with respect to yield (D. McGrath, personal communication, 2005), as have studies evaluating other row crop systems throughout the United States (Petersen et al., 1986; West et al., 1996; Hoyt, 1999; Rutledge, 1999; Dick et al., 1991). One common thread in integrated systems with suppressed yield is the soil type. Heavy, poorly drained soils tend to result in lower yields when managed using reduced tillage (West et al., 1996; Dick et al., 1991). In comparison, integrated systems on well-drained, low organic matter soils tend to result in comparable or greater yields than do conventional systems in the same soil type (Abdul-Baki et al., 1997; Harrison et al., 2004).

The effect of reduced tillage and cover crops on yield has been studied largely on field crops but relatively few studies have investigated impacts on vegetable systems in silty clay soils. Therefore, the objective of this study was to determine how an integrated reduced-tillage and cover-cropped management system would affect vegetable yields over three years in a silty clay loam soil in Western Oregon. We hypothesized that an integrated reduced-tillage, cover-cropped management system would increase soil quality, and maintain or increase vegetable yield over conventional systems. Any decreases in yield were thought to be associated with specific soil quality properties that may not improve after the adoption of an integrated system.

MATERIALS AND METHODS

Site, experimental design, and soil sampling

The experimental site is located at the Oregon State University Vegetable Research Farm in Corvallis, Oregon, in the Willamette Valley of Western Oregon. The climate is Mediterranean with warm, dry summers and cool, wet winters. The soils are classified as Chehalis silty clay loam (fine-silty, mixed, superactive, mesic Cumulic Ultic Haploxerolls). The soils are very deep and well drained, formed in mixed alluvium on the flood plain along the Willamette River. The average soil texture at this site is 5.1, 66.5, and 28.4 kg kg^{-1} sand, silt, and clay, respectively, with other properties shown in Table 3.1.

The experiment was a completely randomized block design with four replications and three treatments: 1) strip tillage with winter cover crop (Strip-CC); 2) conventional tillage with winter cover crop (Till-CC); or 3) conventional tillage left fallow in winter (Till-WF). Each treatment within a block was established in a 10 x 40 m plot.

Table 3.1. Selected soil characteristics among blocks at the Vegetable Research Farm for an integrated vegetable experiment in Western Oregon.

	Vegetable Research Farm Field Blocks			
Soil characteristics	Block 1	Block 2	Block 3	Block 4
Total N (g kg^{-1})	0.25 a*	0.29 b	0.24 a	0.25 a
Total C (g kg^{-1})	1.85 a	1.93 a	1.89 a	1.95 a
pH	6.0 a	5.9 a	5.9 a	5.8 a

*Means followed by the same letter within a row are not significantly different ($p < 0.05$).

Both Till-CC and Till-WF plots received fall and spring tillage with one pass of a moldboard plow, one pass of a disc, and two passes of a rotary tiller plus a roller. Strip-CC plots received fall tillage of one pass with a disc, and two passes with a rotary tiller plus a roller prior to planting the winter cover crop, which is the current practice of growers who use this system. Winter cover crops were sprayed in early spring with 1.2 L ha^{-1} glyphosate. In late spring the Strip-CC plots received one pass with a Northwest Strip Tiller (Northwest Tillers, Inc., Yakima, WA), which tills four strips approximately 30 cm apart and 15 to 20 cm deep. The sequence of vegetables and cover crops are shown in Table 3.2. Each vegetable crop was planted with an application of 44 kg N ha^{-1}, 46 kg P ha^{-1}, 30 kg K ha^{-1}, and 29 kg S ha^{-1}.

Cover crop biomass was determined by harvesting a 1 m^2 area at three randomly selected locations within each plot during the early spring just prior to spraying the cover crop. Cereals and legumes were separated, dried for five days in a 60° C oven and weighed. Gravimetric soil moisture was determined in the spring prior to cover crop spraying and again in the summer approximately 30 days after planting the summer crop.

Baseline soil samples were collected in July 2001, followed by the establishment of cover crop or winter fallow treatments in September 2001. Soil samples were then collected twice a year in 2002, 2003 and 2004: one sample date was in early spring (approximately the last week of March) prior to cover-crop spraying, and the other was in summer approximately 30 days after planting of the vegetable crop. In the spring sampling, 10 to 15 10-cm cores were collected, composited and homogenized for three randomly chosen sub-replicate locations within a plot. For Strip-CC plots, the 0-5 cm portion and 5-10 cm portion were divided and collected in separate bags. Summer sampling mirrored spring sampling with the exception that samples were collected perpendicular to the row to proportionally represent soil from within and outside the row.

Table 3.2. Crop sequence and specifications over three years of an integrated vegetable experiment in Western Oregon (2002-2004).

Year	Winter cover crop	Cover crop seeding ratio	Cover crop seeding rate	Summer vegetable crop	Vegetable spacing	
					Within rows	Between rows
		Cereal:legume	kg ha^{-1}		cm	cm
1	Oat (*Avena sativa* L.), vetch (*Vicia sativa* L.)	1:1	84	Broccoli (*Brassica oleracea* L.), transplanted	30.5	76
2	Barley (*Hordeum vulgare* L.), field pea (*Pisum sativum* L.)	1:2	84	Snap bean (*Phaseolus vulgaris* L.), seeded	5	76
3	Barley (*Hordeum vulgare* L.), vetch (*Vicia sativa* L.)	1:2	84	Sweet corn (*Zea mays* L.), seeded	18	76

Crop yield

All vegetable yield measurements were taken in the field during harvest. Weights were therefore reported as fresh weights.

All crops were harvested in 3-m lengths of 3 randomly selected rows within the center two-thirds of the plots. Broccoli was hand-harvested 18 cm from the base and weighed. The whole plant of bush beans was hand-harvested and then individual beans were removed and weighed. A random sub-sample of 100 beans was selected and each bean was examined for insect and mold damage. The beans were then individually graded by hand and placed into one of seven grade classes based on width. Beans measured as class two, three, or four were considered "number ones"; those measured as class five or six were considered "number twos"; and those measured as class one or seven were considered "culls". Corn ears were hand-harvested and weighed. A random sub-sample of 10 ears was selected and measured for ear length and width.

Biological Measurements

Microbial biomass-carbon (MB_C) was measured in the spring and summer on fresh soils within three days of sampling. The chloroform fumigation-incubation method as outlined by Jenkinson and Powlson (1976) was performed. In brief, soils were exposed to chloroform vapors for 24 hours under vacuum and then incubated in the dark at 25°C for ten days. Following incubation, a gas chromatograph was used to measure CO_2 produced, and MB_C was calculated without subtracting the control using a k_C value of 0.41 (Voroney and Paul, 1984).

Beta-glucosidase activity levels were measured on air-dried soils in the spring and summer as described by Tabatabai (1994). After a one-hour incubation in the presence of the substrate (*p*-nitrophenyl-β-D-gluco-pyranoside) the product (*p*-nitrophenol, PNP) color intensity was determined on a spectrophotometer set at a 420 nm wavelength. Two analytical replicates and one control were analyzed for each soil sample, and activity reported as μg PNP g^{-1} soil hr^{1}.

Physical Measurements

Water stable aggregates (WSA) were measured according to Kemper and Rosenau (1986) with the following modification. Field moist soil samples collected in the summer were initially passed through a 2 mm sieve and allowed to air-dry for 48 h prior to collection of the 1-mm size fraction. Aggregates were initially sieved in a wet sieving machine at a frequency of 35 cycles min^{-1} in 75 mL of de-ionized water (DI) during which unstable aggregates were collected in the DI water. Following this, any aggregates remaining on the sieves were then wet-sieved in 75 mL of sodium polyphosphate dispersing agent (DS) at a concentration of 2 g L^{-1}. Soils retained in the DI and the DS solutions were oven-dried in the respective containers, allowed to cool for five minutes after removing from the oven, and then weighed. Percent WSA were calculated as follows:

$$\text{Percent WSA} = \frac{(soil_{DS} - 0.16) * 100}{(soil_{DS} + soil_{DI}) - 0.16}$$

Subtraction of 0.16 g was included to compensate for the mass of the dispersing solution.

Soil bulk density was measured in the summer using a Troxler nuclear density gauge (Troxler Electronic Laboratories Inc., Research Triangle Park, NC). Bulk density readings were taken both within and between rows at 5, 10, 20, and 30 cm depths at three sub-replicate locations within each plot.

Water infiltration was measured using a constant-head infiltrometer. Three sub-replicate measurements were taken from each plot on a relatively uniform soil surface. Measurements were taken during active crop growth approximately three weeks prior to harvest date. Metal infiltration rings (30 x 30 cm) were placed between rows, and inserted to a depth of 15 cm. Soil was pre-moistened by filling each ring with 6 L of tap water which was allowed to infiltrate for 15 to 20 minutes. A mark was then made on the inside of the ring, 5 cm from the bottom of the soil surface, and water was added to form a 5 cm head in the infiltration ring. Marriot suction devices were inserted into the rings and the water flow was adjusted on the 20 L Marriot tube container to maintain the 5 cm head. This procedure was continued for two hours or until the 20 L drained, whichever occurred first; all times were recorded using a stopwatch. Marks were made on the 20 L container at the commencement and completion of the process. At completion, each 20 L container was backfilled with water in order to determine the amount of water that had infiltrated in the given time, and the infiltration rate was expressed as $L\ h^{-1}$.

Statistical Analysis

Analysis of variance of the data was done as a randomized block design at each sampling date. Fisher LSD was used to separate main effects at a 95% confidence level. Data were analyzed using the statistical software package S-Plus (Insightful Corporation, Seattle, WA). Simple correlations were determined using the Pearson product moment correlation coefficient.

RESULTS AND DISCUSSION

Tillage alone did not appear to influence yields over all the sampling periods (Fig. 3.1). However, Till-WF consistently had the highest yields each year, suggesting a cover-crop effect, but this was statistically significant ($p < 0.05$) only the first year with broccoli (Fig. 3.1). Brassicas have previously been found to increase in yield when grown following a cereal/legume or legume winter cover crop (Schonbeck et al., 1993; Harrison et al., 2004), but decrease following solely cereal cover crops (Abdul-Baki et al., 1997; Roberts et al., 1999). In this study, the winter cover crop biomass preceding the broccoli crop (year one) had the highest cereal:legume ratio in all cover cropped treatments compared to all other years (Table 3.3). Furthermore, total cover crop biomass in all cover cropped treatments was greatest during year one (Table 3.3). To alleviate inherent differences associated with summer crop type, yields for both cover cropped treatments were standardized to the control treatment (Till-WF) and correlated with cover crop biomass and cereal:legume ratio. Cereal cover crops alone do not fix nitrogen (N) and can immobilize soil N if decomposing residues have a high

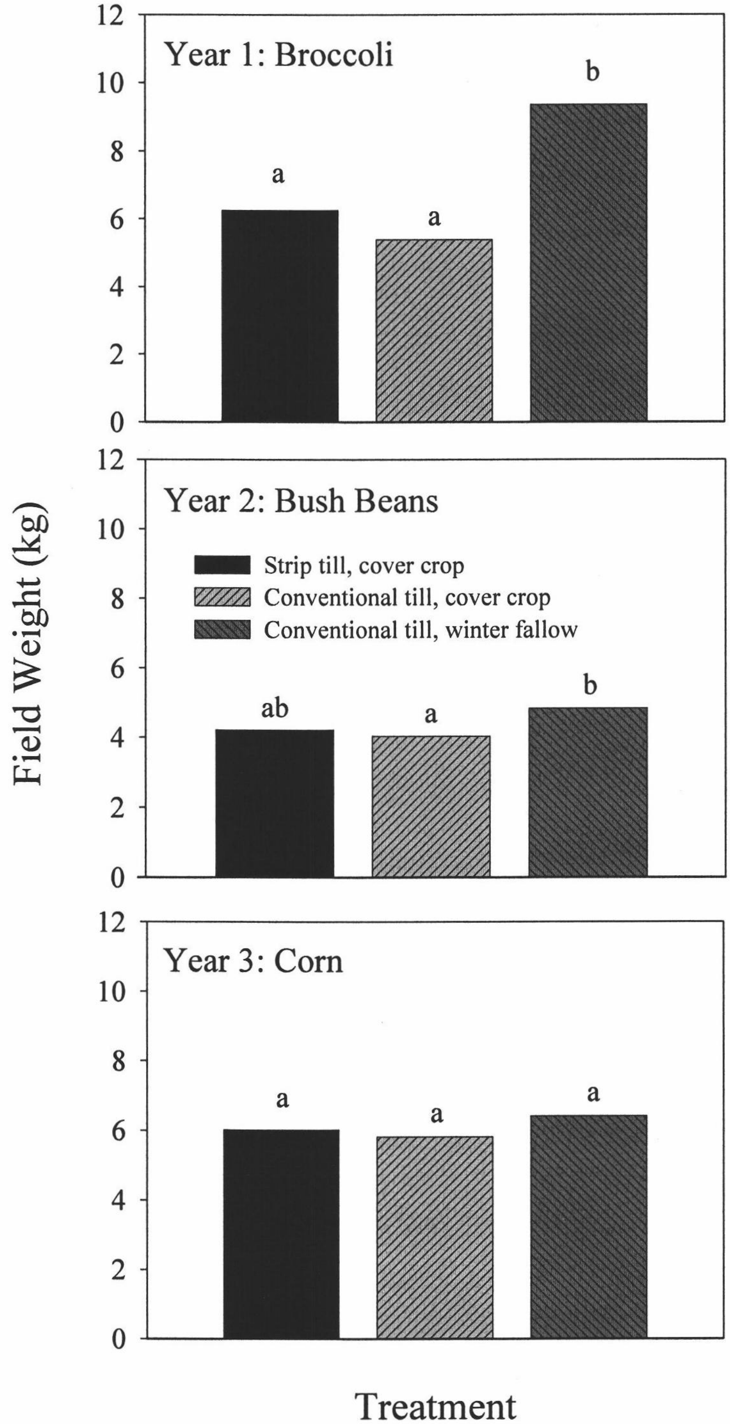

Fig. 3.1. Field weight measurements of crop yield by treatment at the Vegetable Research Farm over three years. Bars followed by the same letters are not significantly different at $p < 0.05$.

Table 3.3. Total cover crop biomass and cover crop cereal:legume ratio during three years of an integrated vegetable experiment in Western Oregon (2002-2004).

Year of Study	Total Cover Crop Biomass	Cereal:legume ratio
	kg ha^{-1} dry weight	
2002	4599	309
2003	2976	17
2004	2021	7

C:N ratio, thus negatively impacting yield. In this study, however, all treatments received an equal application of N fertilizer which should have compensated for any immobilized N due to cover crop decomposition. It is therefore interesting that a strong correlation exists between vegetable crop yield (r = -0.75; $p < 0.001$) and cover crop biomass and cereal:legume ratio (r = -0.68; $p = 0.008$).

One possible explanation involves the soil moisture content in each treatment (Fig. 3.2). Soil moisture from cover crops can inhibit early entry of tillage equipment and subsequently a later planting date may be necessary (Munawar et al., 1990). In this study, all treatment plots were tilled over the course of a single day. It is therefore possible that soils under cover crop residue were not at the ideal moisture content for tillage. The soil moisture data (Fig. 3.2) would suggest this to be an important consideration. Despite summer irrigation during the 2002 sampling year, the Till-WF plots were significantly lower in soil moisture compared to cover cropped treatments both prior to and after the tilling date. Although soil moisture was not measured the day of tillage, if soil moisture was high, this could have resulted in destruction of soil structure, which may account for decreased yields in cover-cropped treatments (Fig. 3.1).

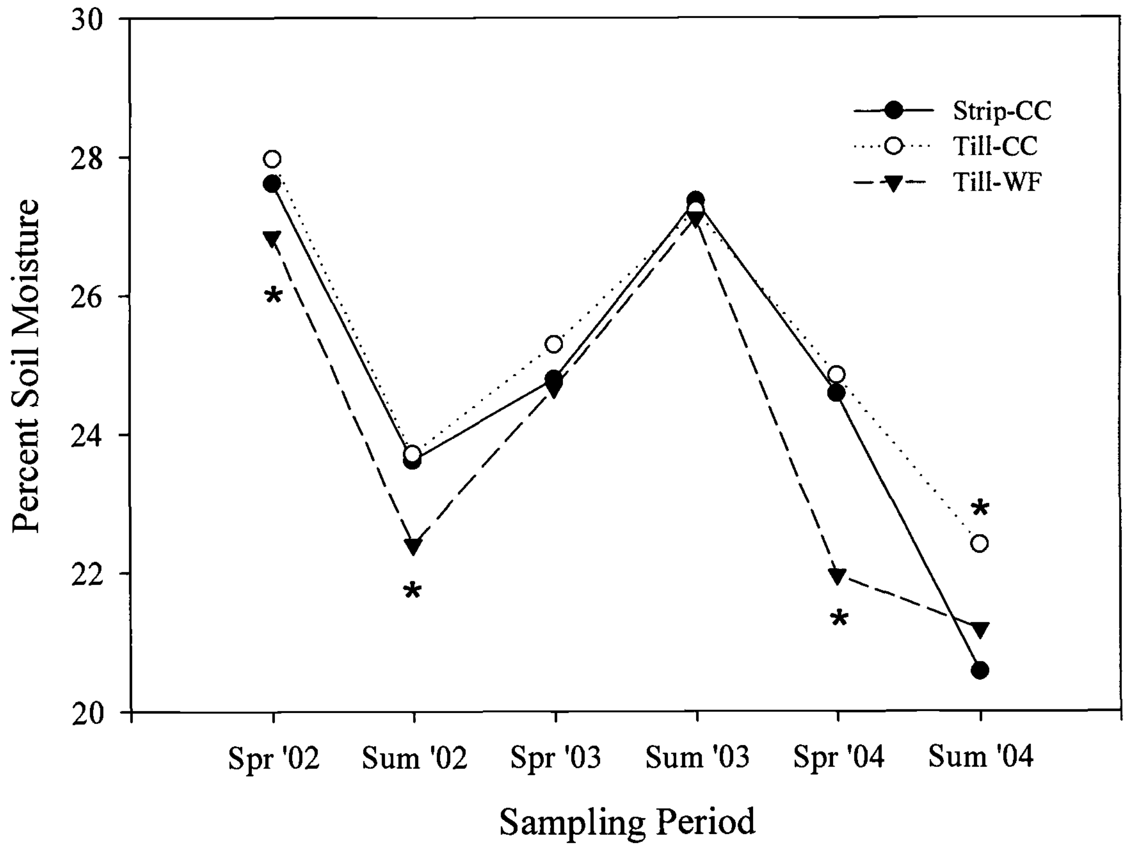

Fig. 3.2. Soil moisture over six sampling periods in an integrated vegetable experiment in Western Oregon (* indicates significant treatment effect at $p < 0.05$).

It is important to monitor how soil quality is impacted when considering cover crop and tillage effects on yield. Several biological and physical soil properties can be used as indicators of soil quality, including MB_C, β-glucosidase activity (Dick, 1994; Fauci and Dick, 1994; Ndiaye et al., 2000; Carter, 2002; Knight and Dick, 2004), earthworm abundance, percent WSA, water infiltration, and bulk density (Buller, 1999). During the first year of integration, strong negative associations existed between these soil quality parameters and vegetable crop yield (Table 3.4), particularly the biological soil properties.

When only considering vegetable yield, it would appear that a conventional tillage, winter fallow system is the most profitable option (Fig. 3.1), yet increased biological indicators of soil quality responded rapidly to decreases in tillage and cover crops (Chapter 2). Furthermore, these negative associations between yield and soil quality seem to decrease over time and become less negatively correlated during the second and third year (Table 3.4).

There also is evidence that Strip-CC yields were approaching Till-WF yields by the third year (Fig. 3.1) suggesting that it may take more than three years of this integrated system to improve soil quality in a silty clay loam soil to equal the yield of a tilled soil. This contradicts prior research in the tropics where a strong correlation existed between aggregate stability and crop productivity (Stine and Weil, 2002), but corroborates with the findings of Dick et al. (1991) who report initially suppressed corn yields in reduced tillage plots compared to conventionally tilled plots. In the Dick et al. (1991) study, it took approximately 10 years for corn yields in reduced

Table 3.4. Pearson correlation coefficients (r) between vegetable crop yield and soil biological or physical properties measured in the spring or summer over three years of an integrated vegetable experiment in Western Oregon (2002-2004).

	Soil Biological Properties					Soil Physical Properties		
	MB_C		β-glucosidase		Earthworm abundance	% WSA	Water infiltration	Bulk density
	Spring	Summer	Spring	Summer	Spring	Summer	Summer	Summer
					2002			
r	-0.57	-0.64	-0.31	-0.53	NA	-0.18	NA	NA
p-value	<0.001	<0.001	0.06	<0.001	NA	0.28	NA	NA
					2003			
r	-0.30	-0.22	-0.31	-0.24	-0.30	-0.29	0.001	-0.10
p-value	0.09	0.19	0.07	0.17	0.08	0.09	0.99	0.57
					2004			
r	-0.15	-0.10	-0.16	-0.06	-0.13	NA	-0.04	-0.21
p-value	0.54	0.52	0.50	0.69	0.45	NA	0.82	0.28

tillage plots to equal levels of conventionally tilled plots in a poorly drained soil. A similar trend was observed by Griffith et al. (1988) where corn yields were initially suppressed in no-till soils for the first three years, and by West et al. (1996) who found soybean yields to improve with time in no-till fields. Aside from one study that reported equal sweet corn yields in strip- and conventional-tilled plots (Luna and Staben, 2002), there have been no other studies besides ours that investigated reduced tillage vegetable systems in the Willamette Valley. It is therefore unknown whether longer periods beyond 3 years could cause integrated vegetable systems to equal or exceed conventional systems.

Although soil bulk density did not correlate with yield, it may be a factor in the strip-tilled treatment (Table 3.4). Between-row bulk density was significantly higher ($p < 0.05$) than were tilled plots (Chapter 2). Compacted soils have been found to decrease corn yield with subsequent yield increases when the compacted soils were tilled (Abu-Hamdeh, 2003). Furthermore, Wolfe et al. (1995) reported decreases not only in vegetable crop yields with soil compaction, but also determined the greatest yield decreases in cabbage, followed by snap bean, and then sweet corn. This was related to secondary effects on vegetable crops due to compaction such as poor drainage and increased insect pest pressure (Wolfe et al., 1995). The trend observed in our study supports this finding in that the greatest difference between yields in the Strip-CC and Till-WF plots occurred with broccoli, followed by smaller differences in snap bean, and sweet corn, respectively.

PERSPECTIVES

Suppressed vegetable yields were evident in the reduced tillage and cover-cropped plots compared to the conventionally tilled, winter fallow plots over three years of the study, with significant differences apparent in year one. Cover crop biomass and cereal:legume ratio of the cover crop stand was strongly correlated with vegetable crop yield which may be a factor in these outcomes. However, all treatments were given supplemental fertilizer, making immobilization of N unlikely in years when the legume cover crop component was minimal.

Correlations between biological and physical soil quality indicators and yield were found to be negative in the first year of our study, and became less so after three years, suggesting there was a trend of improving soil quality and crop yields and that it may take several more years for vegetable yield to respond to reduced-tillage/cover-cropped systems. Moreover, soil health was mainly improving biologically, whereas bulk density (an index of compaction), continued to remain higher in reduced tillage treatments than tilled treatments during the summer growing period.

Several factors should be considered for future studies of integrated vegetable systems in the Pacific Northwest. This includes decreasing the cereal:legume cover crop ratio to determine the effect on vegetable yields, and timing tillage with soil moisture to establish an ideal soil moisture content that would balance any yield reductions associated with a later planting date. Longer studies are needed to determine whether soils under an integrated reduced-tillage/cover-cropped system can reach a new equilibrium for physical properties in a silty clay loam in the Willamette Valley, and where this improved soil quality is reflected in crop yield.

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CHAPTER 4

EARTHWORMS IN INTEGRATED AGROECOSYSTEMS: INSIGHTS ON METHODS FOR FIELD-SCALE EARTHWORM SAMPLING AND ASSOCIATIONS WITH SOIL PROPERTIES

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Prepared for submission to:
Soil Science Society of America Journal

ABSTRACT

Earthworms have the potential to improve soil quality through burrowing and soil ingestion. Relatively little information is available about managing soils to stimulate earthworm activity in agroecosystems. Additionally, simple methods are needed to assess earthworm abundance to guide development and monitoring of sustainable agricultural systems. The objective of this study was to compare the impacts of various combinations of cover crops and tillage on earthworms, to assess abundance using non-destructive field-scale earthworm sampling methods, and to compare earthworm activity with other indicators of soil quality. Field treatments (four replications) were established in a randomized block and included strip tillage with winter cover crop (Strip-CC); conventional tillage with winter cover crop (Till-CC); and conventional tillage left fallow in winter (Till-WF). Earthworm populations were determined by fresh midden counts and mustard solution extraction; an imbedded study used an electroshocking device to remove earthworms from the soil. Midden counts were found to be a relatively quick and non-destructive method to determine earthworm abundance, but were limited to seasons when earthworms were most active, and accounted for anecic species only. Mustard solution extraction accounted for both anecic and endogeic species in addition to aestivating earthworms, but was time consuming and disturbed the soil. Electroshocking required a relatively weed-free soil surface and adequate control of amperage through the circuit. Using the former two techniques, earthworm abundance was found to be greatest in Strip-CC

treatments with significant correlations to microbial biomass-C (MB_C), β-glucosidase activity, water stable aggregates (WSA), and bulk density ($p < 0.02$).

INTRODUCTION

Earthworms have long been perceived to improve soils, which was first proposed by Charles Darwin in the historical book, *The Formation of Vegetable Mould, through the Action of Worms* (Darwin, 1896). Earthworm activity through burrowing and ingestion of soil and organic material would be expected to impact soil microbial and physical properties.

Soil that has passed through the microbially active earthworm gut is excreted as earthworm castings which have been shown to have greater microbial activity compared to undigested soil (Barois and Lavelle, 1986). This increase in microbial activity includes increases in bacteria, fungi, and actinomycetes (Dkhar and Mishra, 1986), which affects nutrient cycling. Nutrient availability (C, N, P, K, Ca) is increased due to this greater microbial activity as organic matter is transformed to more available forms (Satchell, 1967), and earthworms have been found to influence decomposition rates (Shaw and Pawluk, 1986).

Earthworms affect physical properties of soils by ingesting soil and organic material, and by burrowing as a means to gather further debris and for protection. The development of burrows and deposition of castings increases large pores in the soil profile (Edwards and Lofty, 1977). Large amounts of organic material consumed by some earthworm species, combined with their internal secretions, result in the formation of water stable aggregates which improve soil structure and productivity

(Hopp and Slater, 1948). The combination of increased aggregation and porosity from earthworm activity also reduces surface crusting and surface run-off, which in turn increase infiltration and water retention. The subsequent improved soil quality promotes root growth and penetration, and decreases erosion potential.

Earthworms also affect the flow of water by increasing the rate of water infiltration through their burrow systems. However, due to different burrowing habits, the extent to which infiltration is increased varies depending on the earthworm species. Large, vertical channels can rapidly conduct water through macropores and contribute to direct, or preferential flow (Bouma, 1991; Trojan and Linden, 1992; Blair et al., 1995; Trojan and Linden 1998; Lamgmaack et al., 1999). Advantages to this rapid infiltration include increased drainage which can be beneficial for plants growing in heavy soils. However, this can facilitate preferential movement to groundwater of pollutants such as pesticides and fertilizers.

Earthworms are divided into three categories, epigeic, endogeic, and anecic earthworms, based on habitat adaptations and food preferences. Epigeic earthworm species live among or near surface litter, and feed mostly on coarse-textured organic material. Endogeic earthworm species inhabit the soil profile and ingest both soil and organic material. Their burrowing habits occur near the soil surface, and therefore influence surface soils more than deeper soils (Tomlin et al., 1992), however, their burrows are not permanent. Anecic earthworm species also inhabit the soil profile and primarily ingest surface litter drawn into their burrows (Blair et al., 1995). Anecic earthworms create networks of permanent deep burrows, most commonly vertical channels that are used repeatedly, resulting in dense, slick burrow walls (Trojan and Linden, 1998).

Mounds of surface litter that have been pulled into the burrow, along with cast soil, are common at the aperture of such burrows, and referred to as middens. Middens are easily visible during the spring and autumn when earthworms are most active. Due to the abundance and habits of anecic earthworms to ingest high amounts of organic material and create permanent deep burrows, they are especially influential to the agricultural soil ecosystem.

Intensification of land use has been shown to affect earthworm populations and species diversity (Decaëns and Jiménez, 2002), indicating that earthworms are sensitive to soil management. However, the majority of documentation of this has been concentrated in tropical environments (Lavelle and Pashanasi, 1989; Dangerfield, 1990; Fragoso et al., 1997; Decaëns and Jiménez, 2002).

When sampling earthworm populations, it is important to consider the moisture content and temperature of the soil. During dry seasons, along with seasonal extremes in temperature, earthworms may migrate to deeper soil or young earthworms may remain in their protective cocoon until conditions become favorable. This migration also entails a period of decreased activity, or aestivation (Edwards and Lofty, 1977).

Prior research has evaluated the use of several field-scale techniques to sample earthworm abundance including hand sorting (Edwards and Bohlen, 1996), formalin extraction (Edwards and Bohlen, 1996), and electroshocking (Rushton and Luff, 1984; Schmidt, 2001). In this study, it was desired that a sampling technique be minimally destructive, sensitive to management strategies, and relatively simple, so that it may be used by growers or agricultural professionals as an index for land use effects on earthworms.

The first objective of this study was to evaluate three sampling methods used to measure earthworm abundance or activity, and to summarize advantages and disadvantages for each. The second objective was to determine the effect of soil management on earthworm presence and activity in a Western Oregon vegetable agroecosystem with varying levels of tillage and cover crops. The third objective was to investigate possible correlations between earthworm abundance and soil biological and physical properties. It was hypothesized that reduced tillage, in combination with winter cover crops, would increase earthworm abundance by decreasing soil disturbance and providing a food source. Furthermore, earthworm abundance would positively correlate with other soil biological and physical properties that act as soil quality indicators.

MATERIALS AND METHODS

The research was done on the Oregon State University Vegetable Research Farm (VRF) in Corvallis, Oregon, located in the Willamette Valley of western Oregon. The climate is Mediterranean with warm, dry summers and cool, wet winters. The soil was a Chehalis silty clay loam (fine-silty, mixed, superactive, mesic Cumulic Ultic Haploxerolls). The soils are very deep and well drained, formed in mixed alluvium on the flood plain along the Willamette River. The average soil texture at this site was 5, 67, and 28 kg kg^{-1} sand, silt, and clay, respectively.

Our study was conducted within a field study on the impacts of reduced tillage and cover crops relative to soil quality. The experimental design was a randomized complete block with four replications and three treatments: 1) strip tillage with winter cover crop (Strip-CC); 2) conventional tillage with winter cover crop (Till-CC); or 3) conventional tillage left fallow in winter (Till-WF).

Both Till-CC and Till-WF plots received fall and spring tillage with one pass of a rollover plow, one pass of a disc, and two passes of a rotary tiller plus a roller. Strip-CC plots received fall tillage of one pass with a disc, and two passes with a rotary tiller plus a roller prior to planting the winter cover crop. In the spring, the Strip-CC plots received one pass with a Northwest Strip Tiller (Northwest Tillers, Inc., Yakima, WA), which tills four strips approximately 30 cm apart and 15 to 20 cm deep. The sequence of winter cover crops and summer vegetable crops are shown in Table 4.1. Each vegetable crop was planted with an application of 43.6 kg N ha^{-1}, 45.8 kg P ha^{-1}, 30.2 kg K ha^{-1}, and 29.04 kg S ha^{-1}.

Table 4.1. Crop planting at Vegetable Research Farm during three years of the experiment (2002-2004).

Year of Study	Winter Cover Crop	Summer Vegetable Crop
1	Oat (*Avena sativa* L.), vetch (*Vicia sativa* L.)	Broccoli (*Brassica oleracea* L.; transplanted)
2	Barley (*Hordeum vulgare* L.), field pea (*Pisum sativum* L.)	Snap bean (*Phaseolus vulgaris* L.; seeded)
3	Barley (*Hordeum vulgare* L.), vetch (*Vicia sativa* L.)	Sweet corn (*Zea mays* L.; seeded)

Earthworm Measurements

Mustard solution extraction. Ground yellow mustard seed (*Brassica alba*) was dissolved in tap water at a ratio of 30 mL $liter^{-1}$, according to the Soil Quality Test Kit Guide (United States Department of Agriculture, et al., 1999). A 0.03 m^3 hole was excavated with a sharp-shooter shovel, and the soil was collected on a tarp. Two liters of the mustard solution (vermifuge) was slowly added to the excavated hole. Each hole was monitored for five minutes following vermifuge application and earthworms were removed as they appeared, followed by hand sorting and total counts. Three sub-replicates were conducted in each treatment plot during the summer of 2003.

Fresh midden abundance. Midden abundance was estimated by counting all middens on the soil surface within a 0.5 m^2 quadrant. One midden was defined as a single mound, as distinguished by an aperture where debris had been pulled into the burrow, coupled with evidence of fresh castings. If more than one aperture was visible in a mound, that mound was considered to represent two middens. Three sub-replicates were counted in each plot during the spring of 2003 and 2004.

Electroshocking. Based on the work of Rushton and Luff (1984) and Blair et al. (1995), an electroshocking device was designed and constructed. The device consisted of four, 50-cm long and 1-cm wide threaded steel rods, inserted into a two-by-four block of Douglas fir wood, and evenly spaced. Rods were attached by threading bolts and washers on both ends and tightening onto the block of wood. Two probes were built, one for the positive electrode and the other for the negative electrode. To the top bolts on each rod, a wire was soldered to create a series circuit;

all exposed wires were covered with electrical tape. A multimeter (Radio Shack, Fort Worth, TX) was wired in series on the circuit to monitor amperage and a plug was attached to the end. This device was connected to a gasoline-powered generator supplying 220 volts of alternating current. Leather gloves and rubber boots were worn by the operator during application.

If sampling in the summer at low soil moisture content, the soil was moistened by gently sprinkling with a hose to add an adequate amount of water to conduct the electricity. Each probe was then placed in the ground roughly one meter apart and pounded into the soil with a board and mallet. Alternating current was applied for 20 minutes, while monitoring the multimeter to ensure the amperage was between 0.2 and 0.4 A. Earthworms were collected and counted as they appeared. One application of electricity was applied for each plot during the summers of 2002, 2003, 2004 and spring of 2004.

Microbial Measurements

Microbial biomass (MB_C) was measured on fresh soils within three days of sampling. The chloroform fumigation-incubation method as outlined by Jenkinson and Powlson (1976) was performed on soil samples collected in spring and summer of 2002-2004. In brief, soils were exposed to chloroform for 24 hours under vacuum and then incubated in the dark at 25°C for 10 days. Following incubation, a gas chromatograph was used to measure CO_2, and MB_C was calculated without the subtraction of the control using a k_C value of 0.41 (Voroney and Paul, 1984).

Beta-glucosidase activity levels were measured as described by Tabatabai (1994). Air-dried soils were used, and after a one-hour incubation in the presence of the substrate (*p*-nitrophenyl-β-D-gluco-pyranoside) the product (*p*-nitrophenol, PNP) color intensity was determined on a spectrophotometer set at a 420 nm wavelength. Two analytical replicates and one control were analyzed for each soil sample, and activity reported as μg PNP g^{-1} soil hr^{1}.

Physical Measurements

Water stable aggregates were measured according to Kemper and Rosenau (1986) with the following modification. Field moist soil samples were initially passed through a 2 mm sieve and allowed to air-dry for 48 h prior to collection of the 1-mm size fraction. Aggregates were initially sieved in a wet sieving machine at a frequency of 35 cycles min^{-1} in 75 mL of de-ionized water (DI) during which unstable aggregates were collected in the DI water. Following this, any aggregates remaining on the sieves were then wet-sieved in 75 mL of sodium polyphosphate dispersing agent (DS) at a concentration of 2 g L^{-1}. Soils retained in the DI and the DS solutions were oven-dried in the respective containers, allowed to cool for five minutes after removing from the oven, and then weighed. Percent water stable aggregates were calculated as follows:

$$\text{Percent WSA} = \frac{(soil_{DS} - 0.16) * 100}{(soil_{DS} + soil_{DI}) - 0.16}$$

Subtraction of 0.16 g was included to compensate for the mass of the dispersing solution.

Soil bulk density was measured using a Troxler nuclear density gauge (Troxler Electronic Laboratories Inc., Research Triangle Park, NC). Bulk density readings were taken both within and between rows at 5, 10, 20, and 30 cm depths at three sub-replicate locations within each plot.

Water infiltration was measured using a constant-head infiltrometer. Three sub-replicate measurements were taken from each plot on a relatively uniform soil surface. Measurements were taken during active crop growth approximately three weeks prior to harvest date. Metal infiltration rings (30 x 30 cm) were placed between rows, and pushed in to a depth of 15 cm. Soil was pre-moistened by filling each ring with 6 L of tap water which was allowed to infiltrate for 15 to 20 minutes. A mark was then made on the inside of the ring, 5 cm from the bottom of the soil surface, and water was added to form a 5 cm head in the infiltration ring. Marriot suction devices were inserted into the rings and the water flow was adjusted on the 20 L Marriot tube container to maintain the 5 cm head. This procedure was continued for two hours or until the 20 L were drained, whichever occurred first; all times were recorded using a stopwatch. Marks were made on the 20 L container at the commencement and completion of the process. At completion, each 20 L container was backfilled with water in order to determine the amount of water that had infiltrated in the given time, and the infiltration rate was expressed as $L\ h^{-1}$.

Statistical analysis

Analysis of variance of the data was done as a randomized block design at each sampling date. Fisher LSD was used to separate main effects at a 95%

confidence level. Data were analyzed using the statistical software package S-Plus (Insightful Corporation, Seattle, WA). Correlations were determined using the Pearson product moment correlation coefficient.

RESULTS AND DISCUSSION

Earthworm measurements

Mustard solution extraction. The advantages of this method are that mustard solution remains a less toxic alternative to formalin-based vermifuges, and both anecic and endogeic earthworm species are captured and counted using this procedure. In addition, earthworms in aestivation within the excavated soil also are captured, which is useful for sampling during summer months when earthworm activity is low.

Drawbacks of this approach are that it is the most destructive sampling method of the three, and a single extraction is both time- and labor-intensive. Because soil excavation is necessary, the site location and subsequent impact needs to be considered before using this technique.

This method was sensitive in detecting field management effects on earthworm activity. Earthworm counts were significantly greater in strip tilled plots with cover crops compared to conventionally tilled plots left fallow in winter (Fig. 4.1). Total earthworm numbers remain low, compared to other sampling techniques, and variability is high (CV = 30%, 108%, 200% for Strip-CC, Till-CC, Till-WF, respectively). This could be caused partially by the time of sampling in the summer when soil temperatures are high and earthworm activity is low. A more likely reason

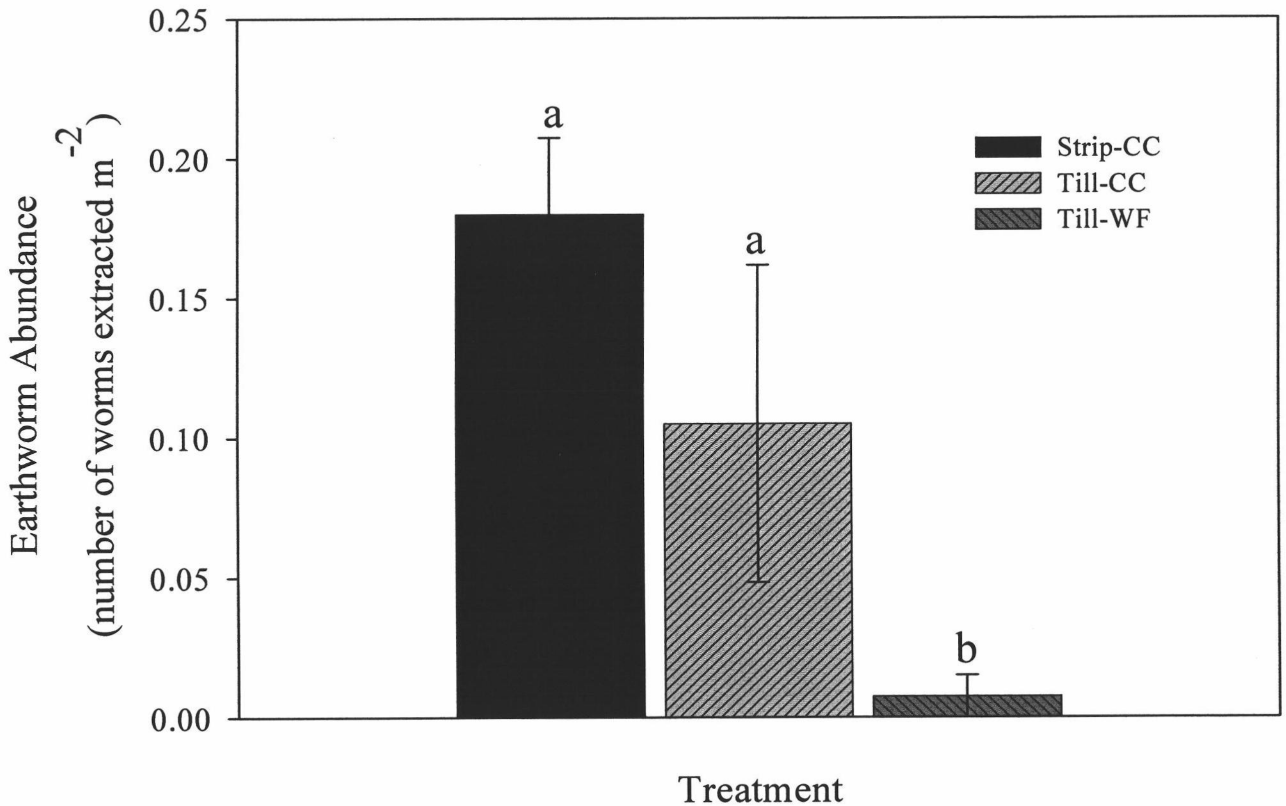

Fig. 4.1. Earthworm abundance as measured by mustard solution extraction and hand sorting in an integrated vegetable experiment in Western Oregon in 2003. Bars with the same lower case letters are not significantly different at $p < 0.05$.

may be high spatial variability and thus more replication than we had is needed. However, increased replication of this method is difficult because it is very time consuming.

Fresh midden abundance. One advantage to this method is the relatively short time required to count middens, compared to the other two methods, enabling more replicates to be performed and to reduce spatial variability. Another advantage is the low cost of materials needed to count middens. A potential limitation is identification of a “single” midden. During periods of heavy rainfall, individual middens may become indistinguishable due to slaking of fresh castings. Presence of crops or cover crops makes midden counting more time consuming. Also, plants can obscure middens, particularly since middens often are located at the base of the mature plants where older leaves are dying. Another complicating factor is that this method can be done only at times of the year when earthworms are active and when soils are not regularly tilled.

Fresh midden counts provide a much higher numerical rating per unit area compared to mustard solution counts (Fig. 4.2). In part, this may be due to midden counts having been done in the spring when earthworms were most active due to temperature and established cover crops, as compared to mustard counts which were done in the summer when soil temperatures were higher. Midden counts provided a lower variability within treatments than did mustard solution extractions and also were sensitive in detecting treatment effects (Fig. 4.2). Midden counts appears to be a useful method to compare treatments and monitor earthworm activity.

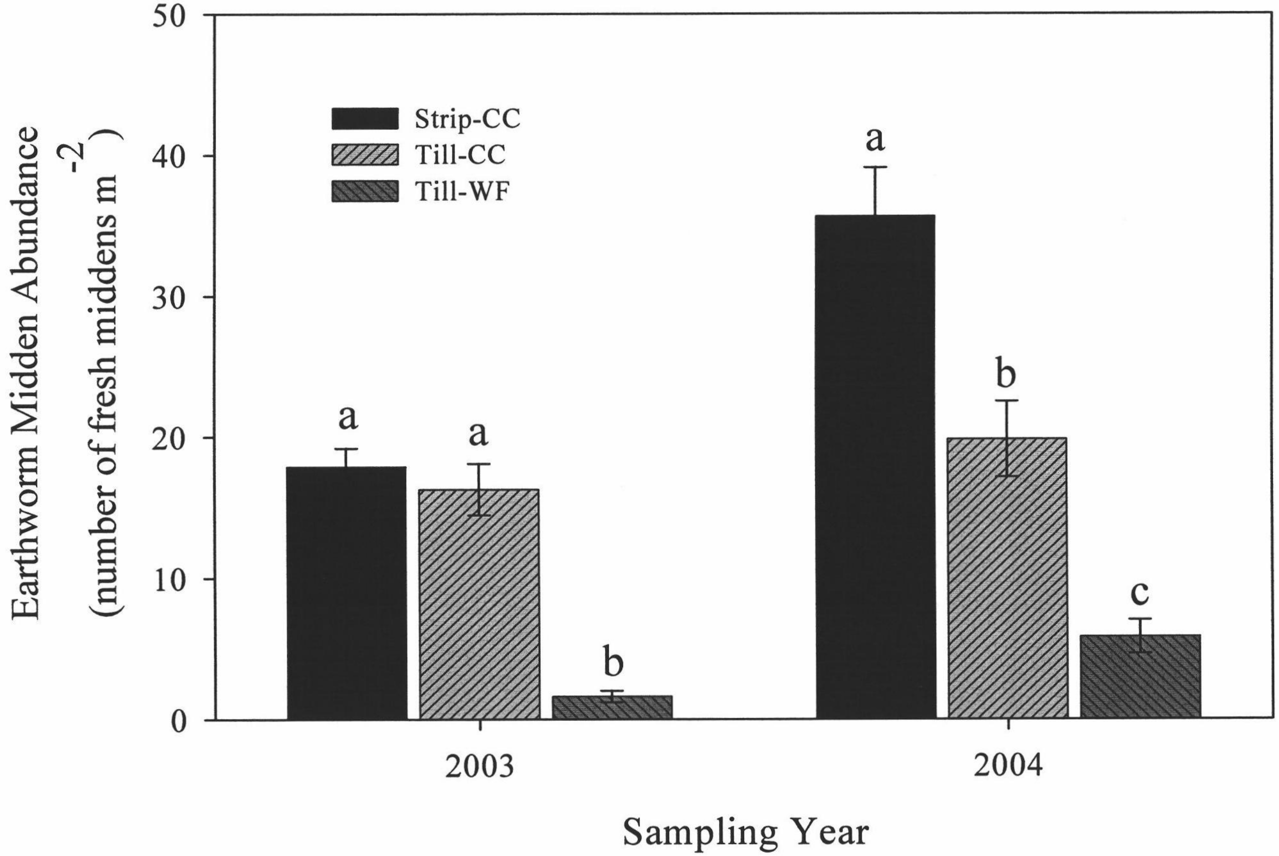

Fig. 4.2. Earthworm abundance as measured by fresh midden counts in an integrated vegetable experiment in Western Oregon in 2003 and 2004. Bars within a sampling year with the same lower case letters are not significantly different at $p < 0.05$.

Electroshocking. We are reporting on the use of electroshocking for research purposes to reduce earthworm populations in contained plots. Earthworms were successfully recovered using this method (data not reported). However, the method has some constraints and technical considerations. The presence of mature plants makes it difficult to see emerging earthworms; the soils should be weed free. On the other hand it may be necessary to collect earthworms at times of the year when their activity is high, such as when winter cover crops are present.

Controlling the amperage delivered through the circuit is another difficulty. The multimeter provides a means to observe the amperage; however, the best way to alter the current is to adjust the depth to which the probes are inserted in the ground. At times, high amperage is inadvertently delivered, which may kill earthworms in the subsoil. The amperage can be lowered by positioning the probes at a lower depth. Previous studies have found that electroshocking is efficient at extracting earthworms near the surface of the soil (Rushton and Luff, 1984). If electroshocking is confined to the surface layer, it may cause an underestimate of deep-dwelling anecic species such as *Lumbricus terrestris* which are common in agroecosystems.

Recommendations. The choice of earthworm sampling method depends on the objective. When soil disturbance, time, and cost are issues in determining earthworm abundance, anecic-type activity can best be evaluated by fresh midden counts. Because anecic earthworms are common in agroecosystems, they are likely important in affecting soil quality and crop productivity. Mustard solution extraction remains a good option for detecting both anecic and endogeic earthworms, enabling their recovery during periods of aestivation. Although time consuming, it is the best method for research purposes. Electroshocking requires the construction of the electroshocking device which must be tested and calibrated to deliver accurate amperage. If plants cover the surface of the soil, this method poses a challenge in collecting and counting earthworms as they are difficult to see emerge. The use of this device is also quite cumbersome, making it a less ideal choice for growers.

Earthworm Responses to Tillage and Cover Cropping

Earthworm abundance was affected by both tillage and cover cropping, as detected by mustard solution extraction (Fig. 4.1) and fresh midden counts (Fig. 4.2). The Strip-CC provided the most suitable habitat for earthworms with Till-WF being significantly less suitable ($p < 0.01$). These results are consistent with other studies that show the importance of adequate food and minimal disturbance to promote earthworm activity (Schmidt et al., 2003). Additional support for these findings are that midden counts at several on-farm sites were significantly higher in cover-cropped fields than in winter fallow fields ($p < 0.0001$; data not shown).

The strong earthworm response to winter cover crops is due to abundant food available for anecic earthworms such as *L. terrestris* which pull organic material from the surface into their burrows for feeding. In tandem with cover cropping, reduced tillage enables earthworm burrows to remain undisturbed in a large portion of the field, and can decrease mortality of large-bodied anecic earthworms, thus increasing populations (Wyss and Glasstetter, 1992).

Our study suggests that cover crops were more important than tillage in promoting earthworms. This shows the importance of a year-around food source which a combined summer crop and winter cover crop provides. The second most important factor was tillage as the disturbance of conventional tillage reduced earthworm indexes. Indeed, the destructive effects of tillage were greatly offset by cover cropping because the indexes for cover crops plus tillage were in between the Strip-CC treatments and the Till-WF treatment (Fig. 4.1 and 4.2).

Earthworm Midden Correlations with Soil Properties

Earthworm abundance as determined by fresh midden counts did correspond to several soil properties (Table 4.2). Although the r-values were somewhat low, midden counts were significantly correlated with other soil properties. The positive correlation with MB_C and β-glucosidase activity may be due to soil passage through the earthworm gut which results in increased microbial activity found in cast soil than in undigested soil (Barois and Lavelle, 1986; Shaw and Pawluk, 1986). Another possible explanation is that the decrease in soil management intensity, including the addition of cover crops and reduced tillage, increases both earthworm abundance (Decaëns and Jiménez, 2002) and microbial activity by direct effects of organic inputs on microorganisms (Lynch and Panting, 1980; Bandick and Dick 1999; Staley, 1999; Ndiaye et al., 2000). The Strip-CC and Till-CC treatments provide an energy source, via cover crops, and habitat destruction is reduced with the strip tillage system.

Table 4.2. Pearson correlation coefficients (r) for association between soil properties and earthworm midden abundance in an integrated vegetable agroecosystem in Western Oregon in 2003.

	MB_C	β-glucosidase activity	Percent WSA
r	0.40	0.42	0.50
p-value	0.02	0.01	0.004

Water stable aggregates showed a significant correlation with midden counts (Table 4.1). This supports other studies that have found earthworm activity to aid in the formation (Blanchart, 1992) and stability (Blanchart, 1992; Ketterings et al., 1997) of soil aggregates through the ingestion of soil and organic material.

These trends of the relationships of earthworms with improved soil quality as measured by the above soil properties may, however, be coincidental. Earthworms have been found to increase soil macroporosity (Edwards and Lofty, 1977) and casts have been found 10-20% higher in porosity than surrounding soil (Larink et al., 2001). Despite these expected benefits, the Strip-CC treatments had the highest bulk density in this study (Chapter 2). It is possible that the improved microbial measures and stable aggregates seen in Strip-CC treatments (Chapter 2) were simply due to cover crop residues and decreased disturbance. Nonetheless, midden counts were highest in Strip-CC soils in the spring. A previous study by Langmaack et al. (1999) found burrows of *L. terrestris* to become less branched and less continuous in compacted soils possibly as a means to reduce energy expenditure when burrowing through dense soil. Given this, it may well be that more time is needed for earthworms to improve soil structure in Strip-CC soils and ameliorate the increased soil compaction.

PERSPECTIVES

Our research indicates that the adoption of integrated reduced tillage and cover cropping by vegetable growers should result in increased earthworm abundance in their fields. To monitor activity of earthworms we would recommend counting middens as a non-destructive, low-cost and relatively quick method to obtain an earthworm index which will reflect soil management impacts. The horizontal burrowing endogeic species are not accounted for with this method; this fact should be considered if using the method as a research tool for which total population counts are required. In addition, midden counts should be used primarily in the spring when earthworms are actively feeding. This method is practical and could be adopted by growers or agricultural professionals to observe and compare earthworm activity in fields with different soil management, as it is sensitive to changes in land use.

Earthworm activity was found to be associated with increased microbial measures and water stable aggregates, which have been considered as soil quality indicators (Fauci and Dick, 1994; Dick, 1994; Ndiaye et al., 2000; Carter, 2002). Given these relationships, earthworm activity could be added to the suite of indicators used to gauge changes in soil quality.

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CHAPTER 5

SUMMARY

The first objective in this study was to evaluate the use of biological and physical soil quality indicators to monitor the impact of integrated and conventional systems on soil biological and physical properties. The major findings associated with this objective were:

- Microbial biomass-carbon (MB_C) and β-glucosidase activity responded rapidly to changes in management.
- Beta-glucosidase activity was more consistent than MB_C over seasons, suggesting it may be a more useful tool for growers and agricultural professionals to gauge soil quality when comparative controls are not available.
- Percent water stable aggregates (WSA) are sensitive to cover crops but not tillage within the first three years of adopting an integrated management system.
- Water infiltration measurements were highly variable possibly due to the fact that infiltration rings are place-bound and therefore subject to high short-distance variability.

The second objective was to explore soil quality changes to better understand the mechanisms driving soil ecosystem dynamics after the adoption of a strip-tilled/cover-cropped agroecosystem. The major findings associated with this objective were:

- Microbial biomass-carbon, β-glucosidase, and earthworm activity increased with reduced tillage and cover crops. This increase was evident after the first year of implementing an integrated management system.

- Percent WSA improved with cover crops, but soils became more compacted, as measured by bulk density, with a reduction in tillage.

The third objective of this study was to assess differences in vegetable yield with integrated and conventional systems and investigate relationships between yield and soil quality measurements. The major findings associated with this objective were:

- Vegetable yields were suppressed with reduced tillage and cover crops, although this trend was significant only during the first year with broccoli.
- A strong correlation existed between cover-crop biomass and yield as well as cover crop cereal:legume ratio and yield.
- Correlations between biological and physical soil quality indicators and yield were found to be negative during the first year, and became less so after three years, suggesting that it may take several more years for vegetable yield to respond to reduced-tillage/cover-cropped management systems.

The fourth objective of this study was to determine how a reduced-tillage/cover-cropped system would affect earthworm abundance and evaluate several methods to monitor earthworm activity. The major findings associated with this objective were:

- The adoption of a reduced-tillage/cover-cropped system should result in an increase in earthworm abundance.
- We would recommend that growers and agricultural professionals use midden counts as a non-destructive, low-cost and relatively quick method to obtain an earthworm index that reflects soil management impacts.

The fifth objective of this study was to specifically assess the role of earthworms as an indicator of soil quality in a reduced-tillage/cover-cropped system by correlating earthworm activity with other soil quality indicators. The major findings associated with this objective were:

- Earthworm activity was found to be associated with increased microbial measures and WSA. Given this finding, earthworm activity could be added to the suite of indicators used to gauge changes in soil quality.

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