What constitutes “long-term” research may be as apparent as collectable art; although many are quick to identify the plots in Rothamsted-UK, started in 1843, as the gold standard of long-term research. When researchers conduct experiments in reference to a hypothesis that determines treatment application, the test duration usually lapses after a few “climatically representative” years. Mr. O. Reggie Jones initiated his deep plowing experiment in September of 1971 to test the hypothesis that deep plowing a Pullman soil to break-up dense subsoil layers would increase dryland crop yield through increased rooting that expands the amount of soil explored for water. Any question of treatment durability or the sustainability of a management practice constituted an additional hypothesis. Nevertheless, sustained benefits of deep plowing depend on processes of soil consolidation and re-development of the dense subsoil layers, and these processes could span a growing season or, possibly, decades.

The summer of 1971 was also my first time to work at the Bushland Research Center as a student, armed with a nearly new driving permit. I helped collect soil and plant samples, and I quizzed practically everyone about the assortment of nearby experiments. These included on-going groundwater recharge experiments using excavated basins and efforts to quantify soil profile modification and deep plowing effects on the growth and yield of irrigated crops. One recurrent concern about some of these tillage practices was that the effects may be short lived.

My professional appointment with the USDA-Agricultural Research Service at Bushland began in September of 1997. Agency leaders stressed that research conducted by ARS scientists should

Precipitation on the semiarid Southern Great Plains, during an average year, provides approximately 25 percent of the potential evapotranspiration (ET) for crop water use. Dryland cropping systems rely on stored soil water to supplement precipitation during dry years. The Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) is the dominant soil found on the Southern Great Plains region, occupying 1.5 million ha (Unger and Pringle, 1981), and features a very slowly permeable subsoil layer from 0.15 to 0.7 m depth. This layer may impede infiltration of rain for crop use and delay internal drainage of ponded water. Eck and Taylor (1969) proposed a one-time deep, > 0.4 m, plowing modification of the soil profile to eliminate the dense subsoil to increase infiltration of rain and irrigation. Several studies at Bushland evaluating the effects of soil profile modification have consistently reported decreased bulk density (BD) and increased infiltration for a period of up to 26 years (Eck and Taylor, 1969; Eck, 1986; Eck and Winter, 1992; Unger, 1993). Another benefit of disrupting dense subsoil layers with deep plowing was decreased penetration resistance (PR) and, consequently, an expanded volume of soil explored by roots of irrigated crops. There is little information documenting the longevity of deep plowing effects on soil physical properties or growth and yield of dryland crops.

Another consequence of increased infiltration in deep plowed soil profiles is the potential for increased internal drainage leading to ground water recharge. Aronovich et al. (1972) ponded water using 0.4 ha basins excavated into the caliche layers beneath the Pullman soil and observed its progress down to and through the caprock strata overlying the Ogallala formation. The estimated recharge rates in these basins approached 0.4 m d^-1; however, the limited area of recharge basins restricts potential groundwater recharge. Deep plowing gently sloping Pullman soil in leveled bench terraces constructed around playa lakes may expand potential groundwater recharge using the
emphasize regionally important topics of “high-risk” or requiring “long-term” study. From my perspective, practically any Bushland landmark identifying an old experiment could be a long-term study. Some of the research assets I now manage were originally established by V.L. Hauser in the 1950’s and had been the site for Reggie Jones’ deep plowing experiment. I also received a collection of unreported data from these studies along with “historical” observations from Reggie. One of those emphasized the rapid drainage on his old deep-plow plots. I suppose it was luck, but I saw this difference in drainage following a large rain and revised Reggie’s original hypothesis that deep plowing to break-up dense subsoil layers would have a sustained effect to increase infiltration and drainage for a Pullman soil.

The folders from the deep-plow experiment contained growth, water use, and yield data for crops grown since the summer of 1972. These were combined with more recent paired crop observations. Soil measurements taken at the onset of the study were repeated after about 30 years with the goal of documenting any sustained “long-term” tillage benefit. In that report, it was concluded that the 1971 moldboard plowing of a Pullman soil to 27 in. (0.7 m) decreased subsoil penetration resistance and bulk density and increased infiltration. The intermittent yield increase with deep plowing was attributed to improved drainage (just like Reggie observed) that reduced flood injury to seedling sorghum. Proof of increased drainage due to deep plowing came from a cooperating scientist, Bridget Scanlon, who analyzed soil chloride concentrations with depth. Drainage through a Pullman with normal sweep tillage for weed control resulted in a chloride concentration bulge at about 10 ft (2.8 m). In contrast, the chloride bulge had moved to a depth of about 40 ft (12.0 m) because of increased drainage with deep plowing. From long-term results, we conclude that deep plowing increased sorghum grain yield through improved infiltration and drainage of rain.

normal runoff from contributing watersheds. To quantify subsurface water movement and evaluate potential groundwater recharge Scanlon et al. (2007) analyzed the distribution of native chloride concentrations with depth as a tracer to determine ion displacement. This method can be used to verify the long-term impact of deep plowing to modify the soil profile on the infiltration and internal drainage processes for possible groundwater recharge.

In addition to characterizing the effects of profile modification and deep plowing on soil physical properties, several studies reported consistently greater yields under full or limited irrigation (Eck and Taylor, 1969; Schneider and Mathers, 1970; Eck, 1986; Eck and Winter, 1992). Dryland crop production systems, however, were not evaluated. We hypothesize 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.

METHODS

The long-term (1972-2005) effects of soil profile modification using deep plowing on crop yield and selected soil physical properties were evaluated at Bushland, TX as described by Baumhardt et al. (2008). Briefly, a pair of contour-farmed level conservation bench terraces (24 m by 410 m or larger) were either untreated (control) or deep plowed to 0.7 m in September of 1971. The 1.0-m single blade moldboard was adjusted to retain topsoil in the top part of the profile (Fig. 1). Afterwards, stubblemulch tillage was performed at a 0.10 m depth as needed for weed control. Wheat (Triticum aestivum L.) and grain sorghum (Sorghum bicolor L.)

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Moench] were uniformly cropped on the runoff contributing terrace watersheds using the wheat-sorghum-fallow (WSF) rotation. The level benches were planted to various annual crops, but grain sorghum, seeded at 8 seed m\(^{-2}\) during early to mid-June in single 0.75-m rows permitted the greatest number of paired yield comparisons during the study (i.e., 15 growing seasons). We used herbicides for seasonal weed control and applied N fertilizer as needed for sorghum crops on benches. Sorghum grain yields were determined by combine harvesting triplicate plot areas.

Soil BD for both deep plowed and control terraces was measured at 3 to 4 locations ~ 100-m apart to ~ 1 m depths in 1975 and 2002. In 1975, infiltration was estimated from periodic measurements of ponding depth beginning 10 hours after a 56 mm natural rainfall and continued for up to 50 h. In 2002, we timed ponded infiltration of four applications of well water added to 1.0 by 1.5 -m framed areas in 25 or 50 mm increments (total depth of 100 and 200 mm) with ~ 72 h delay between each application to permit drainage. Soil PR was determined with depth in 2002 according to Allen and Musick (1997) using triplicate measurements taken within each of the infiltration frames after allowing them to drain for one week. This decreased the variable effect of the initial soil water content on PR. The approach to evaluate impacts of deep Cl\(^{-}\) plowing on subsurface water movement was the measurement and analysis of deep profiles (Scanlon et al., 2007). That is, continuous soil cores were obtained from December 2006 to August 2008 using a direct-push drill rig (Model 6620DT, Geoprobe, Salina, KS) to depths up to ~25 m. The core samples were encased in 1.2 m plastic sample sleeves for storage and were sectioned in the laboratory for analyses of various ions, water content, and soil Cl\(^{-}\) concentration. Our analyses compared the control and deep plow effects on soil properties and crop yield using a t-test procedure for two sample populations assuming unequal variances (SAS Inst., 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 were analyzed according to a t-test procedure of plowing treatment effects paired for the common years of observation.

RESULTS

Soil Properties

The effects of the 1971 deep plowing on soil BD was evaluated twice during this experiment at four and 31 years after profile modification. Soil bulk density was expected to be higher in control plots than where deep plowed; however, density measured in 1975 averaged a similar 1.4 and 1.46 Mg m\(^{-3}\) for the control and tilled profiles, respectively. After 31 years, in 2002, the profile density remained relatively unchanged; averaging ~ 1.43 Mg m\(^{-3}\) for deep plowed plots compared with the not significantly different 1.45 Mg m\(^{-3}\) for control plots. Our measured PR (Fig. 3) was similar for the control and deep plow treatments above the dense subsoil layers (Continued on page 11)
beginning at the 0.3 m depth. Penetration resistance below 0.3 m, however, was consistently lower in the deep plowed compared with control plots and significantly lower with deep plowing at 0.38 m and 0.53 m (Fig. 3). Deep plowing had a sustained impact to reduce the PR through the dense subsoil. In the absence of this subsoil layer after tillage root proliferation could increase and expand the volume of soil explored by crop roots. Using the core break method we observed deeper rooting in deep plowed plots.

The effect of deep plowing on ponded infiltration was evaluated twice at four and 31 years after profile modification. Measured infiltration of rain in 1975 was 8 mm h⁻¹ with deep tillage or a 6-fold increase over the control. In 2002, a second comparison of deep plowing effects on ponded infiltration was conducted using multiple 25 and 50 – mm water applications. These applications mimic typical overhead irrigations with 72 hours between applications that totaled 100 and 200 mm. Measured total time required for the observed incremental cumulative infiltration is shown in Fig. 4. Time for infiltration of 25, 50, and 75 – mm of water did not vary with tillage probably because the estimated wetting front position was above most of the 0.2-0.8 m deep flow-restricting subsoil layer. Beginning with the 100 mm water application, the subsoil impeded water movement in the control plots and significantly increased ob-

served time of infiltration over the deep plowed soil. Compared with control plots, the impact of deep plowing further increased the difference in infiltration as the water application depth increased. Overall, ponded infiltration into the deep tilled plots required 30% less time than in the untreated control plots (r²=0.94). These data show that deep moldboard plowing disturbed the subsoil and increased pore space and size, which eliminated a flow restricting subsoil layer and increased infiltration due to improved drainage for > 30 years.

Crop Yield

We hypothesized that deep plowing the dense 0.2-0.6 m subsoil layer in the Pullman clay loam increased the volume of soil explored by crop roots and, consequently, the available soil water and yield of dryland crops. Annual sorghum grain yield (Fig. 5) revealed no large yield increase during the years immediately after

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plowing (1972-1974) when crop rooting would benefit the most. Also, we observed no gradual decline in yield differences between deep plowed and control plots due to soil consolidation as a result of periodic tillage and traffic on the plots. Dryland sorghum grain yield measured during 15 growing seasons from 1972-2005 averaged 2.86 Mg ha\(^{-1}\) after deep plowing compared with the significantly lower 2.61 Mg ha\(^{-1}\) average for the control plots. The 15 year cumulative sorghum grain yield with deep plowing was \(\approx 3.75\) Mg ha\(^{-1}\) more than the control; however, conspicuously large yield increases over control treatments were observed with deep plowing in 1984 (0.92 Mg ha\(^{-1}\)), 1999 (1.11 Mg ha\(^{-1}\)), 2003 (0.84 Mg ha\(^{-1}\)), and 2004 (0.47 Mg ha\(^{-1}\)).

The cumulative yield increase with deep plowing accounted for \(\approx 90\%\) of the yield difference during the 15 year study. We reviewed the precipitation during these four years and determined that early growing season precipitation for brief, \(< 5\) days, periods varied from 60 to 100 mm and was sufficient to flood the unplowed terrace benches (Fig. 6). 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 plowed plots. 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.

**Drainage and Ion Displacement Profiles**

Natural ecosystems in semiarid regions are generally characterized by near surface Cl\(^{-}\) accumulations where drainage and recharge is limited (Scanlon et al., 2008). However, increased drainage below the root zone will displace the Cl\(^{-}\) bulge downward through the profile. The Cl\(^{-}\) profile sampled beneath native rangeland
Bushland exhibit a bulge-shaped peak at ~1.0 m depth and a concentration of 3042 mg L\(^{-1}\) (Fig. 7a). The near surface high Cl\(^{-}\) concentrations were attributed to concentration by evaporation of atmospherically deposited Cl\(^{-}\) from precipitation and dry fallout and indicate that no recharge has occurred in this setting during the Holocene. The Cl\(^{-}\) profile for the conventionally tilled bench terrace system was displaced to 2.8 m depth (Fig. 7b), which translates to a surface water flux of 9 mm yr\(^{-1}\). In contrast, displacement of Cl\(^{-}\) bulges to depths of 10.7, 12.3, and 13.7 m (Fig. 7c) were observed in the deep-plowed bench terrace. These data indicate that deep plowing disrupted the flow-limiting subsurface layer, leading to increased drainage below the root zone as suggested during the interpretation of sorghum yield data. The difference in Cl\(^{-}\) displacement for the deep plowed and conventionally tilled bench terraces during the 35-yr experiment averaged ~0.26 m yr\(^{-1}\) with corresponding water drainage averaging ~72 mm yr\(^{-1}\) with deep plowing. Minimum estimates of drainage beneath the root zone were observed in the conventionally tilled profile. Deep plowing that eliminated flood injury of crops following intense precipitation may also have the potential to increase recharge of groundwater resources.

**SUMMARY**

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 evaluated the effects of deep plowing the dense subsoil, which reduced subsoil PR and BD while increasing ponded infiltration and crop yield. These profile modification benefits were sustained >30-year; thus, indicating that the dense subsoil layer did not completely redevelop. The decreased BD and PR with deep plowing promoted root growth and expanded the volume of soil explored for water by dryland sorghum. However, the 10% increase in mean grain sorghum yield on deep plowed plots was largely (~90%) attributed to overcoming infrequent soil surface flooding. Compared with conventional tillage, the estimated drainage through the Pullman soil increased 8 fold to 72 mm yr\(^{-1}\) with deep plowing and may lead to successful recharge of groundwater resources. For a Pullman soil, deep plowing may be an economical soil modification because of the sustained soil and yield benefits that extend the time to recoup the 1971 installation cost of $160 ha\(^{-1}\).

**REFERENCES**