Tomato Root Growth Is Influenced by Tillage, Cover Cropping, and Nitrogen Fertilization

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Abstract. The influence of tillage (no-till (NT) vs. moldboard plowing (MP)), cover crop [hairy vetch (Vicia villosa Roth) (HV) vs. no hairy vetch (NHV)], and N fertilization (0 and 180 kg·ha⁻¹ N) on root distribution and growth rate of tomato (Lycopersicon esculentum Mill.) transplants was examined in the field from May to August in 1996 and 1997. Experiments were conducted on a Norfolk sandy loam (fine-loamy, siliceous, thermic, Typic Kandiudults) in central Georgia. Root growth was estimated every 1 to 2 weeks with minirhizotron tubes installed in the plot. Roots were well distributed at soil depths between 1 and 58.5 cm and a maximum root count of 3.14 roots/cm² soil profile area was found at 19.5-cm depth with MP and no N fertilization in 1996. In general, NT with HV or with 0 kg·ha⁻¹ N increased root proliferation at a depth of 6.5 to 19.5 cm, while MP with 180 kg·ha⁻¹ N increased root proliferation at greater depths. Total root count between 1 and 58.5 cm was not influenced by management practices, but increased linearly at rates of 0.35 roots/cm² per day from 20 June to 11 July 1996, and 0.03 roots/cm² per day from 16 May to 5 Aug. 1997. Root growth thereafter was minimal. Because of the higher temperature during early development, growth rate and number of roots were greater in 1996 than in 1997. Superior moisture conservation, accompanied by increased N availability, may have increased root proliferation in the surface soil in NT with HV or with 0 kg·ha⁻¹ N compared with NT with NHV or with 180 kg·ha⁻¹ N, and MP with or without HV or with or without N fertilization. Root growth, however, was not related with aboveground tomato yield.

Optimum root growth and distribution is needed for proper shoot anchorage, water and nutrient uptake, and crop yield. Stress in the root zone can be expressed in the shoots, thereby influencing dry-matter partitioning between root and shoot and crop yields (Brower and de Wit, 1969; Leskovar and Stofella, 1995). Quantification of root growth is essential for characterizing partitioning of photosynthates (Box, 1996), for examining water and nutrient movement and uptake (Bland and Dugas, 1988; Klepper and Rickman, 1990), and for modeling root, plant, and soil characteristics (Murphy and Smucker, 1995; Sainju and Good, 1993).

Management practices, such as tillage, cover cropping, and N fertilization, can alter soil properties, and therefore influence root and shoot growth. While no-till can promote root growth relative to conventional tillage by conserving moisture and providing cooler temperature (Klepper et al., 1984; Merrill et al., 1996), it also can lead to the development of root-restricting layers because of increased soil compaction (Bauder et al., 1981; Kaspar et al., 1991; Voorhees, 1983). Similarly, cover cropping can promote root growth by increasing the amount of plant residue returned to the soil, thereby increasing soil organic matter concentration, decreasing bulk density, decreasing or increasing temperature, and increasing the density of biopores in the soil profile, where roots of succeeding crops can grow even in the root-restricting layers (Box, 1996; Karlen et al., 1994). Fertilization with N increases tomato root growth (Garton and Widders, 1990; Weston and Zandstra, 1989; Widders, 1989).

The soil separation method is the most reliable destructive method for measuring root length density in soil samples. However, the method is tedious and may lead to inaccuracies because of variation in the degree of root recovery, particularly of fine roots, from the soil and difficulty in separating living from dead roots (Merrill and Upchurch, 1994). Installation of minirhizotron observation tubes provides a nondestructive video imaging method of estimating root growth in the soil profile (Bland and Dugas, 1988; Box et al., 1989; Upchurch and Ritchie, 1983, 1984). Root growth can be estimated over extended periods of time without disturbing the soil profile (Hendrick and Pregitzer, 1992b; Upchurch and Ritchie, 1983). The minirhizotron root count (MRC) correlates well with root length density measured by the soil separation method (Box and Ramsuer, 1993; Merrill and Upchurch, 1994; Sainju et al., 1998). Lateral and basal roots of vegetable transplants often grow better than those of direct-seeded crops (Leskovar and Cantliffe, 1993; Leskovar et al., 1989; Stofella et al., 1988). Thus, the minirhizotron method may provide a better index of fine root growth in transplants than does the soil separation method because it estimates the number of roots, rather than measuring root length density or biomass. The number of fine roots per unit soil profile area is more important than the number of large roots in nutrient and water absorption (Box, 1996). The disadvantages of using the minirhizotron are that it cannot accurately estimate root growth near the soil surface because of soil shrinkage and drying, discontinuity of soil capillaries from the disruption of subsoil by the tube, and light leaks at the surface (Box, 1996).

Little is known about the combined effects of tillage, cover cropping, and N fertilization on root growth and distribution of tomato transplants in soil. Our objective was to determine the influence of tillage, hairy vetch cover cropping, and N fertilization on distribution and growth rate of the roots of such transplants as estimated by the minirhizotron method. This method was chosen, rather than the soil separation method, because of the rapidity with which root density can be estimated over extended periods of time without disturbing the soil profile.

Materials and Methods

Field conditions. The experiment was conducted at the Agricultural Research Station farm, Fort Valley State Univ., Fort Valley, Ga. The minirhizotron are that it cannot accurately estimate root growth near the soil surface because of soil shrinkage and drying, discontinuity of soil capillaries from the disruption of subsoil by the tube, and light leaks at the surface (Box, 1996).

Table 1. Some physical and chemical properties of Norfolk sandy loam (fine-loamy, siliceous, thermic, Typic Kandiudults) used in studying tomato root distribution.

| Depth (cm) | Bulk density (Mg m⁻³) | Mechanical analysis | Organic (g kg⁻¹) |
|-----------|----------------------|---------------------|-----------------|
|           | Sand  | Silt  | Clay |                | pH |  C  | N  |
| 0 to 5    | 1.27  | 760   | 140  | 100             | 6.0 | 9.12| 740 |
| 5 to 15   | 1.48  | 800   | 100  | 100             | 5.9 | 7.45| 855 |
| 15 to 30  | 1.44  | 680   | 140  | 180             | 5.9 | 3.83| 799 |
| 30 to 45  | 1.57  | 600   | 140  | 260             | 5.6 | 2.87| 633 |
| 45 to 60  | 1.53  | 560   | 160  | 290             | 5.5 | 2.41| 525 |

1Determined by the Walkley-Black method (Nelson and Sommers, 1982).
2Determined by the method described by Bremner and Mulvaney (1982).
The soil was a Norfolk sandy loam (fine-loamy, siliceous, thermic, Typic Kandiudults). Bulk density increased from 1.27 Mg·m⁻³ at the 0 to 5 cm depth to 1.57 at 30 to 45 cm, and clay concentration increased from 100 g·kg⁻¹ at 0 to 5 cm to 280 at 45 to 60 cm (Table 1). In contrast, organic C and N concentrations decreased with depth. Temperature and rainfall data were collected from a weather station 20 m from the study site.

Treatments. The treatments included two levels of tillage [no-till (NT) vs. moldboard plowing (MP)], two levels of cover crop [hairy vetch (HV) vs. no hairy vetch (NHV)], and two levels of N fertilization (0 and 180 kg·ha⁻¹ N). The MP consisted of harrowing (15 to 20 cm depth), followed by plowing (20 to 25 cm depth) and leveling (10 to 15 cm depth). The NT plots were left undisturbed except during planting of the cover crop and tomato plants when lines were drawn with a driller or planter. Hairy vetch is a suitable cover crop in Georgia. Tomato yields in this study, after the HV residue was incorporated into the soil, were similar to yields produced by the addition of 90 to 180 kg·ha⁻¹ N. The recommended dose of N fertilizer for tomato in central Georgia is 180 kg·ha⁻¹ N (University of Georgia, 1995).

The treatments were arranged in a split-split plot design, where tillage and cover crops were used as main plots, N fertilization was used as split plot, and soil depth or date of root measurement was used as split-split plot. These were arranged in a randomized complete block with three replications. The size of a split plot was 7.2 m × 7.2 m.

On 17 Sept. 1995 and 11 Oct. 1996, MP 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 28 kg·ha⁻¹, with a row spacing of 15 cm. No fertilizer, herbicide, or pesticide was applied to the cover crops. On 11 Apr. 1996 and 3 Apr. 1997, HV at the flowering stage was harvested from two 30 × 50 cm² areas within the plot for yield and N concentration determinations. In the NHV plot, weeds [dominated by henbit (Lamium amplexicaule L.) and cut-leaf evening primrose (Oenothera laciniata L.)] were collected as above. Plant materials were oven-dried at 60 °C, weighed, and ground to pass a 1-mm screen. Immedi-

Fertilizer and pesticide applications, irrigation, and transplanting. On 25 Apr. 1996 and 17 Apr. 1997, P (from triple superphosphate) and K (from KCI) were broadcast, each at the rate of 56 kg·ha⁻¹ based on soil test in all plots, along with 3.35 a.i. of diazinon [diethyl 0-(2-isopropyl-6-methyl-4-pyrimidyl) phosphorothioate] to control cutworms and 0.57 kg·ha⁻¹ of trifluralin [2,6-dinitro-N-dipropyl-4-( trifluoromethyl)]benzenamine] to control weeds. The fertilizer, pesticide, and herbicide were incorporated into the soil by plowing in the MP treatment. Irrigation was applied in all plots immediately after fertilizer and pesticide applications to minimize their losses. Using a planter, lines were drawn at 0.9 m apart in all plots, and holes (15-cm diameter × 15-cm depth) were dug at every 0.9 m in the lines where 5-week-old tomato (cv. Sunbeam) seedlings were transplanted. Starter solution containing 3 g·L⁻¹ (0.4 kg·ha⁻¹) of N, P, and K was drenched to the roots of each tomato plant for rapid establishment. Nitrogen fertilizer (NaNO₃) was split into three applications and broadcast at 3-week intervals from the date of transplanting. Overhead irrigation (reel rain gun, equivalent to 25 mm rain) was applied 1 d after fertilization and during tomato growth whenever soil moisture was at <60% field capacity. The plots were irrigated on 15 and 27 Apr., 9 and 22 May, and 25 and 26 June in 1996, and on 13 and 19 Apr., and 6 and 18 May in 1997.

Root Imaging. On 25 June 1996 and 17 May 1997, two minirhizotron acrylic tubes (5 cm diameter × 91 cm long) were installed 3 m apart in the middle rows from 0 to 70 cm soil depth at an angle of 15° with the vertical and 15 cm away from the base of the plant (Box, 1996; Box et al., 1989). Root image observations were taken every 1 to 2 weeks at 6.5-cm increments from 1 to 58.5 cm depth from June to Aug. 1996 and from May to Aug. 1997 using a minirhizotron camera (1.8 cm × 1.25 cm) attached to a rod (Bartz Technology, Santa Barbara, Calif.). The camera was inserted into the tube, and the pictures were transmitted to a videocassette recorder attached to a backpack and recorded on a tape.

Laboratory analysis. The N concentration in the cover crop sample was determined by the H₂SO₄-H₂O₂ method as described by Kuo et al. (1997b) and C concentration was determined by the wet digestion method as described by Kuo et al. (1997a). The N and C accumulations in the cover crop were determined by multiplying dry-matter biomass yield by N and C concentrations, respectively. Root images recorded by minirhizotron camera were displayed on a monitor and the number of roots/cm² soil profile area (MRC) was calculated. The MRC of two tubes per plot was averaged to minimize variation within the plot and the average value was used for a treatment (Hendrick and Pregitzer, 1992a). Total minirhizotron root count (TMRC) was calculated by adding MRC from 1 to 58.5 cm depth.

Data analysis. Tomato MRC and TMRC data were analyzed statistically using the MIXED procedure of SAS containing fixed and random effects (Littell et al., 1996). Sources of variation included tillage, cover crop, N fertilization, soil depth, root measurement date, and their interactions. The least square means test was used to determine the significance of differences between means. The analysis of repeated measures was used for the regression of TMRC over the date of measurement. Statistical significance was evaluated at P ≤ 0.05.

Results and Discussion

Climate. In 1996, average daily temperature (ADT) increased steadily from 9 °C on 6 Apr. to 28 °C on 23 May, dropped to 20 °C on

![Fig. 1. Average daily temperature and total daily rainfall near the study site from April to August in 1996 and 1997. Day 0 = 1 Apr., Day 153 = 31 Aug.](Image)

**Table 2. Dry-matter biomass yield (dry weight) and C and N accumulations in cover crop vs. weeds.**

| Biomass yield | C accumulation | N accumulation |
|---------------|----------------|----------------|
|               | 1996           | 1997           | 1996           | 1997           | 1996           | 1997           | 1996           | 1997           | 1996           | 1997           |
| Cover crop    |                |                |                |                |                |                |                |                |                |                |
| Hairy vetch   | 5.47 a         | 4.15 a         | 2391 a         | 1802 a         | 2053 a         | 66.7 a         |                |                |                |                |
| No hairy vetch| 1.94 b         | 1.90 b         | 656 b          | 817 b          | 36.9 b         | 27.9 b         |                |                |                |                |

*Mean separation within columns by the least square means test, P ≤ 0.05.*
and tomato root growth in the soil profile can be affected by variation in soil properties with depth, such as increasing bulk density and clay concentration or decreasing organic C and N concentrations (Table 1). Therefore, the effects of soil properties and management practices on tomato root growth are described during the early (May to June) stage after transplants were well established, and during the maximum (July) growth stage when fruit yields peaked (Figs. 2 and 3).

Roots were well distributed between 1 and 58.5 cm (Figs. 2 and 3). Although roots had grown to a depth of 39.5 cm on 20 June 1996 and 30 May 1997, when plants were at an early establishment stage, they had extended to a depth of 45.5 cm, especially in the MP plots receiving 180 kg·ha⁻¹ N, when fruit yield peaked on 22 July 1996 (Fig. 2B). The decreased root growth below 39.5 cm may have resulted from increased soil bulk density and clay concentration or decreased organic C and N concentrations (Table 1), because these soil properties influence root distribution (Sainju and Good, 1993; Sainju and Kalisz, 1990). Below a depth of 45.5 cm, root proliferation increased from early establishment to peak growth in 1996 (Fig. 2) but not in 1997 (Fig. 3).

The MRC was significantly influenced by tillage × N fertilization × depth interaction on 22 July 1996 and the tillage × cover crop × depth interaction on 30 May and 28 July 1997 (Table 3). Compared with other treatments, NT with 0 kg·ha⁻¹ N or with HV increased root proliferation at 6.5 to 13.0 cm and MP with 180 kg·ha⁻¹ N increased root proliferation at 26.0 to 45.5 cm (Figs. 2 and 3).

The increased root proliferation in NT with 0 kg·ha⁻¹ N at 6.5 to 13.0 cm (Fig. 2) could be due to increased moisture conservation and/or cooler temperature (decreased by 1 to 3 °C) relative to MP with or without N fertilization, as suggested by Merrill et al. (1996). Plant residue accumulated at the soil surface in NT

Table 3. Analysis of variance for minirhizotron root count of tomato at early (20 June 1996 and 30 May 1997) and maximum (22 July 1996 and 28 July 1997) growth as influenced by tillage (Till), cover cropping (Ccrop), N fertilization (Fert), and soil depth (Depth).

| Source        | 20 June | 22 July | 30 May | 28 July |
|---------------|---------|---------|--------|---------|
| Till          | NS      | NS      | NS     | NS      |
| Ccrop         | NS      | NS      | NS     | NS      |
| Fert          | NS      | NS      | NS     | *       |
| Ccrop × Fert  | *       | *       | *      | NS      |
| Depth         | *       | ***     | *      | NS      |
| Till × Fert × Depth | *     | NS     | NS   | NS      |
| Till × Ccrop × Depth | NS  | NS     | *    | **      |

* NS, **NS, ***NS Nonsignificant or significant at P ≤ 0.05, 0.01, or 0.001, respectively.
can act as mulch, thereby promoting root development (Merrill et al., 1996). Similarly, the increased root proliferation in NT with HV at 13.0 to 19.5 cm (Fig. 3) may have resulted from increased moisture conservation and/or N released from HV residue because plots with HV had higher N accumulation than did those with weeds in the NHV treatment (Table 2). Cover cropping can improve soil properties by adding more biomass and nutrients to the soil (Kuo et al., 1997b) and by increasing the density of biopores that are favorable for root growth (Singh and Sainju, 1998). In contrast, the increased root proliferation in MP plots with 180 kg·ha⁻¹ N at 26.0 to 45.5 cm (Fig. 2B) could be attributed to less soil impedance and increased N availability for root growth from N fertilization and/or increased soil N mineralization. Singh and Sainju (1998) observed that the number of tomato roots/cm² soil profile from 19.5 to 58.5 cm was 65% greater with MP than with NT. Increased root growth in the depth-restricting layers following conventional tillage vs. NT was noted by Bauder et al. (1985) and Bhagat and Acharya (1987). Similarly, increased root growth in tomato following N fertilization was observed by several researchers (Garton and Widders, 1990; Weston and Zandstra, 1989; Widders, 1989).

As indicated by MRC levels (Fig. 3 A and B), roots grew very gradually between 30 May and 28 July 1997. In contrast, MRC increased 2-fold from 20 June to 22 July 1996. This could be due to higher temperatures in May and June in 1996 than in 1997 (Fig. 1 A and B), thereby increasing N mineralization and availability from cover crop residues and soil. Tomato root growth increases linearly with increasing temperature up to 30 °C (McMichael and Burke, 1998), and soil N mineralization increases with increasing temperature up to 35 °C (Stanford et al., 1975). Higher temperature in 1996 also increased aboveground tomato yield relative to 1997. Root growth, however, was not related with aboveground yield. The effect of temperature on the aboveground growth in 1996 and 1997 will be discussed in a separate paper. Excessive rain in June to Aug. 1997 (Fig. 1D) may have slowed root growth.

**Rate of root growth.** The MRC varied significantly with date of measurement in both years, but interaction between date and depth was nonsignificant (data not shown). As MRC cannot be averaged across depths, TMRC was used to determine root growth over time as influenced by tillage, cover cropping, and N fertilization. Date of measurement significantly influenced TMRC in 1996 and 1997, but its interactions with tillage, cover cropping, and N fertilization were nonsignificant (Table 4). As a result, the regression analysis of TMRC over date of measurement was described by a quadratic model in 1996 ($R^2 = 0.89$, $P \leq 0.01$) and a linear model in 1997 ($R^2 = 0.58$, $P \leq 0.05$) (Table 4, Fig. 4). Because TMRC cannot be averaged across dates of measurement because of continuous growth, the effects of tillage, cover cropping, N fertilization, and their interactions were not considered.

In 1996, roots grew linearly from 58 d (20 June) to 79 d (11 July) after transplanting, after which growth stopped (Fig. 4A). Root counts dropped after 100 d. In 1997, root growth was linear from 23 d (16 May) to 104 d (5 Aug.) after transplanting (Fig. 4B). Variation in root growth with time results from the emergence of new roots and decay of old roots as the plant matures (Hendrick and Pregitzer, 1993; Klepper and Rickman, 1990; Merrill et al., 1996). The daily rate of TMRC growth was 0.35 roots/cm² from 20 June to 11 July 1996 and 0.03 roots/cm² from 16 May to 5 Aug. 1997. As a result, TMRC was 4-fold greater in 1997 than in 1996 (Fig. 4). The difference in the quantity and the rate of growth of TMRC between 1996 and 1997 could be explained by the differences in temperature and rainfall patterns. Because of the greater slope of temperature increase and higher average monthly temperature from April to June in 1996 (16 to 25 °C) than in 1997 (16 to 22 °C) (Fig. 1 A and B), roots grew more rapidly from June to July in 1996 than in 1997 (Figs. 4A and 4B). Tomato root growth peaks at 30 °C (McMichael and Burke, 1998), and increasing soil temperature of 5 to 7 °C with mulching enhances early root growth and P nutrition (Wien et al., 1993). When plants reached fruiting stage in July and August, root growth slowed or declined. Little rain in April to May 1996 was compensated for by timely irrigation, thereby promoting root growth, but cooler temperatures during the same months in 1997 slowed root growth. Most of the rain that fell during June to Aug. 1997 was too late to promote root growth and may have inhibited it because of the plant’s phenological development.

**Conclusions**

Our data indicate that root proliferation from 6.5 to 19.5 cm was greatest with NT with HV or with 0 kg·ha⁻¹ N, probably because of increased soil moisture conservation and/or N availability from HV residue. The MP plus 180 kg·ha⁻¹ N increased root proliferation only at a depth >26.0 cm, probably because of less soil impedance and/or increased N availability from soil N mineralization or N fertilization. The total number of roots between 1 and 58.5 cm was not influenced by management practices, but increased rapidly with date of measurement because of increased temperature. Therefore, NT with HV cover cropping is

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**Table 4.** Analysis of variance for total minirhizotron root count of tomato between 1 and 58.5 cm soil depth in 1996 and 1997 as influenced by tillage (Till), cover cropping (Ccrop), N fertilization (Fert), and date of root measurement (Date).  

| Source          | 1996   | 1997   |
|-----------------|--------|--------|
| Till            | NS     | ***    |
| Ccrop           | NS     | NS     |
| Fert            | *      | NS     |
| Till × Ccrop    | **     | NS     |
| Till × Fert     | *      | NS     |
| Ccrop × Fert    | ***    | *      |
| Till × Ccrop × Fert | NS | *      |
| Date            | ***    | *      |

**Regression analysis**

| Date          | Q**    | L**   |
|---------------|--------|-------|
| = "***"      | "*"   | "*"   |

"**" indicates values predicted by regression models. Day 20 = 9 May, Day 120 = 22 Aug. Note the difference in the y-axis scale for 2 years.
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