HortScience 42(7):1690–1694. 2007.

Overcoming Compaction Limitations on Cabbage Growth and Yield in the Transition to Reduced Tillage

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Additional index words. *Brassica oleracea* var. capitata, conservation tillage, minimum tillage, zone tillage, strip tillage, vegetable production, soil temperature, soil quality

***Abstract*. Vegetable producers are increasingly interested in adopting conservation tillage practices to maintain or enhance productivity and soil health, but reducing tillage may reduce yields in cool climates. Strategies to transition from full-width tillage to zone tillage systems for cabbage (*Brassica oleracea* L. Group capitata) were tested with the goals of overcoming soil temperature and compaction limitations and producing crop yield and quality equivalent to conventionally tilled. Designed to achieve differential soil temperature and compaction levels, the treatments were factorial combinations of two widths of zone tillage (15 and 30 cm) and two depths of zone tillage (10 and 30 cm) plus a conventional rototilled treatment (full width and 20-cm depth) as a control. To assess the effect of treatments in the transitional year to reduced tillage, the experiment was conducted in 2003 and 2004 at different fields that were previously conventionally tilled. Increasing tillage width from 15 cm to 30 cm increased soil temperature by 1 °C in both years but had a limited effect on cabbage growth and no effect on yield. Tillage width and soil temperature may have greater impact on an earlier planting. By contrast, increasing tillage depth from 10 cm to 30 cm reduced soil penetrometer resistance by up to 1 MPa, increased plant growth by 28%, and increased yield by 22%. Growth and yield in 30-cm depth treatments were similar to conventional tillage, indicating the undisturbed, between-row areas in zone tillage treatments did not restrict growth. Zone tillage did not affect cabbage maturity or quality. Tillage depth was more important to the success of this system than tillage width; vertical tillage to 30-cm depth left between 60% and 80% of the soil surface area undisturbed and can be an effective transition to conservation tillage for transplanted cabbage.**

In a cool, rainy climate such as the northeastern United States, field operations in vegetable systems are often based on stringent production schedules rather than ideal soil moisture conditions (Wolfe et al., 1995). Cabbage production is particularly susceptible to a decline in soil quality because field operations are often required when the soil is wet, both early in the spring and the late fall (Reiners, 2004).

Received for publication 4 Mar. 2007. Accepted for publication 8 July 2007.
Funding for this research was received from the Northeast Sustainable Agriculture Research and Education Program.
We thank Betsy Ingall, Steve McKay, William Ketchum, and Dave Becker for on-farm technical support and Karen Grace-Martin and Francoise Vermeylen for statistical consultation.
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Conservation tillage, any practice that minimizes soil and water loss and maintains 30% surface cover with cash or cover crop residue (Soil Science Society of America, 2005), could potentially balance some of the negative production-based impacts on soils. In practice, conservation tillage can be achieved by minimizing tillage operations temporally and spatially (e.g., reducing the number of times over a field or in the width or depth tilled) and managing surface residues (Magdoff and van Es, 2000). Research in conservation tillage has been ongoing since the 1960s and its success and adoption in agronomic crops such as field corn is well documented (Bentley, 1977; Cox et al., 1992; Young and Phillips, 1973).

Adoption of conservation tillage for vegetable crops grown in the Northeast, however, has been slow despite years of study with no tillage (directly seeding or transplanting into residue) or zone tillage (tillage within the planting zone of ≈10 to 15 cm width and depth). The primary reasons for limited adoption are reduced yields and delayed harvest for crops such as winter squash, tomatoes, and peppers (Loy et al., 1987; McKeown et al., 1988; Teasdale and Mohler, 1993; Johnson and Hoyt, 1999). The lack of tillage coupled with residue on the soil surface maintains cooler soil temperatures for longer periods in the spring (Teasdale and Mohler, 1993) and may explain much of the discrepancy of success for conservation tillage production between northern and southern climates.

Compaction is another yield-limiting factor in the transitional years to conservation tillage (Magdoff and van Es, 2000). For example, no-till soil is often more resistant to penetration than soil prepared by moldboard or a chisel plow in the first 2 years, particularly in the surface 7 to 8 cm (Kline, 1984). Moreover, cabbage plants are particularly sensitive to compaction with biomass and yield reduction as high as 60% and 70%, respectively (Wolfe et al., 1995).

The goal of this study was to overcome initial vegetable yield reductions associated with the transition to conservation tillage in cool climates by establishing reduced tillage treatments in a different field each year that had been previously conventionally tilled. Because tillage affects soil surface roughness and therefore reflection and retention of heat (Cruse et al., 1982) and can break previously compacted soil layers, zone tillage treatments were modified by width and depth of tillage to examine the relative importance of these two potential yield-reducing factors associated with transitioning to reduced tillage—cool soil temperature and high soil penetration resistance—and to identify the amount of tillage that maximized conservation values without reducing cabbage yield.

Materials and Methods

Cultural practices and experimental design

Plots were established in 2003 and 2004 at the Homer C. Thompson Vegetable Research Farm at Freeville, NY. Different fields were used each year to study the transition to conservation tillage. Each field had the same soil type, Howard gravelly loam (Glossoboric Hapludalf, loamy skeletal mixed mesic). Previous crops were dry beans (*Phaseolus vulgaris* L.) in 2002 and pumpkins (*Cucurbita pepo*) in 2003, each followed by cereal rye (*Secale cereale* L.) seeded at a rate of 190 $kg \cdot ha^{-1}$.

Fertilizer was broadcast at rates based on soil test results and recommendations for transplanted cabbage (Reiners, 2004): 68 $kg \cdot ha^{-1}$ of nitrogen (N), 34 $kg \cdot ha^{-1}$ of phosphorus (P), and 34 $kg \cdot ha^{-1}$ of potassium (K) in 2003 and 68 $kg \cdot ha^{-1}$ of N and 89 $kg \cdot ha^{-1}$ of P in 2004. An additional 68 $kg \cdot ha^{-1}$ of N as ammonium nitrate was sidedressed by hand at the cabbage cupping stage in both years.

Tillage treatments were established 3 to 5 d before transplanting. First, a subsoiling implement (Tuf-line; Monroe, Columbus, MS) with gauge wheels tilled to 10- and 30-cm depths (Table 1). This vertical tillage was followed by a single pass of three eight-wave coulters (Rawson; Farwell, MI) (each wave 17 cm in length) per row to establish 15- and 30-cm widths of disturbed soil (Table 1). Conventional tillage was approximated using a rototiller (model B180C; Maschio, Campondansego, Italy) to a depth of 20 cm in both bare and mulched plots.

The experimental design was a randomized complete block with four replications. Each subplot had four plant rows and measured 7.6 × 9.1 m.

Cabbage 'Fresco' seeds, treated with thiram, iprodione, and metalaxyl fungicides, were planted in trays with 162 cells (50 × 25 × 3.8 cm). Day and night temperatures in the greenhouse were ≈24 and 10 °C, respectively. Transplants were moved outdoors to a coldframe 1 week before planting. A no-till transplanter (model RJV600; RJ Equipment, Blenheim, Ontario, Canada) was used to plant seedlings on 9 June 2003 and 7 June 2004. Between-row spacing was 76 cm and in-row spacing was 36 cm between plants. Skips or misplaced plants were transplanted by hand the next day.

Glyphosate was applied to kill the rye and may have provided some weed control. Further control was achieved with pretransplant oxyfluorfen (2.4 L·ha^{-1} product) and post-transplant s-metolachlor (1.2 L·ha^{-1} product).

Plants were scouted weekly for flea beetles (*Phyllotreta cruciferae*) using a damage threshold of eight beetles per plant in 2003. In 2003, both permethrin (0.44 L·ha^{-1} product) and lamda-cyhalothrin (0.28 L·ha^{-1} product) were applied once each for control. The threshold was reduced to five flea beetles per plant in 2004, and plants were sprayed once each with carbaryl (1.1 kg·ha^{-1} product), endosulfan (2.4 L·ha^{-1} product), permethrin (0.44 L·ha^{-1} product), and lamda-cyhalothrin (0.22 L·ha^{-1} product).

Irrigation to supplement rainfall in 2003 was applied three times based on gypsum moisture block readings less than 50% saturation (model 5910A; Soil Moisture Equipment Corp., Santa Barbara, CA). No supplemental irrigation was necessary in 2004. Both seasons had higher than average precipitation. With 160 mm in July 2003, rainfall exceeded the 30-year average by 78%; in 2004, both July (240 mm) and August (172 mm) exceeded the 30-year average by 167% and 100%, respectively (Northeast Regional Climate Center, 2004).

Table 1. Tillage treatments for conservation tillage cabbage trials in 2003 and 2004 at Freeville, NY.

Width (cm)	Depth (cm)	Volume (cm^3)
15	10	150
30	10	300
15	30	450
30	30	900
70 (full width)	20	1400

Plant measurements

Aboveground biomass sampling. Three plants per plot were destructively sampled at 14, 28, 58, and 71 d after planting (DAP) in 2003 and 14, 29, 44, 56, and 71 DAP in 2004. Plants were randomly chosen from the two center rows of each plot and cut at the soil line. Each sampled plant had all neighbors intact to avoid sampling bias. Plant fresh and dry weight (after oven-drying at 41 °C) were recorded.

Harvest yield and quality. Head yield and quality were sampled from a 2.7-m^2 area in the center of each plot. The areas were harvested twice, 77 and 91 DAP in 2003 and 80 and 93 DAP in 2004, in case maturity was delayed in some treatments. Because there were no treatment differences in maturity, yield data from both harvests were summed for analysis. Three representative heads from each plot were cut in half to assess internal characteristics and quality. Head length and width and core length and width were measured. Overall head appearance, including external color, blemishes, and density, was qualitatively assessed on a point scale ranging from poor (1) to excellent (5).

Soil measurements

Soil temperature. Thermocouples were installed 15 cm below the soil surface in the plant row 10 d after planting in 2003 and 1 d after planting in 2004. Soil temperatures were recorded every hour using an AM 416 Multiplexer with a CR10X datalogger (Campbell Scientific, Logan, UT); data were output as mean temperatures every 2 h.

To analyze variation within a 48-h period, we examined bihourly temperatures at the beginning and end of an 8-d period preceding an increased rate of plant growth: 22 to 23 and 27 to 28 DAP in 2003 and 19 to 20 and 24 to 25 DAP in 2004. To analyze variation within the entire 8-d interval, the maximum and minimum temperatures were calculated for each day between 22 and 29 DAP in 2003 and between 19 and 26 DAP in 2004. Soil temperature was measured for the entire season, but analysis of data at the middle and end of the season indicated no differences (data not shown).

Penetrometer resistance. Soil resistance to penetration as a function of depth was assessed by averaging three in-row measures per plot. In 2003, a Bush recording cone-tip penetrometer (Findley, Midlothian, Scotland), registering every 3.5 cm to a depth of 31.5 cm, was used 16 and 106 DAP. In 2004, resistance was measured 17 and 104 DAP using a Rimik CP20 recording cone-tip penetrometer (Agridry, Toowomba, Australia) every 2.5 cm to a depth of 30 cm. Soil water content consistently ranged from 0.11 to 0.13 g·g^{-1} at the time of sampling for both years (data not shown). This soil type was up to 50% stones by volume, which resulted in higher penetrometer resistance values than equivalent root penetration resistance in a nonstony soil; the penetrometer resistance values presented are comparable among these treatments only. Although the established threshold of 3.0 MPa to limit plant growth in coarse-textured soils (Laboski et al., 1998) may not be applicable to all the values presented, it is included in figures as a point of reference.

Statistical analyses and data presentation

Analysis of variance to determine tillage treatment effects and their interaction was performed using the SAS Mixed procedure (SAS systems, Cary, NC). Multiple comparisons were performed with the overall error rate controlled by Tukey-Kramer or Bonferroni adjustment. Contrasts were performed when appropriate, grouping tillage treatments by width and depth. Because of significant treatment-by-year interactions, data were analyzed and presented within each year. Tillage width was not found to be a significant factor affecting soil penetrometer resistance and tillage depth was not found to be a significant factor affecting soil temperature; data are therefore presented by factor.

Results and Discussion

Conservation tillage has the potential to inhibit growth by reducing soil temperature, but this trend was not observed in this study. Reduced tillage treatments (15- and 30-cm width) had minimal effect on soil temperature on each day sampled in 2003; soils were cooler by 1 °C or less compared with full-width tillage (70 cm) only between 2200 and 2400 HR ($P < 0.10$; Fig. 1A–B). In 2004, treatments tilled to 15-cm width were cooler than both the 70-cm and 30-cm width treatments ($P < 0.10$) between 2000 and 2400 HR 19, 20, and 24 DAP (Fig. 1D–E), but temperature differences were also less than 1 °C. Although narrow tillage did not affect daily maximum temperatures, daily minimum soil temperatures for treatments tilled to 30- and 15-cm width were cooler than those tilled to 70-cm width between 22 and 29 DAP in 2003 ($P < 0.10$; Fig. 1C) and between 21 and 25 DAP in 2004 ($P < 0.10$; Fig. 1F).

Other researchers exploring conservation tillage for cabbage attributed yield reduction to temperature differences up to 4 °C between mulched and bare-ground treatments (Hoyt, 1999). By contrast, temperature differences of up to 3 °C did not reduce cabbage growth (Knavel and Herron, 1981). Wilhoit et al. (1990) recorded a 1.5 °C difference between mulched and bare-ground treatments but concluded these differences were not enough to account for yield reductions observed because soil temperatures for all treatments ranged between 23 and 25 °C, within the range conducive for plant growth.

In this study, increased tillage width from 15 cm (20% surface disturbance) to 30 cm (40% surface disturbance) had minimal effect on plant growth and yield (Tables 2 and 3) and no effect on internal color, external color and quality, or maturity date (data not shown). These results indicate that wider widths of soil disturbance did not increase soil temperature enough to improve

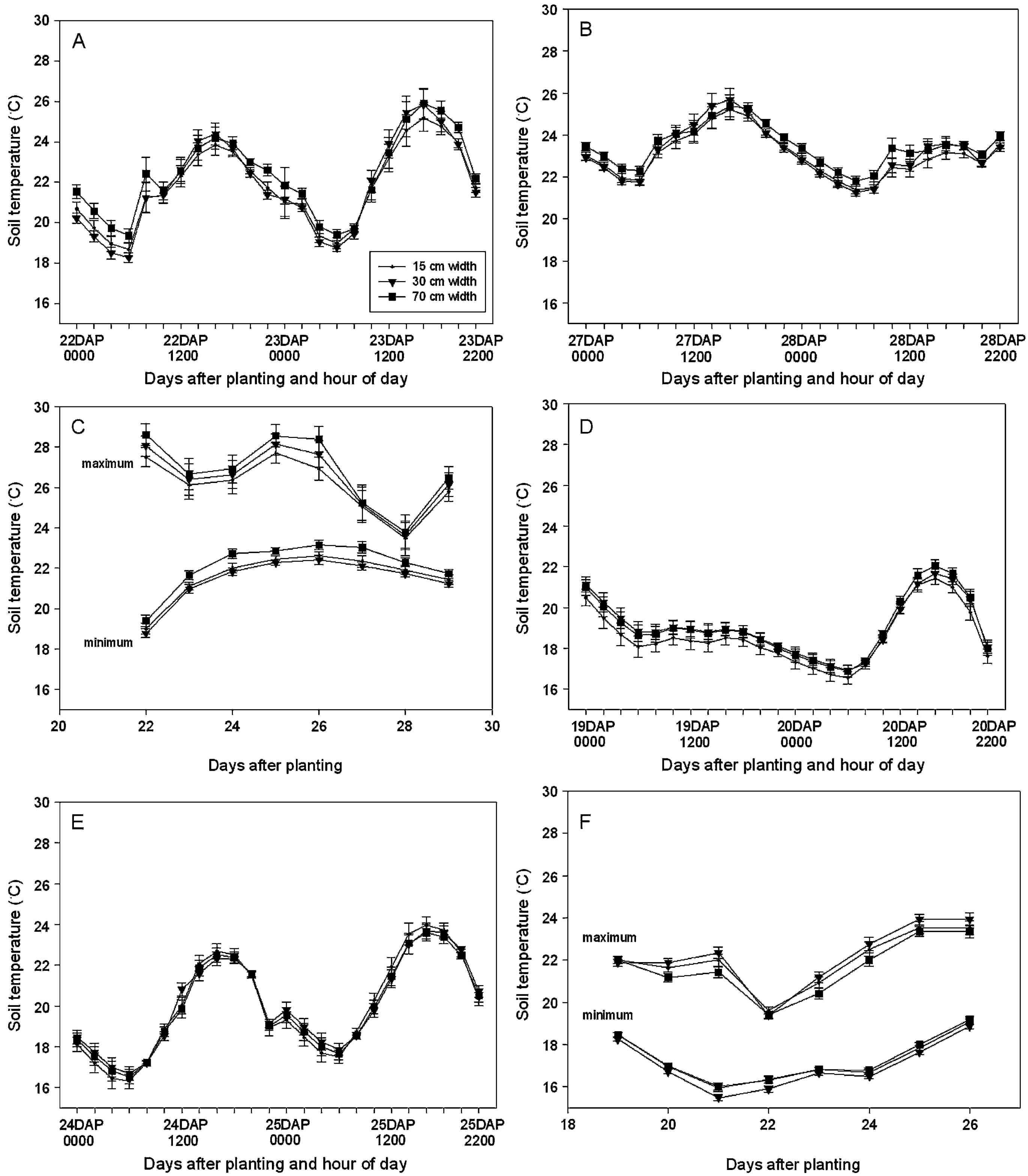

Fig. 1. Effect of tilled width on soil temperature. Data from 2003 include 2-hour average soil temperature (**A**) 22 to 23 d after planting (DAP) and (**B**) 27 to 28 DAP and (**C**) daily soil temperature maximum and minimum 22 to 29 DAP. Data from 2004 include 2-hour soil average temperature (**D**) 19 to 20 DAP and (**E**) 24 to 25 DAP and (**F**) daily soil temperature maximum and minimum 19 to 26 DAP.

crop performance in this reduced tillage system.

Later-season planting (June) allowed soils to warm and probably minimized the soil temperature reduction from reduced tillage treatments and potential delayed crop maturity. Delaying planting until soils warm can be an important management practice for success with this system in cool climates. For example, early-season planted tomatoes in the mid-Atlantic were delayed, but yields for the June-planted crop were not reduced (Abdul-Baki and Teasdale, 1993). Similarly, no-till dry beans planted in New York in early June were not delayed because soil warming was less influential for crop establishment compared with earlier in the year (Kline, 1984).

Table 2. Effect of tillage width, depth, and volume on aboveground biomass accumulation (grams per plant) in 2003 and 2004.[z]

	2003 DAP[y]				2004 DAP				
	14	28	58	71	14	29	44	56	71
Tillage									
Width (cm)									
15	8	77	983	2461	7	67	450	1069	1350
30	7	88	1119	2725	7	67	424	939	1475
	NS	NS	NS	NS	NS	NS	NS	NS	NS
Depth (cm)									
10	7	72	970	2419	6	60 b[x]	375 b	852	1239
30	8	92	1131	2767	8	74 a	499 a	1155	1585
	NS	NS	NS	NS	NS	*	*	NS	NS
Volume (cm^3)									
150	7	61	871	2193	7	68 ab	412 b	907	1250 b
300	7	84	1069	2646	6	51 b	338 b	798	1228 b
450	9	92	1094	2729	8	68 ab	488 ab	1231	1450 ab
900	7	92	1168	2805	8	82 ab	510 ab	1080	1721 a
1400	6	77	1022	2481	8	104 a	658 a	1188	1708 ab
	NS	NS	NS	NS	NS	*	*	NS	*

[z]Planting dates were 9 June and 7 June, respectively.
[y]Days after planting.
[x]Same letter denotes nonsignificant (NS) comparison in columns by treatment.
[*]Significant at $P < 0.10$.

Table 3. Effect of tillage width, depth, and volume on cabbage yield and head weight.

	Yield (T per ha)		Head wt (kg)	
	2003	2004	2003	2004
Tillage				
Width (cm)				
15	48	51.6	1.7	1.7
30	52.7	47.5	1.8	1.5
	NS	NS	NS	NS
Depth (cm)				
10	45.2 b[z]	47.7	1.6 b	1.6
30	55.5 a	51.4	1.9 a	1.6
	***	NS	***	NS
Volume (cm^3)				
150	42.9 c	52.7	1.5 c	1.7
300	47.5 bc	42.6	1.6 bc	1.5
450	53.1 ab	50.4	1.8 ab	1.6
900	57.9 a	52.3	1.9 a	1.5
1400	53.9 ab	44.0	1.7 ab	1.7
	***	NS	*	NS

[z]Same letter denotes nonsignificant (NS) comparison in columns by treatment.
[*,***]Significant at $P < 0.10$ and 0.001 respectively.

Reducing tillage may inhibit crop growth by failing to break previously compacted soil, which can physically restrict root growth or reduce soil-to-root contact. Early in the 2003 season, treatments tilled to 30-cm depth were less resistant than 10- and 20-cm depth treatments ($P < 0.01$) at 10 and 28 cm below the soil surface (Fig. 2A); these differences continued for the duration of the 2003 season, measurable 106 d after planting between 14 and 24.5 cm below the soil surface (Fig. 2B). Early in the 2004 season, treatments tilled to 30-cm depth were less resistant than 10-cm depth treatments between 5 and 30 cm below the soil surface ($P < 0.10$; Fig. 2C). The treatments tilled to 30-cm depth were also less resistant than 20-cm depth treatments between 17.5 and 25 cm below the soil surface at 17 d after planting in 2004 ($P < 0.10$; Fig. 2C). By 104 d after planting in 2004, there were no differences in soil resistance among treatments (Fig. 2D). The effect of 30-cm depth tillage to minimize soil resistance was less significant at the start of 2004 ($P < 0.01$) compared with 2003 ($P < 0.10$) and, with higher than average rainfall, did not persist to the end of the season. Penetrometer resistances for all treatments in the 2004 field were relatively low at both the beginning and end of the season.

Tillage depth did not affect plant biomass accumulation in 2003 (Table 2), but significantly increased both cabbage head weight and yield ($P < 0.001$; Table 3). No differences attributable to tillage depth in head appearance, quality, or maturity were noted (data not shown). The 30-cm depth treatments yielded 23% more and had 19% higher head weights compared with 10-cm depth treatments in this year ($P < 0.001$; Table 3). Treatments that included 30-cm depth as part of the disturbed soil volume (450 and 900 cm^3) had yield and head weights similar to conventional tillage (1400 cm^3, the maximum volume of soil disturbance) (Table 3).

Tillage depth was a significant factor affecting plant growth in 2004 ($P < 0.10$; Table 2). Treatments tilled to 30-cm depth increased plant biomass accumulation 23% and 33% at 29 and 44 d after planting, respectively, compared with 10-cm depth treatments ($P < 0.10$; Table 2). At these dates, plants grown in the largest volume of tilled soil (70-cm width and 20-cm depth, rototilled) were up to 90% larger than those grown in 150 cm^3 (10-cm width and 15-cm depth) and 300 cm^3 (30-cm width and 10-cm depth) ($P < 0.10$; Table 2). By 71 d after planting, however, plants with a tilled volume of 900 cm^3 (30-cm width and 30-cm depth) had outgrown those in 150 and 300 cm^3 treatments by 40% ($P < 0.10$; Table 2) and were similar to those in 450 cm^3 (15-cm width and 30-cm depth) and similar to those in rototilled plots (Table 2). Despite these growth differences, tillage depth did not affect yield, head weight (Table 3), or head quality (data not shown) in 2004, in which higher than average rainfall may have reduced plant stress associated with soil compaction.

Cabbage growth and yield were similar among conventional tillage and reduced tillage systems that disturbed at least 450 cm^3 per plant, indicating the undisturbed area between the rows in the zone tillage treatments did impede cabbage roots, which proliferate in a shallow mat (Weaver and Bruner, 1927; Wolfe, et al., 1995). The reduced tillage treatments left between 60% and 80% of the soil surface area undisturbed compared with conventional tillage and therefore prevented further tillage-induced compaction.

Increasing depth of tillage was more important to the success of this system than increasing width of tillage. Several reduced tillage studies for cabbage (Knavel and Herron, 1981; Wilhoit et al., 1990; Bottenberg et al., 1997) found soil temperature differences greater than those observed in this study, but only soil temperatures greater than ≈4 °C generated a cabbage response (Hoyt, 1999). Instead, soil compaction was the main factor associated with reduced yields (Knavel and Herron, 1981; Bottenberg et al., 1997), as was the case in this study. Conservation tillage for transplanted cabbage therefore requires active management of soil compaction, whereas soil temperature is of secondary importance.

Soil compaction management in reduced tillage systems balances the need to make previously compacted layers more friable without causing further compaction with tillage passes. Tillage to 30-cm depth reduced compaction in this soil type and minimized surface disturbance compared with conventional tillage, but had similar cabbage growth and yield. Implementing a reduced tillage system that includes vertical tillage to 30-cm depth can be an effective transition to conservation tillage without increasing soil penetration resistance or reducing cabbage growth and yields.

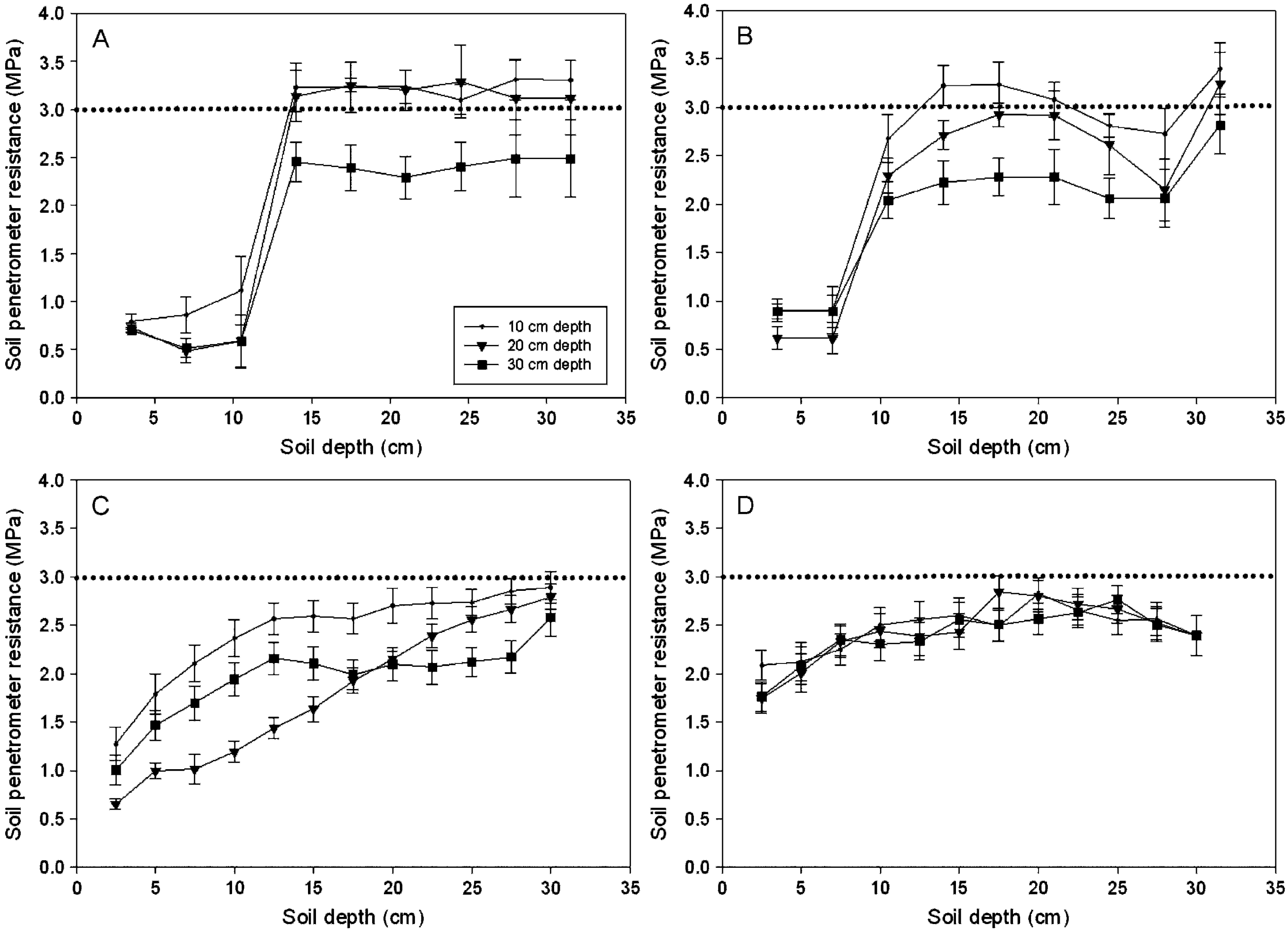

Fig. 2. Effect of tilled depth on penetration resistance. Data are penetrometer resistance values as a function of soil depth. Data from 2003 include (**A**) 16 d after planting (DAP) and (**B**) 106 DAP. Data from 2004 include (**C**) 17 DAP and (**D**) 104 DAP. The 3.0-MPa threshold above which plant growth may be limited is highlighted by a dotted line.

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