

Long-Term Effects of Profile-Modifying Deep Plowing on Soil Properties and Crop Yield

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Increasing precipitation storage as plant-available soil water increases dryland crop yields on the semiarid southern Great Plains. The dominant soil in this region is a Pullman clay loam (fine, mixed, superactive, thermic Torric Paleustoll), which features dense subsoil layers that limit infiltration and root proliferation. Deep (~0.7 m) plowing may eliminate these layers, but the duration of treatment efficacy must be sufficient to recoup costs. Our objective was to quantify the long-term effects of deep plowing on soil bulk density (BD), penetration resistance (PR), ponded infiltration, and crop yield. In fall 1971, paired 24- by 460-m level conservation bench terrace plots at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX (35°11' N, 102°5' W) were moldboard plowed to 0.7 m or untreated and, subsequently, maintained with conventional sweep tillage. Grain sorghum [*Sorghum bicolor* (L.) Moench] was grown intermittently during the next 34 yr for 15 paired yield comparisons. Compared with the control, deep plowing significantly decreased BD and PR and increased water infiltration. Long-term mean grain yield of 2.86 Mg ha⁻¹ with deep plowing was greater ($P < 0.05$) than the 2.61 Mg ha⁻¹ yield in control plots. Approximately 89% of the 15-yr 3.75 Mg ha⁻¹ cumulative yield increase with deep plowing occurred during 4 yr with large early growing season rains. We attributed this yield increase with deep plowing to greater internal drainage that reduced crop injury during infrequent floods and not greater root growth through the dense subsoil. Thirty years after deep plowing, high water intake suggests that flow-limiting subsoil layers had not yet redeveloped. The sustained deep-plowing benefit extends the period to recoup the 1971 plowing costs of US\$160 ha⁻¹.

Abbreviations: BD, bulk density; PR, penetration resistance; WUE, water use efficiency.

Precipitation on the semiarid southern North American Great Plains, during an average year, provides approximately 25% of the potential evapotranspiration for crop water use. To offset the resulting crop water use deficit under dryland conditions, terrace structures have been adapted to reduce stormwater runoff. Hauser (1968) described a level bench terrace system constructed in 1958, which features a gently sloping (2%) watershed two times larger than the smaller conservation bench that receives the runoff (Fig. 1). Compared with conventional level terraces that concentrate watershed runoff in narrow, ~5-m strip areas along the terrace structures, the level bench terraces evenly distribute watershed runoff throughout a wider, >24-m bench so that the resulting soil water storage remains within the rooting zone for crop use. Delayed internal

drainage of this concentrated runoff, however, has the potential to flood crops planted on the benches.

The Pullman clay loam is the dominant soil found in the southern Great Plains region and occupies 1.5 million ha (Unger and Pringle, 1981). It features a very slowly permeable montmorillonitic silty clay illuvial Bt subsoil layer from 0.15- to 0.7-m depth, with vertical cracks, medium blocky structure, continuous clay films, and few fine roots between hard wedge-shaped peds. A one-time deep, >0.4-m, plowing modification of the soil profile was proposed by Eck and Taylor (1969) as a way to eliminate the dense, flow-limiting subsoil layers and increase infiltration of rain and irrigation. This is in contrast to intensive surface, ~0.2-m tillage practices that temporarily increase soil porosity and infiltration until soil crusting and reconsolidation negate or reverse these benefits (Green et al., 2003). Another possible consequence of disrupting dense subsoil layers with deep plowing is to decrease PR and expand the volume of soil explored by crop roots, which increases the potential plant-available water. For example, PR was reduced and yield increased in wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.] and corn (*Zea mays* L.) when using subsoil tillage to fracture dense layers formed in a loamy sand soil (Busscher et al., 2000, 2001). With irrigation, deep plowing to 0.9 m and soil profile modification to maximum depths of 1.5 m successfully disrupted the dense subsoil layers, thus increasing infiltration and the depth from which crops removed soil water (Schneider and Mathers, 1970). In the short term, deep plowing may disrupt subsoil layers that limit crop rooting for increased water availability and water movement within the profile including drainage; however, there is little information on the longevity of profile modification by deep plowing.

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Soil Sci. Soc. Am. J. 72:677-682

doi:10.2136/sssaj2007.0122

Received 30 Mar. 2007.

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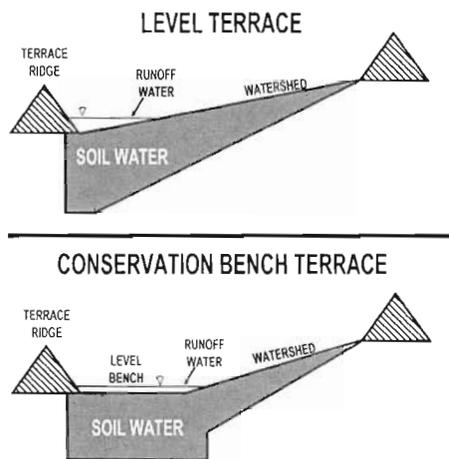


Fig. 1. Cross-sectional diagram of conventional level terraces (top) and conservation-bench level terraces (bottom) that concentrate runoff water from adjacent watersheds for annual crop production during most years. Compared with conventional level terraces, watershed runoff is evenly distributed on larger bench areas of the conservation-bench terraces.

Several studies evaluating the effects of deep soil profile modification have consistently indicated decreased BD and PR along with increased infiltration and crop rooting for a period of up to 26 yr (Eck and Taylor, 1969; Eck, 1986; Eck and Winter, 1992; Unger, 1993). As a consequence of the improved soil physical conditions, these studies have also reported consistently greater yields under full or limited irrigation; however, dryland crop production systems were not evaluated. We hypothesized that profile-modifying deep plowing to eliminate dense subsoil layers will have a sustained effect on soil properties and crop yields under dryland conditions. Our objectives were to quantify the long-term effects of deep plowing soil with a flow-restricting subsoil layer on selected physical properties including infiltration, BD, and PR, and long-term crop yield and water use.

MATERIALS AND METHODS

The long-term (1972–2005) effects of soil profile modification using deep plowing on crop yield and selected soil physical proper-



Fig. 2. Moldboard plow used to till conservation benches to 0.70-m depth without inverting the soil. Plow was pulled by a D-8 Caterpillar tractor.

ties were evaluated at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX. Our rests occupied a pair of contour-farmed fields, comprised of level conservation-bench terraces that ranged from 24 to 40 m wide and 410 to 460 m long and contributing watersheds twice as large as the level bench. Fields were sufficiently large, 2.8 and 4.1 ha, to permit three or more replicated sampling zones 50 to 80 m apart. In September of 1971, the terrace benches were either deep plowed to 0.7 m using a 1.0-m single-blade large moldboard plow adjusted to retain topsoil in the top part of the profile (Fig. 2) or maintained as an unplowed control. Estimated plowing cost for this single treatment in 1971 was US\$160 ha⁻¹, primarily for the D-8 Caterpillar tractor rental. After applying the deep-plow or control treatments, stubble-mulch tillage residue management was performed as needed for weed control (approximately four times annually) using 3.0- to 4.6-m-wide sweep-plow implements with overlapping V-shaped blades operated at a 0.10-m depth (Baumhardt and Jones, 2002b). Precipitation and runoff contributions from the watershed areas were contained within the contours of the level terrace benches.

The terrace watersheds were uniformly cropped from 1971 to 2005 with wheat and grain sorghum according to the wheat–sorghum–fallow (WSF) rotation sequence described by Jones and Popham (1997) that produces two crops in 3 yr with 11-mo fallow periods between crops. The level benches typically received sufficient runoff from the watersheds to support various annual cropping systems with an intervening winter fallow-like idle period; however, grain sorghum crops permitted the greatest number of paired yield comparisons during the study (i.e., 15 growing seasons). Grain sorghum (various cultivars) was seeded during early to mid-June in single rows spaced 0.75 m apart for a final population of 8 seed m⁻² using unit planters such as Max-Emerge (John Deere, East Moline, IL). Growing-season weed control was accomplished with 1.7 kg a.i. ha⁻¹ propazine [6-chloro-*N,N*-bis(1-methylethyl)-1,3,5-triazine-2,4-diamine] applied pre-emergence after sorghum planting. We added 50 kg ha⁻¹ N fertilizer broadcast for sorghum crops on benches, which is consistent with N mineralized in dryland WSF cropping systems at Bushland (Eck and Jones, 1992). The Pullman soil provides adequate P to minimize dryland crop response to P fertilizer (Eck, 1969, 1988), while the Pullman clay mineralogy supplies sufficient K to diminish crop response to fertilizer K (Johnson et al., 1983); therefore, we applied no K or P fertilizers.

Measurements

Four Years after Deep Plowing

In 1975, soil BD and water infiltration were determined after three cropping seasons. Triplicate soil BD measurements were taken in both deep plowed and control terraces at locations >100 m apart. Soil cores were 100 mm long and 50 mm in diameter, and samples were centered at 0.075-, 0.225-, 0.45-, 0.75-, and 1.05-m depths. Later, beginning 10 h after a 56-mm natural rainfall plus runoff had inundated the terrace benches on 23 July, ponded infiltration was estimated using single 0.6-m-diam. rings pressed 50 mm into the soil. Infiltration rate was calculated from multiple observations of the change in ponded water depth measured using water-level recorders and dividing it by the corresponding elapsed time. These measurements continued for an additional 6 and 50 h in deep-plowed and control plots, respectively. This technique provided a steady ponded infiltration rate for the deep-plowed and control soil profiles.

Thirty Years after Deep Plowing

During the summer of 2002, soil physical properties including water infiltration, soil BD, and PR were again determined in four replicated subsites ~100 m apart within each of the control and deep-plowed fields. In each subsite, we recorded the time required for ponded infiltration of well water (pH of 7.7, electrolyte concentration of 819.0 mg kg⁻¹, and a Na adsorption ratio of 0.49) applied to test areas in either 25- or 50-mm depth increments, which are consistent with commonly applied irrigation depths. Four water applications were made with approximately 72-h delay between each to permit drainage for a total infiltrated depth of 100 and 200 mm. All eight test areas were contained within 1.0-m-wide by 1.5-m-long by 200-mm-high metal frames pressed 50 mm into the soil.

From areas adjacent to the infiltration sites, we determined soil BD to a depth of 0.9 m using 100-mm-long, 50-mm-diam. soil core samples centered at 0.01-, 0.30-, 0.50-, 0.70-, and 0.90-m depths. Penetration resistance was determined with depth using triplicate measurements taken within each of the infiltration frames after allowing them to drain for approximately 1 wk. In this way we decreased the variable effect of reduced initial soil water content on the recorded PR. We used the same tractor-mounted hydraulically driven penetrometer as Allen and Musick (1997) to record PR of the 30°, included-angle, 20.3-mm-diam. cone tip to a depth of 0.6 m in 0.075-m increments.

Seasonal Measurements 1971 to 2005

The June to November growing season and the intervening fallow period water balance measurements include precipitation from a nearby standard rain gauge, watershed runoff contributions estimated using gauged flumes on adjacent watersheds of identically managed graded terraces (Hauser, 1968), and soil water content at planting and harvest reported as plant-available soil water (water held between 0.03- and 1.5-MPa suction). That is, gravimetric soil water content was measured at planting and after harvest using triplicate soil cores taken to a 1.8-m depth in 0.3-m increments. Volumetric soil water was subsequently calculated as described in Jones et al. (1994). Fallow efficiency was calculated as the ratio of stored soil water, or the difference in soil water content at harvest and planting, to the fallow precipitation. Crop water use (i.e., crop evapotranspiration) during the growing season was calculated as the sum of precipitation, contributed runoff from the watersheds, and the change in the profile soil-water content between planting and harvest. Using an iterative procedure, Schwartz et al. (2008) estimated profile drainage for a nearby bare Pullman soil to be 5% of the precipitation averaging ~11 mm during our 15 growing seasons. We, therefore, considered growing-season water loss due to deep drainage beyond the >1.5-m grain sorghum rooting zone (Moroke et al., 2005) to be negligible (Baumhardt and Jones, 2002b). Sorghum grain yields, reported at a standardized moisture of 130 g kg⁻¹, were determined by combine harvesting triplicate plot areas.

Statistical Analysis

Our analyses approach was to compare the control and deep-plow effects using a *t*-test procedure for two sample populations assuming unequal variances (SAS Institute, 1988). In this way, plowing treatment effects on the observed BD and PR were compared by depth interval, while infiltration was compared, incrementally, by water application depth. Seasonal measurements of yield, fallow efficiency, soil water at planting, growing season water use, and sorghum water use efficiency (WUE) were analyzed according to a *t*-test procedure of plowing treatment effects paired for the common years of observation.

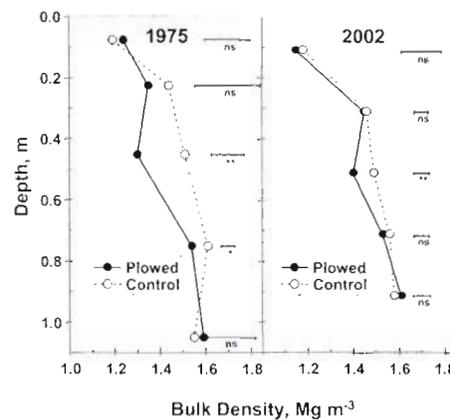


Fig. 3. Mean soil bulk density determined with soil depth for early and long-term deep plowing effects after 4 yr ($n = 3$) and 31 yr ($n = 8$), respectively. Error bars represent the least significant difference (* $P = 0.05$, ** $P = 0.01$, ns = not significant).

RESULTS AND DISCUSSION

Soil Density and Penetration Resistance

Deep plowing was used to modify the soil profile to 0.7 m by disrupting any dense subsoil layer that can limit both infiltration and root growth. The overall soil profile BD from 0 to 1.05 m measured 4 yr after the 1971 deep plowing averaged 1.4 ± 0.04 Mg m⁻³ and was not significantly lower than the profile BD of the control plots that averaged 1.46 ± 0.04 Mg m⁻³. After 31 yr, in 2002, the profile density from 0 to 0.9 m remained relatively unchanged; averaging 1.43 ± 0.02 Mg m⁻³ for deep-plowed plots compared with the not significantly different 1.45 ± 0.01 Mg m⁻³ for control plots. These data suggest rapid soil consolidation possibly due to compaction by subsequent cropping system tillage and traffic. Also, evaluation of deep-plowing effects to decrease soil profile BD compared with control plots were probably confounded by observations below the 0.7-m plowing depth.

A more revealing view of the profile-modifying plowing effects on soil BD measured in 1975 and again in 2002 is plotted with depth for the deep-plow and control plots (Fig. 3). In both 1975 and 2002, soil bulk density in deep-plowed plots was significantly ($P < 0.01$) lower than control plots at 0.45-m and 0.50-m depths, the midpoint of the dense subsoil layer. In 1975 but not 2002, the soil bulk density in deep-plowed plots was significantly ($P < 0.05$) lower at 0.75 m or the approximate limit of the plow depth. No treatment effect was expected, or measured, 0.2 to 0.3 m below the 0.7-m plow depth in 1975 or 2002. Surface (top 0.25 m) soil consolidation and possible compaction during stubble-mulch tillage for weed control rapidly negated deep-plowing effects on soil density after only 4 yr, which is similar to shallow sweep tillage compaction effects reported by Baumhardt and Jones (2002a) for a nearby Pullman silty clay loam and by Pikul and Aase (2003) for sandy loam and loam soils. In 2002, almost identical soil bulk densities were measured above the 0.3-m depth for both the deep-plowed and control plots. These data show that, compared with the control, deep plowing to 0.7 m significantly fractured and eliminated a dense subsoil layer for approximately 30 yr after treatment, but stubble-mulch residue management with repeated sweep tillage operations for weed control during

the study has contributed to soil consolidation of the upper 0.3 m of the soil profile.

Reduced PR under deep plowing compared with the control was measurable after 31 yr; however, no corresponding 1975 PR data are available for comparison. Overall, deep tillage decreased the mean soil profile PR measured in 2002 to 1.09 MPa, compared with 1.22 MPa for control plots. Penetration resistance is shown with depth in Fig. 4. In the soil surface above the 0.30-m depth, PR varied from 0.41 to 1.33 MPa but was unaffected by the deep plowing, probably because of necessary weed control tillage and cropping system traffic. Penetration resistance through the underlying 0.3- to 0.6-m subsoil layers averaged ~ 1.38 MPa in control plots, which approaches but is less than root-growth-limiting soil strength (Busscher et al., 1986). Penetration resistance in the deep-plowed plots at 0.38 and 0.53 m averaged 1.13 and 1.04 MPa, respectively, and were significantly ($P < 0.05$) less than the corresponding control plots below 0.3 m. Although not significantly different, PR for the control plots at 0.45 and 0.6 m tended to be consistently greater than the corresponding deep-plowed plots by an average of ~ 0.17 MPa. Our data show that deep plowing decreased PR through a flow-limiting subsoil layer for 31 yr. The decreased PR of this subsoil layer due to deep plowing could also increase root proliferation and expand the volume of soil explored by crop roots. Our study did not initially assess the effect of deep plowing on rooting, but observations of rooting depth made in 2006 using the soil core-break method (Böhm, 1979) indicated that roots reached 0.51 m for deep-plowed plots compared with the significantly ($P < 0.01$) lower 0.44-m rooting depth for control plots.

Ponded Infiltration and Soil Water Storage

Deep-plowing effects on ponded infiltration were evaluated twice during this experiment, at 4 and 31 yr after profile

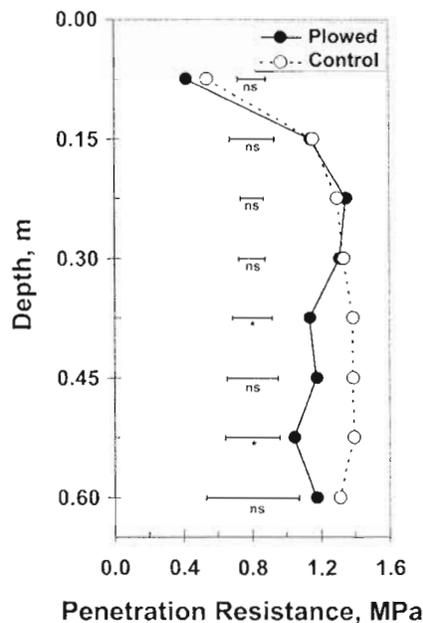


Fig. 4. Long-term effects of deep plowing on mean soil penetration resistance determined with depth ($n = 8$) after 31 yr. Error bars are the least significant difference ($* P = 0.05$, ns = not significant).

modification. Steady ponded infiltration determined at 10 to 48 h after a 56-mm rain that inundated the bench on 23 July 1975 averaged 8.1 mm h^{-1} for deep-plowed plots compared with 1.2 mm h^{-1} for the control plots. The measured infiltration rate for the control plots was identical to previously reported values for the Pullman soil profile (Taylor et al., 1963; Unger and Pringle, 1981). In the short term, deep tillage increased steady infiltration six-fold compared with the control. The increased soil permeability with deep plowing after the first 4 yr could also promote soil water storage in the lower profile.

In 2002, a second comparison of deep-plowing effects on ponded infiltration was conducted for multiple 25- and 50-mm water applications. These applications were designed to mimic typical overhead irrigations with 72 h between applications that totaled 100 and 200 mm. The total time required for the observed incremental cumulative infiltration is shown in Fig. 5. Time for infiltration of 25, 50, and 75 mm of water did not vary significantly ($P = 0.05$) with the deep-plowing treatments, probably because the estimated wetting front position would not have passed the 0.15- to 0.70-m-deep flow-restricting subsoil layer. Beginning with 100 mm of water application, the subsoil layer impeded water infiltration sufficiently in the control plots to significantly ($P = 0.05$) increase (by ~ 30 min) the time for infiltration compared with infiltration into the deep-plowed plots. This deep-plowing effect continued to increase the difference in the time required for infiltration up to 55 min as the application depth increased to 200 mm. Overall, water infiltration into the deep-plowed plots required 30% less time than in the control plots ($r^2 = 0.94$). We did not quantify lateral water movement during infiltration measurements on deep-plowed and control plots; however, lateral water movement often results when water tables form in more conductive soil above flow-restricting layers (Bouwer, 1986). In our test, deep plowing removed the flow-restricting layer at 0.15 to 0.70 m and, consequently, reduced lateral water movement compared with control plots. The resulting increased infiltration through the soil profile with deep plowing compared with the control treatment is a conservatively estimated benefit. These data show that deep plowing eliminated a flow-restricting subsoil layer and increased infiltration due to improved drainage after >30 yr.

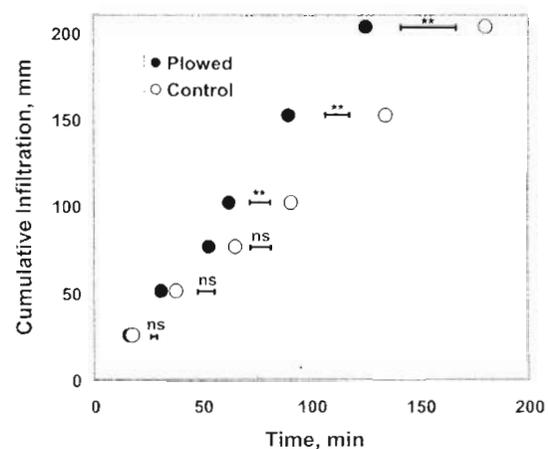


Fig. 5. Long-term deep plowing effects on mean cumulative infiltration ($n = 4$) with increasing time. Error bars represent the least significant difference ($** P = 0.01$, ns = not significant).

One consequence of rapid infiltration and drainage with deep plowing could be redistribution of water to greater soil depths that, consequently, reduces evaporation losses. This can contribute to increased fallow efficiency or the ratio of soil water stored to precipitation received during fallow, assuming that infiltrating water not lost to evaporation because of internal drainage remains within the soil profile. Mean fallow efficiencies and available soil water at planting from deep-plowed and control plots are listed in Table 1 for the 15 paired cropping periods within our 34-yr test. During this time, fallow efficiency averaged 0.26 m stored water m⁻¹ of fallow precipitation in control plots, which is consistent with the 0.27 m m⁻¹ reported for similarly managed continuous dryland sorghum (Jones and Popham, 1997). For deep-plowed plots, the fallow efficiency increased to 0.38 m m⁻¹, possibly due to reduced soil water evaporation; however, the small 0.12 m m⁻¹ difference was not significant. The resulting available soil water storage at planting for these 15 crop yr did increase ($P < 0.10$) 12% from 160 mm in control plots to 178 mm in deep-plowed plots. Dryland sorghum crop yields typically benefit from even small increases stored soil water at planting (Unger and Baumhardt, 1999); therefore, we expect that the increased soil water at planting in deep-plowed plots will increase sorghum yield.

Crop Yield

Deep plowing to fracture the dense 0.15- to 0.70-m subsoil layer in the Pullman clay loam decreased soil strength and promoted greater root exploration of the soil, which could increase the potential soil water available to dryland crops and the corresponding yield. Annual sorghum grain yield (Fig. 6), however, revealed no large dryland yield response to deep plowing during the years immediately after treatment (1972–1974) when crop rooting would probably have benefited the most. Also, we observed no gradual decline in yield differences between deep-plowed and control plots from 1972 to 2005 that could be attributed to soil profile consolidation resulting from sustained weed control tillage and traffic on the plots.

During our test, grain sorghum yields typically increased with increasing growing-season precipitation or if fallow precipitation increased the amount of stored soil water at planting (data not shown), as reported by Unger and Baumhardt (1999). Dryland sorghum grain yield measured during 15 growing seasons from 1972 to 2005 averaged 2.86 Mg ha⁻¹ after deep plowing compared with 2.61 Mg ha⁻¹ for the control plots. The mean annual grain yield difference between deep-plowed and control plots of 0.25 Mg ha⁻¹ was significant ($P < 0.05$) for annual paired *t*-test comparisons (Table 1). The corresponding sorghum water use for the 15 sorghum crop yr tested did not vary significantly with plowing treatment (Table 1), averaging 319 mm with deep plowing and 310 mm for control plots. This is consistent with the 362- to 367-mm mean water use for dryland sorghum reported in other studies that achieved greater yields (Jones and Popham, 1997; Baumhardt and Jones, 2002b). Compared with control plots, deep plowing increased sorghum grain yield with similar water use; however, the resulting WUE of 1.28 kg m⁻³ (Table 1) with deep plowing was not significantly greater than the WUE of 1.12 kg m⁻³ for sorghum grown on control plots, assuming negligible drainage beyond the root zone of the growing crop. The WUE for

Table 1. Mean \pm standard error for fallow efficiency (i.e., stored soil water divided by precipitation), plant-available soil water at planting, and sorghum grain yield, water use, and water use efficiency from annual paired *t*-tests ($n = 15$) of deep plowing and control effects. The significance level (P) of treatment effects was based on two-tailed comparisons.

Parameter	Effects		<i>P</i> value
	Plowed	Control	
Fallow efficiency, m m ⁻¹	0.38 \pm 0.17	0.26 \pm 0.15	0.19
Available soil water– planting, mm	178 \pm 15.3	160 \pm 12.9	0.08
Sorghum grain yield, mg ha ⁻¹	2.86 \pm 0.13	2.61 \pm 0.12	0.04
Sorghum water use, mm	319 \pm 42.7	310 \pm 45.4	0.55
Sorghum water use efficiency, kg m ⁻³	1.28 \pm 0.40	1.12 \pm 0.29	0.34

dryland continuous sorghum grown on level terrace benches tended to be higher than has been reported for sorghum on nearby graded and level terraces, which ranged from 0.74 to 0.91 kg m⁻³ (Jones and Popham, 1997; Baumhardt and Jones, 2002b). Under the conditions of this study, mean sorghum grain yield increased with deep plowing and resulted in a 15-yr cumulative yield increase of 3.75 Mg ha⁻¹ more than the control.

In 4 of the 15 growing seasons compared in this study (Fig. 6), deep plowing produced yield increases over control plots that exceeded 150% of the 0.26 Mg ha⁻¹ mean yield difference. That is, deep plowing increased sorghum grain yield 0.92 Mg ha⁻¹ in 1984, 1.11 Mg ha⁻¹ in 1999, 0.84 Mg ha⁻¹ in 2003, and 0.47 Mg ha⁻¹ in 2004 compared with the unplowed control. The cumulative yield increase of 3.34 Mg ha⁻¹ for deep tillage compared with the control plots accounted for 89% of the total yield difference during the study. Elimination of these 4 yr reduced the annualized growing-season grain sorghum yield increase with deep plowing from 0.26 Mg ha⁻¹ (Table 1) to 0.03 Mg ha⁻¹ for the remaining 11 crop yr. The corresponding paired *t*-test of sorghum grain yields indicated no significant difference due to plowing treatments, although sorghum grain yields on unplowed plots trended higher in 5 of those 11 crop yr. These data suggest that deep plowing the Pullman soil provides a dryland sorghum grain yield benefit realized during unique growing seasons.

To explain above-average sorghum grain yield increases with deep plowing during 1984, 1999, 2003, and 2004, we contrasted their growing season precipitation with the remaining 11 study

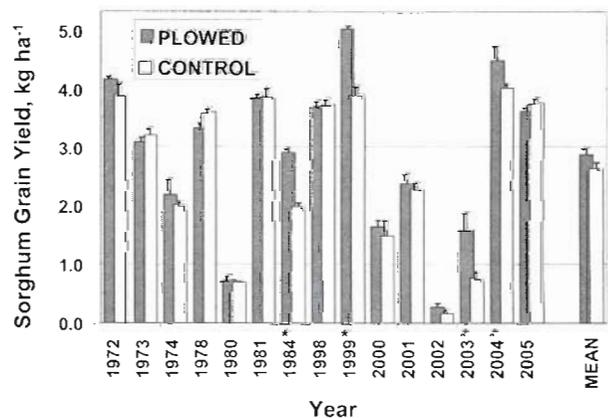


Fig. 6. Mean sorghum grain yield ($n = 3$) with standard error bars for paired tillage treatments plotted by year. Asterisks denote those years with early post-planting precipitation >75 mm that may have resulted in temporary flooding and crop injury.

years. During these 4 yr, early growing-season precipitation for brief, <5-d periods varied from 60 to 100 mm and was sufficient to flood the unplowed terrace benches. Our ponded infiltration measurements show that deep plowing has a sustained effect to increase infiltration and improve profile drainage. Consequently, the potential for flooding injury to growing crops in 1984, 1999, 2003, and 2004 was prevented in deep-tilled plots. We speculate the greater surface drainage with deep plowing limited water ponding compared with the control. Eck et al. (1977) noted a similar benefit for irrigated alfalfa (*Medicago sativa* L.) grown on soil profiles similarly modified to 0.9 m in 1964.

CONCLUSIONS

Crops grown on the southern Great Plains under dryland conditions rely on stored soil water to augment growing season precipitation, but the extensive Pullman clay loam found in this region features a dense and very slowly permeable subsoil layer that limits infiltration and root growth. We tested the hypothesis that profile-modifying deep plowing would disrupt this dense subsoil layer and improve soil physical properties while increasing infiltration and crop yield. We also evaluated the longevity (>30 yr) of a single deep plowing on soil properties and crop growth.

Bulk density within the dense subsoil layer and PR below the surface 0.3 m decreased significantly with deep plowing for up to 30 yr after treatment. Measured ponded infiltration of 100 to 200 mm water was ~30% greater with deep plowing because of improved drainage through the subsoil. Benefits of deep tillage were sustained during this 30-yr test, thus indicating that the dense subsoil layer did not completely redevelop. Although it is difficult to characterize all the factors governing crop yield response to deep plowing, decreased BD and PR with deep plowing may have encouraged greater root growth during most years and increased the volume of soil explored by dryland sorghum. Compared with control plots, the mean grain sorghum yield for 15 crop yr increased 10% for deep-plowed plots. The resulting 15-yr cumulative grain yield increase due to deep tillage of ~3.75 Mg ha⁻¹ was valued at US\$280 ha⁻¹ based on the year-specific yield differences multiplied by the corresponding mid-November sorghum grain prices reported by the National Agricultural Statistics Service (2007) for each year. Most of the yield increase (89%) for deep-plowing effects was attributed to overcoming an infrequent (4 out of 15 yr) surface water drainage problem during growing seasons with brief periods of rain exceeding 60 mm. For a Pullman soil, deep plowing achieved long-term soil profile modification that affected the soil physical properties. Although the increased yield with deep plowing was relatively small, that sustained yield benefit extends the period to recoup the US\$160 ha⁻¹ cost of deep plowing.

ACKNOWLEDGMENTS

The technical assistance of Mr. Grant Johnson for general long-term plot management and his work as custodian of these data records are gratefully acknowledged.

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