ABSTRACT

BELL, MELISSA CATHERINE. A Multidisciplinary Approach to Assessing Changes in the Soil Quality of Diverse Farming Systems. (Under the direction of Michael Wagger.)

Soil quality methodology can be used to characterize and define management factors contributing to soil degradation. A minimum data set of indicators, measured collectively, can elucidate changes within the soil ecosystem. Physical (bulk density, infiltration rate), chemical (pH, inorganic N, organic N and C), and biological (soil respiration, fluorescent *Pseudomonas* bacteria and entomopathogenic nematode populations) indicators were measured over two years in a best management practice (BMP) conventional tillage (CT) and no-tillage (NT), organic, and successional (fallow) systems. At this early stage in the systems development, statistical differences between systems are few, but developing trends are evident. Preliminary results show higher microbial activity in undisturbed systems and where crop residue is left on the soil surface. Soil respiration values were higher in the BMP (NT) and successional systems throughout the growing seasons. Whereas Db was higher in the BMP (NT) and successional system, values were not root restrictive. Measurements of fluorescent *Pseudomonas* and entomopathogenic nematodes serve to act as a survey of endemic populations at this early stage in a long-term experiment. Treatment effects on infiltration time were masked by differences in soil type. This baseline information will be used to evaluate the amount, direction and speed of change in the systems over the long term and to assess the value of this set of indicators in relatation to soil quality and crop productivity.

A Multidisciplinary Approach to Assessing Changes in the Soil Quality of Diverse Farming Systems

by

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BIOGRAPHY

Melissa Catherine Bell was born in Dayton, Ohio on November 25, 1969. She graduated from Chaminade-Julienne High School in 1988. She received a Bachelor of Science Degree in Botany from Ohio University in November of 1993 and entered United States Peace Corps service in 1994. She served two years as an Agroforestry extension agent in Gilgil, Kenya.

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Chapter 1

Literature Review

Interactions between agricultural management practices and soil biological, chemical, and physical processes affect the productivity of agricultural soils and their impact on environmental quality (Doran et al., 1996). Since the 1980's, severe degradation the productive capacity of the soil has occurred on more than 10% of the earth's vegetated land as a result of soil erosion, atmospheric pollution, cultivation, over-grazing, land clearing, salinization, and desertification (Sanders, 1992). More recent assessments conducted on regional and global scales indicate that human-induced degradation is causing the loss of millions of hectares of agricultural land every year (Janke and Papendick, 1994). Assessments of degradation are important; but a methodology that can be used to characterize and define management factors that contribute to such degradation and suggest methods for improvement is lacking. In the past much of soil science research has focused on characteristics, or state of the soil. However, for these measurements to be useful in predicting soil degradation levels, an understanding of how soil characteristics are linked to soil performance and management practices is needed. Such methodologies are emerging within the area of soil quality research. Soil quality research has been proposed as a method to quantitatively assess the effect that farming practices have on the soil's ability to produce food and to perform certain environmental functions (Janke and Papendick, 1994). Soil quality methodology asks how the whole production system (tillage, fertility, pest management, crop rotation,

etc.) alters pest, water, and nutrient cycles, which in turn affect farm productivity and water quality over the long term.

The use of the specific term "soil quality" since the early 1980's is related to issues of sustainability, particularly with regard to agricultural sustainability (Lal, 1998). The emphasis of soil quality is on the interactions among soil processes rather than on soil components in isolation. Doran and Parkin (1994) defined 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. Larson and Pierce (1994) added that soil quality is also important in partitioning and regulating water flow in the environment, and as an environmental buffer. Common to all definitions is the idea that the soil function effectively now and in the future. The most distinctive contribution of the soil quality concept is the study of the linkages among four components of the soil system: 1) management practices and systems, 2) observable soil characteristics, 3) soil processes, and 4) soil performance (Lewandowski, 1999). Management decisions based on soil quality should be site and goal specific.

A system to evaluate sustainability required the identification of soil attributes that serve as indicators of change in soil health and the methodology to relate these changes to productivity (Doran and Parkin, 1996). Traditional assessments of bulk density, infiltration rate, pH, soil organic matter content, and nutrient concentrations are used to document the physical and chemical condition of the soil, but they illustrate little about the overall quality of the soil ecosystem. The biologically active components of soil organic matter (e.g. constituents of soil microbial biomass and energy sources like organic C and N) have been shown to be sensitive indicators of changes in soil

management (Kennedy and Papendick, 1995). Soil organisms constitute a large dynamic source and sink of nutrients in ecosystems and play a major role in plant litter decomposition and nutrient cycling (Smith and Paul, 1989). When traditional physical and chemical measurements are combined with measurements of the biological component of the soil, we gain a more holistic view of how management practices are affecting soil quality. Doran and Parkin (1996) suggested that soil quality indicators be easily measured, either directly or through an associative property, and relate to crop productivity. For example, aggregate stability can be used as an indicator of a soils resistance to erosion. A measure of soil microbial biomass can indicate a soil's ability to store and recycle nutrients, whereas water infiltration rate can be used to judge a soils permeability to air and water and degree of compaction.

Physical Indicators

The physical condition of a soil has direct and indirect effects on crop production and environmental quality. Soil texture, organic matter levels, and the degree of soil aggregation can influence soil bulk density. Bulk density in conjunction with soil texture can be used to estimate critical bulk density values at which root growth is severely affected (Jones, 1983), and bulk density measurements taken each time the soil is sampled permits adjustment of results to a volumetric basis, allowing for a valid comparison of management effects between soil types (Doran and Parkin, 1996). Physical indicators such as bulk density are strongly affected by soil management practices. Logsdon et al. (1993) compared in-row bulk density among alternative farming

systems (5-yr. rotation, ridge-tilled, no herbicides and manure applications) and conventionally managed systems (2-yr. rotation, chisel plow and field cultivator, pesticides and chemical fertilizers) and found bulk density and runoff higher (1.41 vs. 1.14 Mg/m^3 and 9.05 vs. 4.17 μm/s) for the conventional and alternative farming systems, respectively.

Penetration resistance is another indicator that is sensitive to the effects of farm equipment traffic. Unger (1996*)* determined the effects of tillage treatments and controlled traffic on soil bulk density, penetration resistance, and hydraulic conductivity in a winter wheat (*Triticum aestivum*.) and grain sorghum (*Sorghum bicolor*) rotation. The treatments consisted of no-till with crop residues standing, no-till with residues shredded, no-till after wheat, and conventional tillage after sorghum (residues incorporated). Determinations were made in the traffic furrow, non-traffic furrow, and row positions. Tillage did not affect any of the variables but row position significantly affected penetration resistance, which was greatest in the traffic furrow. Differences in hydraulic conductivity were significantly affected by depth and tended to be greater in the row than in furrow positions. The author concluded that the development of adverse physical conditions under no-till management is limited to designated traffic zones. Controlled traffic has consistently been shown as an important part of no-till management. Wagger and Denton (1989) also found soil physical properties strongly influenced by row position. They measured bulk density, hydraulic conductivity and soil porosity on a Goldsboro sandy loam after 3 yr of no-till management. Measurements were made in tracked, untracked, and plant row areas. Bulk density was significantly

higher and hydraulic conductivity lower, in the tracked compared with untracked position.

A primary function of soil quality, relative to erosion by water, is to accommodate entry of water into the soil matrix through infiltration (Karlen and Stott, 1994). Infiltration rate is an important factor for reducing runoff and for storing plant available water, thereby providing an indirect assessment of how soil management influences hydrologically effective macroporosity, surface seals, and soil density (Logsdon et al. 1993). Bruce et al. (1995) found large increases in rainfall infiltration and reduced soil erodibility when grain sorghum was no-till planted into crimson clover (*Trifolium incarnatum*), compared to conventional tillage. Vervoort et al. (2001) also examined tillage and row position influence on infiltration rate. The authors compared three positions (plant row, nontracked interrrow, and tracked interrow) and tillage (chisel plow, disk, or no-till). Ponded infiltration rates were not influenced by tillage but were significantly affected by row position. Infiltration rates were 86.5 mm h^{-1}in the row, 18.6 mm h^{-1} in the nontracked interrow, and 2.38 mm h^{-1} in the tracked interrow. Although not significant, numerically the water infiltrated faster in the no-till system. The authors concluded that preferential flow through biological and structural macropores may have contributed to the faster infiltration times in the no-till. Lindstrom et al. (1981), however, found that no-till may result in a consolidated soil surface with low infiltration capacity. They used simulated rainfall to determine the effects of row position (wheel-tracked and non-wheel tracked interrows) on infiltration rate in continuous corn (*Zea mays*) under three tillage treatments (conventional, conservation, and no-till) after 10 yr. Differences were observed in soil bulk density and infiltration for both position and tillage treatments.

The conservation and conventional tillage non-wheel-tracked interrrows had greater infiltration after runoff started than the wheel-tracked interrows and the no-till system. The no-till system was susceptible to high volumes of runoff during severe rainfall events.

Surface residues also influence water infiltration rates. Baumhart and Lascano (1996) conducted a field experiment in which they simulated rainfall (65 mm/h for 1 hr) on a bare and residue-covered soil. They found cumulative infiltration lowest (28.7 mm) on bare soil. Infiltration increased curvilinearly with increases in surface residue.

Soil aggregates are the basic components of soil structure. Aggregate stability is important in decreasing surface crusting, and in turn soil erosion, and in increasing air and water movement through the soil. Biotic processes such as the production of organic glues by microorganisms, networks of fungal hyphae and the aggregating effect of organic matter, and abiotic processes such as the flocculation of clay particles and freezing and thawing cycles influence soil aggregate stability. The organization of surface soils into relatively large structural aggregates provides for low bulk density and a high proportion of macropores, which is desirable for most soils (Brady and Weil, 2002). The Natural Resource and Conservation Service Laboratory uses the wet sieving method to measure aggregate stability. This process, which simulates the action of flowing water, is used to determine the amount of water-stable aggregates. Another method, mean weight diameter (MWD), is an index based on weighing the masses of aggregates of the various size classes according to their respective sizes and is commonly used to determine dry aggregate stability. Tillage can have both favorable and unfavorable effects on aggregation. Immediately after plowing, total porosity is

increased, but over the long term tillage hastens organic matter oxidation and decreases aggregate stability (Brady and Weil, 2002). Karlen et al. (1994) evaluated soil quality following a long-term tillage study on continuous corn by measuring bulk density and water stable aggregates as part of a larger set of indicators. Plots that had been managed no-till for 12 yr had higher total C, microbial activity, and stable surface soil aggregates. In a related study, they also found that increased surface residue was associated with an increase in water stable aggregates (Karlen et al. 1994). Short-term benefits of no-till on aggregate stability can also be apparent. Rhoton (2000) found higher levels of total soil organic matter (SOM) and increased aggregate stability under no-till after only four yr. Initial SOM contents ranged from an average 19.5 g kg^{-1} in the 0-2.5 cm depth. After four growing seasons, no-till had increased SOM an average of 86%. In addition, the conventional till plots lost an average of 10% from the initial SOM contents.

Chemical Indicators

Chemical indicators include soil pH, total organic C and N, inorganic N, P, and K, and soil organic matter. Soil pH and nutrient availability are influenced by cropping and soil management practices, soil organic matter content, and biological activity. Scow et al. (1994) measured a suite of soil fertility and biological parameters in four farming systems (conventional 4 yr, conventional 2 yr., low input and organic) over four yr at the Sustainable Agriculture Farming Systems at UC Davis. At the end of four yr., they found pH and total N concentration were consistently greater in the organic and low input plots than the conventional plots. They also found P and K levels higher in the organic treatments. Electrical conductivity (EC), which is related to the total cations or anions in soil solution, has generally been associated with soil salinity, but can also serve as a

measure of soluble nutrients (Smith and Doran, 1996). Thus within a specific range, EC would indicate food nutrient availability for plants, with the low end indicating nutrient poor soil that is structurally unstable and disperses readily and the high end salinity problems (Smith and Doran, 1996). Soil organic matter is a complex and dynamic soil component that exerts a major influence on soil behavior, properties, and function in the ecosystem (Brady and Weil, 1996). The biologically active components of soil organic matter (e.g. constituents of soil microbial biomass and energy sources such as organic C and N) have been shown to be sensitive indicators of changes in soil management (Kennedy and Papendick, 1995). Bolinder et al. (1998) studied the response and consistency of different soil organic matter attributes to changes in soil management practices conservation (no-till, rotation, organic amendments) and conventional (moldboard plowing, continuous cropping, no organic amendments) management practices. They found light fraction N and macro-organic matter N to be the most sensitive soil organic matter attributes to conservation management practices. Light fraction C, macro-organic matter C, and microbial biomass C also were highly sensitive to management practices; however, the sensitivity of the attributes was site specific. Wander et al. (1994) believe that soil organic matter is the key to productivity when fertility is biologically mediated and that particulate organic matter serves as the best index of biologically active soil organic matter. The authors examined how ten yr of organic or conventional management affected biologically active soil organic mater pools. They compared soil CO_2 evolution, labile organic N pools, N mineralization rates, and particulate organic matter fractions in three treatments: an organic animal based rotation, an organic grain based rotation and a conventionally managed cash-grain-based

rotation. After ten years, the conventionally managed soil did not accumulate soil organic matter and had the smallest particulate organic matter pool. It also had the lowest levels of biological activity, measured by soil respiration rate, compared to cover cropped soils or those receiving animal manure. Greater C and N turnover rates of the animal-based treatment soil were suggested by its comparatively rapid soil respiration rates and its relatively high N supply capacity. The authors concluded that the animal based rotation improved the quality of active organic matter. They also found the conventional treatment had the lowest nutrient supply potential in terms of available and mineralized N. Total C was greatest in the cover-cropped, intermediate in the animal-based, and least in the conventionally treated soils.

Biological Indicators

Microbial populations can provide advanced evidence of subtle changes in soil long before they can be accurately measured by changes in soil organic matter (Powlson et al., 1987). Carter (1991) suggests that the proportion of total organic matter present in microbial biomass may be a useful parameter to characterize tillage-induced changes in soil biological properties. They compared the organic matter dynamics in tillage experiments to long-term conditions in grassland sites for 10-40 yr. They determined the ratio of biomass C to total organic C in the surface layer (0-5cm) in a range of reduced tillage treatments (direct drilling, chisel plowing, shallow tillage). Microbial biomass C was related to organic C and the average proportion of organic C in the biomass of the reduced tillage soils was greater than in the plowed soils, and similar to that in grassland soils. The reduction in soil tillage caused a redistribution of biological properties within

the soil, such that zero tillage increased microbial biomass C and N in the 0 to 5 cm depth by 10 to 23%.

Nutrient dynamics are different in organic and low-input systems compared with conventionally managed systems. Gunapala and Scow (1998) sought to improve soil fertility and structure through a better understanding of soil microbial communities and their activities. They measured C and N associated with the microbial biomass and found fumigation-extractable C in the 0-15 cm depth to be significantly greater in organic (93 $\mu g\ g^{-1}$) and low input systems (105.9 $\mu g\ g^{-1}$) compared to conventional 2 yr (47.4 $\mu g\ g^{-1}$) and 4 yr (55.4 $\mu g\ g^{-1}$) systems. Fumigation-extractable N was also greater in organic and low input systems. Other research has shown that substantial increases in inorganic N concentrations correspond to declines in soil microbial biomass (Bonde et al., 1988), and whereas Gunapala and Scow found this to be true in the conventional systems, they found the inverse to be true in the organic system. The authors assumed that plant-available N was continuously released from the microbial biomass. Schnurer et al. (1985) also looked at changes in soil fertility caused by increasing SOM with farmyard manure applications. Microbial biomass estimates and activity measurements significantly correlated with SOM, with the manure treatment increasing soil organic matter 1.5% times more than the fallow treatment. Calderon et al. (2000) investigated the effects of tillage on microbial communities by measuring soil respiration immediately following tillage. Tillage was simulated by sieving intact soil cores and respiration measured 1 d prior to and for 2 weeks following sieving by incubation in sealed chambers. Respiration decreased immediately after sieving and continued to decline through the next 14 d. The authors attributed this change in soil response to a decrease in soil moisture.

While CO_2 evolution is a useful indicator of total microbial biomass, it gives no indication of the diversity of the microbial population. Other techniques can be used to give a clearer picture of specific microbial communities. Most Probable Number (MPN) techniques and the use of specific substrates can be used to enumerate select populations of microorganisms. One such group of bacteria is plant growth promoting rhizobacteria (PGPR), whose presence in the soil is often linked to the ability of some soils to suppress plant diseases. Some PGPR protect plants against pathogen infection through induction of systemic resistance, without provoking any symptoms themselves (Pieterse et al., 1996). Van Peer et al. (1991) investigated the mechanism of biological control of *Fusarium oxysporum* of carnation (*Dianthus caryophyllus*) by *Pseudomonas* sp. strain WCS417r. They found a 30% reduction in diseased plants when roots were bacterized with the *Pseudomonas* sp. strain one week prior to inoculation with *F. oxysporum* but could not isolate the strain from the plant stem tissue. The authors concluded that signals provided by strain WCS417r at the root system induce defense against *F. oxysporum* in the stem. Likewise, Liu et al. (1995) found *Pseudomonas putida* strain 89B-27 to induce systemic resistance against F. oxysporum in cucumber (*Cucumis sativus* L.). Krishnamutrhy and Gnanamanickam (1998) found fluorescent *Pseudomonads* Pf7-14 to suppress up to 68% of rice (*Oryza sativa*) blast when applied as a seed treatment followed by foliar applications. These PGPR's also aid plant growth by the production of antibiotics, chitinases, and glucanases, which can lyse microbial cells (Van Loon, et al., 1998).

Minimum Data Set

Because it is neither practical nor desirable to measure all soil functions for a soil quality assessment, a 'minimum data set' (MDS) of indicators can be selected. A MDS is a suite of quantitative attributes that allow for the evaluation of a system's chemical, physical, and/or biological function of interest. Larson and Pierce (1994) suggest the following measurements as part of a MDS: aggregate stability, bulk density, penetrometer resistance, rooting depth, water holding capacity, inorganic N, pH, electrical conductivity, total organic C, and labile C. Another example of a MDS might include measurements for infiltration rate, saturated hydraulic conductivity, organic matter content, potentially mineralizable N, microbial biomass C and N, and soil respiration.

The concept of soil quality is site and function specific and indicators should be chosen with respect to individual priority. Specific attributes that comprise a MDS will vary according to the system function of interest. One way to integrate the information obtained from a MDS is to develop a soil quality index. Such an index could be used to monitor and predict effects of farming practices on soil quality and thus provide an early sign of soil degradation (Lal, 1998). Smith et al. (1994) developed an approach to integrate an unlimited number of indicators into an overall soil quality index. This approach, Multiple Variable Indicator Transform Kriging, integrates the criteria chosen to represent enhanced soil quality and transforms data values into a soil quality index. Indicator kriging can then be used to estimate values for locations that have not been sampled. A framework for evaluating site-specific changes in soil quality was described

by Karlen and Stott (1994), whereby indicators that quantify soil functions (i.e. accommodating water entry, retaining and supplying water to plants, resisting erosion) are identified and assigned a priority or weight that reflects its relative importance. Seybold et al. (1998) suggest a different approach. They suggest establishing baseline values for indictors in a MDS and then monitoring changes in these indicators over time. If change in the indicator is positive, and more is considered better, then the soil can be regarded as improving with respect to that indicator. Lack of change would indicate a sustaining system, whereas a negative change would indicate a decline in quality and management practices should be reviewed. This approach allows soil quality to be site and management specific.

Applying Soil Quality Research

The goal behind defining soil quality and generating indicators is to help farmers, extension agents, and scientists make practical determinations as to the sustainability of farming systems and to include them as active participants in quantitative assessment of soil quality on their own farm. To this extent, John Doran (USDA-ARS, University of Nebraska, Lincoln) developed a soil quality kit. The kit is designed to measure a series of desired and easily interpreted indicators in the field. Measurements that can be made using the kit include soil pH, electrical conductivity, soil moisture content, soil nitrate concentration, water holding capacity, soil temperature, bulk density, infiltration rate and soil respiration at field moisture and at field capacity (Sarrantonio et al., 1996). The kit is useful in on farm demonstration of the immediate and most observable differences that might be associated with management-induced differences in soil function. Preliminary

results obtained with the test kit compare well with standard laboratory procedures that are more time consuming and costly (Liebig et al., 1996). There is also a Soil Health scorecard, developed by the University of Wisconsin's Soil Health program in conjunction with local farmers and scientists. While Doran's test kit is quantitative, the scorecard is qualitative and based on farmer's knowledge of soil health (Romig et al., 1996).

A Systems Approach

Soil chemical, biological, and physical properties interact in complex ways to give a soil it's quality or capacity to function. Thus, soil quality cannot be measured directly but must be inferred from measurable changes in its attributes, referred to as indicators (Lal, 1998). Many factors impact upon the complex biological, chemical and physical processes that govern soil fertility (Poulton, 1996), yet most agricultural experiments change one factor at a time. Management decisions that are inherent in different farming systems influence the soil ecosystem as a whole. For example, research has demonstrated that tillage interacts significantly with other agronomic practices to affect changes in invertebrate communities and the roles that fauna play in agricultural systems (Stinner and House, 1990). Conservation tillage practices, especially continuous no-till, generate complex soil biotic interactions in addition to changes in physical and chemical properties of the soil (Blevins et al, 1983). Elliot and Coleman (1988) found that ecological interactions among functional groups of soil organisms, such as competition and predation, could influence the flow of major elements in ecosystems. When you change one part of the system, you change the entire system. A systems approach involves multiple factor experiments comparing complex combinations of

farming practices (Kafka, 1994). A farming systems approach to research allows the system components to be viewed together and for integrative properties to emerge. Soil quality research is designed to study systems as a whole.

Objectives

Soil quality research has expanded the understanding of linkages and individual components, and promoted development of new measures of biological characteristics. Yet more work is needed to understand how these indicators link to management practices and soil performance (Lewandoski, 1999). In order to gain a better understanding of how diverse agricultural systems affect the soil ecosystem, a holistic approach such as the use of soil quality indicators should be employed on a farming systems level. The objective of this research was to develop a set of key soil quality indicators (physical, chemical, and biological) that reflect current and future farming systems performance potential using a long-term large scale systems site that emphasizes the holistic, interdisciplinary approach to assessing soil quality. The MDS was comprised of physical (bulk density, infiltration rate), chemical (pH, inorganic N, organic N and C), and biological (soil respiration, fluorescent *Pseudomonas* bacteria and entomopathogenic nematode populations) indicators to compare the management effects on soil systems. Measurements were made over the course of two growing seasons in a best management practice (BMP) with conventional till and no-tillage subplots, organic farming, and successional (fallow) systems.

Chapter 2. **A Multidisciplinary approach to assessing changes in the soil quality of diverse farming systems**

Introduction

Farmers in North Carolina and in other states are currently faced with a number of environmental issues, some of which include ground and surface water contamination, soil erosion, and declining soil quality. The problems facing today's farmers are in part the result of agricultural practices that have been shaped by decades of social and economic pressures, which have pushed the farmer to optimize production for maximum profit. Many farms today rely on off farm chemical inputs and bare little resemblance to natural systems. More stable, self-sufficient natural systems capture energy and nutrients through complex interactions, which are simplified and disrupted under agricultural uses (Gliessman, 1990). Interactions between agricultural management practices and soil biological, chemical, and physical processes affect the productivity of agriculture soils and their impact on environmental quality (Doran et al., 1996). Soil quality is also affected by agricultural management practices.

The use of the specific term "soil quality" (since the early 1980's) is related to issues of sustainability, particularly with regard to agricultural sustainability (Lal, 1998). Soil quality methodology looks at how the whole production system (tillage, fertility and pest management, crop rotation, etc.) affects pest populations, water, and soil nutrient cycles. The emphasis is on the interactions among soil processes rather than on soil components in isolation. Doran and Parkin (1994) have defined 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. Par et al. (1991) suggested that soil quality is the capability of a soil to produce safe and nutritious crops in a sustained manner, while Larson and Pierce (1994) suggested that soil quality relates specifically to a soil's ability to function as a medium for plant growth, to partition and regulate water flow in the environment, and as an environmental buffer. The most distinctive contribution of soil quality research is the study of the linkages among four components of the soil system: 1) management practices and systems, 2) observable soil characteristics (bulk density, pH), 3) soil processes (nutrient cycling, organic matter degradation), and 4) soil performance (crop yield and quality) (Lewandowski, 1999).

Soil degradation is a widespread problem having negative consequences on both agricultural productivity and natural ecosystems (Wander and Drinkwater, 2000). Recent assessments conducted on regional and global scales indicate that human-induced degradation is causing the loss of millions of hectares of agricultural land every year (Janke and Papendick, 1994). Long histories of tillage favor the loss of N from systems since tillage can increase rates of nitrification (Calderon et al., 2000). Changes in the soil's physical and chemical properties resulting from tillage greatly alter the matrix supporting growth of the microbial population (Kennedy and Smith, 1995). Along with tillage, production inputs can alter the soil system. Scow et al., (1994) found pH, percentage N, and microbial biomass C lower in conventionally managed production systems compared with organic and low input systems.

To understand and decrease rates of soil degradation, a methodology must be developed that can characterize and define the management factors contributing to degradation. Part of any system to evaluate the sustainability of farming practices requires identification of soil attributes that serve as indicators of change and also relate to productivity. Soil attributes that are sensitive to changes and perturbations in the soil environment can be used as indicators. Soil quality indicators can be measured directly or through an associative property and should relate to crop productivity (Doran and Parkin, 1996). For example, aggregate stability can be used as an indicator of a soil's resistance to erosion. A measure of soil microbial biomass can provide an indication of soil's ability to store and recycle nutrients, whereas water infiltration rate can be used to judge a soil's permeability and degree of compaction. A minimum data set (MDS) is a suite of soil quality indicators designed to measure chemical, physical, and biological soil processes and properties. A MDS can be tailored to meet individual research goals and should be site specific. For example, a soil quality minimum data set might include microbial biomass, potentially mineralizable N, and soil respiration as biological indicators, with pH, organic matter concentration, texture, bulk density (Db) and infiltration as chemical and physical indicators (Wander and Drinkwater, 2000).

John Doran proposed the use of a Soil Quality Test Kit to increase the accessibility of common soil quality tests (Lewandowski, 1999). Doran believes that on-farm measurements allow farmers to better understand cause and affect relationships and to adapt their practices accordingly. The kit was designed so farmers and extension agents can make relatively quick and easily interpretable measurements in the field and laboratory to monitor soil quality changes. Soil measurements that can be made using the

kit include: respiration, infiltration rate, moisture content, temperature, electrical conductivity, pH, bulk density, and NO_3 concentration. This research employed this soil quality kit as part of a larger MDS to monitor management-induced changes in soil quality in diverse farming systems at the Center for Environmental Farming Systems.

The Center for Environmental Farming Systems (CEFS) is a unique partnership that includes the NC Department of Agriculture and Consumer Services, NC State University, NC Agricultural and Technical State University, nongovernmental organizations, farmers and the citizens of North Carolina. The CEFS has four units: conservation tillage studies, animal systems, organic agriculture systems and farming systems research. An interdisciplinary team of researchers and graduate students are involved in research dedicated to developing farming systems that are environmentally, economically, and socially sustainable. Research reported here was conducted in the Farming Systems Unit at the CEFS. The farming systems unit is divided into five diverse ecological and agricultural systems.

Traditional assessments of Db, infiltration rate, pH, soil organic matter content, and nutrient concentrations in the soil provide only a partial illustration of the overall quality of the soil system. To gain a more holistic view of the soil ecosystem some measure of the biological component must be considered. The biologically active components of soil, such as organic matter, and constituents of soil microbial biomass and energy sources such as organic C and N, have been shown to be sensitive indicators of changes in soil management (Kennedy and Papendick, 1995). Whereas soil cultivation initially increases biological activity due to the incorporation of oxygen and plant residue, long-term tillage can have detrimental affects on soil chemistry and structure, and reduce

biological activity (Dick, 1992). Schnurer (1985) found a significant positive correlation between soil organic matter content and microbial biomass and activity and concluded that different management practices have a profound influence on the size and activity of microbial biomass in soils.

Soil organisms play a major role in plant litter decomposition and nutrient cycling, but they also influence plant disease and protection. The ability of some soils to suppress plant disease is attributed to indigenous beneficial rhizosphere microflora, especially pseudomonad bacteria (Dowling and O'Gara, 1994). For example, some fluorescent *Pseudomonas* are termed plant growth promoting rhizobacteria (PGPR) and their presence in the soil is considered beneficial. Some PGPR protect plants against pathogen infection through induction of systemic resistance, without provoking any symptoms themselves (Pieterse et al., 1996). They can also stimulate growth and improve plant stand under stressful conditions (Van Loon et al., 1998). One of the mechanisms of plant growth promotion and disease protection is thought to be in the production of siderophores, which can bind free Fe^{3+} in the rhizosphere. The bacteria thus inhibit plant pathogens by out-competing them for Fe^{3+}, an essential nutrient. These PGPR also aid plant growth by the production of antibiotics, chitinases and glucanases, which can lyse microbial cells (Van Loon, et al., 1998).

Also beneficial in the soil are nematodes in the families Steinernematidae and Heterorhabditidae, which are termed entomopathogenic nematodes. Theses are insect-parasitic nematodes that are currently available commercially for biocontrol of soil insects. These nematodes occur in a wide range of habitats, including agricultural soils. The free-living, non-feeding infective juveniles of these nematodes possess attributes that

are characteristic of both insect parasitoids and microbial pathogens (Kaya and Gaugler, 1993). Entomopathogenic nematodes are being promoted for the control of insect soil pests in a variety of markets including ornamental, nursery, turf, perennial and annual agriculture (Millar, 2001). They have been effective as biocontrol agents against the soil dwelling stages of numerous insect pests (Reed and Carne, 1967; Jacques et al., 1968; Villani and Wright, 1988; Brust, 1991; Gaugler, 1999). The nematodes are symbiotically associated with a mutualistic bacterium, which allows them to kill their hosts quickly and thus gives them an advantage over other predators. They are compatible with certain chemical pesticides (Hara and Kaya, 1982) and are virulent against a broad range of insects (Kaya and Gaugler, 1993). These nematodes, as other soil organisms, are affected by perturbations in the soil environment. The effects of different soil physical factors are interrelated and often difficult to separate (Barbercheck, 1992). Nematode survival and pathogenicity is affected by tillage (Brust, 1991; Millar, 2001), temperature (Molyneux, 1985; Griffin 1993), other microorganisms (Kaya and Thurston, 1993), soil type (Kung et al., 1990; Georgis and Poinar, 1983), pore size (Wallace, 1963), and soil moisture (Molyneux and Bedding, 1984; Kung et al., 1991). It is unclear, however, exactly how the efficacy of these nematodes is influenced by soil biotic and abiotic factors and further research into these interactions is warranted.

The focus of this manuscript was a MDS, which emphasized biological measurements. Populations of both fluorescent *Pseudomonas* and entomopathogenic nematodes in genera *Steinernema* and *Heterorhabditis* were monitored to determine how management practices affected their populations. Soil respiration was also used as an indirect measure of microbial biomass activity. The objectives of my research were: (i)

to develop a set of key soil quality indicators (chemical, physical, biological) that reflect current and future systems performance potential using a long-term, large-scale systems research site, and (ii) to assess the ability of these chosen indicators to reflect management-induced changes in the soil ecosystem.

Materials and Methods

Experimental Design

Research was conducted at the Center for Environmental Farming Systems (CEFS) near Goldsboro, NC. The design at CEFS is a randomized complete block consisting of three replications of five farming systems (Appendix, Fig. A1). The agricultural production systems include a conventional system using best management practices (BMP) currently used by farmers, an integrated crop and animal system, and an organic system. The BMP system is split into conventional and no-tillage subplots. The two remaining systems are a successional ecosystem (old field succession), which represents one of the important standards for comparison, and a plantation forestry /woodlot of commercially valued forest species (Table 2.1). The experimental site was approximately 80 ha with individual plots ranging in size from 0.81 to 4.05 ha. Soil on the entire 80 ha was mapped using GPS technology. The Neuse River borders the CEFS on three sides and spatial variability in soil type is high, which is characteristic of river systems. The dominant soil type within each replication was termed the diagnostic soil. The diagnostic soil types are either Wickham (fine-loamy, mixed, semiactive, thermic Typic Hapludult) or Tarboro (mixed, thermic, Typic Udipsamment) (Appendix Fig A2). Blocking was done by soil type, such that all samples in a system were taken from the same diagnostic soil in a given block.

Three of the five systems that are the most divergent with respect to management and were the most likely to reflect early changes in our soil quality indicators were the

focus of this master's research project. Soil chemical (pH, inorganic N, organic C and N), physical (bulk density (Db), infiltration time), and biological (soil respiration, and entomopathogenic nematode and pseudomonad populations) indicators were measured in organic, best management practices (BMP), both conventional and no-till subplots; and the successional ecosystems.

The entire Farming Systems Unit was planted to a rye (*Secale cereale*) cover crop in October 1998. The rye cover was mowed in early March 1999 and incorporated (organic and BMP conventional-till) or chemically desiccated with glyphosate [N-(phophonomethyl) glycine] (Appendix, Table A3) in the BMP no-till system on 30 March 1999. System treatments were initiated in the spring of 1999. The rotation for the BMP and organic systems is presented in Table 2.1. Appendix Tables A1 and B give a detailed description of the field activities in both systems. Tillage for all crops in the organic system and the conventional-till subplots of the BMP system consisted of fall disking, followed by chisel plowing in early spring to a nominal depth of 12 cm, and then disking for cover crop incorporation. The organic system also received periodic row cultivation for weed control using a rotary hoe and rolling cultivator. In 2000, this system was also ridged and bedded (101 cm on center) for sweet potatoes (*Ipomoea batatas*). No-tillage planting in the BMP subplot was performed using a double disk opener planting assembly following a fluted coulter.

In March 1999, five stratified random sampling points were selected in each plot using a transect line oriented lengthwise from the farthest corners. A random number program was used to determine the starting point on the transect tape at each point. The random number program was also used to designate the distance from the transect line

into the field at each point. For each of these five points, a randomly designated number of paces was stepped off from alternating sides of the transect line. These points were physically marked and then geo-referenced using a Trimble® backpack GPS unit. These points were stored on a GIS database and the location for all subsequent sampling.

Soil Sampling

At each sample site, a composite of thirty, 2.54-cm diameter by 15 cm deep cores were taken adjacent to the plant row on the untracked side in a random manner near the geo-referenced point. The composite samples were placed in large buckets lined with plastic bags and thoroughly mixed. The composite sample was then divided in the field into three equal portions of approximately 200 g. Samples for bacterial analysis were placed on ice in plastic bags for transport back to the laboratory. Samples for nematode assessment were placed in plastic bags and those for soil fertility analyses were placed in paper sacks for subsequent air-drying. Therefore, the same soil sample was used for chemical (pH, organic C, total N, $N0_3$ and NH_4-N) analyses and for quantifying entomopathogenic nematode and fluorescent *Pseudomonas* populations. A subsample was also removed from the composite sample for determination of gravimetric soil water content. Baseline soil sampling was conducted in March 1999. Additional samples were collected over the course of the 1999 growing season, in spring shortly after planting, mid-season at peak crop growth, and post harvest sampling in late October. The same sampling cycle was repeated in the 2000 growing season.

Soil Fertility Indicators

Soil was air-dried and then ground to pass through a 2-mm sieve. Soil pH was determined using a 1:1 soil to water ratio (Smith and Doran, 1996). Ten ml of deionized water was added to 10 g of soil. The mixture was stirred with a glass rod for 1 min and then allowed to settle for 20 min before taking a pH reading. For inorganic N (NH_4 and $N0_3$) determinations, 50 g of air-dried, ground soil was weighed into a 50-ml plastic centrifuge tube. Fifty ml of a 1 M KCL solution was then added to the tube and the mixture shaken for 1 hr. The tubes were then centrifuged at 1000 rpm for 12 min, after which time approximately 5 ml of the supernatant was pipetted into plastic vials and frozen until further analysis. The thawed supernatant was poured into culture tubes (10 x 75 mm) for automated $N0_3$ and NH_4 analysis using a Latchat QuikChem Method 10-107-04-1-A and 10-17-05-A, respectively (Latchat, 1992). Total soil organic C and N were determined by combustion on a Perkin-Elmer 2400 CHN Elemental Analyzer (Perkin Elmer Corp., 1988).

Soil Respiration

The closed chamber method (Doran and Parkin, 1996) was used to measure soil respiration *in situ* as an indirect measure of microbial biomass activity. Measurements were made in the field in May, July, and October 1999 and in June, August, and October of 2000. A PVC ring 7.6 cm in diameter and 7.6 cm deep was installed slightly to the

side of the crop row on the untracked interrow side. To determine the headspace within each ring, the ring was lined with saran wrap and 2.54 cm of water added. The distance from the water surface to the top of the ring was recorded at four adjacent locations on the ring using a measuring tape. These headspace measurements were later used to convert the volumetric CO_2 measurement into kg C evolved ha^{-1} d^{-1}. The saran wrap was then removed, allowing the water to drain into the soil within the ring and the ring was capped so as to be airtight. After 24 hr, a 100-cm^3 gas sample was withdrawn from the closed chamber using a syringe and a Dreager® gas detector tube. The Dreager tubes are filled with an inert reagent carrier material and impregnated with indicating reagent, which produces a colorimetric response to CO_2 (Fisher Scientific, 1998). After withdrawing the gas sample, the concentration of CO_2 gas was converted using the headspace volume in the chamber (Sarrantonio et al., 1996). Evolved CO2 on an area basis was calculated with the following equation.

[Eq. 1.]: Soil respiration (kg C ha^{-1} d^{-1}) = [TF x (% CO_2-0.035) x 116.4]

Where, temperature factor (TF) = (soil temperature in °C +273) ÷273

Following the CO_2 measurement, a soil sample (2.54-cm deep) was taken from within the ring to determine gravimetric soil moisture at field capacity.

Infiltration

A PVC ring 7.6 cm in diameter and 15-cm deep was installed just to the side of the crop row on the untracked interrow side. These rings were installed after planting in

the spring and remained in place for the duration of the cropping season. Time for 2.54 cm of deionized water (non-constant head) to infiltrate the soil surface was recorded in minutes. Infiltration was considered complete when the soil surface glistened.

Bulk Density

A Uhland core sampler (Blake and Hartge, 1986) was used to obtain surface (upper 7.5 cm) bulk density on intact cores (7.6 cm in diameter by 7.6 cm in length) three times over the course of the two years, in March and November 1999, and November 2000. Measurements were taken in the crop row near the sample point in the agricultural systems and randomly near the sample point in the successional system.

Entomopathogenic Nematodes

A 10-d bioassay was used to detect entomopathogenic nematodes in soil samples. This method, which entails "baiting" the sample with insect larvae and then searching for cadavers, is commonly called the *Galleria* bait method. It is popular among researchers because the wax moth larva *Galleria mellonella* had proven to be an excellent general-purpose host for successfully isolating entomopathogenic nematodes from the soil (Kaya and Stock, 2002) . The *Galleria mellonella* larvae are normally not exposed to nematodes, and therefore, are very susceptible to infection (Bedding and Ankhurst, 1975). Each plastic bag, which contained approximately 200 g of soil, was baited with five larvae placed on the soil surface. The bags were sealed and incubated in the dark for

five d. At the end of this time period, all five larvae were removed and the cause of death determined for the cadavers. Larvae infected by entomopathogenic nematodes are distinctive because while the inside of the insect has been destroyed, the integument remains soft and intact. The nematode family is determined by the color of the cadaver. An ocher color indicates the presence of *Xenorhabdus nematophilus*, the associated bacterium of *Steinernema*, while red indicates the presence of *Photorhabdus luminescens*, the associated bacterium of *Heterorhabditis* (Alatorre-Rosas and Kaya, 1990). If there was uncertainty as to the infecting nematode species the cadavers were dissected. The bags were then re-baited with five fresh larvae, incubated for an additional five days and a final determination made.

Bacterial Analyses

Populations of fluorescent *Pseudomonas* bacteria were determined using the most probable number (MPN) technique. This technique is a means to estimate microbial population sizes in a liquid substrate based on the calculations of Halvorson and Ziegler (Woomer, 1994). The method is used to estimate microbial population sizes when quantitative assessment of individual cells is not possible (Woomer, 1994). A dilution series using a procedure modified from Gardener (2001) was used to determine *Pseudomonas* sp. population estimates in liquid King's B medium (Schaad, 2001). Samples were diluted ten-fold by adding 1g of soil to 9 ml of sterile distilled water. This ten-fold dilution was sonicated for 1 min. and then vortexed for 15 s and allowed to rest for 15 s. The vortexing process was repeated three times. A dilution series was then

prepared using 96-well microtiter plates (Evergreen Scientific (CA)) that had "untreated flat bottoms". Seventy μl was removed from the 10^{-1} soil dilution and added to 210 μl of King's B medium in the top row (row A). Samples 1 through ten were plated across the top row in columns 1 through 10. Column 11 was left blank and column 12 was filled with medium only to insure that the medium was not contaminated. Each sample was replicated three times (i.e. the entire microtiter plate containing samples 1-10 was replicated 3 times). Once a plate was full with ten samples along row A, a 12-channel multipipetter was used to remove 70 μl from row A and transfer to row B, pipetting up and down to mix the solution. This was repeated using clean tips until the final row (row H) was reached, thus providing a four-fold dilution series. The covered microtiter plates were then placed in plastic boxes and incubated in the dark at room temperature for 15 hr. At the end of this incubation period, a flame sterilized 96-pronged cloning stamp was used to stir each well and then transfer a drop (~ 20-25 μl) of culture from each well to a fresh microtiter plate containing 210μl King's B medium. These plates were then grown out in covered plastic boxes in the dark at room temperature for five days. At the end of the 5-day incubation, the culture plates were scored for fluorescence on an ultraviolet transilluminator (Fotodyne Inc., New Bern, WI). An Excel spreadsheet program, adapted from Briones and Reichardt (1999), was used to calculate the most probable number (MPN) estimate of bacterial cells per gram of dry soil. Statistical analysis was performed on $\log_{10}$ transformed MPN population estimate data.

Statistical Analyses

Analysis of variance (Statistical Analysis Systems, SAS Institute, Cary, NC) procedure was carried out separately for each variable: log CO_2 evolved (kg C ha-1 d-1), log infiltration time (minutes), log NO_3 (mg kg^{-1}) and logNH_4 (mg kg^{-1}) and log MPN, and square root of nematode induced deaths of bait insects. Data was transformed to stabilize variance. Pairwise comparisons were carried out on means at each date when the date by rotation effect was significant. Systems were treated as a whole plot factor, rotation in system as a subplot factor, and date as a sub-sub plot factor. Following preliminary F tests, whole plot and subplot errors were pooled where possible, and the analysis was carried out with rotation as the whole plot factor and date as the subplot factor.

Results and Discussion

Biological Indicators

Soil respiration

Analysis was performed on log-transformed data. Results were significant by date and between systems on each date (Fig. 2.1). Baseline soil respiration measurements were made in May of 1999 in organic and both BMP systems. The successional system was not sampled at this time because the rye cover crop had not yet been harvested and thus measurements would not represent baseline conditions. In May 1999, CO_2 evolved in the BMP/NT system was three fold greater (635 kg C ha^{-1} d^{-1}) than the organic (169 kg C ha^{-1} d^{-1}) and BMP/CT (195 kg C ha^{-1} d^{-1}) systems (Fig. 2.1). By mid-season (July), systems were similar. In the fall CO_2 evolved in the organic system was significantly greater (186 kg C ha^{-1} d^{-1}) than the BMP/CT (98 kg C ha^{-1} d^{-1}). A decline in soil respiration by fall was expected because the crop had been harvested and soil temperature was cooler than at mid-season measurements. Weil et al. (1993) also found rates of $C0_2$ evolution to be 30 to 35% lower in fall than in spring. The increase in CO_2 evolved in the organic system in the fall is probably the result of hurricane Floyd (September 1999), which prevented the harvest of the organic soybean (*Glycine ma*) crop and thus provided a readily available substrate for stimulate microbial activity.

In 2000, the initial measurements were made in June. The organic system was not sampled at this time because the fields had just been ridged and bedded in preparation for sweet potato planting. Differences between systems were not significant on this date. By the mid-season sampling date in August, a spike in CO_2 evolution occurred in the BMP/CT (600 kg C ha^{-1} d^{-1}), the BMP/NT (633 kg C ha^{-1} d^{-1}) and the successional system (631 kg C ha^{-1} d^{-1}). The three systems were similar and three-fold greater than the organic system (215 kg C ha^{-1} d^{-1}). Values in the organic system were low as a result of the late sweet potato planting date (Appendix, Table A1b). By October, CO_2 evolution again declined and systems were statistically similar.

Carbon evolved in the BMP/NT and in the successional system was similar on all sampling dates. Values in these systems also fluctuated the most over the growing season, while values in the BMP/CT showed little fluctuation in 1999 but paralleled the BMP/NT and successional systems in 2000. The organic system fluctuated little in either year. Past research has shown similar results, i.e. soil biological activity is enhanced in systems that minimize tillage (Weil et al. 1993), and no-till systems mimic natural system behavior to a greater extent than conventionally tilled systems (House and Brust, 1989).

It has been suggested that microbial activity is highly correlated with the degree of soil disturbance and with the amount of surface residue (Carter, 1986; Weil et al., 1993; Karlen et al., 1994). Tillage and the incorporation of surface residues can stimulate microbial respiration initially, but a reduction in tillage can lead to increased microbial biomass C and N (Carter, 1986; Karlen et al., 1994; Carter and Rennie, 1982). Distinctive similarities existed between the BMP/CT and the organic system and between the BMP/NT and the successional system. Surface residues resulting from no-till

practices provide a continuous substrate for many decomposer organisms (House and Alzugary, 1989) and likely contribute to the higher CO_2 evolution values in the BMP/NT and successional systems on all dates. Undisturbed systems and tillage practices that leave residue on the surface protect soil organisms from extreme temperature and moisture fluctuations. Residue decomposition rates are also lower under such conditions. These benefits are reflected in the higher CO_2 evolution baseline values in the BMP/NT and successional systems, higher CO_2 evolution values throughout the growing season, and in the fall compared to the conventionally tilled systems.

The systems behaved differently with respect to CO_2 evolution over the course of the 1999 versus the 2000 growing season. This difference could be the result of weather conditions or crop rotation. On the first sampling date in 1999, CO_2 evolution in the BMP/NT system was greater than 600 kg C ha $^{-1}$ d^{-1} and then steadily declined to below 200 kg C ha $^{-1}$ d^{-1}. Values in the successional system also declined from mid-season to fall, whereas in the organic and BMP/CT CO_2 evolution fluctuated little during the 1999 season. In contrast, CO_2 values in the spring of 2000 season were lower than Spring 1999 in both the BMP and successional systems, and all three systems increased over the course of the season to peak in mid summer (August) 2000 (Fig. 2.1). The three systems then each decreased to levels relatively equal to early season CO_2 evolution values. The large peak in CO_2 evolution in the BMP systems in August of 2000 is most likely a combination of the weather conditions and crop [corn (*Zea mays*) vs. peanut (*Arachis hypogaea*)] effects on the soil environment. Air temperatures were slightly cooler in August 2000 compared to August 1999 (25.7 °C vs. 27.8 °C) and rainfall was greater (18.3 cm vs. 13 cm) (Appendix, Tables A2.1 and A2.2). These environmental conditions

could have been more conducive to soil microbial biomass activity. Also, it may be that peanut supports a higher level of microbial activity than corn because of the denser soil canopy provided by the peanut biomass compared with corn.

Entomopathogenic nematodes

Statistical analysis was performed on square root transformed data and data was significant only by date. Due to the low number of entomopathogenic nematode-induced *G. mellonella* mortality on all sampling dates, statistical analysis was based on the total number of nematodes ("pathogen") detected in each system on each sampling date. Three species of entomopathogenic nematodes were detected in the Farming Systems Unit at CEFS; *Steinernema carpocapsae*, *Steinernema glaseri*, and *Heterorhabditis bacteriophora* (Fig.2.2). Although there were no significant differences between systems, numerically greater numbers of entomopathogenic nematodes were detected in the BMP/NT than in the other systems (Fig. 2.3).

A number of factors could have affected the distribution of nematodes that we detected at CEFS, namely the presence and intensity of soil disturbance, and weed density and diversity. Species of entomopathogenic nematodes have been separated based on foraging behaviors. Those referred to as "ambushers" tend to remain sedentary at or near the soil surface and wait for potential hosts, whereas "cruisers" tend to be highly mobile and aggressively search the soil for hosts (Kaya and Thurston, 1993*). Steinernema carpocapsae* is categorized as an ambusher and would therefore be more sensitive to tillage and likely to persist in undisturbed systems, which tend to have greater soil moisture and cooler surface temperatures. Indeed, we detected *Steinernema carpocapsae*

most in the BMP/NT and the successional systems. *Steinernema glaseri* and *Heterorhabditis bacteriophora* are categorized as "cruisers". They tend to move through the soil matrix and may be able to escape disturbance, making them less sensitive to tillage. *Steinernema glaseri* was detected in all systems, and seemed less affected by tillage. The fact that *H. bacteriophora* was not present in the BMP/NT or successional systems on any date suggests that it may prefer or tolerate disturbed systems. Millar (2001) observed a tendency for *H. bacteriophora* to be relatively tolerant to disturbance compared to *S. carpocapsae.* This conclusion is supported by a study by Millar and Barbercheck (2002), who also found that the detection of Steinernema carpocapsae was negatively affected by tillage.

The difference in weed populations between disturbed and undisturbed systems could also influence insect host and nematode populations. In general, soil under no-till possesses higher populations of soil inhabiting pests, and greater weed density and diversity (Stinner and House, 1990). Increased pest populations and diversity implies an increase in potential hosts for entomopathogens. Also, higher weed populations in general create a different soil environment compared to conventionally tilled, less weedy soils. Weeds help to shade the soil, keeping soil temperatures cooler and improving soil moisture content and increasing soil organic matter. It is possible that these conditions are more conducive to entomopathogenic nematodes

MPN Population Estimates

Statistical analysis was performed on log-transformed data and populations were significantly different by date (Fig. 2.3). Fluorescent *Pseudomonads* populations are presented as the log value of most probable number (log MPN g^{-1}) population estimates averaged over all systems. At baseline measurements in March 1999, May 1999, and October 1999 fluorescent *Pseudomonads* populations in all systems were similar (log MPN g^{-1}= 6.2). At the mid-season measurement in July 1999, populations were significantly lower in all systems (log MPN g^{-1}= 5.2). This decrease was probably the result of high temperatures (mean daily high air temp. of 27°C and 29 °C for June and July, respectively) and rainfall in June of 28 cm. Microbial populations commonly are higher in the spring and decline during the summer months as a result of higher soil temperatures and lower soil moisture (Ladd et al, 1986; Gunapala and Scow, 1998). Population levels increased slightly in the fall, returning to levels that were observed in March and May.

In March 2000, fluorescent *Pseudomonas* populations were 1.2 orders of magnitude greater than in March 1999 (log MPN g^{-1} 7.6). The increase probably was the result of the mild winter temperatures in 2000 rather than the establishment of system management effects. The average soil temperatures in degrees Celsius ranged from 4-10°C in December 1999, 1-4°C in January 2000, 4-10°C in February 2000, and mid to high 10's in March. In June of 2000 population levels declined drastically in all systems. Climatic conditions in June contrasted sharply with the comparable May 1999 sample date. Approximately two-fold more rainfall occurred in June 2000 than in May 1999

(27.9 and. 15.7 cm for June 2000 and May 1999, respectively) and air average temperatures were greater.

Chemical Indicators

Inorganic N

Nitrate and ammonium concentrations were determined separately, but NH_4 was low enough to be inconsequential, thus NO_3 and NH_4 values were combined and results reported as total inorganic N. Statistical analysis was performed on log-transformed data, but all results and figures report untransformed data. Sources of variance are shown in Table 2.3. Iorganic N concentrations differed significantly between systems. There was also a significant date by system interaction (Fig. 2.4). Significant differences between systems occurred during the growing seasons, but not in the spring or in the fall, suggesting that inorganic N concentrations in the systems reflected fertilizer N inputs (Appendix, Table A1a). In 1999, corn was fertilized with 30% universal ammonium nitrate solution (UAN) once in April (14 kg N ha^{-1}) and twice in June (total of 132 kg N ha^{-1}). As a result, inorganic N concentrations were greater in the BMP system in both May (CT= 18 mg kg^{-1}; NT= 17 mg kg^{-1}) and July (CT= 13 mg kg^{-1}; NT= 13 mg kg^{-1}) sampling dates compared to the organic system (7 mg kg^{-1} and 6 mg kg^{-1} for May and June, respectively). Differences in inorganic N concentrations between systems in October 1999 were not significant, but soil inorganic N concentration in the organic system increased while soil inorganic N in the other systems decreased from July to October. A hurricane in September 1999 flooded the entire experimental area, leaving the soybean crop unharvestable in the organic system plots. Consequently, the fall

sampling on 28 October 1999, may reflect some N mineralization from decomposing soybeans. The increase in inorganic N observed in the successional ecosystem in the fall of 1999 and early 2000 may reflect mineralization of native soil N.

In March 2000, inorganic N concentrations were low in all systems. However, inorganic N concentration in the organic system (21 mg kg^{-1}) was greater than the BMP/NT (12 mg kg^{-1}) and successional system (6 mg kg^{-1}) in June and greater than all systems in August 2000 (30 mg kg^{-1} compared to 4, 5, and 4 mg kg^{-1} in the organic, BMP/CT, BMP/NT and successional systems respectively). Greater inorganic N in the organic system on these dates can be attributed to a turkey litter application (4.5 Mg ha^{-1}) and incorporation on 5 May, 2000 prior to sweetpotato planting. The difference between the BMP/CT (18. mg kg^{-1}) and BMP/NT (12. mg kg^{-1}) in June 2000 was significant. Higher concentrations in the BMP/CT perhaps reflected a flush of microbial activity following cover crop incorporation on 5 May. Inorganic N concentrations increased to 30 mg kg^{-1} by August in the organic system, presumably reflecting the slower mineralization of organic N. By fall, however inorganic N in the organic system decreased to 5 mg kg^{-1} as a result of crop uptake by sweet potato. In the BMP system, inorganic N concentrations were approximately equal or lower during the 2000 growing season compared to 1999 because the BMP crop (peanut) in 2000 did not receive any inorganic N inputs. The three to five fold higher N concentrations in the organic system in 2000 compared with 1999 explain the significant date and date by systems interaction.

Organic C and N

Soil total C and N concentrations were very low (below 9000 mg kg^{-1} C and 800 mg kg^{-1} N) and were significantly different only by replication (Table 2.3). Blocking was done by soil type, so that in a given replication all samples were taken from the same diagnostic soil. The diagnostic soil in replications B and C is a Wickham (fine-loamy, mixed, semiactive, thermic Typic Hapludult), whereas in replication A it is a Tarboro (mixed, thermic, Typic Udipsamment) soil. The Wickham series is classified as very deep, well drained and moderately permeable whereas the Tarboro series is somewhat excessively drained and rapidly permeable. Soil organic C and N were significantly higher in replication B compared with replications A and C. The sandy, excessively drained soil of replication A would understandably have lower C and N concentrations, but the significantly lower C and N concentrations in replication C is more difficult to explain. The water table is higher under most of replication C, which borders the Nuese river (Appendix, Fig. 1). This area of the farm is often wet and after rainfall the soils remain saturated much longer than other areas of the farm. High soil water content slows decomposition and results in higher C and N concentrations. It is not surprising that few differences were found in total C and N concentrations at this early stage in the systems development. Whereas some studies do show differences in total C concentration over the long term (Wander et al, 1994; Karlen et al., 1994) and short term (Needleman et a., 1999) between no-till and conventional till, Rice et al. (1986) found no differences in total N concentrations after ten years between tillage systems.

Soil pH

Soil pH differences were significant by date (Fig. 2.5). The successional ecosystem had the lowest pH among systems on most dates, a trend that will likely continue because many soil biological processes are acidifying and the system will receive no inputs to raise pH. Our systems probably have not been in place long enough to detect changes due to management.

Physical Indicators

Bulk Density

Dr. Charles Razcowski of North Carolina State University A & T University measured bulk density (Razcowski, unpublished data, 2002). Analysis of variance showed that surface (0-15 cm) Db varied significantly between systems and that the date by system interaction was significant (Table 2.4). In the two systems receiving tillage, (organic and the BMP/CT), Db declined over time, whereas in the two systems that did not receive tillage, (BMP/NT and the successional), Db increased over time (Fig. 2.6). Systems were not significantly different at the baseline measurements in March 1999. By the end of the first growing season tillage induced changes in Db were apparent, with the organic and the BMP/CT system Db significantly lower than both the BMP/NT and successional systems. In these systems, Db had increased to 1.48 Mg m^{-3} from 1.35 Mg m^{-3} in the BMP/NT and to 1.45 Mg m^{-3} from 1.34 Mg m^{-3} in the successional system. This trend continued through the next growing season and Db measurements in

November 2000, revealed quite low values in the organic system. This system received extensive tillage in 2000, because of a delay in sweetpotato planting, which resulted in repeated field conditioning and bedding. The decrease in the BMP/CT was not as great as the decrease in the organic system, reflecting management differences between systems. Herbicide is used for weed control in the BMP/CT and the system therefore receives less tillage than the organic system. Bulk density values in all systems were below critical (root limiting) levels for the soil types at CEFS (Jones, 1983).

Although Unger (1996) found Db to be unaffected by tillage treatments, natural increases can occur in the upper 15-cm can occur with no-till management (Unger, 1996). Research by Voorhees et al. (1985) found the effects of no-tillage management on Db to be highly variable and dependent on equipment type, number of passes, soil type, and soil water content at the time of field activities. Research has shown that proper management, such as controlled traffic, can reduce the potential for the development of adverse soil conditions under no-till management (Unger 1996; Wagger and Denton, 1989). Bulk density increased over time in the successional system. The increase in Db in the successional system was caused by lack of tillage, which breaks the surface layer and incorporates air into the soil.

Infiltration Time

Statistical analysis was performed on log-transformed data but results are presented as time in minutes. Log infiltration time was significant by replication and by date (Table 2.4). Although there were no significant differences between systems, a seasonal trend was evident with shorter times recorded in early spring and infiltration

time increasing over the course of the growing season. These differences are probably attributable to spring tillage and the amount of rainfall (Appendix, Table A3), as rainfall was less in the spring compared to the summer months. Initial infiltration times in May 1999, were quite short in all systems, with mean infiltration times for 2.54 cm deionized water of 1, 2, and 8 min in the organic, BMP/CT and NT systems, respectively. Spring tillage and installation of the rings just prior to these measurements probably contributed to the short infiltration times. Time for infiltration increased in all systems by July, and initial infiltration times in the successional system were extremely long (mean 89 min). By the fall, infiltration times had decreased in all systems. In June 2000, infiltration times were more than ten-fold slower in the BMP/CT and BMP/NT compared to May 1999. The organic system was not sampled in June because the fields had just been conditioned, ridged, and bedded for sweet potato planting, and field conditioning just prior to the infiltration measurements would have compromised the data. Infiltration times increased in all systems from June to August 2000 (Table 2.5). Longer infiltration times were likely influenced by rainfall (>18 cm) in August, which resulted in greater soil moisture content. By October mean infiltration times were 5, 10, 49, and 18 min in the organic, BMP/CT, BMP/NT, and successional systems respectively.

Time for infiltration was shorter in 1999 than in the 2000-growing season on most sampling dates. Higher rainfall throughout the 2000-growing season probably contributed to the difference between years.

The significant replication effect (Table 2.5) was the result of the differences in soil type between replicates (Appendix, Fig 2). The soil in blocks B and C is Wickham (Fine-loamy, mixed, semiactive, thermic Typic Hapludult), and in block A Tarborro

(Mixed, thermic Typic Udipamment). The Wickham series consists of very deep, well-drained, moderately permeable soils, whereas the Tarboro series is somewhat excessively drained and highly permeable. The high degree of spatial variability within a plot may be the result of random vehicle traffic resulting in patchy areas of extreme compaction. Compaction caused by wheel traffic on certain areas of fields can cause localized areas of slower infiltration rates (Vervoort et al., 2001; Wagger and Denton, 1989). We have attempted to control traffic patterns in the experimnent, but the area has a long history as a North Carolina Department of Agriculture production farm. Vervoort et al. (2001) conducted a study to determine if crop, tillage system, and position relative to plant row would alter the rate and pattern of water infiltration. They compared infiltration time in the row, the nontracked, and the tracked interrow and concluded that compaction caused by wheel tracks resulted in slower infiltration rates. Also confounding our results is the use of the infiltration ring itself. The infiltration rings were installed (adjacent to the crop row on the untracked side) immediately after planting in the spring and remained in position all season. In the successional system the rings were installed in May 1999 and never moved. However, sometimes individual rings were disturbed or accidentally disturbed during mid season tillage operations and had to be reinstalled.

While Lindstrom et al. (1981) found no-till to result in a consolidated soil surface with low infiltration capacity; many researches have found that no-till practices increase surface infiltration over time (Baumhart and Lascano, 1996; Vervoort et al. 1993; Vervoort et al. 2001). Baumhart and Lascano (1996) conducted a field experiment to determine the influence of residue cover on infiltration. They simulated rainfall on bare soil and a residue covered soil. Cumulative infiltration was lowest on bare soil and

increased curvilinearly with increasing residue amounts. The shorter infiltration times found in other no-till systems and the preferential flow observed in no-till systems (Ehlers, 1975) probably are the result of biological channels and structural macropores, which have not yet formed in the BMP/NT and successional systems of this study. In general, the infiltration times measured in the field using infiltration rings were ineffective at reflecting short-term management induced changes in the soil systems because of the differences in soil type and unknown prior history of traffic patterns.

Summary and Conclusions

A distinguishing characteristic of soil quality research is the use of multidisciplinary approaches to soil assessment. To this effect we chose chemical, physical, and biological indicators and measured them collectively and at the same locations over time. At this early stage in the systems development of the systems at CEFS, statistical differences between systems are few, but developing trends are evident. Preliminary results show higher microbial activity in systems that are undisturbed and where crop residue is left on the soil surface. The BMP/NT and the successional system behaved similarly with respect to CO_2 evolution, and Db, as did the BMP/CT and the organic system. Whereas Db was higher in the BMP/NT and successional system, values were not root restrictive. The systems have not developed sufficiently to determine if Db and infiltration times in the BMP/NT and the successional systems will continue to increase. Research has shown that long-term no-till can result in increased aggregate stability and organic matter content (Rhoton, 2000). Follow-up measurements in four to

five yr will give a more complete picture of management effects. However, at this stage the benefits of no-till management seem most apparent in drier conditions. Carbon evolved was two to three times greater in the BMP/NT and successional systems in mid-summer 1999 compared with the organic and BMP/CT systems, whereas the differences between systems in the wetter 2000- growing season were less apparent.

The other biological indicators we monitored, i.e., populations of fluorescent *Pseudomonas* and entomopathogenic nematodes, act more as a survey of endemic populations at this early stage in a long-term experiment. With respect to fluorescent *Pseudomonas* populations, systems were similar and followed a seasonal trend, which seemed dictated by soil moisture and temperature. The data suggest that the entomopathogenic nematode species are differentially affected by soil disturbance; i.e., *Steinernema glaseri* was detected most in the systems that received tillage, whereas *Steinernema carpocapsae* was detected most often in the BMP/NT and the successional system. Although statistically these indicators show little differences between systems, these early measurements are extremely valuable because they document the population distribution of these organisms at system inception. We consider these organisms to be indicative of a healthy soil and our goal is to learn how populations of these beneficial organisms are affected by the different management systems over time.

We found that measuring CO_2 evolution in the field using closed chambers gave quick and easily interpreted results as to the general level of microbial activity and to the magnitude of differences between systems. Lower respiration values in the organic and BMP/CT were most likely the result of tillage because values were on average two fold greater in both the BMP/NT and successional systems. However, it is difficult to discern

if we are seeing increased microbial activity in these systems that minimize tillage and increase surface residue or if we were simply measuring increased surface residue decomposition as a result of these practices. The timing of our CO_2 measurements also could have missed the flush of microbial activity following cover crop incorporation yet we saw sustained higher respiration in the undisturbed systems and where residue is left on the surface. Carbon evolution values in the organic system were low on most dates. The positive effects of organic amendments probably are masked at this stage by the negative effects tillage can has on CO_2 evolution and microbial biomass C and N.

Treatment effects on infiltration time were masked by differences in soil type, and in this case, the use of an infiltration ring to measure infiltration was ineffective as a soil quality indicator. The results, however, illustrate the inherent and sometimes extreme soil spatial variability of river systems and the importance of controlled traffic patterns.

Inorganic N measurements adequately reflected system inputs. Although no differences exist now for total soil organic C and N and soil pH, these measurements are valuable as baseline data in a long-term study.

Stated simply, sustainable farming means employing agricultural practices that strive to insure the soil functions effectively now and in the future. These soil quality indicators will be measured again, in the near future and in the long-term after system treatment effects may become more apparent. We expect that during the next three yr the systems will begin to diverge and indicators will reflect management-induced changes in the soil ecosystem. The data gathered here document the condition in the farming systems experiment at its inception. This baseline information will be used to evaluate the

amount, direction and speed of change in the systems and to assess the value of this set of indicators to relate to soil quality and crop productivity.

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TABLES AND FIGURES

Table 2.1. Description of the five systems that comprise the Farming Systems Unit at the Center for Environmental Farming Systems near Goldsboro, NC.

System	Subplot	Rotation	General Description
Conventional Cash Crop (BMP: Best Management Practices)	1. Conventional till 2. No-till	3-yr corn-cover crop-peanut-cover crop-cotton	System represents a standard for comparison (a positive control). It is characterized by management practices commonly used by growers.
Integrated Crop/Animal	1. CA_1 entry point 1 2. CA_2 entry point 2 3. CA_3 entry point 3	15-yr Three rotation entry points designated 1, 2, and 3†	System includes cover and pasture crops for every field in the rotation.
Organic	1. Four subplots; one organic, and the other three part of a nested transition to organic study with three starts.	3-yr transition soybean-cover – sweet potato-cover-wheat/cabbage	The initial focus is to evaluate alternative transition strategies from conventional to organic production.
Plantation Forestry/Woodlot (commercially valued forest species)	1. green ash 2. baldcypress 3. longleaf pine 4. black walnut	20 – 75 years	System maintains the identity of a woodlot ecosystem while maintaining appropriate silvicultural practices.
Successional Ecosytem (old field succession)	none	none	Represents one of the important standards (negative control) for the comparison of the environmental impacts among farming systems.

CA_1=5 years pasture followed by cotton-corn-peanut-sweet potato-wheat/soybean.
CA_2= corn-wheat/soybea-cotton-corn-peanut-sweetpotato-5 years pasture.
CA_3= cotton-corn-peanut-sweet potato-wheat/soybean.

Table 2.2. Sources of variance and level of significance for three biological soil quality indicators.

Source	CO_2 evolved	MPN†	Entomopathogenic nematodes
Rep	**	NS	**
System	**	NS	NS
Date	**	**	**
System x Date	**	NS	NS
CV, %	6.29	10.22	64.04

*, ** Indicates significance at the 0.05 and 0.01 levels of probability, respectively.
NS= Non-significant.
† Most probable number bacterial count.

Table 2.3. Sources of variance and level of significance for four chemical soil quality indicators.

Source	Total Inorganic N	Soil organic C	Soil organic N	pH
Rep	**	**	**	**
System	*	NS	NS	**
Date	**	NS	NS	**
System x Date	**	NS	NS	NS
CV, %	17.25	8.57	28.98	3.15

*, ** Indicates significance at the 0.05 and 0.01 levels of probability, respectively.
NS = Non-significant.

Table 2.4. Surface (0-15 cm) soil pH in organic, Best Management Practices (BMP) and successional systems at the Center for Environmental Farming Systems near Goldsboro, NC

System	March	May	July	October
Organic	5.5	5.6	5.8	5.2
BMP/CT	5.6	5.4	5.4	5.4
BMP/NT	5.7	5.6	5.6	5.6
Successional	5.3	†	5.4	5

	2000			
System	March	June	August	October
Organic	5.7	5.3	5	5.1
BMP/CT	5.8	5.3	5.2	5.2
BMP/NT	5.8	5.6	5.2	5.1
Successional	5.5	5.3	5.2	5.1

Table 2.5. Sources of variance and level of significance for two physical soil quality indicators.

Source	Bulk density	Infiltration time
Rep	NS	**
System	**	NS
Date	NS	**
System x Date	**	NS
CV, %	4.83	44.01

*, ** Indicates significance at the 0.05 and 0.01 levels of probability, respectively.
NS = Non-significant.

Table 2.6. Time in minutes for 2.54 cm deionized water to infiltrate the soil surface in organic, Best Management Practices (BMP) and successional systems on three sampling dates during the 1999 and 2000 growing seasons at the Center for Environmental Farming Systems near Goldsboro, NC.

	1999								
	May			July			October		
	min								
System	low	average	high	low	average	high	low	average	high
Organic	0.2	1.3	7.8	0.3	14	96	0.7	6.7	30
BMP/CT	0.3	1.5	6	1.1	8.1	20.1	0.92	6.1	23.2
BMP/NT	0.25	8.5	30	2.1	12.3	26.9	0.52	8.4	26.5
Successional		†		0.6	88.7	403	0.25	3.6	7

	2000								
	June			August			October		
	min								
System	low	average	high	low	average	high	low	average	high
Organic		‡		1.2	21.3	74.7	0.42	4.8	22
BMP/CT	0.65	29.5	254	0.57	36.6	190.5	0.45	10.1	20.1
BMP/NT	0.38	103.2	770	1.7	159.7	381	3.25	48.6	381
Successional	0.52	75.5	700	1.32	86.8	381	0.73	17.6	76

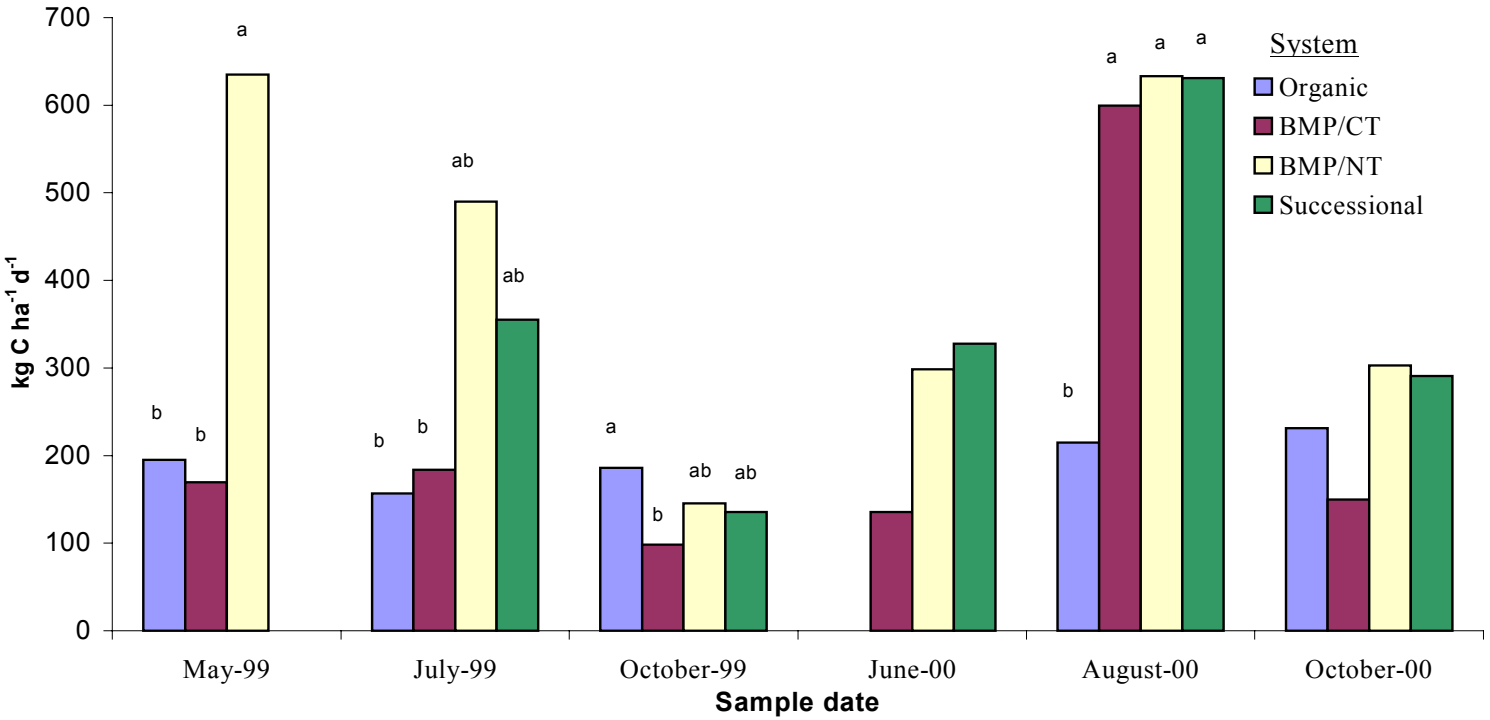


Fig. 2.1. Soil respiration as measured by CO_2 evolution in organic, best management practice (BMP), and successional systems at the Center for Environmental Farming Systems near Goldsboro, NC. Means without a common letter differ significantly at the 0.05 probability level using the protected LSD procedure.

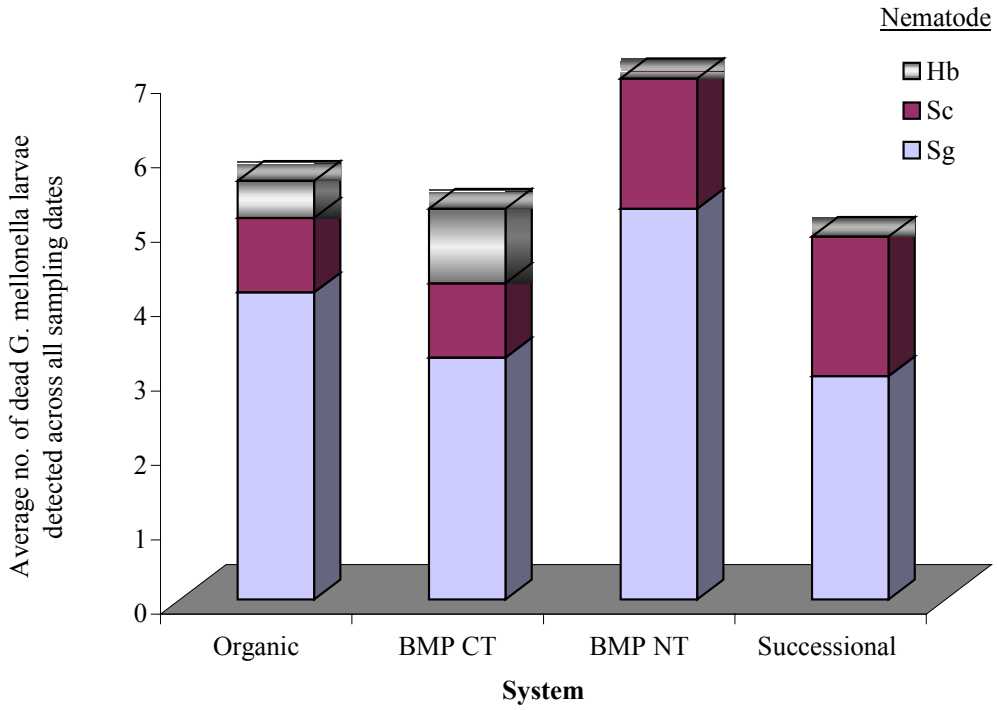


Fig. 2.2. Cumulative distribution of entomopathogenic nematodes in organic, best management practice (BMP), and successional systems at the Center for Environmental Farming Systems (CEFS) near Goldsboro, NC. Nematode species distribution among the systems was not significantly different.

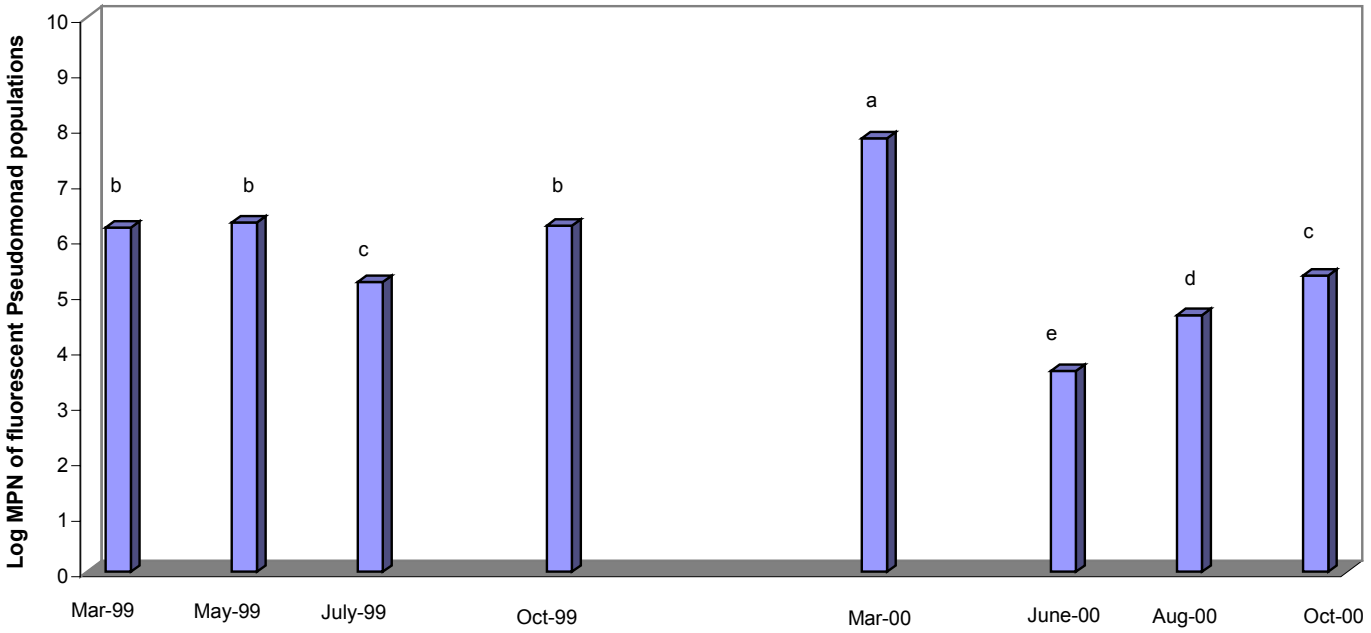


Fig. 2.3. Log of the Most Probable Number (MPN) population estimates for fluorescent Pseudomonas bacteria in organic, best management practices (BMP), and successional systems at the Center for Environmental Farming Systems near Goldsboro, NC. Dates without a letter in common differ significantly at the 0.05 probability level.

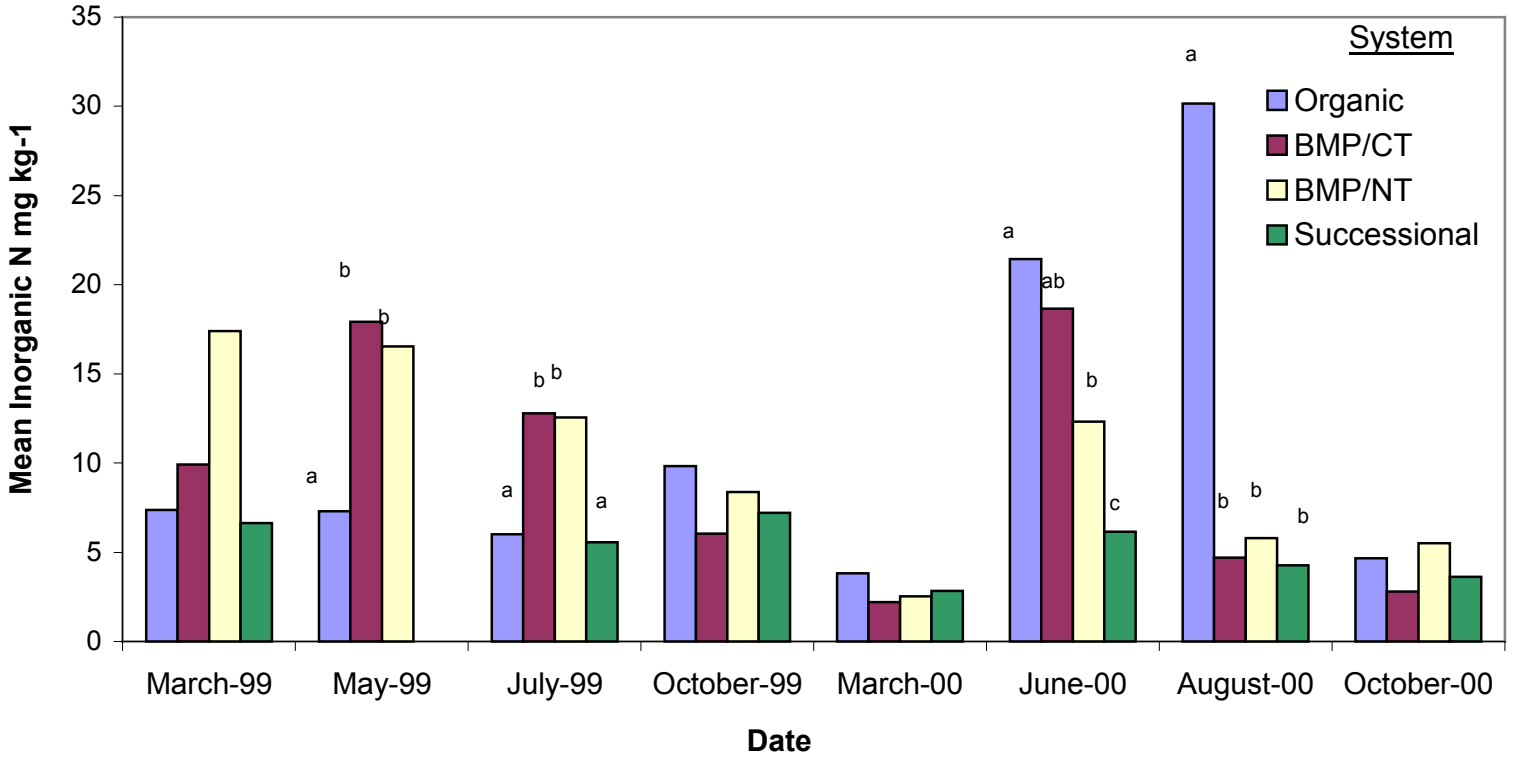


Fig. 2.4. Total surface (0-15 cm) soil inorganic N in an organic, a best management practice (BMP), and successional systems at the Center for Environmental Farming Systems near Goldsboro, NC. Means without a letter in common differ significantly using the protected LSD procedure at significance level 0.05.

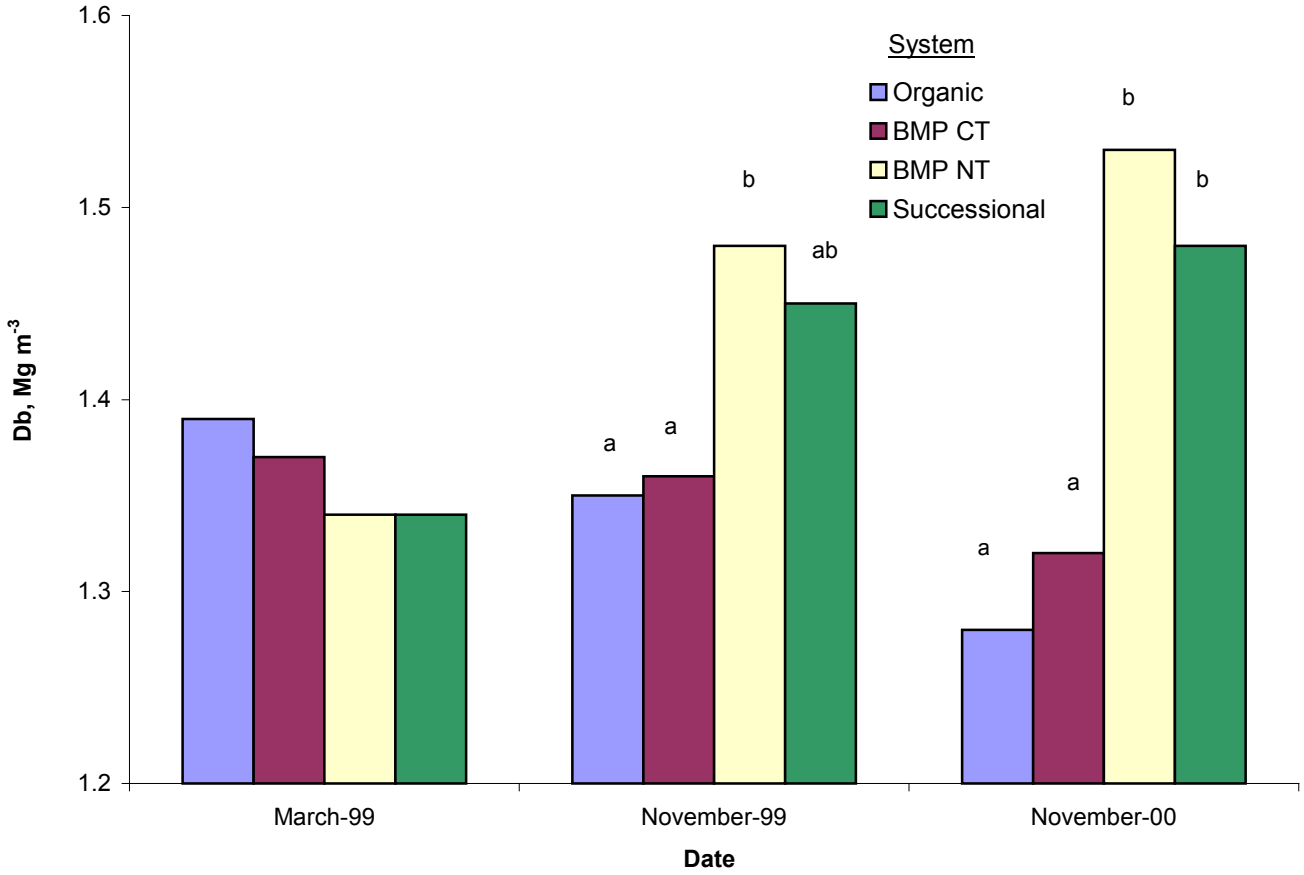
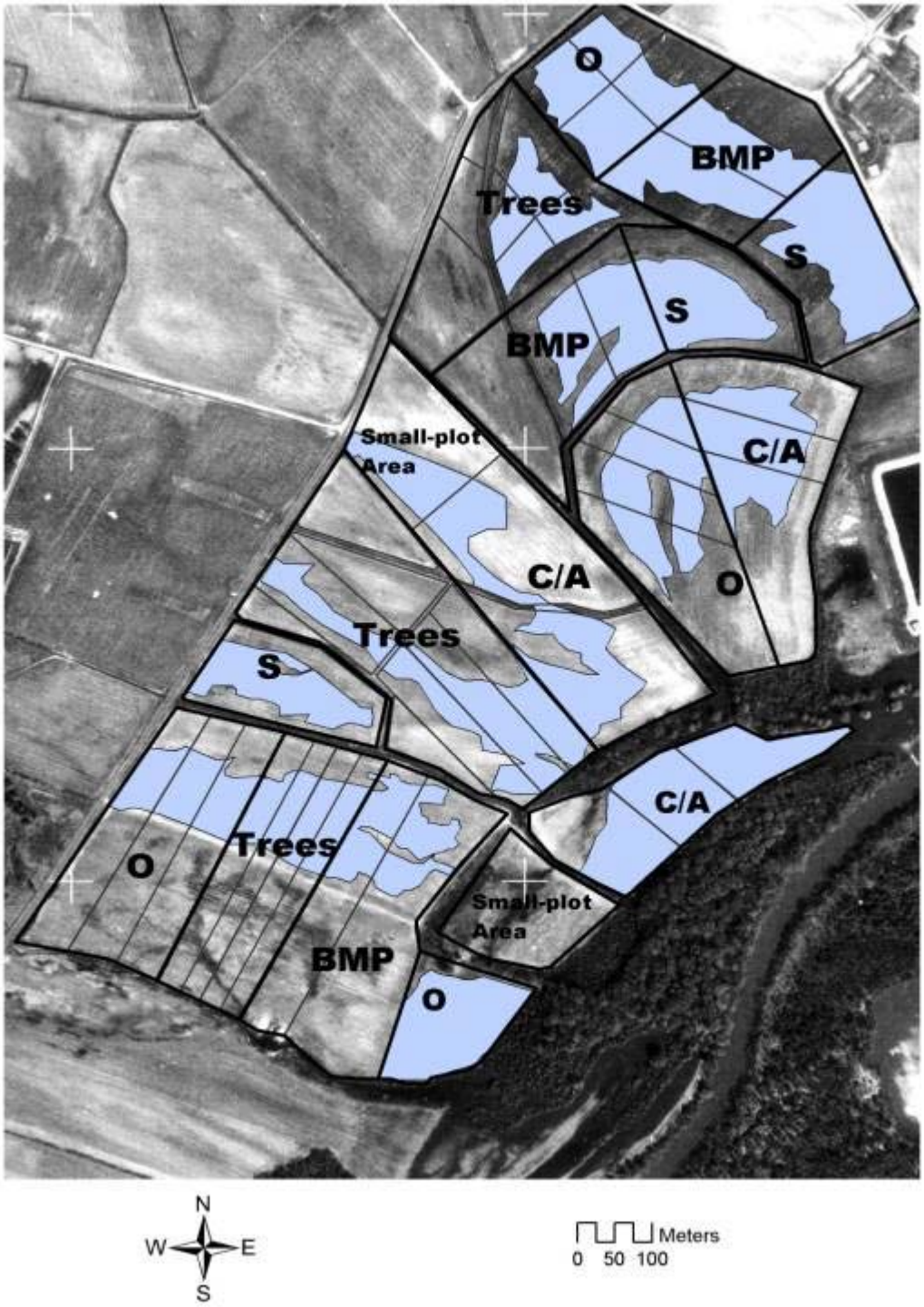
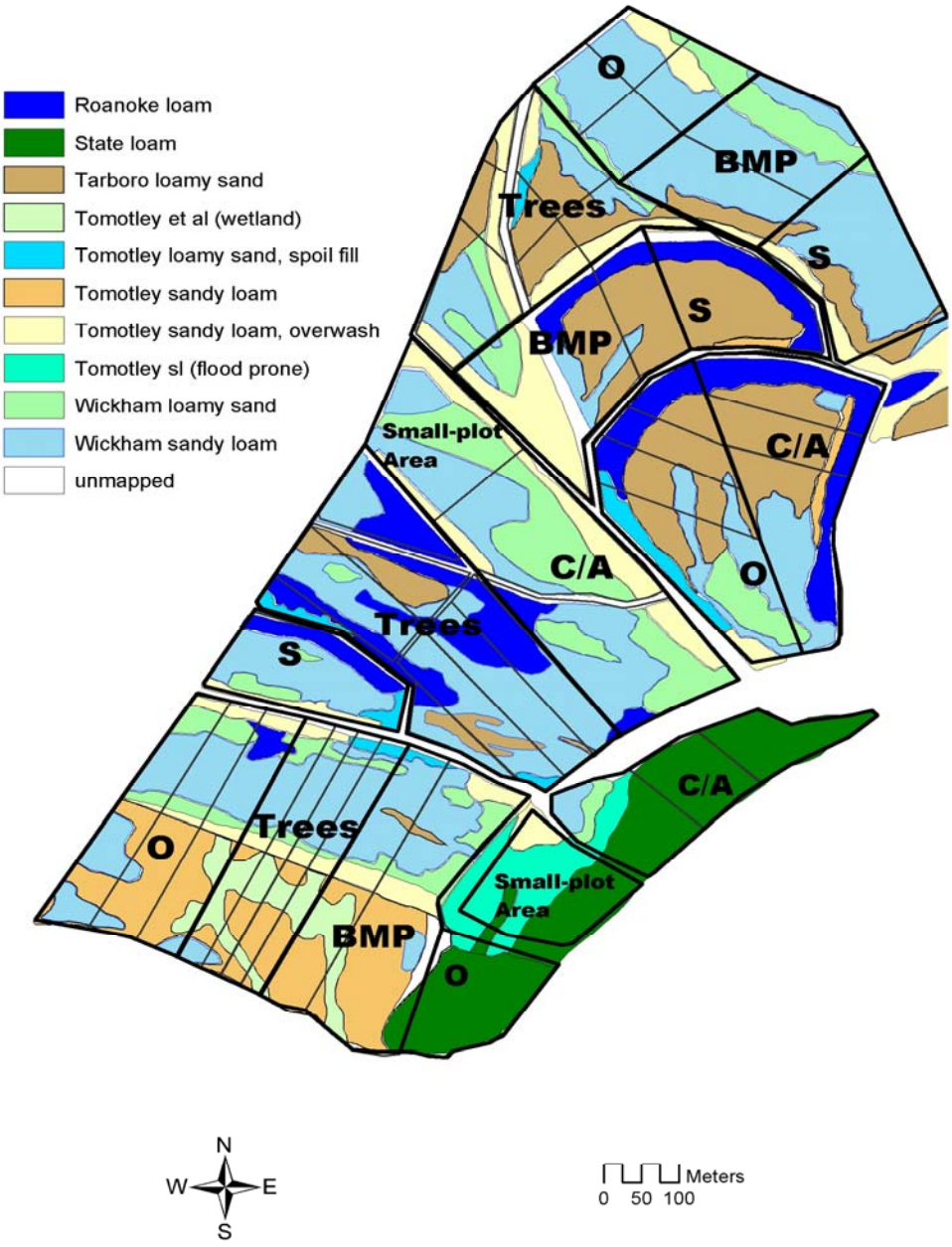


Fig. 2.5. Soil bulk density (Db) measurements on undisturbed soil cores (7.6 cm in diameter by 7.6 cm in length) taken with a Uhland core sampler from organic, best management practices (BMP), and successional systems on three in 1999 and 2000 at the Center for Environmental Farming Systems near Goldsboro, NC. Means without a common letter differ significantly at the 0.05 probability level using the protected LSD procedure.

Appendix



Appendix Fig. 1 Experimental design of the Farming Systems Unit at the Center for Environmental Farming Systems in Goldsboro, NC.



Appendix Fig. 2 Soils map for the Farming Systems Unit at the Center for Environmental Farming Systems in Goldsboro, NC.

Appendix Table 1a Field activities for the best management (BMP) at the Center for Environmental near Goldsboro, NC.

Date	Plots	Activity/ Chemical	Comment/Rate
3/8/1999	all	rye cover crop mowed	
3/30/1999	NT	Roundup Ultra	Roundup Ultra, 524-475, Monsanto @ 2.34 L ha^{-1}
3/31/1999	CT	tillage	disked
4/5/1999	CT	tillage	chisel plow
4/5/1999	all	Potash	60% @ 0.112 Mg ha-1
4/12/1999	all	corn planted	DK-714 @11336 pop ha^{-1}
4/13/1999	all	Bicep II	100-710, Novartis @ 2.34 L ha^{-1}
4/13/1999	all	Nitrogen fertilizer (30% UAN)	13.6 kg N ha^{-1}
5/6/1999	CT	tillage	rotary hoe
6/1/1999	all	Nitrogen fertilizer (30% UAN)	65.75 kg N ha^{-1}
6/7/1999	13[†]	tillage	rotary hoe
6/14/1999	all	Nitrogen fertilizer (30% UAN)	65.75 kg N ha^{-1}
6/14/1999	all	Evik-DF	Evik-DF, 100-786, Novartis @ 2.464 kg ha^{-1}
9/13/1999	all	corn harvest	
11/30/1999	all	rye cover crop planted	drilled @ 67.2 kg ha^{-1}
3/13/2000	all	spring soil sampling	
4/1/2000	all	tillage	disk/chisel/disk
4/11/2000	all	potash, 60%	134.4 kg ha^{-1}
5/25/2000	all	Peanuts planted (NCV-11)	112 kg ha^{-1}
5/25/2000	all	Temick	7.84 kg ha^{-1}
5/25/2000	all	Rhizo-flo	16.8 kg ha^{-1}
5/26/2000	CT	Frontier	0.195 L ha^{-1}
5/26/2000	CT	Pursuit-70DG	0.105 L ha^{-1}
5/26/2000	NT	Roundup Ultra	2.34 L ha^{-1}
6/9/2000	NT	Starfire	Starfire 10182-103, ICI @0.803 L ha^{-1}
6/19/2000	13	Basagran	2.34 L ha^{-1}
6/13/2000	NT	Dual 8E	metolachlor, 100-597, Novartis @ 2.92 L ha^{-1}
6/19/2000	13	Starfire	Starfire 10182-103, ICI @0.803 L ha^{-1}
6/21/2000	NT	Select, crop oil, Blazer	0.58 L ha^{-1}/ 2.34 L ha^{-1} / 1.17 L ha^{-1}
7/5/2000	5	Blazer (spot spray)+Select+Crop oil	1.17 L ha^{-1}/ 0.584L ha^{-1} / 2.34 L ha^{-1}
7/5/2000	CT	Select, crop oil, Blazer	0.58 L ha^{-1}/ 2.34 L ha^{-1} / 1.17 L ha^{-1}
7/10/2000	all	Gypsum	Land plaster, 896 kg ha^{-1}
7/14/2000	all	Lorsban	14.56 kg ha^{-1}
7/17/2000	NT	Select	0.58 L ha^{-1}
7/19/2000	all	Bravo Weather Stick	1.75 L ha^{-1}
8/9/2000	all	Bravo Weather Stick	1.75 L ha^{-1}
8/1/2000	all	mid season SQ	
8/22/2000	all	Brazo Weather Stick	1.75 L ha^{-1}
[†]9/8/2000	all	Brazo Weather Stick	1.75 L ha^{-1}
11/15/2000	all	planted rye cover	drilled @ 67.2 kg ha^{-1}

CT = conventional tillage
NT = no-tillage

plots 5, 13, and 38 are conventional till. Plots 6, 12, and 37 are no-till.

Appendix Table 1b. Field activities for the organic system at the Center for Environmental Farming Systems near Goldsboro, NC.

Date	Plot	Activity/Chemical	Comments/Rate
3/18/1999	all	baseline soil sampling	
5/6/1999	1, 18	tillage	moldboard plow
5/15/1999	all	soil quality †	
5/20/1999	30	tillage	moldboard plow
6/1/1999	30	tillage	disc tandem harrow
6/2/1999	1, 18	tillage	disc tandem harrow
6/3/1999	all	plant soybean	26 seeds m^{-1} Asgrow 5944
6/24/1999	all	tillage	rotary hoe
6/28/1999	all	cultivate	sweep cultivator
7/19/1999	all	cultivate	sweep cultivator
12/1/1999	all	plant rye	134 kg ha^{-1}
12/1/1999	all	plant crimson clover	Dixie/inoculated 6.72 kg ha^{-1}
4/17/2000	all	mow rye	
4/18/2000	all	tillage	moldboard plow
5/2/2000	all	manure application	turkey litter, 4.48 $Mgha^{-1}$
5/3/2000	all	tillage	disc harrow
6/14/2000	all	tillage	ridge formation
6/27/2000	all	tillage	rototill/bed shape
6/28/2000	all	plant sweetpotato	30975 plants ha-1, 31 cm row
7/7/2000	all	soil quality	
7/10/2000	all	tillage	rolling cultivator
7/18/2000	all	tillage	rolling cultivator
10/1/2000	all	soil quality	
10/14/2000	all	harvest	sweetpotato
10/25/2000	all	plant crimson clover	Dixie-inoculated, 28.6 kg ha^{-1}

† SQ= soil quality and includes soil samples for the quantification of entomopathogenic nematodes, and Pseudomonas bacterial populations, determination of soil inorganic N, pH, organic C and N, infiltration rate and soil respiration measurements.

Appendix Table 2a. Mean Monthly Temperatures for Goldsboro, NC

—— mean temp. Celcius ——

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999	18.2	18.2	18.6	22.6	24.4	27	29.2	25.7	25.7	22.7	21	17.2
2000	15	17.6	20.2	21.5	26.2	27.8	27.8	27.8	25.1	18.3	18	13.7

Appendix Table 2b. Monthly Rainfall for Goldsboro, NC

—— rainfall in cm ——

Year	April	May	June	July	August	September
1999	8.1	7.4	27.9	13.5	13	85.3
2000	7.4	3.6	15.7	13.7	18.3	21.1

Appendix Table 3. Chemical formulations

Common name	Chemical name	formula
Roundup Ultra	Glyphosphate	N-(phosphonomethyl)glycine
Bicep	Atrazine	2-chloro-4ethylamino-6-isopropylamino
Temik	Aldicarb	C7H14N2025
Evik-DF	Ametryn	2-ethylamino-4-isopropylamino-6-methlthio-s-triazine
Frontier	Dimehtanamio	2-chloro-N-[(1-methyl-2-mehoxy)ethyl]-N-(2, 4-dimethyl-thien-3-yl)acetamide
Pursuit	Imazethapyr	2[-4, 5-dihydro-4-(-1-methyl)-5-oxo-1H-imadozol-z-yl]-5-ethyl-3-pyridinecarboxylix acid
Starfire	Paraquat Dichloride	(1, 1-'dimethyl-4, 4'-bipyridinium) dichloride
Basagran	Bentazon	3-(1-methylethyl)-1H-2, 1, 3-benthiadiazin-4(3H) one 2, 2-dioxide)
Blazer	Sodium Salt of Acifluorfen	sodium 5-[2-chloro-4 -(trifluoromethyl)phenoxy]2-nitrobenzoate
Lorsban	Chlopyrifos	0, 0-diethyl-0-(3,4,6-trichloro-2-pyridinyl) Phosphorothioate
Select	Clethodim	[(E)-2{1-{{(3-chloro-2-propenyl)oxy}imino}propyl}-5{2-ethyl-thio)propyl}3-hydroxy-2-cyclohexen-1-one]
Bravo Weather Stick	Chlorothalonil	tetrachloroisophthalonitrile