Rye Mulch Management Affects Short-term Indicators of Soil Quality in the Transition to Conservation Tillage for Cabbage

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Abstract. If benefits of conservation tillage can be quantified even in the transition year from conventional tillage, growers will more likely integrate practices that maintain or enhance soil quality and productivity. The management of surface residue is an important component of conservation tillage, especially in cool, rainy climates where vegetable growth and yield reductions have been observed when heavy residue is present. Cereal rye (*Secale cereale* L.), grown until flowering, was killed with glyphosate and was then cut and removed (stubble treatment) or rolled or chopped to form a surface mulch (mulched treatment) before transplanting cabbage. Rolled mulch increased soil wet aggregate stability by 4% and reduced soil penetrometer resistance by up to 0.5 MPa compared with rye stubble treatments in 2003. In 2004, frequent rains saturated soils and may have accelerated the decomposition of chopped mulch, minimizing treatment effects. Rolled mulch reduced soil temperatures by up to 2 °C in 2003, but June transplanting of cabbage probably minimized the impact of soil temperature. Mulched treatments did not delay cabbage maturity or affect head quality characteristics such as color or uniformity. Although rolled mulch reduced cabbage growth by as much as 30% and yield by 21% in 2003, chopped mulch did not affect growth or yield in 2004. Yield reduction may be overcome by killing the rye relatively early in the spring or retaining only the surface stubble; these strategies may maintain or measurably improve soil quality even in the transition year to conservation tillage.

Conservation tillage systems minimize soil disturbance and maintain 30% cover with surface residue (SSSA, 2005). Despite potential improvements in soil physical and biological properties, the adoption of conservation tillage practices for vegetable crops in the Northeast has been slow. Early research reported harvest delays and yield reductions for crops such as winter squash, tomatoes, and peppers in areas with cold, wet weather (Loy et al., 1987; McKeown et al., 1988;

Teasdale and Mohler, 1993). Plant residue on the soil surface maintains cooler soil temperatures for longer periods in the spring (Hoyt, 1999; Teasdale and Mohler, 1993). Furthermore, a growing cover crop may compete for nutrients with the main crop if there is inadequate kill (Bottenberg et al., 1997). A decomposing cover crop can lead to immobilization of nutrients by soil microbes (Hoyt, 1999). In addition, allelopathic chemicals, from rye (*Secale cereale* L.) in particular, may interfere with the growth and yield of the main crop. For example, allelochemicals from rye completely inhibited germination of small-seeded crops such as tomato (*Lycopersicon esculentum*) and lettuce (*Lactuca sativa*) in laboratory trials (Burgos and Talbert, 2000) and reduced root growth of cucumber (*Cucumis sativus*) seedlings (Burgos et al., 2004). Growth and yield was not reduced, however, for transplanted tomatoes (Smeda and Weller, 1996), field corn (Duiker and Curran, 2005), and barley and sugar beets

(Garwood et al., 1999) in field trials after rye cover cropping.

Rye is often used in the Northeast because it is winter hardy and can be planted relatively late (Stivers-Young, 1998). Rye scavenges the remaining soil nitrogen (Johnson and Hoyt, 1999; Stivers-Young, 1998), resulting in reduced nitrate leaching compared with nonmulched plots (Jackson et al., 2003). Rye surface mulch also increases soil microbial biomass (Jackson et al., 2003), suppresses weeds similar to herbicide-treated plots (Bottenberg et al., 1997), and has lower insect pests in conservation tillage systems (Bottenberg et al., 1997).

If soil quality benefits can be demonstrated early in the transition to conservation tillage with minimal or no crop yield reduction, growers will more likely to integrate these practices for vegetable crops. We examined the individual components of conservation tillage–the reduction of tillage, reported in a separate paper, Mochizuki et al. (2007), and in the concurrent study discussed here, the management of surface residue. We evaluated strategies with the potential to overcome initial vegetable yield reductions in the transitional year from conventional tillage, hypothesizing that dense surface residue would increase aggregate stability, reduce compaction, and increase soil water content, and natural decomposition of the mulch would eliminate negative impacts on cabbage growth and yield.

Materials and Methods

Treatments and experimental design. Cereal rye was seeded at a rate of 190 kg·ha⁻¹ during the fall before each planting year at the Homer C. Thompson Vegetable Research Farm at Freeville, New York (42°31′N, 76°20′W). In late May, the well-developed rye (head stage, 2828 kg·ha⁻¹ dry weight in 2003 and 3308 kg·ha⁻¹ in 2004) was sprayed with glyphosate (0.26 L·Ha⁻¹) to kill the plants and roots and to provide some weed control in the field. The rye was then cut on one-half the plots using a pull-type forage harvester (New Holland; New Holland, PA) so that 2 to 4 cm of intact rye and roots or "stubble" remained; the cut rye, blown into a wagon trailing the harvester, was removed from the field. On the remaining plots, the standing rye was rolled flat using a roller implement (Rotavator; Howard-Konskilde, Exeter, Ontario, Canada) in 2003 and a rolling stalk chopper (Buffalo; Fleischer Manufacturing; Columbus, NE) in 2004 to form a dense surface mulch, referred to as the "mulched" treatments. The experimental design was a randomized complete block with four replications of two surface rye treatments, "stubble" and "mulched." Because the focus of this study was the transition to conservation tillage, a different field with the same soil type, Howard gravelly loam (Glossoboric Hapludalf, loamy skeletal mixed mesic), was evaluated each year. Previous crops were dry beans in 2002 and pumpkins in 2003.

Based on the results of analytical soil fertility tests conducted in the fall before rye cover crop seeding and maximum recommendations for transplanted cabbage (Reiners, 2004), fertilizer was broadcast at a rate to provide nitrogen to the cabbage in the case of immobilization with heavy surface residue: 68 kg· ha⁻¹ of N, 34 kg· ha⁻¹ of P, and 34 kg· ha⁻¹ of K in 2003 and 68 kg· ha⁻¹ of N and 89 kg· ha⁻¹ of P in 2004. An additional 68 kg·ha⁻¹ of N as ammonium nitrate was sidedressed by hand at the cabbage cupping stage in both years.

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 about 24 °C and 10 °C, , respectively. Transplants were raised in the greenhouse for 32 d and were hardened in a coldframe for 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 between plants and in-row spacing was 36 cm between plants. Skips or misplaced plants

were transplanted by hand the next day. Each plot had four plant rows and measured 7.6 × 9.1 m.

Oxyfluorfen (2.4 L· ha⁻¹ product) was applied pretransplant for broadleaf weed control and s-metolachlor (1.2 L· ha⁻¹ product) was applied post-transplant for annual grass control (Reiners, 2004). Plants were scouted weekly for flea beetles (*Phyllotreta cruciferae*) using a damage threshold of eight beetles per plant in 2003. In 2003, 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, July (240 mm) and August (172 mm) exceeded the 30 year average by 167% and 100%, respectively (Northeast Regional Climate Center, 2004).

Soil wet aggregate stability. The soil was sampled 14 and 105 d after planting (DAP) in 2003 and 23 and 100 DAP in 2004. Two in-row and two between-row soil samples were taken per plot to a depth of 15 cm. Each sample was mixed thoroughly and was

Table 1. Effect of surface rye mulch on the percentage of stable soil aggregates sampled to a 15-cm depth in a gravel loam at Freeville, New York. Standing rye was cut and removed in the "stubble" treatment and was rolled or chopped (2004) in the "mulched" treatment.

Treatment	2003		2004	
	14 DAP	103 DAP	23 DAP	100 DAP
Stubble	23%	26% bᶻ	14%	15%
Mulched	23%	30% a	16%	15%
P-value	NS	*	NS	NS

ᶻMean separation in columns.
ᴺˢ, *Nonsignificant or significant at $P \leq 0.05$.
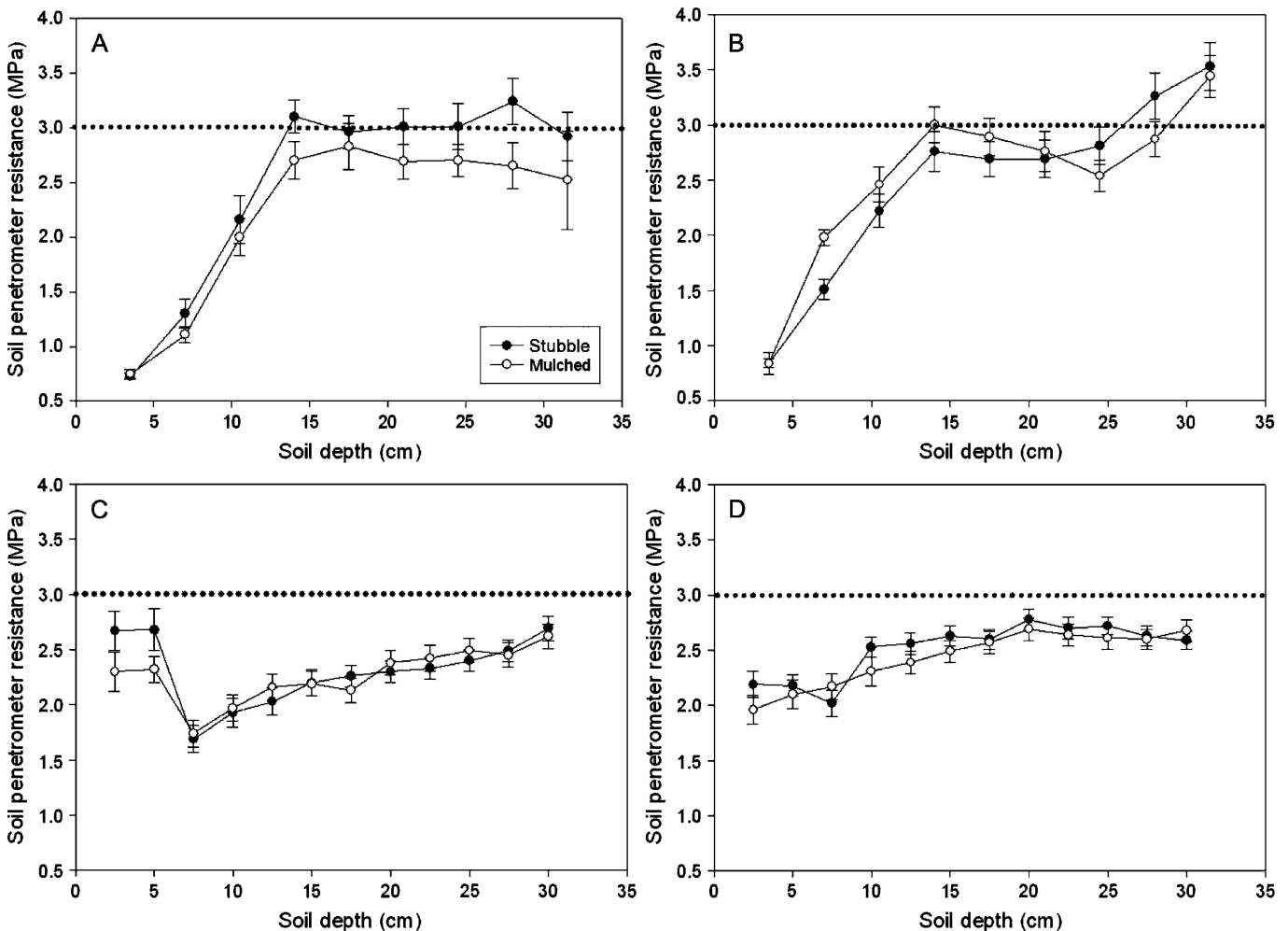DAP, days after planting.

Fig. 1. Effect of surface rye mulch on soil penetrometer resistance as a function of soil depth in a gravel loam at Freeville, New York. Standing rye was cut and removed in the "stubble" treatment and was rolled or chopped (2004) in the "mulched" treatment. Data from 2003 include (**A**) 16 DAP and (**B**) 106 DAP. Data from 2004 include (**C**) 17 DAP and (**D**) 104 DAP. Standard error bars indicate the variability for the mean of each treatment and depth. The 3.0 MPa threshold above which plant growth may be limited is indicated by a dotted line.

allowed to air dry for 24 to 48 h. Aggregate stability was evaluated following the methods of van Es et al. (2006). Briefly, soil was separated into two aggregate fractions (2–8 mm and 250 μm–2 mm) by shaking for 10 s with U.S. standard 8-mm, 2-mm, and 250-μm sieves on an automated coarse sieve shaker (W.S. Tyler, St. Catharines, Ontario, Canada). The weight of the fraction larger than 8 mm was used to calculate the percentage of gravel content of the soil and the fraction smaller than 250 μm was discarded.

A subsample of aggregate crumbs, ≈70 g of large size (2–8 mm) and 30 g of small size (250 μm–2 mm), were evenly distributed on 2-mm and 250-μm sieves, respectively. The samples were subjected to simulated rainfall using the Cornell Sprinkle Infiltrometer (Ithaca, NY) for 5 min to deliver 2.5 J of energy (1.25 cm of water column), approximating the brief but intense rains common in the Northeast. The amount of aggregates remaining on the sieve surface after the rainfall simulation was corrected for the water, rock, and particulate organic matter content of the sample by weight to indicate the percentage of stable soil aggregates.

Soil water content. Gravimetric soil water content was measured 8, 55, and 105 DAP in 2003 and 23 and 100 DAP in 2004. Two in-row and two between-row soil samples were taken per plot to a depth of 15 cm. Each sample was thoroughly mixed before removing a subsample into sealed moisture cans or plastic bags to prevent desiccation. In the laboratory, ≈2 g of soil from each can was oven-dried for 24 to 48 h at 61 °C. The dry weight of soil was subtracted from the fresh weight; the difference was divided by the fresh weight to calculate the percent of water by weight.

Soil 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, UK), 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. This soil type was up to 50% stones by volume, which undoubtedly resulted in penetrometer resistance values larger than the established threshold of 3.0 MPa shown to limit plant growth in coarse-textured soils (Laboski et al., 1998).

Soil temperature. Thermocouples were installed at a soil depth of 15 cm 10 DAP in 2003 and 1 DAP in 2004 and were connected to a AM 416 Multiplexer with a CR10X data logger (Campbell Scientific, Logan, UT.). 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).

Aboveground biomass sampling. Three plants per plot were destructively sampled at 14, 28, 58, and 71 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 were 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-m² 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.

Statistical analysis. Analysis of variance was performed using the SAS Mixed Procedure (SAS systems, Cary, NC). Because of significant treatment by year interactions, data were analyzed and presented within each year.

Results and Discussion

The presence of dense rye mulch increased soil aggregate stability by the end of the 2003 season (Table 1). Aggregates under rolled mulch were 30% stable compared with 26% for the stubble treatment ($P < 0.05$). What constitutes meaningful differences in soil aggregation in conservation tillage using the rainfall simulation technique is not yet known; however, several studies using traditional wet sieve methods have compared heavy residue systems and reduced tillage with conventional tillage. For example, after 20 years in which conventional, no tillage, and a reduced tillage with stubble mulch was alternated with fallow, Cambardella and Elliot (1993) found a 5% increase in aggregate stability for no tillage compared with stubble mulch for the 53- to 250-μm size fraction but no differences in the other size fractions. No tillage aggregates in the 53- to 250-μm size fraction were 10% more stable than conventional tillage aggregates. By contrast, Seybold et al. (2002) found aggregate stability was increased by 40% in the 26th year of no-till compared with conventional tillage, and Leibig et al. (2004) found that a rotation of spring wheat, winter wheat, and sunflower followed by no tillage had 35% more stable aggregates compared with a spring wheat, fallow, conventional tillage system.

The dense surface mulch may have provided organic matter to soil microorganisms that bind soil particles in addition to the rye roots that were present in surface and stubble treatments. Aggregate stability using the traditional wet sieving technique has been correlated to soil carbon content (Stine and Weil, 2002). Furthermore, an increased proportion of macroaggregates with particulate organic matter were found in no tillage compared with conventional (Cambardella and Elliot,1993). The potential correlation to biological activity of soil aggregate stability using the rainfall simulation technique of this study must still be established.

In 2004, however, the presence of dense mulch did not affect wet aggregate stability (Table 1). Although both sampling years were wetter than average, in 2004, July and August exceeded the 30 year average by 134% (Northeast Regional Climate Center, 2004). The heavy rains probably accelerated the decomposition of the surface mulch, minimizing its impact on soil quality. In addition, aggregate stability was less overall in 2004 compared with 2003; the physical impact of frequent rain droplets likely fragmented soil aggregates in mulched and stubble plots to the point where the treatments were indistinguishable.

Soil under dense rye mulch was up to 0.5 MPa less resistant to penetration compared with the stubble treatment between 14 and 28 cm depths, 16 DAP in 2003 ($P < 0.10$; Fig. 1A), likely resulting from about 1% higher water contents at the beginning and middle of the 2003 season ($P < 0.0001$; Table 2). By the end of 2003, there were no significant differences in resistance (Fig. 1B) or soil water content (Table 2) attributable to mulch. In 2004, differences in penetrometer resistance between mulched and stubble plots were found only at one or two soil depths, with no clear trend emerging at 17 or 104 DAP (Fig. 1, C and D). Similarly, there were no differences in soil water content in 2004 (Table 2), presumably because of higher-than-average precipitation that saturated soils in both treatments.

Surface residue may decrease evaporation, reduce surface runoff, and improve

Table 2. Effect of surface rye mulch on soil water content (percentage water of fresh soil by weight) sampled to a 15-cm depth in a gravel loam at Freeville, New York.

Treatment	2003			2004	
	5 DAP	55 DAP	105 DAP	23 DAP	100 DAP
Stubble	13% b[z]	12% b	14%	13%	13%
Mulched	14% a	13% a	14%	12%	13%
P-value	***	**	NS	NS	NS

[z]Mean separation in columns.
[NS, **, ***]Nonsignificant or significant at $P \leq 0.01$ or 0.001, respectively.
DAP, days after planting.

infiltration, all of which can increase soil water content (Raper et al., 2000; Vyn et al., 1998). Wilhoit et al. (1990) found that even small differences of 2% in soil moisture during the middle of the summer season were important to cabbage growth and yield. Particularly in drier conditions, surface mulch can improve yields by preventing evaporation (Johnson and Hoyt, 1999). For example, strip-tilled cabbage with rye surface mulch had 56% higher yield than with rye stubble mulch in one dry year (Wilhoit et al., 1990).

No-tillage with standing rye yielded more pumpkins than disk tillage during an unusually hot, dry growing season (Rapp et al., 2004).

The effect of surface residue on penetrometer and soil water content is not always
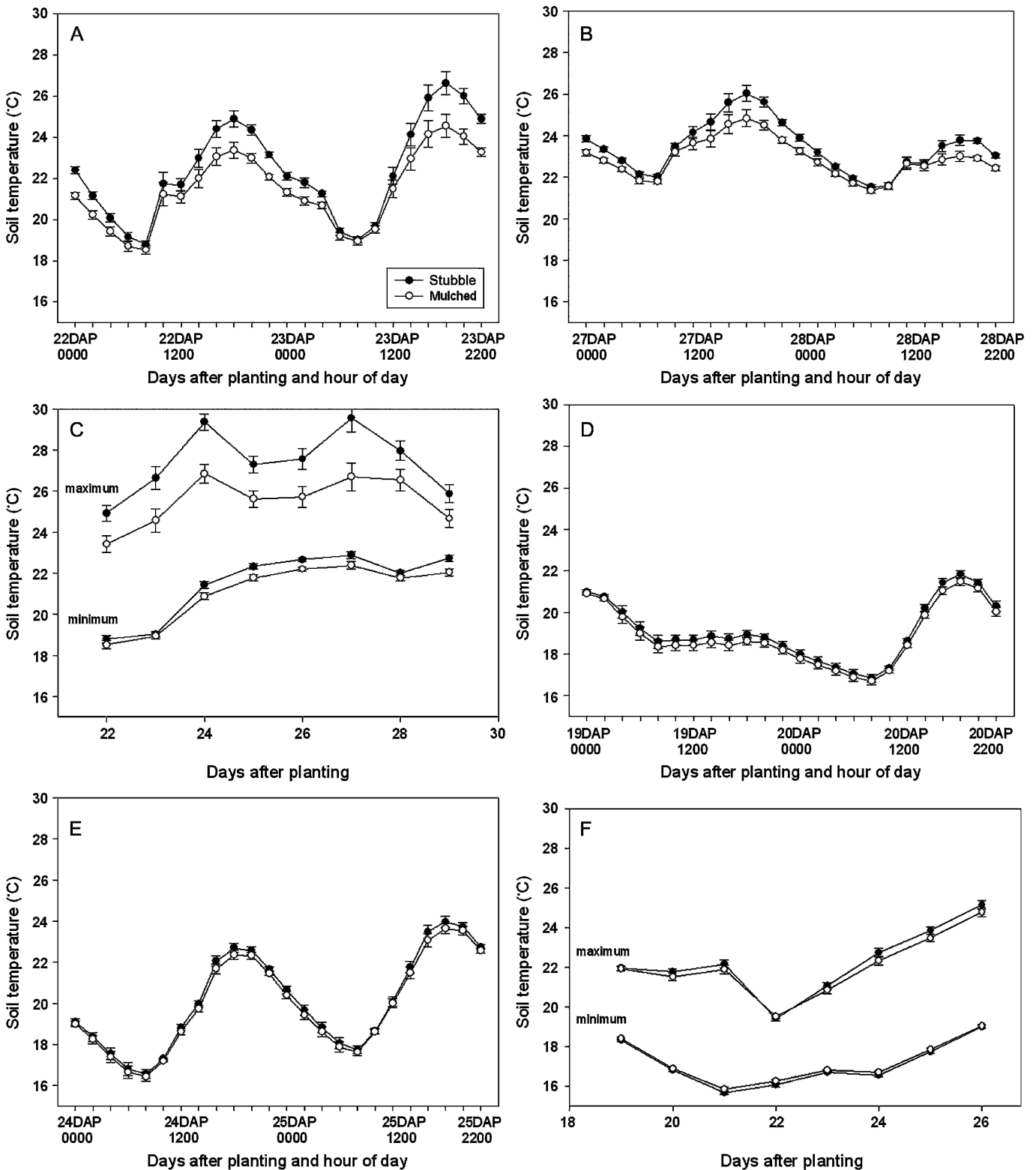

Fig. 2. Effect of surface rye mulch on soil temperature in a gravel loam at Freeville, New York. Standing rye was cut and removed in the "stubble" treatment and was rolled (2003) and chopped (2004) in the "mulched" treatment. Data from 2003 include 2-h average soil temperature (**A**) 22 to 23 DAP and (**B**) 27 to 28 DAP, and (**C**) daily soil temperature maximum and minimum 22 to 29 DAP. Data from 2004 include 2-h 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. Standard error bars indicate the variability for the mean of each treatment and hour or day.

sustained in field trials, however, because of inherent variability in soil and weather conditions (Maiorana et al., 2001; Raper et al., 2000) and by the fact that leaf transpiration from a large crop canopy by the end of the season can be responsible for significant soil water loss.

Increased soil water content attributed to the presence of surface mulch may slow soil warming and reduce early plant growth and later yield of short-season vegetable crops (Hoyt, 1999). In this study, dense mulch reduced diurnal soil temperature up to 2 °C compared with stubble treatments in 2003 (*P* < 0.10; Fig. 2A): mulched soil was cooler in the early morning (0000–0400 HR), the afternoon (when solarization was most intense), and at night, 22 to 23 DAP (Fig. 2A) and 27 to 28 DAP (Fig. 2B). In the following year, mulched and stubble treatments were similar at both sampling dates (Fig. 2, D and E). Mulched soils had a smaller range between maximum and minimum daily temperatures even though minimum daily temperatures were cooler (*P* < 0.10) compared with the stubble treatment in 2003 (Fig. 2C); in 2004, there was no effect of mulch on soil temperature range (Fig. 2F).

The presence of dense mulch decreased plant biomass accumulation by up to 30% between 28 and 58 DAP in 2003 (*P* < 0.0001; Table 3). Even later in the season, by 71 DAP, mulched plants were 15% smaller than stubble treatment plants (*P* < 0.01; Table 3). There were no differences in plant size at all sampling dates in 2004 (Table 3).

Mulch did not delay maturity and harvest date in either year. Mulched treatments, however, yielded 26% less than stubble treatments in 2003 (*P* < 0.0001; Table 4), primarily because individual heads were smaller: marketable head weight for mulched cabbage was 19% lower than for stubble plots (*P* < 0.001; Table 4). Average head width and core length were lower for mulched treatments (*P* < 0.05 and 0.01, respectively; data not shown), also reflecting smaller head size. Other quality measures such as color and uniformity were unaffected by the heavy surface residue. No differences in yield and head weight (Table 4) or head quality (data not shown) were attributed to mulch in 2004.

Soil temperature differences between mulched and stubble plots were relatively small: other researchers exploring conservation tillage for cabbage found soil temperature differences of up to 4 °C but concluded the differences were not enough to account for observed yield reductions because soil temperatures for all treatments were within optimum range for cabbage growth (Wilhoit et al., 1990) or could be attributed to other factors such as soil compaction (Bottenberg et al., 1997; Knavel and Herron, 1981).

In this study, no differences in nitrogen content were found in analyses of leaf petiole sap at cupping stage and cabbage head tissue at harvest; all samples were in sufficiency range or higher regardless of mulch treatment (data not shown). Moreover, the presence of

mulch neither delayed head maturity nor affected cabbage quality parameters such as color and uniformity, which could indicate nutrient deficiency or allelopathic interference. On the other hand, smaller cabbage plants and heads in 2003 may have resulted from rye allelopathy that was minimized in 2004 with the use of an implement that cut smaller pieces of mulch and more rain, both contributing to more rapid degradation of rye allelopathic compounds compared with 2003. The amount of rye biomass may affect suppression of weed seed by physical impedance and light exclusion (Teasdale and Mohler, 2000), but likely impacts the quantity of allelochemicals present in field as well (Reberg-Horton et al., 2005). Killing the rye earlier or reducing the seeding rate such that the total biomass and therefore the level of allelochemicals is reduced or choosing a different cover crop such as hairy vetch may be alternatives to avoid allelopathic interference. However, the amount of allelochemicals present in the rye tissue also depends on cultivar, and many cultivars actually have higher amounts of allelochemicals at an earlier kill date (Reberg-Horton et al., 2005). Killing the rye earlier or reducing seeding rate to reduce total biomass, however, may limit the short-term soil quality benefits.

Conclusions

Dense surface residue provided tangible benefits to the soil that were measurable within one growing season in 1 or 2 years of study. The addition of organic matter as stubble or dense residue to conservation tillage treatments has the potential to improve soil structure and nutrient content in the long term (Johnson and Hoyt, 1999) and corroborates other conclusions that soil quality indicators are most strongly influenced by amount of residue returned to the soil (Leibig et al., 2004; Thomas et al., 1996). Maintaining surface residue for soil quality is particularly important for vegetable systems, which tend to return very little residue after harvest. Excessive precipitation may limit the ability to document soil quality improvements with surface residue during the season.

Although we measured a significant reduction in crop growth and yield in 1 year attributable to dense mulch, the importance of surface mulch must be considered in the context of the entire cropping system. When integrated with conservation tillage practices, significant reduction in the cost of field prep-

Table 3. Effect of surface rye mulch on cabbage aboveground fresh biomass accumulation (grams per plant) in 2003 and 2004 at Freeville, New York. Planting dates were 9 June and 7 June, respectively.

| | 2003 | | | | 2004 | | | | |
	14 DAP	28 DAP	58 DAP	71 DAP	14 DAP	29 DAP	44 DAP	56 DAP	71 DAP
Stubble	8 a[z]	98 a	1,237 a	2,586 a	7	75	515	1,145	1,582
Mulched	6 b	66 b	852 b	2,135 b	7	72	447	936	1,360
P-value	**	***	****	**	NS	NS	NS	NS	NS

[z]Mean separation in columns.
NS, **, ***, ****Nonsignificant or significant at *P* ≤ 0.01, 0.001 or 0.0001, respectively.
DAP, days after planting.

aration (Hoyt et al., 1994; Luna and Staben, 2002), fertilizer and pesticides (Magdoff and van Es, 2000), and erosion control (Hoyt et al., 1994) have been reported. These benefits can balance some potential revenue losses from initial yield reduction.

Table 4. Effect of surface rye mulch on cabbage yield and head weight at Freeville, New York.

| | Yield (T per ha) | | Head wt (kg) | |
Treatment	2003	2004	2003	2004
Stubble	57.0 a[z]	50.4	1.9 a	1.6
Mulched	45.1 b	46.3	1.6 b	1.5
P-value	****	NS	***	NS

[z]Mean separation in columns.
NS, ***, ****Nonsignificant or significant at *P* ≤ 0.001 or 0.0001, respectively.

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