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Wheat response and residual soil properties following subsoiling of a sandy loam in eastern Montana

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Abstract

Shallow tillage pans resulting from the use of the same tillage tools may lead to wheat (*Triticum aestivum* L.) yield reductions. We hypothesized that occasional deep tillage to fracture shallow tillage pans would improve water utilization and result in increased wheat yield. Our hypothesis was tested by comparing paired crop and soil responses on plots that were subsoiled using a paratill (PT) or not subsoiled (NOPT). Soil was a Dooley sandy loam (US soil taxonomy: fine-loamy, mixed Typic Argiboroll; FAO taxonomy: Kastanozem) derived in glacial till near Culbertson, Montana, USA. Effects of PT or NOPT were compared in a long-term cropping study that included annual wheat using no tillage (NT), annual wheat using fall and spring tillage (FST) and wheat rotated with fallow (FWCT). Plots that were subsoiled (PT) were paratilled once in autumn 1992 to about 0.3 m deep. Cone index of the top 0.3 m of soil 2.5 years after subsoiling was lower on PT (891 kPa) compared with NOPT (981 kPa). Soil bulk density was 1.34 Mg m^{-3} on PT and 1.36 Mg m^{-3} on NOPT plots. Final water infiltration rate averaged 15 mm h^{-1} on PT and 6 mm h^{-1} on NOPT plots for nine months after subsoiling. Average water content of the top 1.2 m of soil in the spring of the year was 21 mm greater on PT than on NOPT plots. There were no differences due to treatments in wheat yield; average grain yield was 1820 kg ha^{-1} on annual wheat plots and 2380 kg ha^{-1} on wheat/fallow plots. Residual effects of subsoiling on soil properties were detected for 2.5 years after subsoiling, but soil changes attributed to subsoiling had no effect on wheat yield. © 1999 Published by Elsevier Science B.V.

Keywords: Rainfall simulation; Cone index; Soil bulk density; Paratill; Water infiltration rate; Soil subsidence

1. Introduction

Shallow soil pans prevent or restrict soil exploration by plant roots and impede water and gas movement. Occurrence of pans may be a consequence of the native soil or management or both. For example, many soils of the Southeastern Coastal Plain of the USA are weakly structured and prone to soil compaction (Busscher et al., 1986; Sojka et al., 1990). These loamy sands are easily compacted when exposed to traffic or other consolidation forces. Clay loams of the southern Great Plains (Unger, 1993a) have dense Bt1 and Bt2 horizons that limit water infiltration and plant root penetration. Silt loams of the Pacific Northwest

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frequently have shallow layers of high strength that have been implicated as the cause of reduced water infiltration (Pikul et al., 1990) and poor plant performance (Sojka et al., 1993). These pans are commonly referred to as tillage pans and are a consequence of pressure applied by normal tillage operations. The cases cited are but a small sample of typical pans that are mentioned in the literature. In each case, the cause of the pan and the climate were different but tillage was sought as the means to loosen the pan and improve crop performance.

Special subsoiling has been used to loosen soil only in the zone of intended planting. Generally, it is thought that if plants can aggressively explore the soil and efficiently acquire nutrients and water then crop yield may improve. Therefore, subsoiling only the intended seedbed rather than the entire field can minimize power requirements. This tillage uses a system of in-the-row subsoiling and has been called zone-subsoiling (Sojka et al., 1993) or zone tillage (Pierce et al., 1995). Slit tillage (Busscher et al., 1995) is yet another option to reduce power requirements associated with subsoiling. Sojka et al. (1993) found zone tillage to generally increase the quantity and quality of potato (*Solanum tuberosum* L., cv. Russet Burbank) on a furrow-irrigated silt loam soil. Pierce et al. (1995) concluded that zone tillage increased total and marketable yield of Russet Burbank potato on a non-irrigated sandy loam soil in west central Michigan. In a dryland production system for sunflower (*Helianthus annuus* L.) on the Southeast Coastal Plain, year-to-year results were mixed and Sojka et al. (1990) concluded that if the soil had maintained looseness throughout the growing season, a positive yield and quality response of sunflower to zone tillage might have resulted.

Whole field loosening by deep tillage has been used to manipulate soil for purposes similar to that of zone subsoiling. In the Southeastern Coastal Plain, paratill subsoiling was used by Frederick and Bauer (1996) to improve winter wheat yields on loamy sand. These authors concluded that deep tillage increased the yield by increasing head number per plant. In tropical eastern Bolivia, deep tillage of a fine-loamy, siliceous, isohyperthermic Aquic Ustropept increased soybean (*Glycine max* (L.) Merr.) yield for at least three years Barber (1994). In contrast to the above beneficial reports of subsoiling, Busscher et al. (1988) reported no significant differences in yield of corn (*Zea mays* L.) following subsoiling of a loamy sand on the Southeastern Coastal Plain. Variable relations between tillage and soil bulk density have been reported. For example, Rhoton et al. (1993) evaluated chemical and physical characteristics of sandy loam, loam, silt, and sandy clay loams and found few significant differences in soil properties due to conventional and no-tillage treatments. Of the differences reported, most occurred with silt and sandy clay loams.

Our experiment on subsoil tillage was part of a larger cropping study that was designed to test the effects of seedbed preparation and no tillage on yield of annually cropped and rotated hard red spring wheat. The study was started in 1983 and reported on by Pikul and Aase (1995) and Aase and Pikul (1995). Soil measurements made in 1992 revealed the presence of shallow tillage pans, which were evidenced by distinct profile bulges in soil bulk density (ρ_b) and point resistance (Pikul and Aase, 1995, Figs. 4 and 5) at about 0.1 m. Additionally, we found distinct massing of roots at the zones of maximum ρ_b and point resistance (authors unpublished data). We suspected that tillage pans on FST and FWCT treatments were caused by repeated shallow tillage. In this paper, we compare subsoil tillage with no subsoil tillage. Our hypothesis was that deep tillage to fracture shallow tillage pans would improve root development and soil water storage resulting in increased yield. Our objectives were to determine the effects of subsoil tillage on soil properties and wheat yield and evaluate the longevity of any beneficial consequences of subsoil tillage.

2. Materials and methods

2.1. Experimental site

Soil at the research site, located 11 km north of Culbertson, Montana, USA, was mapped as a Dooley sandy loam on about a 2% slope. Dooley sandy loam formed in a mantle of eolian or alluvial material overlying glacial till. Glacial till is at a depth of about 0.5 m. A soil map showing typical heterogeneity of this glacial till soil was shown by Pikul and Aase (1998) for 0.3–0.6 m depth. Average (28 years) annual precipitation was 357 mm, with about 283 mm (80%)

occurring during April through September. In 1992, 1993, 1994, and 1995 total precipitation was 400, 377, 305, and 464 mm, respectively. Precipitation for April through September in 1992, 1993, 1994, and 1995 was 332, 320, 224, and 345 mm, respectively. Additional information on precipitation and winter weather conditions at this research site has been reported by Pikul et al. (1997) and Pikul and Aase (1998).

Pikul and Aase (1995) reported infiltration and soil properties and Aase and Pikul (1995) reported crop response on this cropping study (1983–1993). The experimental area was in grass prior to 1975. Between 1975 and the start of the cropping experiment in 1983, small grains were grown annually and seedbeds were prepared using tandem disk tillage in the spring. Soil analysis on samples taken prior to subsoiling in 1992 revealed an average of 11 g kg^{-1} organic carbon, 600 g kg^{-1} sand, and 180 g kg^{-1} clay in the top 0.2 m (Pikul and Aase, 1995).

Experimental plot layout was a randomized block with four replications. Plots were 30 m long by 12 m wide. Two treatments were annually cropped spring wheat with sweep tillage in the fall and tandem disk tillage for seedbed preparation in the spring (FST) or no tillage cropped annually with spring wheat (NT); a third treatment was fallow-spring wheat rotation using tandem disk tillage in the spring for seedbed preparation (FWCT). Sweep tillage was about 0.1 m deep with 0.45 m wide medium-crown sweeps. Disk tillage was about 0.14 m deep. Our intended experimental plan and actual implementation of the experimental plan differed in years with a dry fall. In dry years, we were unable to penetrate the soil with sweeps and tillage was not done. Following subsoiling in 1992, the NT subplot was lightly disked and swept prior to seeding. This tillage was a departure from customary plot management and was deemed necessary to create surface conditions suitable for seeding wheat. Tillage implement and time of tillage are shown in Table 1.

2.2. Subsoiling

Soil and crop response to subsoiling was compared using a paired plot design for the NT, FST, and FWCT treatments. For each pair, one subplot was subsoiled once in autumn 1992 using a paratill to about 0.3 m

Table 1
Field operations on tillage trials located near Culbertson, Montana, USA during 1992–1995

Operation	Annual wheat, with fall and spring tillage (FST)	Annual wheat with no tillage (NT)[a]	Wheat/fallow with conventional tillage (FWCT) odd-year crop	Wheat/fallow with conventional tillage (FWCT) even-year crop
1992				
Harvest	12 August	12 August	12 August	12 August
Fall tillage	Paratill treatment	Paratill treatment	Paratill treatment	Paratill treatment
	16 October	16 October	16 October	16 October
1993				
Spring tillage	Disk/sweep 26 April	Disk/sweep 26 April	Disk/sweep 26 April	
Plant	26 April	26 April	26 April	
Harvest	1 September	1 September	1 September	
Fall Tillage				Disk/sweep 21 September
1994				
Spring tillage	Disk/sweep 22 April		Sweep 21 June	Disk/sweep 22 April
Plant	22 April	22 April		22 April
Harvest	15 August	15 August		15 August
Fall Tillage			Sweep 16 September	
1995				
Spring tillage	Disk/sweep 15 May		Disk/sweep 15 May	
Plant	16 May	16 May	16 May	
Harvest	16 August	16 August	16 August	
Fall Tillage				Disk/sweep 13 September

[a] No tillage plots were smoothed in April 1993 with a shallow disk/sweep prior to planting.

deep (PT) while the other subplot was not subsoiled (NOPT). Subplots were 15 m long and 12 m wide.

The paratill subsoiler had four shanks (two left facing and two right facing) with point spacing at 0.66 m. Our implement was similar to that illustrated by Unger (1993b, Fig. 1, Fig. 3). Speed was about 1.3 m s^{-1}. Soil water in the top 0.3 m on 17 September prior to subsoiling was about 0.17 m^3 m^{-3} (Pikul and Aase, 1995, Fig. 5). An additional 12 mm of rain fell between 17 September and the 16 October 1992 date of subsoiling. Direction of subsoil tillage was perpendicular to that used for seedbed preparation.

2.3. *Spring wheat management*

Wheat was seeded with a double-disk opener drill at a 0.20 m row spacing in 1993 and with a single-disk opener drill at a 0.19 m row spacing in 1994 and 1995. Rate of seeding was about at 84 kg ha^{-1}. All plots received 34 kg N ha^{-1} as NH_4NO_3 (34-0-0 N–P–K) at seeding. In a given year, all plots were seeded on the same date (Table 1).

Samples for grain yield were obtained by cutting all plants from five 1 m long rows from six areas in each subplot in 1993 and 1995. Bundle samples were weighed and threshed, following which the grain was weighed. In 1994, grain yield was obtained by using a plot combine to take 9.7 by 1.46 m swaths from the center of each subplot. In a given year, plants from all plots were harvested on the same date (Table 1). Statistical comparisons of yield between PT and NOPT were made using a paired *t*-test (Lund, 1991).

2.4. *Soil water content*

Soil water contents were measured using neutron attenuation equipment to determine water storage and use. Our neutron equipment was calibrated in a manner described by Pikul and Aase (1998). On each subplot a permanent access tube was installed enabling volumetric soil water measurements to a depth of 1.2 m at 0.3 m increments. Soil water content was expressed as an average of four replications for each rotation and tillage plot. Measurements were made at seeding and at harvest. Statistical comparisons of soil water were similar to that of wheat yield.

2.5. *Cone index and bulk density*

In spring of 1995, prior to any soil disturbance, cone index measurements were made on PT and NOPT treatments of NT, FST, and FWCT plots. A 1.5 m transect on PT treatments was established adjacent to a 1.5 m transect on NOPT treatments. This transect was perpendicular to the direction of subsoiling on PT treatments. Cone index (CI), defined as the force per unit basal area required to push a cone penetrometer through a specified increment of soil, was measured with a dual rod penetrometer. The cone tip had an included angle of 60° and a base area of 1.5 cm^2. Cone index measurements were made to a depth of 0.3 m at depth increments of 0.03 m. A depth profile of CI was obtained at 0.15 m intervals along each 1.5 m transect, resulting in 10 depth profiles of CI per transect (100 CI measurements).

A single-value index of soil subsidence was developed using data arrays of CI measured on PT and NOPT treatments. Measurements of CI on each transect resulted in 100 measurements consisting of transect position (X), depth (Y) and CI (Z). A three-dimensional plot of these data yielded a response surface showing spatial variation of soil strength. Smoothed surface maps for each transect were prepared using a three-dimensional surface plotting graphics program (Surfer, Golden Software, Golden, CO).

We calculated soil strength response, in units of force, for each smoothed surface in a manner analogous to calculating volume. Strength response (SSR) was defined as the product of (transect length, m)×(soil depth, m)×(cone index, Pa) and had the units of force (Newton). Surfer software (Surfer, Golden Software, Golden, CO) provides three numerical integration recipes for calculating volume using the trapezoidal rule, Simpson's rule, and Simpson's 3/8 rule. Relative error in volume calculation was made by comparing numerical results of the three methods.

Non-dimensional soil subsidence indices (SSI) for each pair of transects (PT and NOPT) were calculated as:

$$\mathrm{SSI} = (\mathrm{NOPT_{SSR}} - \mathrm{PT_{SSR}})/\mathrm{NOPT_{SSR}}, \qquad (1)$$

where $\mathrm{NOPT_{SSR}}$ was the SSR value between Z=0 and the smoothed surface of the NOPT treatment and

PT_{SSR} was the SSR value between $Z=0$ and the smoothed surface of PT treatment. This index was designed such that SSI values approached zero as differences in CI values due to NOPT and PT treatments approached zero.

Soil bulk density and gravimetric water were each measured on the same day and on the same transects used for CI sampling. Bulk density samples were taken with a tube sampler described by Allmaras et al. (1988). The sampler had a cutting tip of 19.6 mm. Three cores were obtained per plot and each 0.30 m core was cut into ten 0.03 m depth increments. Gravimetric water content was determined on each increment. Volumetric water content was calculated as the product of soil bulk density and gravimetric water content. The midpoint of each 0.03 m depth increment for soil bulk density corresponded to the depth at which CI was measured. Statistical comparisons of results from PT and NOPT plots were made using a paired t-test.

2.6. *Water infiltration*

A Palouse rainfall simulator (Bubenzer et al., 1985) was used to apply water at a rate of about 40 mm h^{-1}. Electrical conductivity of Missouri River water (Culbertson, MT municipal water supply) used for the infiltration tests was 0.7 dS m^{-1} and concentration of cations was 0.157 g l^{-1}. The simulator had two rainfall heads that were used to run duplicate infiltration tests for each plot. Simulated rainfall mimics low intensity storms of the inland Pacific Northwest. Typical summer rainstorms in the northern Great Plains are high intensity and short duration. The Palouse simulator produces drop sizes that are about 1.3–1.8 mm diameter. By comparison, natural rainfall with intensities of about 50 mm h^{-1} have drop sizes that are about 1–5 mm diameter (Wischmeier and Smith, 1958). Therefore, the surface of the test soil was not exposed to rainfall energy that exceeded that of naturally occurring storms.

Infiltration tests were conducted on NT and FWCT treatments. Only three of the four replications were tested resulting in three measurements of water infiltration on PT and NOPT treatments of NT and FWCT. Infiltration frames constructed of heavy gauge steel were 1.16 by 1.16 m square and 0.3 m deep. To install a frame to 0.25 m, we carefully dug a shallow and narrow trench around the outside of the frame. As layers of soil were removed, the infiltration frame was forced downward to enclose an undisturbed soil monolith. Particular attention was given to soil outside the frame in the vicinity of the soil disturbance created by the paratill shanks. This soil was removed, backfilled, and packed to eliminate lateral flow of water from inside the frame to outside the frame. Inside edges of the infiltration frames were sealed with bentonite clay to prevent any water leakage along the metal–soil interface.

Water application rate by the rainfall simulator was measured at the start and finish of each infiltration test. Application rate was determined by collecting the runoff from a 1.35 m^2 calibration pan placed over the infiltration frame. Infiltration was calculated as the difference between application rate and runoff rate. Runoff water was removed by a vacuum system. Water was applied in a cycle of 3 h on Day 1, 20 h off, and 3 h on Day 2. This cycle is often described as a dry and wet run and is conducted to reduce the confounding effects of variable soil water content in the infiltration tests.

3. Results and discussion

3.1. *Bulk density*

Soil bulk densities for PT and NOPT subsoil treatments on NT, FST and FWCT treatments are shown in Fig. 1(a)–(c), respectively. In each case there is a zone of maximum ρ_b at about 0.15 m. Maximum ρ_b was 1.49 Mg m^{-3} on NOPT plots of the FST treatment. Previously, we showed that the zone of maximum ρ_b at about 0.15 m was not a consequence of abrupt changes in soil texture (Pikul and Aase, 1995). Methods used to measure soil bulk density in the current study (1995 sampling date) were the same as those used in 1992 and reported by Pikul and Aase (1995). Significant differences in soil water content between 1992 and 1995 samplings preclude a direct comparison of ρ_b between sampling dates because the Dooley sandy loam has a moderate shrink swell potential for depths >0.15 m (Smetana, 1985).

There was a significant difference in soil bulk density due to the PT and NOPT treatments even after 2.5 years. Average ρ_b was 1.345 Mg m^{-3} for PT and

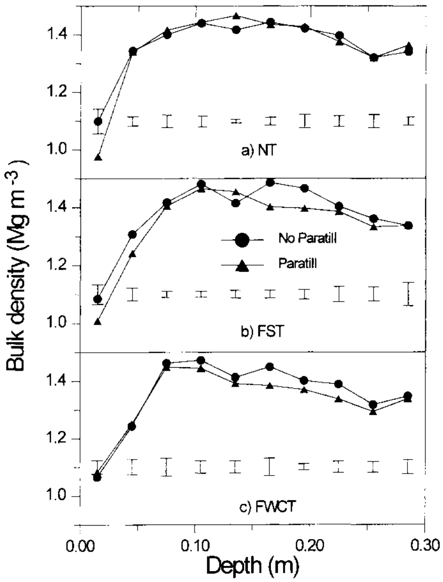

Fig. 1. Soil bulk density for paratill and no paratill treatments of annual wheat using no tillage (NT), annual wheat using fall and spring tillage (FST) and wheat rotated with fallow (FWCT). Brackets show one standard deviation and are an average standard deviation for paratill and no paratill at each measurement depth.

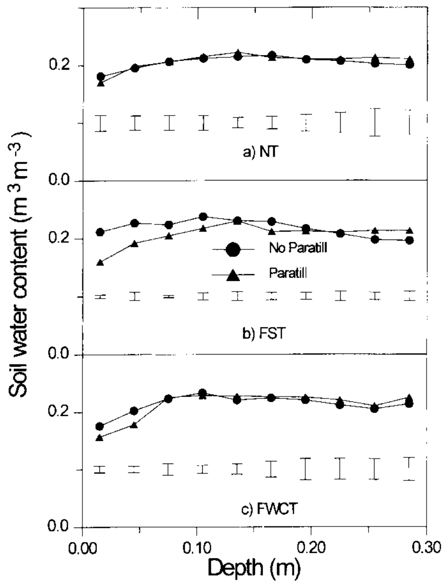

Fig. 2. Volumetric water content for paratill and no paratill treatments of annual wheat using no tillage (NT), annual wheat using fall and spring tillage (FST) and wheat rotated with fallow (FWCT). Brackets show one standard deviation and are an average standard deviation for paratill and no paratill at each measurement depth.

1.365 Mg m^{-3} for NOPT. Pairwise comparisons of ρ_b on PT and NOPT treatments were made for each depth in the top 0.3 m of soil (n=90, Table 2). A similar test was made on volumetric water content (Fig. 2 and Table 2). There were no differences due to PT and NOPT in soil volumetric water content (θ_w). Therefore, we can conclude that differences in bulk density with PT and NOPT treatments were a consequence of soil loosening by subsoiling and not simply soil shrink or swell related to water content.

3.2. Cone index

Differences in soil water content can cause differences in soil strength. Our soil water measurements were taken concurrently with CI measurements. Average θ_w of the top 0.3 m of soil on PT and NOPT treatments was 0.21 m^3 m^{-3}. Differences in cone indices between PT and NOPT (Fig. 3) plots are therefore expected to be a consequence of soil subsidence or soil loosening because θ_w was nearly uni-

Table 2
Selected soil attributes on plots that were paratilled or not paratilled[a]

Soil attribute	Paratill	No paratill	Significance[b]	n
Volumetric water (m^3 m^{-3})	0.21	0.21	ns	90
Bulk density (Mg m^{-3})	1.345	1.365	**	90
Cone index (kPa)	891	981	**	90
Infiltration rate Day 1 (mm h^{-1})	27	15	*	6
Infiltration rate Day 2 (mm h^{-1})	15	6	*	6
Cumulative infiltration after 3 h on Day 1 (mm)	88	60	*	6

[a] Measurements of volumetric water content, soil bulk density, and cone index were made in the top 0.3 m of soil 2.5 years after subsoiling. Water infiltration measurements were made in the summer following subsoiling the previous fall.
[b] Statistical significance indicated as not significant (ns), significant at $P\leq0.05$ (*), and significant at $P\leq0.01$ (**).

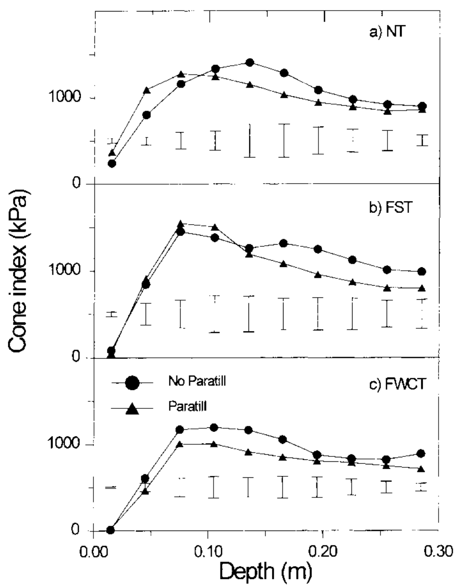

Fig. 3. Cone index for paratill and no paratill treatments of annual wheat using no tillage (NT), annual wheat using fall and spring tillage (FST) and wheat rotated with fallow (FWCT). Brackets show one standard deviation and are an average standard deviation for paratill and no paratill at each measurement depth.

form between treatments (Fig. 2 and Table 2). Pairwise comparisons (n=90) of CI in the top 0.3 m showed that the soil on PT treatment plots had significantly less strength than on NOPT treatment plots (Table 2). Average soil strength was 891 kPa on the PT treatments and 981 kPa on the NOPT treatments.

A pairwise statistical comparison of CI between subsoil treatments was relatively easy to execute. However, an average CI value for the profile fails to show unique distribution of soil strength features. We sought an alternative analysis that could be used to visualize the depth distribution of soil strength features and also provide a means to quantify differences.

Surface plots were used to show visual relations of CI with depth and transect position. Example response surfaces for PT and NOPT treatments on NT treatment plots are shown in Fig. 4. This figure clearly shows the path of the paratill subsoil shanks at approximate transect positions (x-axis) of 0.8 and 1.4 m. The axis showing transect position lies perpendicular to subsoiling direction. Low CI values (z-axis) at depths (y-axis) greater than 0.15 m characterize the path of the subsoil tool. Fig. 4. also shows that the zone of loosened soil (low CI values) was overlain by a layer of consolidated soil (relatively high and uniform CI values).

Following subsoiling in 1992, the NT cropping plots were lightly disked and swept prior to seeding (Table 1). This was the first use of tillage on these plots since the start of the experiment in 1983. We think that tillage for seedbed preparation in 1993 destroyed vertical continuity of macropore channels resulting in a zone of consolidated soil overlying loosened soil as shown in Fig. 4. This layered configuration was present in all of the response surfaces that we examined.

Surface plots were also used to evaluate soil subsidence using a single index (Eq. (1)). For example, the surfaces shown in Fig. 4 had a SSR value of 349 N for the PT and 367 N for the NOPT treatments. These values provide a SSI (Eq. (1)) of 0.049 indicating that soil on PT treatment plots had lower strength than soil on NOPT plots. In six out of nine tests, positive SSI indices indicated that soil on PT treatment plots had less strength than soil on NOPT treatment plots. Positive values ranged from 0.049 (Fig. 4) to 0.314 (not shown). Negative values ranged from −0.009 to −0.132 (not shown). A normal probability plot of SSI values using the Ryan-Joiner goodness-of-fit test (Minitab Statistical Software, Minitab State College, Pa) suggested a normal distribution (p=0.1) of SSI values even with our limited data set (n=9).

3.3. Water infiltration

Water infiltration was consistently greater in PT treatments compared with NOPT treatments. Infiltration rates for PT and NOPT treatments for Day 1 (dry run) and Day 2 (wet run) of the tests are shown in Figs. 5 and 6, respectively. These measurements provide indirect evidence that soil macropore structure created by subsoiling the previous fall was still present in June the following year. During the winter of 1992–1993 the soil froze deeper than 0.9 m and there was 60 mm of precipitation received as snow. Final water infiltration rate on Day 1 of the tests averaged 27 mm h^{-1} on PT plots and 15 mm h^{-1} on NOPT plots. Cumulative water infiltration, during a 3 h test on day 1, was 88 mm on PT plots and 60 mm on NOPT plots (Table 2). On the second day of the infiltration tests, average final water infiltration was

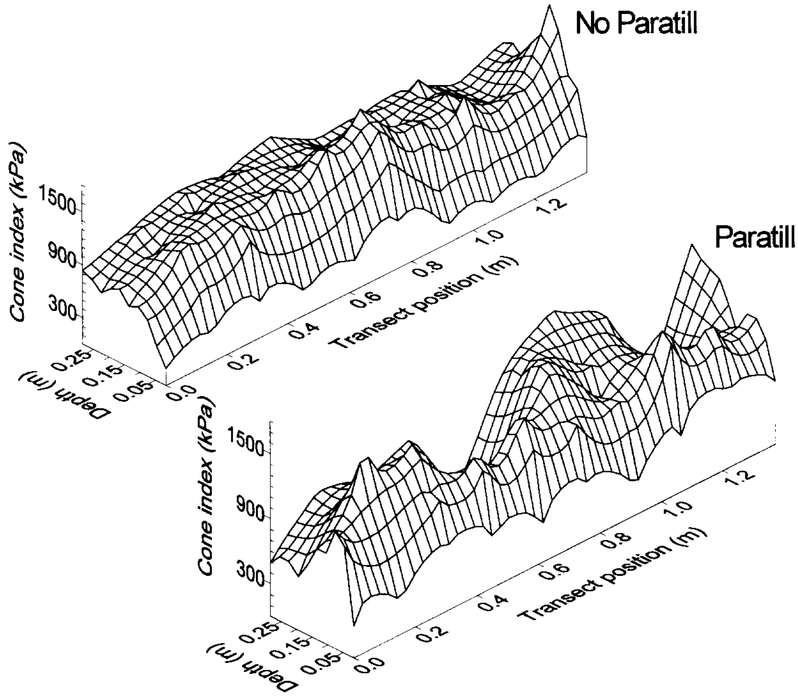

Fig. 4. Surface plots of cone index, termed response surfaces, for paratill and no paratill treatments of annual wheat using no tillage. Low cone index values (z-axis) at depths (y-axis) greater than 0.15 m identify paths of paratill shanks at approximate transect positions (x-axis) of 0.8 and 1.4 m.

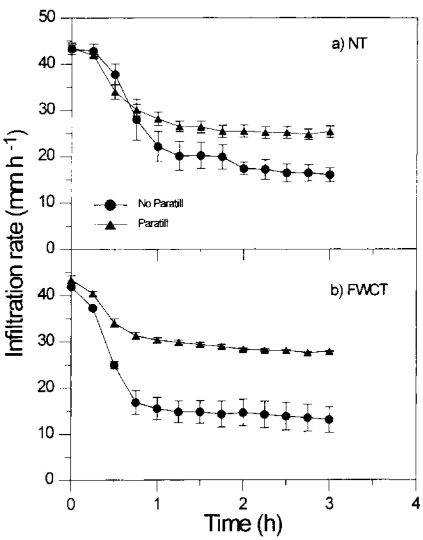

Fig. 5. Water infiltration rate for paratill and no paratill treatments of annual wheat using no tillage (NT) and wheat rotated with fallow (FWCT) on Day 1 (dry run). Brackets show one standard deviation.

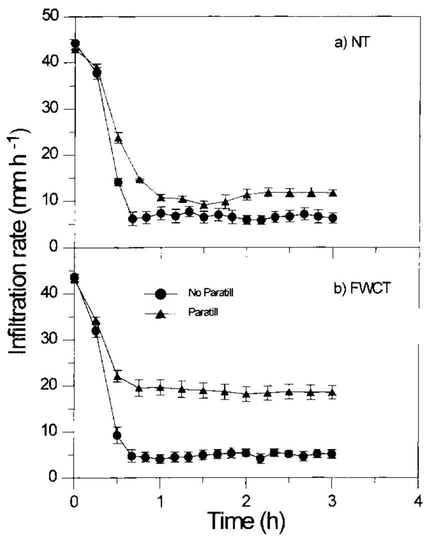

Fig. 6. Water infiltration rate for paratill and no paratill treatments of annual wheat using no tillage (NT) and wheat rotated with fallow (FWCT) on Day 2 (wet run). Brackets show one standard deviation.

Table 3
Average (years 1993, 1994, and 1995) wheat yield and soil water content for paratill and no paratill treatments of plots that were annually cropped with spring wheat and plots that were bi-annually cropped with spring wheat in a wheat/fallow rotation

Rotation	Paratill	No paratill	Significance[a]	*n*
Wheat Yield (kg ha^{-1})				
Annual wheat	1848	1782	ns	24
Wheat/fallow (WF)	2431	2322	ns	12
Soil water (mm)[b]				
Annual wheat	266	250	*	24
WF crop year	293	280	ns	12
WF fallow year	276	241	*	12

[a] Statistical significance indicated as not significant (ns) or significant at $P \leq 0.05$ (*).
[b] Average soil water content for 1993, 1994, and 1995 in the top 1.2 m of soil as measured in the spring of the year.

15 mm h^{-1} on PT plots and 6 mm h^{-1} on NOPT plots (Table 2). In a study similar to the present report, Pikul et al. (1990) reported final infiltration rates of 24 mm h^{-1} for soil that was paratilled and 9 mm h^{-1} for non-paratilled check. This comparison was made on a Walla silt loam near Pendleton, Oregon, USA after one winter.

As discussed above, we think that tillage for seedbed preparation destroyed vertical continuity of macropore channels on plots that had been subsoiled and consequently NT plots (Fig. 6(a), paratill) had lower water infiltration rates than FWCT plots (Fig. 6(b), paratill). There was no secondary tillage of FWCT plots prior to infiltration tests. Final infiltration rate on paratilled subplots was 12 mm h^{-1} with NT compared with 19 mm h^{-1} with FWCT (Fig. 6(a) and (b)).

3.4. Soil water and crop yield

Increased water infiltration capacity may increase soil water storage during years with adequate precipitation and adequate soil–water-storage capacity. A water infiltration measurement demonstrated that there was potential to increase water infiltration into this sandy loam soil during the first year after subsoiling. Average soil water for 1993, 1994, and 1995 in the top 1.2 m of soil at spring planting of annual wheat was 266 mm on PT plots compared with 250 mm on NOPT plots (Table 3). However, there were no differences in water content between PT and NOPT plots following 20 months of fallow (Table 3, WF crop year). Additional water beyond the water storage capacity of this soil was likely lost to deep drainage therefore negating any benefits of improved infiltration capacity on PT treatment plots. Increased water infiltration would have decreased water runoff and possibly reduced soil erosion. Evaluation of soil erosion related to subsoiling was beyond the scope of this study.

We failed to detect significant differences in wheat yield due to PT and NOPT treatments even though we measured increased soil water storage in plots that were subsoiled (Table 3). For these growing conditions, there is a strong relation (Aase and Pikul, unpublished data) between water use and wheat grain yield (r=0.81). Water use was defined as the sum of soil water extracted plus precipitation from seeding to harvest. Differences in soil water storage due to PT and NOPT treatments (Table 3) were not enough to generate improved grain yield. Growing season (April–August) precipitation of 316 mm in 1993, 208 mm in 1994, and 333 mm in 1995 may have been enough to overshadow small gains in soil water storage on PT treatment compared with NOPT treatment plots.

4. Conclusion

We hypothesized that occasional deep tillage to fracture shallow tillage pans would improve water infiltration and consequently soil water storage. Additionally, we speculated that wheat grain yield would increase because of improved root environment and additional soil water. Water infiltration was consistently greater on PT treatment compared with NOPT treatment plots. These measurements provided indirect evidence that soil macropore structure created by subsoiling the previous fall was still present in June the following year. However, there was also evidence from our infiltration tests that even one tillage for seedbed preparation was enough to destroy vertical continuity of macropore channels on plots that had been subsoiled. Residual effects of subsoiling on soil properties were detected 2.5 year after subsoiling. Soil bulk density and cone index values were significantly lower on plots that were subsoiled. We developed an index to evaluate soil subsidence. These indices provide a way to evaluate tillage related structure because they integrated many spatial and depth cone index measurements into one value. In six out of nine tests, positive SSI indices indicated that soil on PT treatment plots had significantly less strength than soil on NOPT treatment plots. There were no significant differences in wheat yield due to PT and NOPT treatments even though we measured increased soil water storage and improved soil physical condition on plots that were subsoiled. Based on wheat yield alone, subsoiling was of little value. However, we cannot discount the benefits of improved water infiltration on plots that were paratilled. Tillage methods that improve water infiltration are a benefit towards reducing water runoff and combating soil erosion by water.

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