TOMATO YIELD AND SOIL QUALITY AS INFLUENCED BY TILLAGE, COVER CROPPING, AND NITROGEN FERTILIZATION

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Abstract. Tomato yield and soil quality may be influenced by management practices and climatic conditions. We examined the effects of tillage (no-till, chisel plowing, and moldboard plowing), cover crop (hairy vetch (*Vicia villosa* Roth) and no hairy vetch), and N fertilization (0, 80, and 160 lb N acre^{-1}) on tomato yield and N uptake, root growth, and soil C and N concentrations in a Norfolk sandy loam (fine-loamy, siliceous, thermic, Typic Kandiudults) in central GA for two years. Tomato yield and N uptake were greater in moldboard or chisel than in no-till in 1996, and with hairy vetch than with no hairy vetch or with 80 or 160 than with 0 lb N acre^{-1} in 1997. In contrast, tomato total number of roots in^{-2} soil profile was greater in no-till than in moldboard in 1997and in no hairy vetch with 160 lb N acre^{-1} than in hairy vetch with 0 lb N acre^{-1}in 1996. Similarly, mineralizable C and N and organic C and N were greater in no-till or chisel than in moldboard at 0- to 4-in depth but were greater or similar in moldboard than in no-till or chisel at 4- to 12-in. Inorganic and mineralizable N were greater with hairy vetch than with no hairy vetch and with N fertilization than without. Greater rainfall increased tomato yield and N uptake in 1997. In contrast, increased temperature promoted root growth and soil C and N mineralization in 1996 better than in 1997. Instead of conventional tillage with or without cover cropping or N fertilization, chisel plowing followed by hairy vetch cover cropping and 80 lb N acre^{-1} should be adopted for improving soil and water quality and sustaining tomato yield.

INTRODUCTION

Management practices can influence crop yield and soil and water quality. While conventional tillage, such as moldboard, has sustained crop productivity, it has decreased soil quality due to increased organic matter mineralization and erosion, and water quality due to increased sedimentation and NO_3 pollution. Excessive N fertilization accompanied by poor soil and crop management practices has increased NO_3 pollution in the groundwater (Linville and Smith, 1971; Follett, 1989; Hallberg, 1989). Agriculture remains a major source of contamination, along with pollution from industrial wastes, municipal landfills, mining, and septic systems (USOTA, 1984; Hallberg, et al., 1985; USEPA, 1992). Therefore, management practices that conserve soil and nutrients are needed for improving soil and water quality and sustaining crop yield.

Tillage reduces soil quality by oxidizing organic C and N, incorporating crop residues, disrupting soil aggregates, and increasing aeration (Dalal and Mayer, 1986; Balesdent et al., 1990; Cambardella and Elliott, 1993). As a result, amendments or plant residues need to be added in the soil to replace organic matter loss by cultivation (Campbell and Souster, 1982; Collins et al., 1992; Cambardella and Elliott, 1993). Practices that reduce residue incorporation, such as no-till or minimum till, can conserve organic matter better than conventional till. Studies have shown that no-till increased organic C and N in the surface soil compared with conventional till (Doran, 1987; Havlin et al., 1990; Franzluebbers et al., 1995). Similarly, cover cropping increased soil organic C and N compared with no cover cropping (Sainju and Singh, 1997). Legume cover crops have increased crop yields and reduced N fertilizer requirements compared with non-legume or no cover crops (Sainju and Singh, 1997).

Tomato is one of the important vegetable crops in Georgia. Compared with cereal crops, vegetable crops such as tomato need intensive management and high input of N (Power and Schepers, 1989). Furthermore, recovery of N from vegetable crops is lower than from cereal crops (Lowrance and Smittle, 1988). As a result, the potentiality for NO_3 to leach from the soil is greater under vegetable than under cereal crops. Therefore, vegetables, such as tomato, need to be grown in a sustainable manner that improves soil and water quality without significantly decreasing yield. One of the ways is to use conservation tillage, followed by legume cover cropping and reduced N fertilization. Little information is available about the combined influences of tillage, cover cropping, and N fertilization on transplanted tomato and soil quality. Our objectives were to determine the effects of management practices such as tillage, cover cropping, and N fertilization, and climatic conditions such as temperature and rainfall, on (1) root and shoot growth of transplanted tomato, and (2) soil C and N concentrations.

MATERIALS AND METHODS

Field Experiment

The experiment began in September 1994 at the Agricultural Research Station farm, Fort Valley State University, Fort Valley, GA, on a Norfolk sandy loam (fine loamy, siliceous, thermic, Typic Kandiudults). The soil had 1288 ton acre^{-1} sand, 496 ton acre^{-1} silt, 198 ton acre^{-1} clay, 6.5 pH, 17.2 ton acre^{-1} organic C, and 1.3 ton acre^{-1} organic N at 0- to 12-in depth. Previous cropping history included double cropping of wheat and soybean (*Glycine max* L.) for two years followed by alfalfa (*Medicago sativa* L.) for eight years. Temperature and rainfall data were collected from a nearby weather station.

The treatments included three levels of tillage (no-till, chisel plowing, and moldboard plowing), two levels of cover crop (hairy vetch and no hairy vetch), and three levels of N fertilization (0, 80, and 160 lb N acre^{-1}). Minimum tillage (chisel plowing) consisted of harrowing (4 to 6 in depth), followed by chiseling (8 to 10 in depth) and leveling (3 to 4 in depth). Conventional tillage (moldboard plowing) consisted of harrowing, followed by moldboard plowing (8 to10 in depth) and leveling. The experiment was arranged in a strip-split plot design, with tillage and cover crop as main treatments and N fertilization as split plot treatment. Treatments were arranged in a randomized complete block with three replications. The split plot size was 24 x 24 ft.

In September and October 1994 to 1996, chisel and moldboard plots were harrowed, plowed, and leveled. No-till plots were left undisturbed except for drilling cover crop seed. Hairy vetch seed was drilled at the rate of 25 lb acre^{-1}, with a row spacing of 6 in. No fertilizer, herbicide or insecticide was applied. In March and April of the following year, hairy vetch was harvested at flowering stage from two 12 x12 in^2 areas within the plot for yield and N concentration determinations. In no hairy vetch plots, weeds (dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenothera laciniata* L.)) were collected as above. Plant residues were oven-dried at 140^{o}F, weighed, and ground to 0.04 in. After sampling, cover crop and weeds were mowed with a tractor-drawn mower, killed by spraying Round-Up [N-(phosphonomethyl) glycine, 3.0 lb acre^{-1}] in no-till plots, and incorporated into the soil in chisel and moldboard plots. Residues were allowed to decompose in the soil for two weeks.

In April from 1995 to 1997, P (from triple superphosphate) and K (from muriate of potash) were broadcast each at the rate of 50 lb acre^{-1}, along with 60 lb acre^{-1} of Diazinon, 5G [Diethyl 0-(2-isopropyl-6 methyl-4 pyrimidinyl) phosphorothioate] to control cutworms and 0.50 lb acre^{-1} of Treflan (2, 6-dinitrianiline) to control weeds. Chisel and moldboard plots were harrowed, plowed, and leveled. Five-week-old tomato seedlings were transplanted at a spacing of 3 ft x 3 ft. Starter solution containing 0.4 oz N, P, and K gallon^{-1} (0.36 lb acre^{-1}) was applied to each tomato plant after one week to encourage rapid establishment. Nitrogen fertilizer (nitrate of soda) was split into three doses, each broadcast at three-weeks interval from the date of transplanting. Irrigation was applied soon after fertilization in dry soil to minimize its loss and as needed.

In July 1996 and 1997, two minirhizotron acrylic tubes (2 in diam. by 36 in long) were installed 10 ft apart in the middle rows from 0 to 28 in soil depth at an angle of 15^o with the vertical and 6 in away from the base of the plant (Box et al., 1989; Box, 1996). Root observations were taken at 2.5 in increment from 1 to 22.5 in depth during tomato growth using a minirhizotron camera (0.6 in by 0.5 in) attached to a rod (Bartz Technology, Santa Barbara, CA). The camera was inserted into the tube and the picture of the root in the soil profile at a particular depth was transmitted to a VCR attached to a backpack and recorded on a tape.

In July and August 1995 to 1997, tomato fruits was harvested every 3 to 4 d as the color turned from green to pink. These were picked from five plants in the two middle rows (45 ft^2 area), cut into slices, weighed, oven-dried, and ground to 0.04 in. At the final harvest in August, tomato plants were cut 1in above the ground, separated into leaves and stems, oven-dried, weighed, and ground to 0.04 in. Soil samples were collected at 0- to 4- and 4- to 12-in depths one month after cover crop incorporation in May 1996 and 1997 from five places within the two middle rows with a push tube (2 in diam.). These were composited, air-dried, and sieved to 0.08 in.

Laboratory Analysis

The N concentration in the cover crop and tomato samples was determined by the method described by Kuo et al. (1997b). The C concentration in the cover crop sample was determined by the Walkley-Black method (Nelson and Sommers, 1982), assuming that all plant C was oxidized during digestion. Nitrogen and C accumulated in the cover crop and N taken up by tomato (leaf+stem+fruit) was determined by multiplying dry matter yield by N concentration.

Nitrate and NH_4 concentrations in the soil were determined by steam distillation (Keeney and Nelson, 1982). Inorganic N concentration was determined as the sum of NH_4 and NO_3. Total N was determined by the Kjeldahl method (Bremner and Mulvaney, 1982), and organic N was determined as the difference between total and inorganic N. Organic C was determined by the Walkley-Black method. Mineralizable C and N was determined by the method described by Franzluebbers et al. (1995).

Root images recorded by minirhizotron camera were displayed in a monitor and number of roots in^{-2} soil profile area were calculated. The number of roots obtained from two tubes per plot were averaged to minimize variation within the plot and average value was used for a treatment (Hendrick and Pregitzer, 1992). Total number of roots (TNR) was calculated by adding number of roots from 1 to 22.5 in depth.

Data Analysis

Data for soil and plant parameters were analyzed statistically using the MIXED procedure of SAS (Littell et al., 1996). Sources of variation included tillage, cover crop, N fertilization, and their interactions. The least square means test was used to determine the significant difference between the means when treatment interactions were significant. Statistical significance was evaluated at *P*#0.05.

RESULTS AND DISCUSSION

Cover Crop Characteristics

Tillage and N fertilization to tomato did not influence cover crop biomass yield, N concentration, N accumulation, C accumulation, or C:N ratio (Table 1). In contrast, hairy vetch had two- to threefold greater biomass yield, one-and-a-half to twofold greater N concentration, three- to sixfold greater N accumulation and two- to fourfold greater C accumulation than weeds in the no hairy vetch treatment. The C:N ratio was lower in hairy vetch than weeds in the no hairy vetch plot. Because of higher N concentration, N accumulation in cover crop was greater in 1996 than in 1997.

Tomato Yield and Nitrogen Uptake

Tillage influenced tomato fresh fruit yield, total (stems + leaves + fruits) dry matter yield, and N uptake in 1996 (Table 2). In contrast, cover crop and tillage x N fertilization interaction influenced tomato fresh fruit and total dry yield and N uptake in 1997. Tomato fresh fruit and total dry yield were significantly greater in chisel or moldboard than in no-till, and N uptake was significantly greater in chisel than in no-till in 1996. In 1997, tomato fresh fruit and total dry yield and N uptake were greater with hairy vetch than with no hairy vetch. Similarly, tomato fresh fruit and total dry yield were greater in moldboard with 80 lb N acre^{-1} or in no-till with 160 lb N acre^{-1} than in chisel with 80 lb N acre^{-1} or in moldboard with 0 lb N acre^{-1}. Nitrogen uptake was greater in no-till with 160 lb N acre^{-1} than in chisel with 80 or 160 lb N acre^{-1} or in moldboard with 0 lb N acre^{-1}.

Lower tomato fresh fruit and total dry yield and N uptake in no-till than in chisel or moldboard in 1996 may have resulted from lower root growth at certain soil depths. In a related study, Singh and Sainju (1998) found that the number of roots in^{-2} soil profile from 7.5 to 22.5 in depth was 65% lower in no-till than in moldboard in 1996. This layer of soil may be important for plant roots to absorb moisture and nutrients, thereby influencing shoot growth. In contrast, greater tomato fresh fruit and total dry yield and N uptake with hairy vetch than with no hairy vetch in 1997 may have resulted from higher N concentration and accumulation (Table 1). Increased tomato growth with hairy vetch compared with no hairy vetch or control were obtained by several researchers (Shennan, 1992; Kelley et al., 1995; Abdul-Baki et al., 1996). Similarly, increased tomato yield with increasing N fertilization rate were reported by Garton and Widders (1990), Liptay and Nicholls (1993), and Vavrina et al. (1998).

Nitrogen recovery [(N uptake in treatment-N uptake in control)/N applied] in tomato total dry yield was 52% for N applied from hairy vetch residue in 1997. Similarly, N recovery from 80 lb N acre^{-1} was 14% and from 160 lb N acre^{-1} was 9%. In 1996, N recovery in tomato was even lower. Sweeny et al. (1987) reported that N recovered by tomato ranged from 32 to 53%. Averaged across the treatments, tomato fresh fruit and total dry yield was 6 % greater and N uptake was 22% greater in 1997 than in 1996. This may have resulted from higher rainfall in 1997 than in 1996. Total rainfall from April to August was 8.02 in greater in 1997 (24.02 in) than in 1996 (16.00 in).

Tomato Root Growth

Tomato TNR was influenced by cover crop x N fertilization interaction in 1996 and tillage in 1997 (Table 3). The TNR was significantly greater in no hairy vetch with 160 lb N acre^{-1} than in hairy vetch with 0 lb N acre^{-1} in 1996. Similarly, TNR was significantly greater in no-till than in moldboard in 1997. Averaged across the treatments, TNR was more than threefold greater in 1996 than in 1997.

Although TNR was similar between no-till and moldboard in 1996, Singh and Sainju (1998) measured 68% greater number of tomato roots from 7.5 to 22.5 in depth in moldboard than in no-till. This was because most of roots grew above 7.5 in depth, regardless of tillage. Highest concentration of roots, especially fine roots, occur near the surface soil which is rich in organic matter, nutrients, cation exchange capacity, and porosity and low in bulk density (Sainju and Good, 1993; Singh and Sainju, 1998). Fine roots constitute a large proportion of total root biomass and are important in water and nutrient absorption (Parker and Van Lear, 1996). In contrast, greater TNR in no-till than in moldboard in 1997 may have resulted from superior moisture conservation and cooler temperature in the surface soil (Merrill et al., 1996).

Greater TNR in no hairy vetch with 160 lb N acre^{-1}

than in hairy vetch with 0 lb N acre^{-1} in 1996 may have resulted from increased N availability from fertilizer N than from hairy vetch residue. This is because hairy vetch may have released N slower than N fertilizer. Legumes release N slower than N fertilizer (Ladd and Amato, 1986; Schepers and Fox, 1989). Increased tomato root growth following N fertilization were observed by several researchers (Weston and Zandstra, 1989; Widders, 1989; Garton and Widders, 1990).

Increased TNR in 1996 compared with 1997 may have resulted from increased temperature and low rainfall. The average monthly temperature in May was 6.5^{o}F greater and in June was 4.3^{o}F greater in 1996 than in 1997. Increased temperature to 95^{o}F stimulates root elongation (Logsdon et al., 1987), rate of branching (Box, 1996), and dry matter biomass (Walker, 1969; Voorhees et al., 1981). Little rain in April and May 1996 was compensated by timely irrigation, thereby promoting root growth. In 1997, excessive rain that fell from June to August may have slowed root growth.

Soil Carbon and Nitrogen

In 1996, tillage influenced mineralizable C, organic C, and organic N at 0- to 4- and 4- to 12-in depths (Table 4). Similarly, N fertilization influenced inorganic N and mineralizable N at 0- to 4- and 4- to 12-in. In 1997, tillage influenced mineralizable C, mineralizable N, and organic C at 0- to 4-in and organic N at 0- to 4-in and 4- to 12-in. Cover crop influenced inorganic N at 4- to 12-in and mineralizable N at 0- to 4- and 4- to 12-in.

Nitrogen fertilization increased inorganic N and mineralizable N compared with no N fertilization in 1996 (Table 5). Inorganic N and mineralizable N, however, were similar with 80 and 160 lb N acre^{-1} at 4- to 12-in. In 1997, mineralizable N was significantly greater in no-till than in moldboard at 0- to 4-in. Similarly, hairy vetch produced greater inorganic N at 4- to 12-in and mineralizable N at 0- to 4- and 4- to 12-in than no hairy vetch.

At 0- to 4-in, mineralizable C and organic N were greater in chisel than in moldboard and organic C was greater in no-till or chisel than in moldboard in 1996 (Table 6). In contrast, at 4- to 12-in, mineralizable C and organic C were greater in moldboard than in no-till or chisel and organic N was greater in moldboard than in no-till. Similarly, in 1997, no-till or chisel had greater mineralizable C, organic C, and organic N than moldboard at 0- to 4-in. At 4- to 12-in, moldboard had greater organic N than no-till.

Greater mineralizable C, mineralizable N, organic C, and organic N in no-till or chisel than in moldboard at 0- to 4-in may have resulted from surface placement or less incorporation of cover crop or tomato residue in the soil. When residue is placed in the surface in no-till or less incorporated into the soil in chisel than in moldboard, soil microorganisms have less contact with the residue for decomposition. As a result, C and N are conserved better at the surface soil in no-till or chisel than in moldboard (Franzluebbers et al., 1995; Havlin et al., 1990; Salinas-Garcia et al., 1997). In contrast, greater mineralizable C, organic C, and organic N in moldboard than in no-till or chisel at 4- to 12-in may have resulted from incorporation of plant residue at greater depth(Blevins et al., 1983). Increased soil organic C and N in no-till compared with conventional till at 0- to 2-in were reported by several researchers (Blevins et al., 1983; Franzluebbers et al., 1995; Havlin et al., 1990; Salinas-Garcia et al., 1997). Similarly, increased soil organic C and N in conventional till compared with no-till at 2- to 6-in was reported by Blevins et al. (1983).

Increased inorganic N and mineralizable N with hairy vetch compared with no hairy vetch in 1997 may have resulted from higher N concentration and accumulation (Table 1). Increased inorganic N and mineralizable N with legumes compared with non-legumes were observed by several investigators (Bonde and Rosswall,1987; Frankenberger and Abdelmagid, 1985; Kuo et al., 1996; Kuo and Sainju, 1998). Similarly, increased inorganic N and mineralizable N with increasing N fertilization were observed by Franzluebbers et al. (1995) and Salinas-Garcia et al. (1997).

Averaged across the treatments, inorganic N was 62% greater, mineralizable N was 43% greater, and mineralizable C was 52% greater in 1996 than in 1997. In contrast, organic C was 17% greater and organic N was 10% greater in 1997 than in 1996. This may be due to the difference in the amount of C and N added in cover crop residues and climatic conditions between 1996 and 1997. Cover crop C and N added to the soil were greater in 1996 than in 1997 (Table 1). As a result, more C and N were mineralized in 1996 than in 1997, thereby resulting in increased inorganic N, mineralizable N, and mineralizable C. Cover crops mineralize half of C and N within 2 to 9 weeks of their incorporation into the soil (Kuo et al., 1997a, b). Furthermore, increased temperature in May and June in 1996 compared with 1997 may have increased C and N mineralization, because soil organic matter mineralizes rapidly with increasing temperature to 95^{o}F (Alexander, 1977). In contrast, decreased mineralization may have increased organic C and organic N in 1997 compared with 1996.

CONCLUSIONS

Management practices including tillage, cover cropping, and N fertilization, and climatic factors such as temperature and rainfall, influenced tomato root and shoot growth and soil organic matter (organic C and N) level. While no-till decreased tomato yield and N uptake, it promoted root growth and increased C and N concentrations in the surface soil compared with moldboard. Because of high N accumulation, hairy vetch increased soil inorganic N, mineralizable N, tomato yield, and N uptake compared with no hairy vetch. Similarly, N fertilization increased tomato yield and N uptake, root proliferation, and soil inorganic and mineralizable N compared with no N fertilization. Warmer weather in 1996 enhanced root growth and soil C and N mineralization, but higher rainfall in 1997 increased tomato yield and N uptake. Because of reduced C and N mineralization and soil erosion but similar tomato yield and N uptake compared with moldboard plowing, minimum tillage, such as chisel plowing, followed by hairy vetch cover cropping and 80 lb N $acre^{-1}$ should be practiced for improving soil and water quality over conventional tillage and for sustaining tomato yield.

REFERENCES

Abdul-Baki, A.A., J.R. Teasdale, R. Korcak, D.J. Chitwood, and R.N. Huettel. 1996. Fresh-market tomato production in a low-input alternative system using cover crop mulch. HortScience 31:65-69.

Alexander, M. 1977. Introduction to soil microbiology. John Wiley and Sons, New York.

Balesdent, J.A., A. Mariotti, and D. Boisgontier. 1990. Effects of tillage on soil organic carbon mineralization estimated from ^{13}C abundance in maize fields. J. Soil Sci. 41:584-596.

Blevins, R.L., G.W. Thomas, M.S. Smith, W.W. Frye, and P.L. Cornelius. 1983. Changes in soil properties after 10 years of continuous non-tilled and conventionally tilled corn. Soil Tillage Res. 3:135- 136.

Bonde, T.A., and T. Rosswall. 1987. Seasonal variation of potentially mineralizable nitrogen in four cropping systems. Soil Sci. Soc. Am. J. 51:1508-1514.

Box, J.E., Jr. 1996. Modern methods of root investigation. p. 193-237. *In* Y. Waisel et al.(eds.) Plant roots: The hidden half. 2nd ed. Marcel Dekker, New York.

Box, J.E., Jr., A.J.M. Smucker, and J.T. Ritchie. 1989. Minirhizotron installation technique for investigating root response to drought and oxygen stress. Soil Sci. Soc. Am. J. 53:115-118.

Bremner, J.M., and C.S. Mulvaney. 1982. Total nitrogen. p. 595-624. *In* A.L. Page et al. (eds.) Methods of soil analysis. Part 2. Chemical and microbiological properties. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Cambardella, C.A., and E.T. Elliott. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57:1071-1076.

Campbell, C.A., and W. Souster. 1982. Loss of organic matter and potentially mineralizable nitrogen from Saskatchewan soils due to cropping. Can. J. Soil Sci. 62:651-656.

Collins, H.P., P.E. Rasmussen, and C.L. Douglass, Jr. 1992. Crop rotation and residue management effects on soil carbon and microbial dynamics. Soil Sci. Soc. Am. J. 56:783-788

Dalal, R.C., and R.J. Mayer. 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. Aust. J. Soil Res. 24:281- 292

Doran, J.W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fertil. Soils. 5:68-75.

Follett, R.F. 1989. Nitrogen management and groundwater protection. Developments in agricultural and managed forest ecology. Vol. 21. Elsevier, New York.

Frankenberger, W.T., Jr., and H.M. Abdelmagid. 1985. Kinetic parameters of nitrogen mineralization rates of leguminous crops incorporated into soil. Plant Soil 87:257-271.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1995. Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci. Soc. Am. J.59:1618-1624.

Garton, R.W., and I.E. Widders. 1990. Nitrogen and phosphorus preconditioning of small-plug seedlings influence processing tomato productivity. HortScience 25:655-657.

Hallberg, G.R. 1989. Nitrate in groundwater in the United States. p. 35-75. *In* R.F. Follett (ed.) Nitrogen management and groundwater protection. Developments in agricultural and managed forest ecology. Vol. 21. Elsevier, New York.

Hallberg, G.R., R.D. Libra, and B.E. Hoyer. 1985. Non-point source contamination of groundwater in Karst carbonate aquifers in Iowa. Perspectives on non-point source pollution. Proc. Natural Conf. USEPA, Washington, DC.

Havlin, J.L., D.E. Kissel, L.D. Maddux, M.M. Claasen, and J.H. Long. 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54:448-452.

Hendrick, R.L., and K.L. Pregitzer. 1992. Spatial variation in tree root distribution and growth associated with minirhizotrons. Plant Soil 143:283-288.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen-inorganic forms. p. 643-698. *In* A.L. Page et al. (eds.) Methods of soil analysis. Part 2. Chemical and microbiological properties. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Kelley, T.C., Y.C. Lu, A.A. Abdul-Baki, and J.R. Teasdale. 1995. Economics of hairy vetch mulch systems for producing fresh market tomatoes in the Mid-Atlantic region. J. Am. Soc. Hort. Sci. 120:854-860.

Kuo, S., and U.M. Sainju. 1998. Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil. Biol. Fertil. Soils. 26:346- 353.

Kuo, S., U.M. Sainju, and E.J. Jellum. 1996. Winter cover cropping influence on nitrogen mineralization, presidedress soil nitrate test, and corn yields. Biol. Fertl. Soils. 22:310- 317.

Kuo, S., U.M. Sainju, and E.J. Jellum. 1997a. Winter cover crop effects on soil organic carbon and carbohydrate. Soil Sci. Soc. Am. J. 61:1

Kuo, S., U.M. Sainju, and E.J. Jellum. 1997b. Winter cover cropping influence on nitrogen in soil. Soil Sci. Soc. Am. J.61:1392-1399.

Ladd, J.N., and M. Amato. 1986. The fate of nitrogen from legume and fertilizer sources in soils successively cropped with wheat under field conditions. Soil Biol. Biochem. 18:417-425.

Linville, K.W., and G.E. Smith. 1971. Nitrate content of soil cores from corn plots after repeated nitrogen fertilizations. Soil Sci. 112:249-255.

Liptay, A., and S. Nicholls. 1993. Nitrogen supply during greenhouse transplant production affects subsequent tomato root growth in the field. J. Am. Soc. Hort. Sci. 118:339-342.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS system for mixed models. SAS Inst., Cary, NC

Logsdon, S.D., R.B. Reneau, Jr., and J.C. Parkers 1987. Corn seedling root growth as influenced by soil physical properties. Agron. J. 79:221- 224.

Lowrance, R., and D. Smittle. 1988. Nitrogen cycling in a multiple crop-vegetable production system. J. Environ. Qual. 17:158-162.

Merrill, S.D., A.L. Black, and A. Bauer. 1996. Conservation tillage affects root growth of dryland spring wheat under drought. Soil Sci. Soc. Am. J. 60:575-583.

Nelson, D.W. , and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 539-579. *In* A.L. Page et al. (eds.) Methods of soil analysis. Part 2. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Parker, M.M., and D.H. Van Lear. 1996. Soil heterogeneity and root distribution of mature loblolly pine stands in Piedmont soils. Soil Sci. Soc. Am. J. 60:1920-1925.

Power, J.F., and J.S. Schepers. 1989. Nitrate contamination of groundwater in North America. Agric. Ecosyst. Environ. 26:165-187.

Sainju, U.M., and R.E. Good. 1993. Vertical root distribution in relation to soil properties in New Jersey Pinelands forests. Plant Soil 150:87-97.

Sainju, U.M., and B.P. Singh. 1997. Winter cover crops for sustainable agricultural systems: Influence on soil properties, water quality, and crop yields. HortScience 32:21-28.

Salinas-Garcia, J.R., F.M. Hons, and J.E. Matocha. 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61:152-159.

Schepers, J.S., and R.H. Fox. 1989. Estimation of nitrogen budgets for crops. p. 221-246. *In* R.F. Follett (ed.) Nitrogen management and groundwater protection. Vol. 21. Elsevier, Amsterdam.

Shennan, C. 1992. Cover crops, nitrogen cycling, and soil properties in semi-irrigated vegetable production systems. HortScience 27:749-754.

Singh, B.P., and U.M. Sainju. 1998. Soil physical and morphological properties and root growth. HortScience 33:966-971.

Sweeney, D.W., D.A. Greatz, A.B. Bottcher, S.J. Locaccio, and K.L. Campbell. 1987. Tomato yield and nitrogen recovery as influenced by irrigation method, nitrogen source, and mulch. HortScience 22:27-29.

United States Environmental Protection Agency (USEPA). 1992. Annual needs survey. USEPA, Office of Water, Washington, DC.

United States Office of Technology Assessment (USOTA). 1984. Protecting the national groundwater from contamination. USOTA, Washington, D.C.

Vavrina, C.S., G.J. Hochmuth, J.A. Cornell, and S.M. Olson. 1998. Nitrogen fertilization of Florida grown tomato transplants: Seasonal variation in greenhouse and field performance. HortScience 33:251-254.

Viets, F.G. 1965. The plant's need for and use of nitrogen. p. 503-549. *In* W.V. Bartholomew and F.E. Clark (eds.) Soil nitrogen. Agron. Monogr. No. 10. ASA and SSSA, Madison, WI.

Voorhees, W.B., R.R. Allmaras, and C.E. Johnson. 1981. Alleviating temperature stress. p. 217-266. *In* G.F. Arkin and H .M. Taylor (eds.) Modifying the root environment to reduce crop stress. Monogr. No. 4. ASAE, St. Joseph, MI.

Walker, J.M. 1969. One-degree increment in soil temperature affects maize seedling behavior. Soil Sci. Soc. Am. Proc. 33:729-736.

Weston, L.A., and B.H. Zandstra. 1989. Transplant age and N and P nutrition effects on growth and yield of tomatoes. HortScience 24:88-90.

Widders, I.E. 1989. Pretransplant treatments of N and P influence growth and elemental accumulation in tomato seedlings. J. Am. Soc. Hort. Sci. 114:416-420.

Table 1. Biomass yield, N concentration, N accumulation, C accumulation, and C:N ratio of cover crops.

	Biomass Yield		N concentration		N accumulation		C accumulation		C:N ratio	
Cover Crop	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
	-----ton acre^{-1}-----		---------%---------		--------------------lb acre^{-1}-----------					
Hairy vetch	2.44aH	1.86a	0.38a	0.19a	184a	69a	2153a	1628a	11.7a	23.6a
No hairy vetch (weeds)	0.87b	0.85b	0.19b	0.14b	33b	24b	594b	775b	18.0b	32.3b

H Within a column, numbers followed by the same letter are not significantly different at *P*#0.05 by the least square means test.
*, **, and *** Significant at *P*#0.05, 0.01, and 0.001, respectively; NS, not significant.

Table 2. Tomato Yield and N Uptake as Influenced by Tillage, Cover Cropping, and N Fertilization.

Treatment	N Rate	Fresh fruit yield		Total (stem + leaves + fruits) dry yields		N Uptake	
		1996	1997	1996	1997	1996	1997
	lb ac^{-1}	ton acre^{-1}		ton acre^{-1}		lb acre^{-1}	
				Tillage			
No-till		15.6b	----	1.22b	----	62.1b	----
Chisel		29.6 a	----	1.66 a	----	96.0 a	----
Moldboard		28.1 a	----	1.58 a	----	90.7 ab	----
				Cover crop			
Hairy vetch		----	28.1 a	----	1.74 a	----	112.7 a
No hairy vetch		----	22.9 b	----	1.42 b	----	89.3 b
				Tillage x N fertilization			
No-till	0	----	23.7 ab	----	1.47 ab	----	93.5 ab
	80	----	26.0 ab	----	1.61 ab	----	101.3 ab
	160	----	29.2 a	----	1.81 a	----	119.9 a
Chisel	0	----	24.0 ab	----	1.49 ab	----	99.4 ab
	80	----	22.4 b	----	1.39 b	----	87.9 b
	160	----	23.1 ab	----	1.43 ab	----	95.1 b
Moldborad	0	----	22.6 b	----	1.40 b	----	87.5 b
	80	----	30.5 a	----	1.89 a	----	117.3 ab
	160	----	28.1 ab	----	1.74 ab	----	106.6 ab
				Significance			
Tillage (Till)		*	NS	*	NS	*	NS
Cover crop (Crop)		NS	*	NS	*	NS	NS
Till x Crop		NS	NS	NS	NS	NS	NS
N Fertilization(Fert)		NS	*	NS	*	NS	*
Till x Fert		NS	*	NS	*	NS	*
Crop x Fert		NS	NS	NS	NS	NS	NS
Till x Crop x Fert		NS	NS	NS	NS	NS	NS

H Within a column of a treatment, numbers followed by the same letter are not significantly different at $P \leq 0.05$ by the least square means test.
* Significant at $P \leq 0.05$; NS, not significant.

Table 3. Tomato total number of roots from 1 to 22.5 in soil depth measured by minirhizotron method as influenced by tillage, cover cropping, and N fertilization.

Treatment	N rate	1996	1997
	lb ac^{-1}	no. roots in^{-2} soil profile	
		Tillage	
No-Till		102.9 a H	40.1 a
Moldboard		111.3 a	17.4 b
		Cover crop x N fertilization (lb $acre^{-1}$)	
Hairy vetch	0	89.7 b	28.6 a
	180	108.6 ab	26.5 a
No hairy vetch	0	130.2 a	37.9 a
	180	99.8 ab	22.1 a
		Significance	
Tillage (Till)		NS	*
Cover crop (Crop)		NS	NS
Till x Crop		NS	NS
N fertilization (Fert)		NS	NS
Till x Fert		NS	NS
Crop x Fert		0	NS
Till x Crop x Fert		NS	NS

H Within a column of a treatment, numbers followed by the same letter are not significantly different at *P*#0.05 by the least square means test. * Significant at *P*#0.05; NS, not significant.

Table 4. Analysis of variance for soil C and N under tomato.

Sources	Inorganic N		Mineralizable C		Mineralizable N		Organic C		Organic N	
Depth (in.)H	0-4	4 -12	0-4	4 -12	0-4	4 -12	0-4	4 -12	0-4	4 -12
					1996					
Tillage(Till)	NS	NS	NS	*	NS	NS	*	*	*	NS
Cover Crop (Ccrop)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Till x Ccrop	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N Fertilization (Fert)	***	*	NS	NS	***	*	NS	NS	NS	NS
Till x Fert	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Ccrop x Fert	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Till x Ccrop x Fert	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
					1997					
Tillage(Till)	NS	NS	**	NS	*	NS	*	NS	*	NS
Cover Crop (Ccrop)	NS	*	NS	NS	*	*	NS	NS	NS	NS
Till x Ccrop	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N Fertilization (Fert)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Till x Fert	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Ccrop x Fert	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Till x Ccrop x Fert	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

H 0 to 4 in soil depth; 4 to 12 in soil depth. *, **, and *** Significant at *P*#0.05, 0.01, and 0.001, respectively; NS, not significant.

Table 5. Soil Inorganic and Mineralizable N under Tomato as Influenced by Tillage, Cover Cropping, and N Fertilization.

Treatment	Inorganic N		Mineralizable N	
Depth (in.) H	0-4	4-12	0-4	4-12
	-- lb acre^{-1} --			
		1996		
		N fertilization (lb acre^{-1})		
0	30.2c'	67.3 b	41.2 b	87.6 b
80	37.6 b	87.6 a	46.2 b	110.1 a
160	46.9 a	77.6 ab	60.3 a	102.2 ab
		1997		
		Tillage		
No-till	22.5 a	56.5 a	38.8 a	80.5 a
Chisel	19.3 a	49.9 a	33.2 ab	69.4 a
Moldboard	16.4 a	49.6 a	26.5 b	64.2 a
		Cover Crop		
Heavy vetch	23.1 a	70.2 a	39.1 a	88.7 a
No hairy vetch	15.5 a	33.8 b	26.6 b	53.9 b

H 0 to 4 in soil depth; 4 to 12 in soil depth. ' Within a column of a treatment, numbers followed by the same letter are not significantly different at *P*#0.05 by the least square means test.

Table 6. Soil mineralizable C, organic C, and organic N under tomato as influenced by tillage.

Tillage	Mineralizable C		Organic C		Organic N	
Depth (in.)H	0-4	4-12	0-4	4-12	0-4	4-12
	---------lb acre^{-1}---------		--------ton acre^{-1}------		--------ton acre^{-1}--------	
			1996			
No-till	202.4ab'	301.8b	8.50a	14.65b	0.40ab	0.70b
Chisel	205.2a	325.2b	8.85a	14.12b	0.46a	0.74ab
Moldboard	168.8 b	414.5 a	7.03 b	17.69 a	0.34 b	0.85 a
			1997			
No-till	151.7a	195.4a	10.3a	20.46 a	0.49a	0.92 a
Chisel	156.7 a	257.4 a	9.07 a	17.95 a	0.44 a	0.86 ab
Moldboard	76.5 b	223.9 a	7.59 b	17.56a	0.33 b	0.77b

H 0 to 4 in soil depth; I 4 to 12 in soil depth. ' Within a column of a treatment, numbers followed by the same letter are not significantly different at *P*#0.05 by the least square means test.