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# PULLMAN SOILS:
# Distribution, Importance, Variability & Management

The Texas Agricultural Experiment Station, Neville P. Clarke, Director, College Station, Texas
in cooperation with
United States Department of Agriculture, Agricultural Research Service and Soil Conservation Service

# Contents

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*Cover photo: The picture on the cover shows wheat being harvested on Pullman clay loam. The landform is typical of the expansive areas of this soil on the Texas High Plains (USDA — Soil Conservation Service photo).*

# SUMMARY

Pullman soils are the most extensive arable soils in Texas, covering 3.8 million acres. The area of Pullman soils in Texas is bounded by the New Mexico-Texas state line on the west, the Canadian River on the north, and the caprock escarpment at the High Plains-Rolling Plains boundary on the east. A catena of loamy soils extending from Farwell to near Lubbock forms the southwest boundary. Pullman soils occupy about 75 percent of the land in this area. The remaining area is composed of soils mainly associated with playa lakes that are found throughout the area.

About 56 percent of the Pullman soil area is cropland, 40 percent is rangeland, and the remainder is in roads, towns, and other non-agricultural uses. Irrigation is used on 53 percent of the cropland area. Major crops are wheat, grain sorghum, cotton, and corn.

To determine the variability of soil characteristics, Pullman soils were sampled at seven widely separated locations. The profiles were described in the field at sampling time, and samples were analyzed in the laboratory for sand, silt, and clay content; organic matter content; pH; bulk density; and water retention. Plant available water was calculated from horizon thickness, bulk density, and water retention values. Water infiltration was measured at the sampling sites.

The thickness of the profile above the calcic horizon was greater in the northern province than in the central province, which in turn was greater than in the southwestern province. Depth to the calcic horizon ranged from 40 to 59 inches. In general, the profiles had less sand and more silt and clay in the northern province than in the central and southwestern provinces. Associated with the higher silt and clay contents were higher mean water retention values, which, along with the deeper profiles, resulted in greater capacity to store plant available water in profiles in the northern province.

Total water infiltration and infiltration rates at 10 minutes generally were higher in the sandier southwestern province than in the northern province. Total infiltration at 20 hours ranged from 4.12 to 4.90 inches, except at Site 7 in the southwestern province where it was only 3.18 inches. This low total infiltration in 20 hours resulted from low infiltration rates for the period from 1 to 20 hours after applying water.

Based on the results of the various measurements, indications are that about 24 hours of water application is needed to fill the profile with water in the southwestern province. The profile has capacity for greater storage in the northern province, but from 8 to 25 more hours would be needed to store each extra inch of water. Applying irrigation water for more than 24 hours is not practical because tailwater runoff losses become excessive. Also, crops such as grain sorghum do not use water from below about 4 feet in Pullman soil. Therefore, unless deeper-rooting crops such as sunflower, wheat, or alfalfa are grown, complete filling of the profile with water may not be desirable. When crops such as sorghum fail to use water from deep in the profile, a rotation involving a deeper-rooted crop can result in more efficient use of water by extracting some of the deeply-stored water, provided the soil throughout the profile contains adequate water for root growth.

Because of declining supplies of water for irrigation, water conservation has received considerable attention in recent years. Practices that conserve water from rainfall, such as conservation-bench and level-bench terraces, contour furrows, blocked furrows, and the limited- and no-tillage systems, are applicable to Pullman soils. These practices conserve water by reducing runoff, increasing infiltration, or reducing evaporation. Crop yields have been increased where these practices were used on Pullman soils. Practices for conserving irrigation water include improved water application techniques, tailwater recovery systems, and no-tillage farming.

*Figure 1.*
*Counties of Texas in which Pullman soils have been mapped are within the heavy-lined area.*

TABLE 1. CLASSIFICATION OF SOILS MENTIONED IN THE TEXT AND FIGURES

| Series | Classification |
|---|---|
| Acuff | Fine-loamy, mixed, thermic Aridic Paleustolls |
| Amarillo | Fine-loamy, mixed, thermic Aridic Paleustalfs |
| Berda | Fine-loamy, mixed, thermic Aridic Ustochrepts |
| Bippus | Fine-loamy, mixed, thermic Cumulic Haplustolls |
| Drake | Fine-loamy, mixed (calcareous), thermic Typic Ustorthents |
| Estacado | Fine-loamy, mixed, thermic Calciorthidic Paleustolls |
| Houston Black | Fine, montmorillonitic, thermic Udic Pellusterts |
| Lipan | Fine, montmorillonitic, thermic Entic Pellusterts |
| Lofton | Fine, mixed, thermic Vertic Argiustolls |
| Mansker | Fine-loamy, carbonatic, thermic Calciorthidic Paleustolls |
| Mobeetie | Coarse-loamy, mixed, thermic Aridic Ustochrepts |
| Olton | Fine, mixed, thermic Aridic Paleustolls |
| Potter | Loamy, carbonatic, thermic, shallow Ustollic Calciorthids |
| Pullman | Fine, mixed, thermic Torrertic Paleustolls |
| Randall | Fine, montmorillonitic, thermic Udic Pellusterts |
| Richfield | Fine, montmorillonitic, mesic Aridic Argiustolls |
| Sherm | Fine, mixed, mesic Torrertic Paleustolls |

# *Pullman Soils:* Distribution, Importance, Variability, and Management

**Paul W. Unger and Fred B. Pringle**

## INTRODUCTION

### Area Occupied by Pullman Soils

Pullman soils[1] occupy parts of 21 counties in the High Plains of Texas (Fig. 1, 2). The portions of different counties occupied by Pullman soil range from about 0.1 to 70 percent (Table 2). The area of Pullman soils is bounded by the New Mexico-Texas state line on the west, the caprock escarpment at the Canadian River on the north, and the caprock escarpment at the High Plains-Rolling Plains boundary on the east. A catena of loamy soils extending from Farwell to near Lubbock forms the southwest boundary of Pullman soils. Within this roughly triangular area, Pullman soils occupy about 75 percent of the land surface.

The area of Pullman soils ranges from about 100° 30′ to 103° 03′ west longitude and from about 33° 31′ to 35° 45′ north latitude. Elevation of the surface of Pullman soils ranges from about 3,000 to 4,200 feet above mean sea level. The area is in a subhumid to semiarid climatic zone where average annual precipitation ranges from about 17 inches at the western edge to about 23 inches at the eastern edge. Some higher precipitation values are presented in Table 3, but they were obtained at cities that are not on Pullman soils and that are at the lower elevations of the Rolling Plains. Also listed in Table 3 are the average length and dates of the frost-free period, average daily maximum and minimum

*Fig. 2. The approximate area of Pullman soils is represented by the part of the map within the solid line. The approximate sampling sites are indicated by the numbered dots.*

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[1] See Table 1 for classification of soils mentioned in this report.

TABLE 2. AREAS OCCUPIED BY PULLMAN SOILS

| County | Slope | Series area | Portion of county | Total series area[1] | Total cropland | Irrigated cropland | Rangeland | Other land[2] |
|---|---|---|---|---|---|---|---|---|
| | % | Acres | % | Acres | | | | |
| Armstrong | 0-1 | 167,850 | 28.8 | 208,670 | 73,650 | 16,550 | 128,750 | 6,260 |
| | 1-3 | 39,470 | 6.8 | | | | | |
| | 1-3, eroded | 1,350 | 0.2 | | | | | |
| Briscoe | 0-1 | 163,000 | 28.6 | 175,420 | 55,330 | 19,170 | 114,830 | 5,260 |
| | 1-3 | 12,420 | 2.2 | | | | | |
| Carson | 0-1 | 251,000 | 43.7 | 302,090 | 159,520 | 100,540 | 133,510 | 9,060 |
| | 1-3 | 37,000 | 6.4 | | | | | |
| | 1-3, eroded | 14,090 | 2.4 | | | | | |
| Castro | 0-1 | 233,240 | 41.4 | 256,580 | 175,000 | 167,330 | 73,880 | 7,700 |
| | 1-3 | 23,340 | 4.1 | | | | | |
| Crosby | 0-1 | 137,260 | 23.5 | 143,600 | 92,740 | 17,110 | 46,550 | 4,310 |
| | 1-3 | 6,340 | 1.1 | | | | | |
| Deaf Smith | 0-1 | 534,820 | 55.4 | 601,070 | 257,780 | 172,280 | 325,260 | 18,030 |
| | 1-3 | 55,050 | 5.7 | | | | | |
| | 1-3, eroded | 740 | 0.1 | | | | | |
| | 0-1, Pullman-Ulysis complex | 7,500[3] | 0.8 | | | | | |
| | 1-3, Pullman-Ulysis complex | 2,970[3] | 0.5 | | | | | |
| Dickens | 0-1 | 25,920 | 4.4 | 29,340 | 4,390 | 600 | 24,070 | 880 |
| | 1-3 | 3,430 | 0.6 | | | | | |
| Donley | 0-1 | 12,290 | 2.1 | 13,150 | 11,840 | 4,730 | 1,180 | 140 |
| | 1-3 | 860 | 0.1 | | | | | |
| Floyd | 0-1 | 422,300 | 66.4 | 446,150 | 259,630 | 165,990 | 173,130 | 13,380 |
| | 1-3 | 23,850 | 3.7 | | | | | |
| Gray | 0-1 | 153,570 | 25.5 | 172,700 | 98,300 | 21,540 | 69,220 | 5,180 |
| | 1-3 | 19,130 | 3.1 | | | | | |
| Hale | 0-1 | 333,590 | 53.2 | 344,040 | 331,910 | 227,560 | 1,810 | 10,320 |
| | 1-3 | 10,450 | 1.7 | | | | | |
| Hemphill | 0-1 | 620 | 0.1 | 620 | 440 | 0 | 160 | 20 |
| Lubbock | 0-1 | 51,980 | 9.1 | 51,980 | 18,880 | 4,030 | 31,540 | 1,560 |
| Motley | 0-1 | 4,540 | 0.7 | 4,540 | 3,180 | 2,630 | 1,220 | 140 |
| Oldham | 0-1 | 115,750 | 12.2 | 129,140 | 63,470 | 12,420 | 61,800 | 3,870 |
| | 1-3 | 13,390 | 1.4 | | | | | |
| Parmer | 0-1 | 69,380 | 12.6 | 72,760 | 55,620 | 50,910 | 14,960 | 2,180 |
| | 1-3 | 3,380 | 0.6 | | | | | |
| Potter | 0-1 | 50,620 | 8.6 | 62,620 | 31,470 | 8,660 | 18,620 | 12,520 |
| | 1-3 | 12,000 | 2.0 | | | | | |
| Randall | 0-1 | 284,500 | 48.3 | 352,750 | 168,450 | 53,350 | 168,700 | 15,600 |
| | 1-3 | 54,850 | 9.3 | | | | | |
| | 1-3, eroded | 3,260 | 0.6 | | | | | |
| | 0-1, moderately shallow | 8,340 | 1.4 | | | | | |
| | 1-3, moderately shallow | 1,800 | 0.3 | | | | | |
| Roberts | 0-1 | 25,090 | 4.4 | 25,090[4] | 17,560 | 8,780 | 7,110 | 420 |
| Swisher | 0-1 | 379,710 | 66.2 | 413,440 | 278,830 | 93,740 | 122,210 | 12,400 |
| | 1-3 | 33,730 | 5.9 | | | | | |
| Wheeler | 0-1 | 350 | 0.1 | 350 | 290 | 0 | 50 | 10 |
| Total | | | | 3,791,980 | 2,158,280 | 1,147,920 | 1,518,560 | 129,240 |

[1] Includes total area for all slopes and conditions. Totals for the different slopes and conditions may not equal the total for series because of rounding values the nearest 10 acres.

[2] Includes land in roads, towns, and other non-agricultural uses.

[3] Values shown are for the estimated area of complex that is Pullman — 40% for 0-1 slope, 60% for 1-3% slope.

[4] Includes some Sherm soil.

temperatures, and average annual precipitation in counties in which Pullman soils are found.

Pullman soils occupy about 3.8 million acres of land (Table 2). Pullman soils are the most extensive arable soils in Texas. Other major arable soils in Texas are Amarillo with 2.5 million acres, Houston Black with 1.5 million acres, and Sherm with 1.3 million acres. There are also about 11,000 acres of Sherm soils in Oklahoma.

### History of the Pullman Series

The Pullman series is classified by soil scientists as a member of the fine, mixed, thermic family of Torrertic Paleustolls. The soil developed from fine-textured sediments of the High Plains eolian (wind deposited) mantle under a dense cover of short grasses (Fig. 3).

The Pullman series was established in the Soil Survey of Potter County, Texas, in 1929. It was named after Pullman Switch, a railroad siding which is east of Amarillo. Before 1929, Pullman soils were included in other series, mainly the Amarillo and Richfield series. The process of cataloging and classifying soils on the High Plains began with the publication of the Reconnaissance Soil Survey of the Panhandle Region of Texas in 1910. In this survey, Pullman soils were called Amarillo silty clay loam. The Amarillo series was established in this survey and included soils ranging from sands to clays.

As soil surveys and investigations continued, differences in the physical and chemical properties of soils were noted. This led to the recognition of other soil series. Early soil surveys of Dickens, Lubbock, and Wheeler counties included these soils in the Richfield series. Further investigations led to the establishment of the Pullman series.

In the 1929 Soil Survey of Potter County and the 1930 Soil Survey of Randall County, three phases of Pullman soils were recognized. These were Pullman silty clay loam, Pullman silty clay loam (bench phase), and Pullman clay loam. Additional studies of landscapes, closer examination of soil properties, and refinements in series criteria resulted in narrowing the limits of the Pullman series. In subsequent soil surveys on the High Plains, the Lofton series replaced the bench phase of Pullman soils. Lofton soils have properties similar to those of Pullman, but receive additional moisture from runoff and have grayish

*Fig. 3. Blue grama grass, the major native grass on Pullman soils.*

TABLE 3. ELEVATION AND CLIMATIC FACTORS IN THE COUNTIES HAVING PULLMAN SOILS

| County | City | Elev. | Avg. lake Evap. | Avg. growing season | | Avg. daily temp.[1] Max. | Avg. daily temp.[1] Min. | Avg. precip.[1] |
|---|---|---|---|---|---|---|---|---|
| | | ft. | in. | days | period | °F | °F | in. |
| Armstrong | Claude | 3,400 | 69 | 198 | Apr. 10-Oct. 25 | 72.0 | 44.5 | 23.24 |
| Briscoe | Silverton | 3,280 | 69 | 214 | Apr. 6-Nov. 6 | 71.7 | 42.6 | 20.77 |
| Carson | Panhandle | 3,450 | 62 | 197 | Apr. 17-Oct. 31 | -- | -- | 22.00 |
| Castro | Dimmitt | 3,855 | -- | 193 | Apr. 16-Oct. 26 | 72.4 | 41.2 | 17.50 |
| Crosby | Crosbyton | 3,105 | -- | 206 | Apr. 10-Nov. 2 | 74.5 | 45.5 | 21.42 |
| Deaf Smith | Hereford | 3,810 | 67 | 185 | Apr. 20-Oct. 22 | 72.1 | 42.3 | 18.04 |
| Dickens | Spur | 2,360[2] | 69 | 217 | Apr. 4-Nov. 7 | 78.1 | 46.9 | 20.43 |
| Donley | Clarendon | 2,700[3] | 68 | 206 | Apr. 9-Nov. 1 | 73.6 | 44.3 | 21.51 |
| Floyd | Floydada | 3,180 | 69 | 213 | Apr. 7-Nov. 6 | 74.2 | 44.9 | 18.75 |
| Gray | Pampa | 3,230 | 65 | 195 | Apr. 15-Oct. 27 | 70.4 | 44.0 | 20.13 |
| Hale | Plainview | 3,370 | 69 | 210 | Apr. 10-Nov. 6 | 73.9 | 44.3 | 19.01 |
| Hemphill | Canadian | 2,335[2] | 64 | 204 | Apr. 9-Oct. 30 | 72.9 | 45.1 | 20.50 |
| Lubbock | Lubbock | 3,150 | 69 | 211 | Apr. 7-Nov. 4 | 72.9 | 47.1 | 18.41 |
| Motley | Matador | 2,280[2] | 68 | 218 | Apr. 3-Nov. 7 | 75.7 | 48.4 | 20.22 |
| Oldham | Vega | 4,000 | -- | --- | ---- | 70.5 | 41.0 | 17.75 |
| Parmer | Friona | 4,010 | -- | 183 | Apr. 20-Oct. 20 | 71.3 | 42.1 | 17.50 |
| Potter | Amarillo | 3,650 | 68 | 191 | Apr. 20-Oct. 28 | 70.8 | 43.9 | 20.28 |
| Randall | Canyon | 3,577 | 66 | 200 | Apr. 15-Nov. 1 | 73.8 | 43.2 | 19.53 |
| Roberts | Miami | 2,800[2] | -- | --- | ---- | 71.6 | 42.8 | 20.66 |
| Swisher | Tulia | 3,500 | 68 | 205 | Apr. 10-Nov. 1 | 72.9 | 42.6 | 17.24 |
| Wheeler | Shamrock | 2,345[2] | 69 | 208 | Apr. 7-Nov. 1 | 74.5 | 46.2 | 23.17 |

[1] Average monthly maximum and minimum temperatures and precipitation are available in the soil surveys for most counties.

[2] Below Caprock escarpment.

[3] Lower than elevation at which Pullman soils are commonly found.

colors throughout the profile. The Olton series was established to accommodate those soils that had previously been classified as Pullman clay loam. They were slightly more red, had lighter textures, and were more permeable.

In 1970, the Sherm series was established for those soils north of the Canadian River that had previously been classified as Pullman. The Sherm series has a mean annual soil temperature of less than 59°F at a 20-inch depth. For Pullman soils, the mean temperature is greater than 59°F.

## Physiography

The topography consists of nearly level to gently sloping, smooth treeless plains (Fig. 4). Surfaces are plane to convex and slopes range from 0 to 3 percent, but are mainly 0 to 2 percent. These broad plains are interrupted only by the numerous playas, or shallow lakes, containing other soils. Except where pitted by playas, the surface is remarkably smooth. The playas range from a few square yards to several square miles in surface area, and from a few inches to more than 50 feet in depth. The average grade of the High Plains is about 10 feet per mile to the southeast. Runoff follows a poorly defined pattern. Water flows mainly into the playas, from which there is no definite outlet. The water collected in playas is lost mainly by evaporation, but some of it is used for irrigation.

Other soils associated with Pullman are Acuff, Drake, Estacado, Lipan, Lofton, Mansker, Olton, and Randall (Fig. 5, 6, 7, and 8). Drake soils are on recent eolian dunes that occupy the eastern rim of some playas throughout the central and southern parts of the area. These dunes are absent in the northern area. Estacado and Mansker soils are on sideslopes around playas and along draws. Lipan and Lofton soils are on low benches around playa bottoms. Acuff and Olton soils are on smooth plains that have slightly convex surfaces. These soils are intermingled with Pullman along the southwest boundary of the area. Randall soils are on playa bottoms.

There are differences in the morphological properties of the Pullman series that are related to geographic location. These differences affect soil water storage capacity, which in turn directly affects water management on these soils. The morphological properties are depth to the calcic horizon, texture, and permeability.

*Fig. 4. Aerial view of the topography of the land occupied by Pullman soils. The circular area near the center is a playa, or shallow lake, which contains other soils (USDA — Soil Conservation Service photo).*

An analysis of soil survey field notes for 17 counties and additional profile observations revealed that depth to the calcic horizon ranges from 30 to more than 72 inches. Observations by soil and plant scientists indicate that calcic horizons containing at least 30 percent calcite inhibit root development of most crops. Based on field determinations using a simple volume calcimeter, the average calcium carbonate content of the Btca horizon of Pullman soils is about 50 percent.

To present a clearer understanding of these soils as they relate to geographical location, it is convenient to divide this large area into three soil provinces (Fig. 2). The northern province includes the High Plains portions of Carson, Donley, Gray, Hemphill, Oldham, Potter, Roberts, and Wheeler Counties and the northern portions of Armstrong, Deaf Smith, and Randall Counties. In the northern province, depth to a strong calcic horizon (>30 percent $CaCO_3$) ranges from 55 to more than 72 inches.

The central province extends southeastward from western Deaf Smith County to western Briscoe County. It includes all or parts of Armstrong, Briscoe, Castro, Deaf Smith, Randall, and Swisher Counties. The southern boundary of this province roughly follows Terra Blanca and Tule Creeks. The depth to a strong calcic horizon ranges from 45 to 55 inches.

The southwest province of Pullman soils is the area south of Terra Blanca and Tule Creeks. Included are parts of Briscoe, Castro, Crosby, Deaf Smith, Dickens, Floyd, Hale, Lubbock, Motley, Parmer, and Swisher Counties. The depth to a strong calcic horizon ranges from 30 to 48 inches, but is mainly from 33 to 45 inches. Along the southwestern boundary, Pullman soils are closely associated with Acuff and Olton soils (Fig. 8). While similar to Pullman soils in appearance, the Bt horizons of these soils are somewhat redder, have loamy textures, and are more permeable. Acuff and Olton soils occupy the same general landscape as Pullman soils, although their surfaces are slightly more convex.

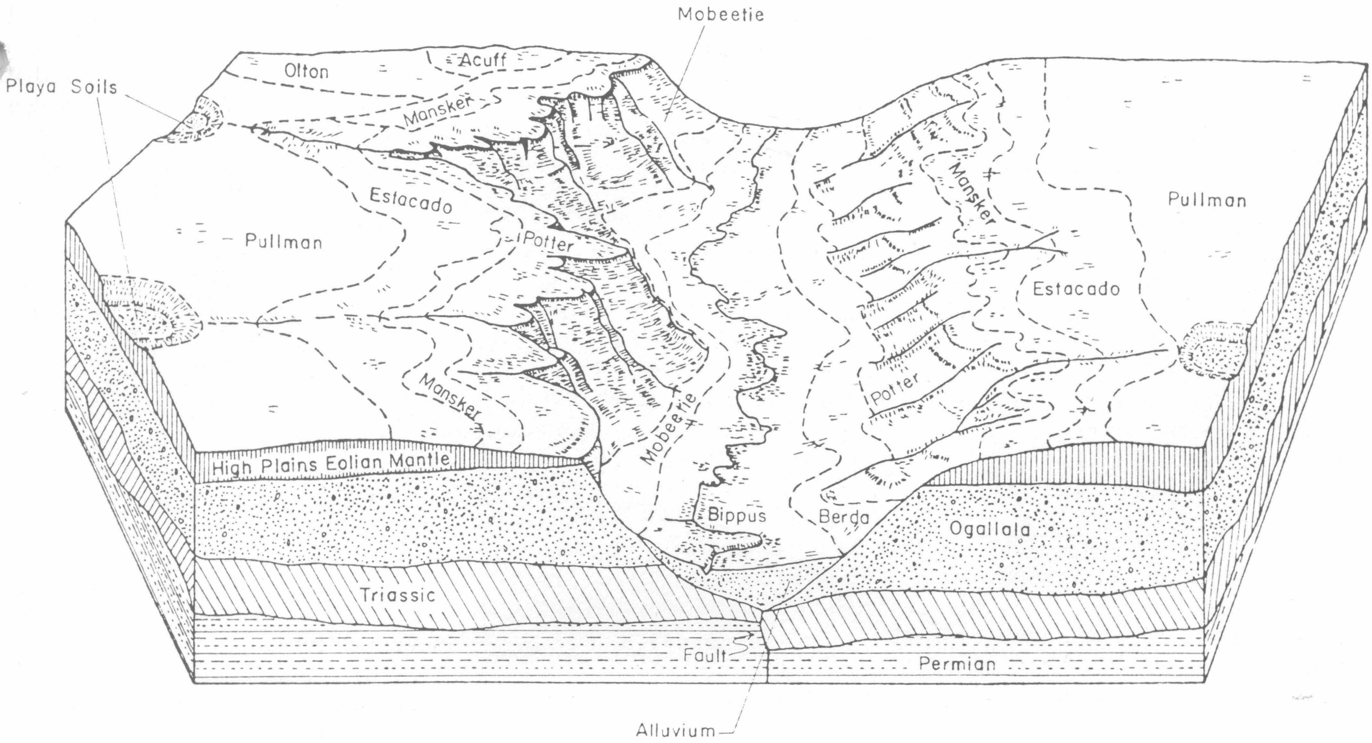

*Fig. 5. Major soils and underlying formations in the area occupied by Pullman soils.*

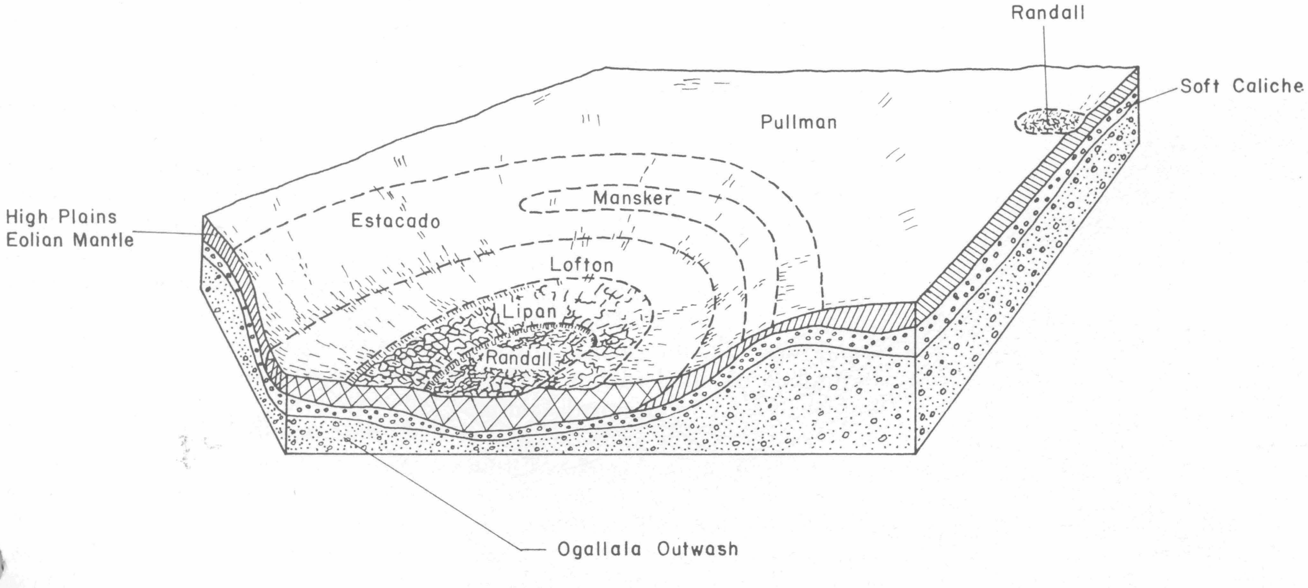

*Fig. 6. Soil pattern in the northern province.*

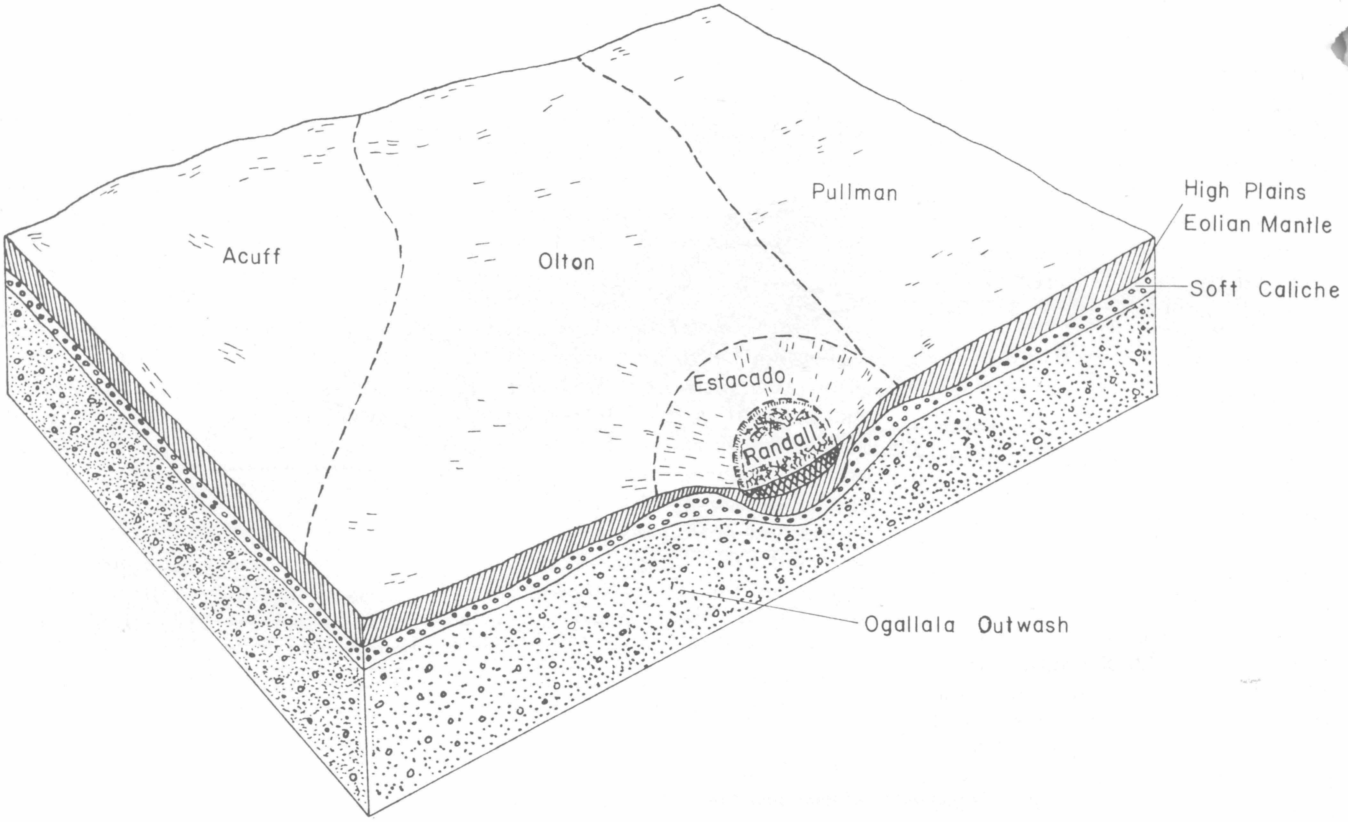

*Fig. 7. Soil pattern in the central province.*

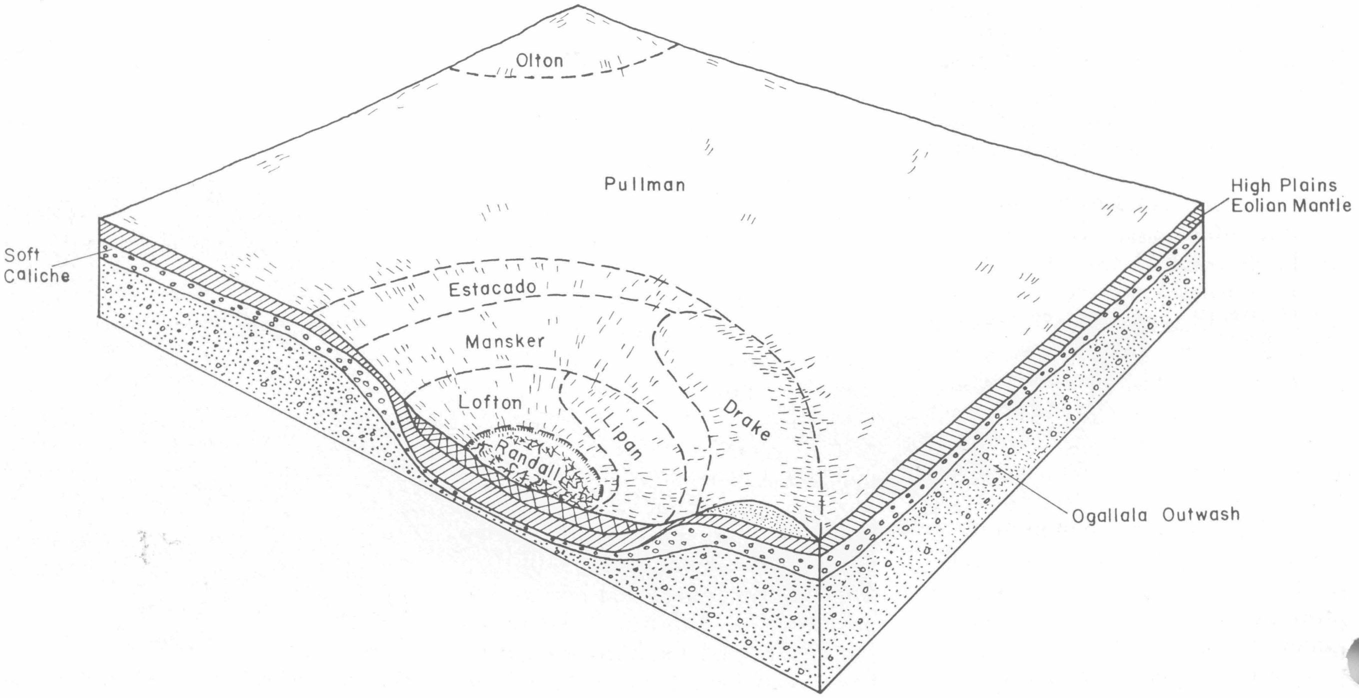

*Fig. 8. Soil pattern in the southwest province.*

*Fig. 9. Surface conditions and soil profile at a typical site of Pullman soil. The site is at the USDA Conservation and Production Research Laboratory, Bushland, Texas (USDA — Soil Conservation Service photo).*

## Uses and Importance of Pullman Soils

Pullman soils are used primarily for agriculture with about 56 percent of their area being used for crop production. Almost 40 percent of the area of Pullman soils is in rangeland. The remaining area is in roads, towns, and other non-agricultural uses. Of the cropland area of Pullman soil, about 53 percent is irrigated and 47 percent is dryland (Table 2). The area of irrigated Pullman soil represents about 13 percent of all irrigated land in Texas. Of the total acreage devoted to wheat (*Triticum aestivum* L.), cotton (*Gossypium hirsutum* L.), grain sorghum [*Sorghum bicolor* L. (Moench)], and corn (*Zea mays* L.) in Texas, about 11, 9, 7, and 11 percent, respectively, were produced on Pullman soils in 1977 (Texas Dept. Agric., 1977). Other major crops grown on smaller areas of Pullman soils are sugar beets (*Beta vulgaris* L.), soybeans (*Glycine max* L.), forage sorghum (*Sorghum* sp.), alfalfa (*Medicago sativa* L.), sunflower (*Helianthus annuus* L.), and vegetables.

Because Pullman soils are located in a subhumid to semiarid region, yields of dryland crops on Pullman soils are relatively low. Irrigation from the Ogallala Aquifer greatly increases yields, but the water supply is limited and being depleted. Also, the cost of energy for pumping water has greatly increased in recent years. Surface water for irrigation is negligible. It is, therefore, essential that the water be used as efficiently as possible so that economic crop production can be maintained and the eventual return to dryland crop production can be delayed as long as possible. When dryland farming replaces irrigated farming, even if only on the Pullman soils, a significant amount of the total production of some crops in Texas will be lost.

## Typical Site for Pullman Soils

Pullman soils developed in a relatively cool, subhumid to semiarid climate from medium- to fine-textured sediments largely or entirely of eolian origin. They occupy extensive smooth areas that are nearly level to gently sloping. Surface slopes range from 0 to about 3 percent toward the playas or shallow basins. Although largely cultivated, the typical native vegetation on Pullman soils was short-grasses, principally blue grama (*Bouteloua gracilis*) and buffalograss (*Buchloe dactyloides*). The surface conditions and profile at a typical site of Pullman soil are shown in Fig. 9 and Fig. 10, respectively. The profile shown is at the Conservation and Production Research Laboratory at Bushland. It is near the site used by Taylor et al. (1963) for their study of Pullman soil and also near Site 3 (Fig. 2) of this study.

The surface horizon of a typical Pullman soil is a brown to dark brown silty clay loam, but the texture may range from loam to clay loam. The thickness of the surface horizon usually ranges from 4 to 7 inches, at which depth there is a rather abrupt boundary to a dark brown to dark grayish-brown clay with blocky structure (Fig. 10). The soil may contain buried horizons of older soils at 3 to 5 feet below the surface. The buried horizons usually have a clay loam texture. At the site used by Taylor et al. (1963), a caliche or calcic horizon occurred at a depth of 53 inches. Based on other samples taken at the Laboratory, depth to the calcic horizon ranges from 5 to 6 feet on 0 to 1 percent slopes and from 2 to 4 feet on 1 to 3 percent slopes. As shown in Fig. 10, the upper boundary of the calcic horizon is clear and wavy. Although depth to the calcic horizon is often considered to be the effective depth of the Pullman soil for crop production purposes, winter wheat and especially

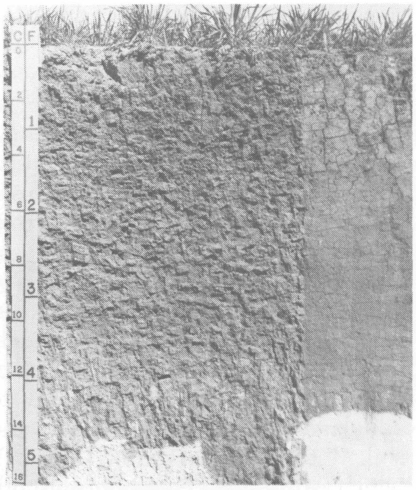

*Fig. 10. A typical Pullman soil profile. Profile shown is at the USDA Conservation and Production Research Laboratory, Bushland, Texas (USDA — Soil Conservation Service photo).*

sunflower use water from well into the calcic horizon. Sunflower roots have been found at a 9-foot depth in Pullman soil (O. R. Jones, Bushland, Texas, unpublished data) and have extracted soil water to about a 10-foot depth (Unger, 1978a).

### Present Water Management Systems

When filled to capacity, Pullman soil at Bushland holds about 17.0 inches of total water and about 7.7 inches of plant available water to a 4-foot depth, and about 24.6 and 10.5 inches to a 6-foot depth (Taylor et al., 1963). Because of erratic precipitation during the growing season, it is desirable to have the soil profile filled to capacity with water at planting of dryland crops. However, the soil is rarely filled to capacity to a 4- or 6-foot depth, even when a fallow period of up to 16 months precedes winter wheat (Unger, 1972). In some newly developed cropping systems involving surface residue maintenance, the soil has been filled to near-capacity during a fallow period of only 10 or 11 months (Unger, 1978b; Unger and Wiese, 1979). These systems involved a rotation of winter wheat and grain sorghum. When the soil is filled to capacity with water at planting time, crops usually experience less severe water stress during the growing season than when the soil contains a limited amount of water. When stress is reduced, crop yields usually are higher.

Although irrigation can provide water to crops, soil water content at planting is still important because any water stored from precipitation reduces the amount required from irrigation. When water storage from precipitation is low, preplant or emergence irrigation is often used to increase the soil water content. Because the Pullman soil is very slowly permeable, relatively long periods of water application are required to add large amounts of water to the soil. With furrow irrigation (Fig. 11), which is the most common method, considerable tailwater runoff is usually permitted so that adequate water is stored at the lower end of the field. Unless effective tailwater recovery systems are used, tailwater runoff reduces the efficiency of water use.

*Fig. 11. Furrow irrigation of cotton on Pullman soil in Swisher County, Texas (USDA — Soil Conservation Service photo).*

In recent years, numerous sprinkler systems have been installed on Pullman soils. These systems, when properly designed and operated, eliminate the runoff problem, but require considerably more energy input than furrow irrigation. With all farming systems on both dryland and irrigated land, a knowledge of the water holding capacity of the soil profile is important for effective water management.

### Objectives of the Study

Most published research information regarding Pullman soils was obtained at the Conservation and Production Research Laboratory at Bushland. Much of it is based on descriptions and analyses performed on samples obtained at the typical site at the Laboratory (Taylor et al., 1963; Coover et al., 1953). The information is generally considered reliable and has been widely used as the basis for managing Pullman soils. These soils, however, cover extensive areas of the High Plains of Texas and are known to vary considerably in profile properties across the region. One property that varies widely across the region is depth to the calcic horizon. Because profile depth strongly influences plant rooting depth and thus the effective depth for storing water, a knowledge of profile depth along with a characterization of other profile properties is important for improved water and crop management on Pullman soil. The objective of this study was to determine the variation in depth, bulk density, texture, organic matter content, pH, and water retention of the different horizons of Pullman soil as affected by location in the region.

## EXPERIMENTAL PROCEDURE

### Site Selection

To obtain samples that would represent a near-complete range in the expected variation in soil properties, sites were selected at seven widely separated locations across the region. The sampling sites were in Armstrong, Carson, Castro, Deaf Smith, Floyd, Randall, and Swisher Counties. Although the locations were widely separated, samples were not obtained at the extreme edges of the region so that zones of transition to other soils were avoided. Likewise, locations of transition to other soils within the region were avoided. The sampling was restricted to typical Pullman soil sites for the particular location in the region.

### Sampling Sites

The seven sampling sites indicated in Fig. 2 are numbered in the order in which the samples were obtained. Site identifications, sampling dates, and locations are given in Table 4. All sites had a nearly level upland High Plains physiographic description. All sites were in cultivated fields that were irrigated, except for Site 3, which was dryland. Sites 1 and 3 were in the northern province, Sites 2 and 6 in the central province, and Sites 4, 5, and 7 in the southwest province.

### Sampling Techniques

At each sampling site, loose soil of the plow layer, usually to the depth of the Ap horizon, was removed before obtaining core samples with a hydraulically-operated, pickup-mounted core sampler. The inside diameter of the cutting tip was 1.625 inches. The first core at each site was used for profile description. Subsequent cores were then taken and separated into depth segments based on the thickness of the different horizons. Two or more cores were obtained to provide adequate material from each depth for making water retention determinations. Immediately after separating the cores by depths in the field, the segments were dipped in a liquified saran solution to provide rigidity to the cores. After the saran had dried, the individual segments were wrapped in newspaper for transport to the laboratory. Two additional cores were obtained and sectioned by horizons for obtaining samples for bulk density determination. In addition to the core samples, two samples of the surface horizon of soil were collected in bags at each site. At a different time, water infiltration was determined at each site by the double-ring infiltrometer method.

### Sample Preparation and Analyses

The core samples to be used for water retention measurements were cut into sections about 0.75 inch long and further reinforced with cellophane tape before making the measurements at −⅓ and −15 bars matric potential. The measurements were made with pressure plate equipment using four sections from each depth at each potential. Some core soil from each depth was ground to pass a 2-mm sieve and then used to determine the wilting points by the sunflower method.

To determine bulk density, the cores were dried at 105°C, then weighed. Soil from these cores was retained and ground to pass a 2-mm sieve. Subsamples of this sieved soil were then used to determine particle size distribution by the hydrometer method (Day, 1965), organic matter content by the Walkley-Black method (Jackson, 1958), and pH (1:1 soil:water ratio).

Samples of surface soil were air-dried, ground, and passed through a 2-mm sieve. Subsamples of surface soil were used for determining water retention, particle size distribution, organic matter content, and pH by the methods described above.

The relationships among various B21t horizon and total profile characteristics and total water infiltration in 10 minutes and 20 hours and infiltration rates at these times were investigated by multiple linear regression analyses. Horizon and profile variables were thickness; sand, silt, clay, and organic matter content; and bulk density. For the B21t horizon, actual values were used. For the entire profile, weighted mean values were calculated from values for the different horizons, thus resulting in one value for each variable of the profile at each site. Besides the partial regression coefficients

TABLE 4. SITE IDENTIFICATION, SAMPLING DATE, AND LOCATION

| Site no. | SCS ident. no. | Date sampled | County and location description |
|---|---|---|---|
| 1 | S79TX-065-1 | March 6, 1979 | Carson County, Texas; in a cultivated field 1000 feet west and 1300 feet north of the intersection of State Highway 207 and Farm Road 293, 0.5 mile north of Panhandle. |
| 2 | S79TX-011-1 | March 6, 1979 | Armstrong County, Texas; in a cultivated field 200 feet south of Farm Road 285, 5.5 miles west of its intersection with State Highway 207, 25 miles south of Claude. |
| 3 | S79TX-381-3 | March 7, 1979 | Randall County, Texas; in a cultivated field 520 feet east of paved county road, 2.0 miles west and 0.6 mile south of the intersection of Interstate Highway 40 and Farm Road 2381 in Bushland. |
| 4 | S79TX-437-1 | March 8, 1979 | Swisher County, Texas; in a cultivated field 150 feet south of county road, 1.1 miles west of Farm Road 2301, at a point 2.0 miles south of its intersection with Farm Road 145 in Claytonville. |
| 5 | S79TX-069-1 | March 19, 1979 | Castro County, Texas; in a cultivated field, 900 feet west of Farm Road 168, at a point 1.5 miles south of its intersection with State Highway 86 in Nazareth. |
| 6 | S79TX-117-1 | March 19, 1979 | Deaf Smith County, Texas; in a cultivated field 2500 feet east of Farm Road 1057, 0.5 mile north of its intersection with Farm Road 1058, 6.0 miles west of Hereford. |
| 7 | S79TX-153-1 | April 18, 1979 | Floyd County, Texas; in a cultivated field, 100 feet west of a county road, 0.5 mile north of U.S. Highway 70, 2.0 miles east of its intersection with State Highway 207 in Floydada. |

and the coefficient of correlation (R), standardized partial regression coefficients and t-values were also calculated (Ezekial and Fox, 1959; Steel and Torrie, 1960). Based on the standardized coefficients, the independent variables were ranked numerically in order of their relative importance for influencing total infiltration or infiltration rates. All independent variables were used in the initial analysis for each set of data. In subsequent analyses, the lowest ranking variable was excluded until the last analysis, which was a simple linear regression analysis.

## RESULTS AND DISCUSSION

### Profile Descriptions

In this section, the profiles at the seven sites are described in detail by horizons. These descriptions are based on examination and determinations made in the field immediately after extracting the cores. Although data in subsequent sections are based mainly on horizons above the calcic horizon, the calcic horizon is included in the profile descriptions. The descriptions are:

Site 1, Carson County,
Sample No. S79TX-065-1-(1-5)

Ap—0 to 6 inches; brown (7.5YR 4/2) silty clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium granular structure; hard, friable; few fine roots; few fine pores; neutral; abrupt smooth boundary.

B21t—6 to 14 inches; dark brown (7.5YR 4/2) silty clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; extremely hard, very firm; few fine roots on ped faces; few fine pores; thin continuous clay films; few vertical cracks; neutral; gradual smooth boundary.

B22t—14 to 26 inches; dark brown (7.5YR 4/2) silty clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; few slickensides 2 to 4 inches across; extremely hard, very firm; few fine roots; few fine pores; thin continuous clay films; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B23t—26 to 39 inches; reddish brown (5YR 5/3) silty clay, reddish brown (5YR 4/3) moist; moderate medium blocky structure; few slickensides 2 to 4 inches across; extremely hard, very firm; few pores; thin clay films on ped faces; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B24t—39 to 59 inches; yellowish red (5YR 5/6) silty clay, yellowish red (5YR 4/6) moist; moderate medium subangular blocky structure; few small pressure faces; very hard, firm; few fine pores; few patchy clay films; common threads and films of calcium carbonate; calcareous; mildly alkaline; clear smooth boundary.

B25tca—59 to 80 inches; pink (7.5YR 8/4) clay loam, pink (7.5YR 7/4) moist; moderate medium subangular blocky structure; very hard, friable; few fine pores; about 45 percent of the soil mass consists of soft masses and concretions of calcium carbonate; calcareous; moderately alkaline.

Site 2, Armstrong County,
Sample No. S79TX-011-1-(1-5)

Ap—0 to 6 inches; brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium granular structure; hard, friable; few fine roots; few fine pores; mildly alkaline; abrupt smooth boundary.

B21t—6 to 13 inches; dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; extremely hard, very firm; few fine roots on ped faces; few fine pores; thin continuous clay films; common vertical cracks; mildly alkaline; gradual smooth boundary.

B22t—13 to 21 inches; dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; few slickensides 2 to 4 inches across; extremely hard, very firm; few fine roots; few fine pores; thin continuous clay films; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B23t—21 to 35 inches; reddish brown (5YR 5/4) clay, reddish brown (5YR 4/4) moist; moderate medium blocky structure; few slickensides 2 to 4 inches across; extremely hard, very firm; few pores; thin clay films on ped faces; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B24t—35 to 50 inches; yellowish red (5YR 5/6) clay, yellowish red (5YR 4/6) moist; moderate medium subangular blocky structure; few small pressure faces; very hard, firm; few fine pores; few patchy clay films; common threads and films of calcium carbonate; calcareous; mildly alkaline; clear smooth boundary.

B25tca—50 to 70 inches; reddish yellow (5YR 7/6) clay loam, reddish yellow (5YR 6/6) moist; moderate medium subangular blocky structure; very hard, friable; few fine pores; about 35 percent of the soil mass consists of soft masses and concretions of calcium carbonate; calcareous; moderately alkaline.

Site 3, Randall County,
Sample No. S79TX-381-3-(1-5)

Ap—0 to 6 inches; brown (7.5YR 4/2) silty clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium granular structure; hard, friable; few fine roots; few fine pores;

neutral; abrupt smooth boundary.

B21t—6 to 16 inches; dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; extremely hard, very firm; few fine roots on ped faces; few fine pores; thin continuous clay films; few vertical cracks; neutral; gradual smooth boundary.

B22t—16 to 29 inches; dark brown (7.5YR 4/2) silty clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; few slickensides 2 to 4 inches across; extremely hard, very firm; few fine roots; few fine pores; thin continuous clay films; few threads and films of calcium carbonate; calcareous; neutral; gradual smooth boundary.

B23t—29 to 44 inches; reddish brown (5YR 5/4) silty clay, reddish brown (5YR 4/4) moist; moderate medium blocky structure; few slickensides 2 to 4 inches across; extremely hard, very firm; few pores; thin clay films on ped faces; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B24t—44 to 58 inches; yellowish red (5YR 5/6) clay, yellowish red (5YR 4/6) moist; moderate medium subangular blocky structure; few small pressure faces; very hard, firm; few fine pores; few patchy clay films; common threads and films of calcium carbonate; calcareous; mildly alkaline; clear smooth boundary.

B25tca—58 to 80 inches; pink (7.5YR 8/4) clay loam, pink (7.5YR 7/4) moist; moderate medium subangular blocky structure; very hard, friable; few fine pores; about 50 percent of the soil mass consists of soft masses and concretions of calcium carbonate; calcareous; moderately alkaline; gradual smooth boundary.

B26tca—80 to 92 inches; reddish yellow (5YR 7/6) clay loam, reddish yellow (5YR 6/6) moist; moderate medium subangular blocky structure; very hard, firm; few fine pores; few patchy clay films; about 20 percent of the soil mass consists of soft masses and concretions of calcium carbonate; calcareous; moderately alkaline.

Site 4, Swisher County,
Sample No. S79TX-437-1-(1-5)

Ap—0 to 6 inches; brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium granular structure; hard, friable; few fine roots; few fine pores; neutral; abrupt smooth boundary.

B21t—6 to 17 inches; dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; extremely hard, very firm; few fine roots on ped faces; few fine pores; thin continuous clay films; few vertical cracks; mildly alkaline; gradual smooth boundary.

B22t—17 to 30 inches; dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; few slickensides 2 to 4 inches across; extremely hard, very firm; few fine roots; few fine pores; thin continuous clay films; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B23t—30 to 42 inches; reddish brown (7.5YR 5/4) clay loam, brown (7.5YR 4/4) moist; moderate medium blocky structure; few slickensides 2 to 4 inches across; extremely hard, very firm; few pores; thin clay films on ped faces; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B24t—42 to 48 inches; light brown (7.5YR 6/4) clay, brown (7.5YR 5/4) moist; moderate medium subangular blocky structure; few small pressure faces; very hard, firm; few fine pores; few patchy clay films; common threads and films of calcium carbonate; calcareous; moderately alkaline; clear smooth boundary.

B25tca—48 to 60 inches; pink (7.5YR 8/4) clay loam, pink (7.5YR 7/4) moist; moderate medium subangular blocky structure; very hard, friable; few fine pores; about 60 percent of the soil mass consists of soft masses and concretions of calcium carbonate; calcareous; moderately alkaline.

Site 5, Castro County,
Sample No. S79TX-069-1-(1-5)

Ap—0 to 6 inches; brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium granular structure; hard, friable; few fine roots; few fine pores; neutral; abrupt smooth boundary.

B21t—6 to 13 inches; dark brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; extremely hard, very firm; few fine roots on ped faces; few fine pores; thin continuous clay films; few vertical cracks; neutral; gradual smooth boundary.

B22t—13 to 20 inches; dark brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; few slickensides 2 to 4 inches across; extremely hard, very firm; few fine roots; few fine pores; thin continuous clay films; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B23t—20 to 32 inches; reddish brown (5YR 5/3) clay, reddish brown (5YR 4/3) moist; moderate medium blocky structure; few slickensides 2 to 4 inches across; extremely hard, very firm; few pores; thin clay films on ped faces; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B24t—32 to 40 inches; reddish brown (5YR 5/4) clay, reddish brown (5YR 4/4) moist; moderate medium subangular blocky structure; few small pressure faces; very hard, firm; few fine pores; few patchy clay films; common threads and films of calcium carbonate; calcareous; mildly alkaline; clear smooth boundary.

B25tca—40 to 65 inches; reddish yellow (5YR 7/6) clay loam, reddish yellow (5YR 6/6) moist; moderate medium subangular blocky structure; very hard, firm; few fine pores; about 30 percent of the soil mass consists of soft masses and concretions of calcium carbonate; calcareous; moderately alkaline.

Site 6, Deaf Smith County,
Sample No. S79TX-117-1-(1-4)

Ap—0 to 6 inches; brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium granular structure; hard, friable; few fine roots; few fine pores; neutral; abrupt smooth boundary.

B21t—6 to 19 inches; dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; extremely hard, very firm; few fine roots on ped faces; few fine pores; thin continuous clay films; few vertical cracks; neutral; gradual smooth boundary.

B22t—19 to 28 inches; dark brown (7.5YR 4/4) clay, dark brown (7.5YR 3/4) moist; moderate medium blocky structure; few wedge shaped peds; few slickensides 2 to 4 inches across; extremely hard, very firm; few fine roots; few fine pores; thin continuous clay films; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B23t—28 to 38 inches; reddish brown (5YR 5/4) clay, reddish brown (5YR 4/4) moist; moderate medium blocky structure; few slickensides 2 to 4 inches across; extremely hard, very firm; few pores; thin clay films on ped faces; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B24t—38 to 52 inches; reddish yellow (5YR 7/6) clay, reddish yellow (5YR 6/6) moist; moderate medium subangular blocky structure; very hard, firm; few fine pores; few patchy clay films; common threads and films of calcium carbonate; calcareous; mildly alkaline; clear smooth boundary.

B25tca—52 to 70 inches; pink (7.5YR 8/4) clay loam, pink (7.5YR 7/4) moist; moderate medium subangular blocky structure; very hard, friable; few fine pores; about 50 percent of the soil mass consists of soft masses and concretions of calcium carbonate; calcareous; moderately alkaline.

Site 7, Floyd County,
Sample No. S79TX-153-1-(1-4)

Ap—0 to 7 inches; brown (7.5YR 4/2) clay loam, dark brown (7.5YR 3/2) moist; weak fine and medium granular structure; hard, friable; few fine roots; few fine pores; neutral; abrupt smooth boundary.

B21t—7 to 18 inches; dark brown (7.5YR 4/2) clay, dark brown (7.5YR 3/2) moist; moderate medium blocky structure; few wedge shaped peds; extremely hard, very firm; few fine roots on ped faces; few fine pores; thin continuous clay films; few vertical cracks; neutral; gradual smooth boundary.

B22t—18 to 30 inches; reddish brown (5YR 4/3) clay, dark reddish brown (5YR 3/3) moist; moderate medium blocky structure; few wedge shaped peds; few slickensides 2 to 4 inches across; extremely hard, very firm; few fine roots; few fine pores; thin continuous clay films; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B23t—30 to 48 inches; reddish brown (5YR 5/4) clay, reddish brown (5YR 4/4) moist; moderate medium blocky structure; few slickensides 2 to 4 inches across; extremely hard, very firm; few pores; thin clay films on ped faces; few threads and films of calcium carbonate; calcareous; mildly alkaline; gradual smooth boundary.

B24tca—48 to 60 inches; pink (7.5YR 8/4) clay loam, pink (7.5YR 7/4) moist; moderate medium subangular blocky structure; very hard, friable; few fine pores; about 50 percent of the soil mass consists of soft masses and concretions of calcium carbonate; calcareous; moderately alkaline.

Based on the field descriptions, profiles at the various sites differed mainly with respect to thickness, color, and texture of the different horizons, and depth to the calcic horizon. The Ap horizon was 6 inches thick at all sites, except at Site 7 where it was 7 inches thick. The Ap horizon represents mainly the plow layer, and the slight difference in horizon thickness possibly resulted from a difference in plowing depth. The Ap horizon was a brown silty clay loam at Sites 1 and 3 and a brown clay loam at other sites.

The thickness of the B21t horizon was 7 inches at Sites 2 and 5, 8 at Site 1, 10 at Site 3, 11 at Sites 4 and 7, and 13 at Site 6. The color was dark brown at all sites, but the texture was silty clay at Site 1, clay loam at Site 5, and clay at the remaining sites.

The B22t horizon was 7 inches thick at Site 5, 8 at Site 2, 9 at Site 6, 12 at Sites 1 and 7, and 13 at Sites 3 and 4. The color was dark brown at all sites, except Site 7 where it was reddish brown. The texture was silty clay at Sites 1 and 3, clay loam at Site 5, and clay at Sites 2, 4, 6, and 7.

The thickness of the B23t horizon ranged from 10 inches at Site 6 to 18 inches at Site 7. Other thicknesses were 12 inches at Site 5, 13 at Sites 1 and 4, 14 at Site 2, and 15 at Site 3. The soil was reddish brown at all sites, except at Site 3 where it was yellowish red. The texture was silty clay at Site 1, clay loam at Site 4, and clay at the remaining sites.

The B24t horizon was the most variable horizon above the calcic horizon with respect to thickness and color. At Site 7, the B24t horizon was the calcic horizon and, therefore, is excluded from further discussion at this point. The thickness of the B24t was 6 inches at Site 4, 8 at Site 5, 14 at Sites 3 and 6, 15 at Site 2, and 20 at Site 1. The soil was yellowish red at Sites 1, 2, and 3, light brown at Site 4, reddish brown at Site 5, and reddish yellow at Site 6. The texture was silty clay at Site 1 and clay at the remaining sites.

Other than horizon thickness, color, and texture, profile conditions that were determined by the field descriptions were identical for all sites for the horizon being considered, except for the B21t horizon at Site 2, which had "common vertical cracks" rather than "few vertical cracks" as was the case at other sites. Also, the B24t horizon was the calcic horizon at Site 7, as previously mentioned.

The depth to the calcic horizon was greatest at Site 1, where it was 59 inches, and least at Site 5, where it was 40 inches. Other depths were 58 inches at Site 3, 52 at Site 6, 50 at Site 2, and 48 at Sites 4 and 7. Depth to the calcic horizon for profiles from different sites and thicknesses of the individual horizons comprising the profiles are illustrated in Fig. 12. This figure illustrates that total depth was not directly related to the thickness of any particular horizon. Although profile depth was greatest at Site 1, only the B24t horizon was thicker at Site 1 than at any other site. All other horizons were thicker at least at one other site than at Site 1. Likewise, profile depth at Site 5 was the least, but only the B22t was thinner at Site 5 than at any other site. All other horizons were as thick or thinner at least at one other site as at Site 5. Site 7, which had the thickest B23t horizon, had a greater depth to the calcic horizon than Site 5, even though the B24t horizon at Site 7 was the calcic horizon and, therefore, was not included in the profile depth determination.

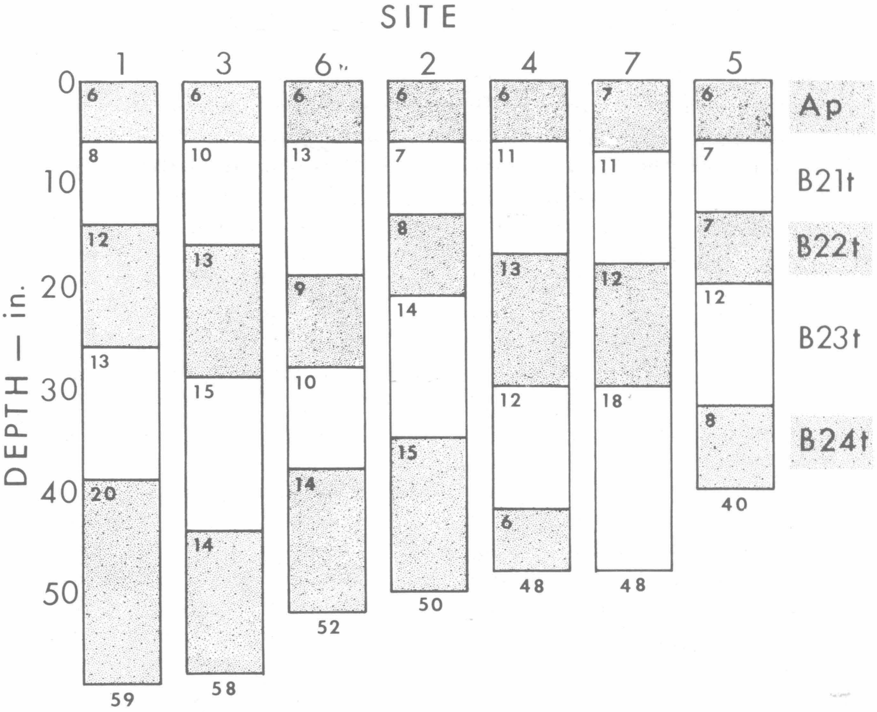

*Fig. 12. Profile depths and thicknesses of the different horizons for the profiles at the different sites of Pullman soil.*

### Particle Size Distribution

Results of particle size distribution analyses are included in Table 5. At Sites 1, 4, and 7, sand content was highest in the Ap horizon, while at Sites 2, 3, 5, and 6, sand content was highest in the B23t (Site 6) or B24t horizon. In intermediate horizons, sand content usually was lower than in either the Ap or the B23t or B24t horizons. Exceptions were at Site 1, at which sand content remained at 12.0 percent for all horizons below the Ap, and at Site 5, where sand content was similar in the Ap, B21t, and B22t horizons, lowest in the B23t horizon, and highest in the B24t horizon. The highest sand content of the Ap horizon (33.0 percent) occurred at Sites 4 and 7. The lowest (17.0 percent) occurred at Site 3, which was only 1 percent lower than that at Site 1.

Silt content of the profile was highest in the Ap horizon at all sites and usually decreased with profile depth. Exceptions were at Site 1, where the B24t horizon contained more silt than intermediate horizons, and at Sites 2, 3, and 7, where the B21t horizon contained less silt than lower horizons. The highest silt content (53.0 percent) in the Ap horizon occurred at Site 3 and the lowest (39.0 percent) occurred at Site 7.

At all sites, the Ap horizon contained less clay than any other horizon. The average for the Ap horizon was 31.0 percent. The highest clay content was either in the B21t or the B22t horizon, except at Site 5 where it was highest in the B23t horizon.

TABLE 5. CHARACTERISTICS OF PULLMAN SERIES AT STUDY SITES

| Site and county | Sample no. | Hor. | Depth | Sand | Silt | Clay | Texture | O.M. | pH | Bulk density | Water content at potential of |  | Plant available water |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |  |  | −⅓ bar | −15 bars |  |  |  |
|  |  |  | in | % |  |  |  | % |  | g/cm$^3$ | % |  | % | in/in | in/hor |
| Site 1 — Carson | S79TX-065-1-1 | Ap | 0-6 | 18.0 | 49.0 | 33.0 | Silty clay loam | 2.52 | 6.58 | 1.26[1] | 28.5[2] | 18.7[3] | 9.8 | 0.123 | 0.74 |
|  | -2 | B21t | 6-14 | 12.0 | 41.0 | 47.0 | Silty clay | 1.41 | 6.87 | 1.48 | 28.6 | 18.9 | 9.7 | 0.144 | 1.15 |
|  | -3 | B22t | 14-26 | 12.0 | 40.2 | 47.8 | Silty clay | 0.94 | 7.31 | 1.62 | 25.8 | 17.9 | 7.9 | 0.128 | 1.54 |
|  | -4 | B23t | 26-39 | 12.0 | 40.3 | 47.7 | Silty clay | 0.84 | 7.45 | 1.56 | 26.1 | 16.5 | 9.6 | 0.150 | 1.95 |
|  | -5 | B24t | 39-59 | 12.0 | 42.1 | 45.9 | Silty clay | 0.62 | 7.57 | 1.57 | 24.5 | 15.0 | 9.5 | 0.149 | 2.98 |
|  | Weighted mean |  |  | 12.6 | 41.9 | 45.5 | --- | 1.03 | 7.30 | 1.53 | 26.1 | 16.8 | 9.3 | 0.142 | --- |
|  | Total |  |  | -- | -- | -- | --- | -- | -- | -- | -- | -- | -- | --- | 8.36 |
| Site 2 — Armstrong | S79TX-011-1-1 | Ap | 0-6 | 24.0 | 47.0 | 29.0 | Clay loam | 2.01 | 7.43 | 1.26[1] | 24.2[2] | 15.4[3] | 8.8 | 0.112 | 0.67 |
|  | -2 | B21t | 6-13 | 18.0 | 33.0 | 49.0 | Clay | 1.42 | 7.35 | 1.48 | 29.7 | 20.6 | 9.1 | 0.134 | 0.94 |
|  | -3 | B22t | 13-21 | 16.5 | 35.7 | 47.8 | Clay | 1.07 | 7.54 | 1.56 | 26.9 | 18.8 | 8.1 | 0.126 | 1.01 |
|  | -4 | B23t | 21-35 | 19.3 | 34.7 | 46.0 | Clay | 0.83 | 7.79 | 1.62 | 24.7 | 16.7 | 8.0 | 0.129 | 1.81 |
|  | -5 | B24t | 35-50 | 25.0 | 31.5 | 43.5 | Clay | 0.53 | 7.65 | 1.65 | 23.7 | 16.0 | 7.7 | 0.127 | 1.91 |
|  | Weighted mean |  |  | 20.9 | 35.1 | 43.9 | --- | 1.00 | 7.60 | 1.56 | 25.4 | 17.2 | 8.2 | 0.127 | --- |
|  | Total |  |  | -- | -- | -- | --- | -- | -- | -- | -- | -- | -- | --- | 6.34 |
| Site 3 — Randall | S79TX-381-3-1 | Ap | 0-6 | 17.0 | 53.0 | 30.0 | Silty clay loam | 2.06 | 6.70 | 1.26[1] | 25.0[2] | 16.0[3] | 9.0 | 0.113 | 0.68 |
|  | -2 | B21t | 6-16 | 13.0 | 38.8 | 48.2 | Clay | 1.29 | 6.77 | 1.48 | 28.8 | 18.5 | 10.3 | 0.152 | 1.52 |
|  | -3 | B22t | 16-29 | 13.0 | 40.0 | 47.0 | Silty clay | 0.95 | 7.24 | 1.60 | 26.7 | 18.1 | 8.6 | 0.138 | 1.79 |
|  | -4 | B23t | 29-44 | 15.0 | 40.8 | 44.2 | Silty clay | 0.76 | 7.58 | 1.58 | 24.8 | 15.7 | 9.1 | 0.144 | 2.16 |
|  | -5 | B24t | 44-58 | 19.3 | 37.2 | 43.5 | Clay | 0.39 | 7.65 | 1.65 | 24.4 | 16.7 | 7.7 | 0.127 | 1.78 |
|  | Weighted mean |  |  | 15.5 | 40.7 | 43.9 | --- | 1.03 | 7.29 | 1.55 | 25.8 | 17.0 | 8.8 | 0.137 | --- |
|  | Total |  |  | -- | -- | -- | --- | -- | -- | -- | -- | -- | -- | --- | 7.93 |
| Site 4 — Swisher | S79TX-437-1-1 | Ap | 0-6 | 33.0 | 37.0 | 30.0 | Clay loam | 1.58 | 7.23 | 1.26[1] | 23.1[2] | 14.8[3] | 8.3 | 0.105 | 0.63 |
|  | -2 | B21t | 6-17 | 25.8 | 33.0 | 41.2 | Clay | 1.36 | 7.54 | 1.48 | 25.6 | 17.4 | 8.3 | 0.121 | 1.33 |
|  | -3 | B22t | 17-30 | 27.5 | 32.4 | 40.1 | Clay | 0.79 | 7.54 | 1.78 | 21.9 | 18.5 | 3.4 | 0.061 | 0.79 |
|  | -4 | B23t | 30-42 | 32.7 | 29.3 | 38.0 | Clay loam | 0.54 | 7.73 | 1.44 | 21.6 | 15.1 | 6.5 | 0.093 | 1.12 |
|  | -5 | B24t | 42-48 | 32.0 | 27.5 | 40.5 | Clay | 0.37 | 7.84 | 1.38 | 22.9 | 15.1 | 7.8 | 0.107 | 0.64 |
|  | Weighted mean |  |  | 26.9 | 31.7 | 38.6 | --- | 0.90 | 7.59 | 1.51 | 22.9 | 16.5 | 6.4 | 0.094 | --- |
|  | Total |  |  | -- | -- | -- | --- | -- | -- | -- | -- | -- | -- | --- | 4.51 |
| Site 5 — Castro | S79TX-069-1-1 | Ap | 0-6 | 28.0 | 42.0 | 30.0 | Clay loam | 2.25 | 6.93 | 1.26[1] | 25.7[2] | 16.5[3] | 9.2 | 0.117 | 0.70 |
|  | -2 | B21t | 6-13 | 28.0 | 38.0 | 34.0 | Clay loam | 2.14 | 7.07 | 1.24 | 27.9 | 15.3 | 12.6 | 0.156 | 1.09 |
|  | -3 | B22t | 13-20 | 28.1 | 32.9 | 39.0 | Clay loam | 1.46 | 7.14 | 1.52 | 24.5 | 20.5 | 4.0 | 0.061 | 0.43 |
|  | -4 | B23t | 20-32 | 25.0 | 32.0 | 43.0 | Clay | 0.98 | 7.40 | 1.60 | 24.0 | 17.9 | 6.1 | 0.098 | 1.17 |
|  | -5 | B24t | 32-40 | 31.5 | 29.0 | 39.5 | Clay | 0.80 | 7.60 | 1.46 | 23.8 | 15.3 | 8.5 | 0.124 | 0.99 |
|  | Weighted mean |  |  | 27.8 | 34.1 | 38.1 | --- | 1.42 | 7.27 | 1.44 | 25.0 | 17.2 | 7.8 | 0.110 | --- |
|  | Total |  |  | -- | -- | -- | --- | --- | -- | -- | -- | -- | -- | --- | 4.38 |
| Site 6 — Deaf Smith | S79TX-117-1-1 | Ap | 0-6 | 23.0 | 40.0 | 37.0 | Clay loam | 1.59 | 7.23 | 1.26[1] | 27.1[2] | 18.3[3] | 8.8 | 0.112 | 0.67 |
|  | -2 | B21t | 6-19 | 21.1 | 35.7 | 43.2 | Clay | 1.14 | 6.95 | 1.49 | 25.7 | 17.5 | 8.2 | 0.122 | 1.59 |
|  | -3 | B22t | 19-28 | 23.0 | 33.4 | 43.6 | Clay | 0.78 | 7.39 | 1.58 | 26.0 | 17.4 | 8.6 | 0.136 | 1.22 |
|  | -4 | B23t | 28-38 | 27.1 | 31.8 | 41.1 | Clay | 0.47 | 7.49 | 1.63 | 23.3 | 16.6 | 6.7 | 0.109 | 1.09 |
|  | -5 | B24t | 38-52 | 27.1 | 31.8 | 41.1 | Clay | 0.37 | 7.49 | 1.63 | 23.3 | 16.6 | 6.7 | 0.109 | 1.53 |
|  | Weighted mean |  |  | 24.4 | 34.0 | 41.6 | --- | 0.79 | 7.31 | 1.54 | 24.8 | 17.2 | 7.6 | 0.117 | --- |
|  | Total |  |  | -- | -- | -- | --- | -- | -- | -- | -- | -- | -- | --- | 6.10 |
| Site 7 — Floyd | S79TX-153-1-1 | Ap | 0-7 | 33.0 | 39.0 | 28.0 | Clay loam | 1.37 | 6.95 | 1.26[1] | 21.1[2] | 13.3[3] | 7.8 | 0.099 | 0.69 |
|  | -2 | B21t | 7-18 | 29.1 | 27.9 | 43.0 | Clay | 0.88 | 7.04 | 1.49 | 24.8 | 19.2 | 5.6 | 0.084 | 0.92 |
|  | -3 | B22t | 18-30 | 26.0 | 30.8 | 43.2 | Clay | 0.68 | 7.47 | 1.64 | 22.8 | 18.0 | 4.8 | 0.078 | 0.94 |
|  | -4 | B23t | 30-48 | 30.0 | 29.0 | 41.0 | Clay | 0.56 | 7.73 | 1.64 | 23.1 | 16.2 | 6.9 | 0.113 | 2.04 |
|  | Weighted mean |  |  | 29.2 | 30.7 | 40.1 | --- | 0.78 | 7.39 | 1.55 | 23.1 | 16.9 | 6.2 | 0.096 | --- |
|  | Total |  |  | -- | -- | -- | --- | -- | -- | -- | -- | -- | -- | --- | 4.59 |

[1] Loosened tillage layer. Bulk density estimated from values obtained from earlier studies.

[2] Calculated by Equation 1, Table 7, of Unger (1975).

[3] Calculated by Equation 2, Table 7, of Unger (1975).

Usually, the B24t horizon contained less clay than horizons above it, except the Ap horizon. Clay content of the Ap horizon was lowest (28.0 percent) at Site 7 and highest (37.0 percent) at Site 6. For all horizons, the highest clay content (49.0 percent) was in the B21t horizon at Site 2. For all sites, the clay content averaged 41.5 percent in the B21t horizon and 44.1 percent in the B22t horizon.

The soil texture of all horizons at all sites, based on the particle size distribution analyses, was identical to that determined at the time of describing the profiles in the field.

### Organic Matter

At all sites, soil organic matter content was highest in the Ap horizon and decreased progressively with soil depth (Table 5). In the Ap horizon, organic matter content ranged from 1.37 percent at Site 7 to 2.52 percent at Site 1. In the B21t horizon, organic matter content ranged from 0.88 percent at Site 7 to 2.14 percent at Site 5. Site 5 also had the highest organic matter content in all deeper horizons. Organic matter content was lowest in the B22t horizon at Site 7, in the B23t horizon at Site 6, and in the B24t horizon at Sites 4 and 6.

### pH

Soil pH generally was lowest in the Ap horizon and progressively increased with depth (Table 5). Exceptions occurred at Sites 2 and 6 where pH of the B21t horizons was slightly lower than that of the Ap horizon and at Site 2 where pH of the B24t horizon was lower than that of the B23t horizon. Reasons for the different trends at these sites are not apparent. The highest weighted mean pH value (7.60) was found at Site 2, which was only 0.01 higher than at Site 4. The mean pH at the remaining sites ranged from 7.27 to 7.39.

### Bulk Density

Bulk density of the Ap horizon was not determined because this horizon, which was the plow layer, was loosened by tillage and remained loose at the time of sampling. Other studies, however, have shown that the bulk density of this horizon is highly variable, depending on type and recentness of tillage. For this study, a bulk density of 1.26 g/cm$^3$ was assumed for the Ap horizon at all sites (Table 5). This value is the average for the Ap horizon in studies by Taylor et al. (1963), U[illegible]ger (1969, 1972), and Unger et [illegible] (1973). An assumed value is provided for calculating the available water content of this horizon in a subsequent section.

Bulk density of the B21t horizon was 1.48 or 1.49 g/cm$^3$ at all sites, except at Site 5 where it was 1.24 g/cm$^3$. The reason for the low value at Site 5 is not clear, but it possibly resulted from loosening of this horizon by deep plowing or chiseling. Bulk density usually increased with profile depths below the B21t horizon, but there were some exceptions. At Sites 1 and 4, bulk density was highest in the B22t horizon. The exceptionally high bulk density of the B22t horizon at Site 4 suggests that soil compaction had occurred, possibly due to tractor or implement traffic. At Site 4, bulk density progressively decreased with depth below the B22t horizon with the value for the B24t horizon being lower than that of all other measured horizons at that site. At Site 5, bulk density of the B24t horizon was lower than that of the B22t or B23t horizon.

Bulk densities found at the different sites are not high enough to prevent root penetration, provided the soil water content is adequately high, but some reduction in root penetration may occur. Resistance to penetration of roots is influenced by soil strength, which is a function of soil bulk density and water content (Taylor and Gardner, 1963). In their study with Amarillo fine sandy loam, Taylor and Gardner (1963) showed that some roots penetrated the soil at a bulk density of 1.75 g/cm$^3$, provided the soil matric potential was −½ bar or higher. For bulk densities equal to or below 1.65 g/cm$^3$, some root penetration occurred when the matric potential was −⅔ bar or higher. Resistance to root penetration at similar soil matric potentials and bulk densities may be different in Pullman soils than in Amarillo soils. Also, the bulk densities measured by core samples may be considerably different than that determined on individual soil peds. With core sampling, the bulk density represents an average density of the sampled volume, which includes the soil and the shrinkage cracks that develop as the soil dries. For individual peds, shrinkage cracks are not included in the sample volume. The density of the peds, therefore, may be considerably higher than those obtained by core sampling and may be high enough to prevent root penetration. Although ped densities were not measured, high density of peds undoubtedly is responsible for roots growing between rather than through the peds of Pullman soil, which has been observed.

### Water Retention

Because cores were not obtained for the Ap horizon, water contents at −⅓ and −15 bars matric potential for these horizons (Table 5) were calculated by equations developed by Unger (1975). These equations are based on the bulk density, organic matter content, and clay content of soil from the horizon. For the remaining horizons, determined values are given. The calculated values should be valid because the correlation coefficients obtained when developing the data were significant at the 0.1% level (Unger, 1975). Also, the values are generally close to those for the B21t horizon. Similar results were obtained by Unger (1969, 1970).

Plant available water per inch of soil for the different horizons was based on plant available water content (−⅓- minus −15-bar value) and bulk density of the horizons (Table 5). Totals for the profile are summations of the values for the individual horizons. The mean water contents are weighted for the thicknesses of the different horizons.

The profile at Site 1 retained 8.36 inches of plant available water, but this was only 0.43 inch more than the amount at Site 3. The profile at Site 1 also had slightly higher mean water retention per inch of soil (Table 5). The differences in total and mean water retention at Sites 1 and 3 probably were not significant and were expected to be slight because the profiles at these sites were similar in depth and other measured characteristics.

The two next highest total water retention values were for profiles at Sites 2 and 6 for which the values were 6.34 and 6.10 inches, respectively. Again, similar values were expected for these sites because the profiles were similar in depth and most other characteristics. An exception was the organic matter content, which was lower at Site 6. The lower organic matter content probably contributed to the lower water retention. However, the slightly lower clay content may have been a factor also because there is a closer relationship between clay content and water retention than between organic matter content and water retention (Unger, 1975).

Total water retention for the remaining sites (Sites 4, 5, and 7) differed by 0.21 inch or less (Table 5). The low total water retention values resulted not only from the low profile depths at these sites, but also from the generally lower clay and higher sand contents at these sites. Sand, silt, and clay contents were similar at these sites. However, the profile at Sites 4 and 7 was 8 inches deeper than at Site 5, yet water retention was not greatly affected. The relatively favorable water retention at Site 5 is attributed to the higher mean organic matter content and lower mean bulk density as compared with those at Sites 4 and 7.

Total water retention at Site 3 was 1.14 inches lower than a value of 9.07 inches calculated from data reported by Taylor et al. (1963) for a nearby location. Such difference could be within the limits of experimental error. However, our −⅓- and −15-bar values, which correspond to their field capacity and wilting point values, generally were higher than their values. Also, our values were higher than the minimum values often obtained at harvest of dryland crops at the laboratory (unpublished data). These findings suggest that plants experiencing water stress for relatively long periods may extract soil water to lower levels than those represented by the −15-bar value, which is normally considered to represent the permanent wilting point. Based on 154 samples taken to a 58-inch depth at the laboratory in 1979, soil water content at harvest of dryland wheat, grain sorghum, and sunflower averaged about 3 percentage units lower than the −15-bar values given in Table 5 for Site 3. Such amount represents an extra 2.7 inches of plant available water at Site 3. This water may not be readily available to plants, but it may help plants survive short-term droughts or allow plants to produce mature seed or grain, which they might not do without this extra water. Data from field sampling are not available from the remaining sites to make a similar comparison. However, if similar differences did occur, the extra amounts of water would range from about 1.5 inches at Site 5 to 2.9 inches at Site 1, with intermediate values for the remaining sites.

### Water Infiltration

The results of water infiltration measurements are shown in Table 6. These data show total water infiltration at 10 minutes and at 20 hours, and infiltration rates at various times from 10 minutes to 20 hours after applying water. Also included in Table 6 are means for the seven sites along with standard deviations from the means.

Total infiltration at 10 minutes was highest at Site 7 (1.64 inches) and lowest at Site 1 (0.80 inch). Infiltration at Site 7 was only 0.12 and 0.24 inch higher than at Sites 5 and 6, respectively. These three sites were near the southwestern boundary of the Pullman soil area where the soil, except for Site 4, has more sand in the profile than at other sites. Sand content and infiltration at 10 minutes were lowest at Site 1.

Multiple regression analyses showed that total infiltration and infiltration rate at 10 minutes were positively related to sand content in the B21t horizon and the weighted mean sand content for the entire profile (Table 7). Other variables included in the multiple regression analyses, both for the B21t horizon and entire profile, were soil depth, silt content, clay content, organic matter content, and bulk density. The levels of significance and rankings of the variables with regard to their effect on infiltration are included in Table 7. Except for the initial analysis with all six independent variables, only those results are shown for which at least one partial regression coefficient was statistically significant.

The infiltration rate at 10 minutes was highest at Sites 5 and 7 and lowest at Site 2. All independent variables included in the analysis for the B21t horizon had a significant effect on infiltration rate at 10 minutes. For the entire profile, only sand content had a significant effect.

Although Site 7 had the highest total infiltration at 10 minutes, it also had the lowest total infiltration at 20 hours (3.18 inches). For the remaining sites, total infiltration at 20 hours ranged from 4.12 inches at Site 3 to 4.90 inches at Site 6, a difference of only 0.78 inch (Table 6). Total infiltration at 20 hours was significantly related (positively) only with silt content in the B21t horizon (Table 7).

The low total infiltration at Site 7 resulted from low infiltration rates from 1 to 20 hours after applying water (Table 6). Except for a rate similar to that at Site 5 at 2 hours, rates at Site 7 were the lowest for the 1- to 20-hour period.

Based on the multiple regression

TABLE 6. AMOUNT AND RATE OF WATER INFILTRATION INTO PULLMAN SOILS

| | Total infiltration at | | Infiltration rate at | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site and County | 10 min. | 20 hr. | 10 min. | 30 min. | 1 hr. | 2 hr. | 5 hr. | 10 hr. | 20 hr. |
| | in. | | in./hr. | | | | | | |
| 1 - Carson | 0.80 | 4.71 | 1.17 | 0.45 | 0.36 | 0.31 | 0.17 | 0.17 | 0.13 |
| 2 - Armstrong | 1.16 | 4.72 | 0.90 | 0.43 | 0.40 | 0.31 | 0.29 | 0.07 | 0.11 |
| 3 - Randall | 1.23 | 4.12 | 1.02 | 0.60 | 0.68 | 0.47 | 0.17 | 0.11 | 0.05 |
| 4 - Swisher | 1.16 | 4.20 | 1.44 | 0.71 | 0.53 | 0.33 | 0.33 | 0.16 | 0.09 |
| 5 - Castro | 1.52 | 4.51 | 2.10 | 0.63 | 0.37 | 0.25 | 0.17 | 0.13 | 0.08 |
| 6 - Deaf Smith | 1.40 | 4.90 | 1.44 | 0.57 | 0.30 | 0.43 | 0.23 | 0.16 | 0.10 |
| 7 - Floyd | 1.64 | 3.18 | 2.10 | 0.67 | 0.29 | 0.26 | 0.14 | 0.06 | 0.04 |
| Mean | 1.27 | 4.33 | 1.45 | 0.58 | 0.42 | 0.34 | 0.21 | 0.12 | 0.09 |
| S. D.[†] | 0.28 | 0.58 | 0.48 | 0.11 | 0.14 | 0.08 | 0.07 | 0.04 | 0.03 |

[†] S. D. = Standard deviation.

TABLE 7. SUMMARY OF MULTIPLE LINEAR REGRESSION ANALYSES ASSOCIATING TOTAL INFILTRATION AND INFILTRATION RATES AT 10 MINUTES AND AT 20 HOURS WITH VARIOUS B21T HORIZON AND PROFILE CHARACTERISTICS OF PULLMAN SOIL OBTAINED AT SEVEN SITES IN TEXAS. RANKINGS BASED ON STANDARDIZED PARTIAL REGRESSION COEFFICIENTS[1] AND LEVELS OF SIGNIFICANCE OF THE PARTIAL REGRESSION COEFFICIENTS[2] BASED ON THE T-VALUE ARE ALSO SHOWN

| Soil zone and dependent variable | Intercept | Independent variables[3] | | | | | | SE[4] | R[5] |
|---|---|---|---|---|---|---|---|---|---|
| | | Depth | Sand | Silt | Clay | O.M. | BD | | |
| B21t horizon | | Partial regression coefficients | | | | | | | |
| Total infiltration in 10 min. | 7.8858 | 0.1057(3)** | 0.0280(4)* | −0.0162(6)NS | 0.0854(2)** | −0.4646(5)* | −7.4075(1)** | 3.047 | 0.999** |
| | 6.2822 | 0.1054(4)** | 0.0441(3)** | -- | 0.1012(2)** | −0.4684(5)** | −7.4022(1)** | 3.982 | 0.999** |
| | 2.8023 | 0.1308(4)** | 0.0573(3)** | -- | 0.1211(1)** | -- | −6.3914(2)** | 6.316 | 0.988** |
| | 0.3274 | -- | 0.0513(1)* | -- | 0.0403(2)NS | -- | −1.3141(3)NS | 0.172 | 0.885* |
| | −0.1781 | -- | 0.0429(1)** | -- | 0.0122(2)NS | -- | -- | 0.169 | 0.870** |
| | 0.4807 | -- | 0.0372(1)** | -- | -- | -- | -- | 0.163 | 0.862** |
| Infiltration rate at 10 min. | 38.0352 | −0.1155(6)** | −0.2281(1)** | −0.2107(3)** | −0.3399(2)** | −2.0651(4)** | −3.8331(5)** | 0.0048 | 0.999** |
| | 48.9242 | -- | −0.3392(1)NS | −0.3404(3) | −0.3930(2)NS | −1.5564(4)* | −6.2056(5)NS | 0.152 | 0.976* |
| | 1.8499 | -- | −0.0439(1)* | −0.0285(2)NS | -- | -- | -- | 0.244 | 0.885** |
| | 0.3172 | -- | 0.0571(1)** | -- | -- | -- | -- | 0.245 | 0.866** |
| Total infiltration in 20 hours | −37.0340 | 0.1478(6)NS | 0.2502(1)NS | 0.2695(3)NS | 0.2970(2)NS | 2.8021(4)NS | 5.7659(5)NS | 0.474 | 0.899NS |
| | 0.6592 | -- | -- | 0.1014(1)** | -- | -- | -- | 0.420 | 0.774** |
| Infiltration rate at 20 hours | 0.3859 | −0.0099(6)NS | −0.0140(1)NS | −0.0107(4)NS | −0.0215(2)NS | 0.0927(5)NS | 0.8861(3)NS | 0.027 | 0.882NS |
| | 0.3265 | -- | −0.0045(1)* | -- | −0.0032(2)NS | -- | -- | 0.027 | 0.697NS |
| | 0.1499 | -- | −0.0030(1)* | -- | -- | -- | -- | 0.028 | 0.635* |
| Entire profile | | Partial regression coefficients | | | | | | | |
| Total infiltration in 10 min. | −20.7023 | −0.0345(4) | 0.1830(1) | 0.2534(2) | −0.0056(6) | −0.3439(5) | 7.3430(3) | 0.023 | 0.999NS |
| | −20.8587 | −0.0284(4) | 0.1859(1)** | 0.2463(2)** | -- | −0.2400(5) | 7.1456(3)** | 0.016 | 0.999** |
| | −21.3388 | −0.0171(4)* | 0.1873(1)** | 0.2316(2)** | -- | -- | 7.2459(3)** | 0.045 | 0.991** |
| | −19.8606 | -- | 0.1926(1)** | 0.2216(2)** | -- | -- | 5.8620(3)** | 0.045 | 0.991** |
| | 0.4794 | -- | 0.0353(1)* | -- | -- | -- | -- | 0.161 | 0.815* |
| Infiltration rate at 10 min. | −20.8263 | 0.5012(1) | 0.4661(2) | −0.3228(5) | 0.4996(4) | 7.4750(3) | −19.9448(6) | 0.335 | 0.960NS |
| | −9.0945 | -- | 0.1770(1)* | 0.1863(2) | -- | -- | -- | 0.269 | 0.865* |
| | 0.2043 | -- | 0.0571(1)* | -- | -- | -- | -- | 0.325 | 0.748* |
| Total infiltration in 20 hours | 72.3905 | −1.0866(1) | −0.5790(4) | 1.0019(3) | −0.4548(5) | −19.9236(2) | 2.1666(6) | 0.768 | 0.853NS |
| Infiltration rate at 20 hours | 3.9947 | −0.0144(2) | −0.0216(1) | −0.0119(5) | 0.0140(6) | −0.3564(3) | −1.6371(4) | 0.016 | 0.977NS |
| | 4.3817 | −0.0294(1) | −0.0287(2)* | 0.0058(5) | -- | −0.6136(3) | −1.1487(4) | 0.014 | 0.966NS |
| | 4.3758 | −0.0260(2)* | −0.0292(1)* | -- | -- | −0.5425(3)* | −1.1615(4)* | 0.012 | 0.964* |

---

[1] Rankings are shown in parentheses immediately after partial regression coefficients. Rankings in order from 1 (highest) to 6 (lowest).

[2] Levels of significance of partial regression coefficients are *0.05, **0.01, and NS (not significant). These are shown after the rankings.

[3] Independent variables are: Depth - inches, sand content - %, silt content - %, clay content - %, organic matter content - %, and bulk density - g/cm$^3$.

[4] Standard error of estimate.

[5] Coefficient of correlation. Levels of significance are: *(0.05), **(0.01), and NS (not significant).

analyses, infiltration rate at 20 hours was significantly related (negatively) to sand content in the B21t horizon and in the entire profile. Other independent variables of the profile that significantly affected the infiltration rate at 20 hours were depth, organic matter content, and bulk density (Table 7).

## IMPLICATIONS FOR MANAGEMENT

### Plant Available Water

The total amount of plant available water retained in the soil above the calcic horizon was influenced by depth to the calcic horizon and by the water holding capacity of soil in different horizons. Total amounts ranged from 4.38 inches at Site 5 to 8.36 inches at Site 1 (Table 5). Therefore, a crop could extract almost twice as much water from soil at Site 1 as at Site 5, provided both profiles were initially filled to capacity with water and the crop's root permeated and extracted water from the entire soil volume above the calcic horizon. Both conditions, however, often are not fulfilled under field conditions at all locations.

Low water infiltration rates limit total irrigation water infiltration to about 5.0 inches in a 24-hour period (Table 6). This amount would fill the profile at Sites 4, 5, and 7, but about 8 to 25 extra hours would be needed to add each extra inch of water to the soil at the remaining sites. Prolonged irrigation is not practical, and the profile at these sites is filled with water only during long wet periods or occasionally with repeated irrigations. Thus, actual available water contents at planting time may be similar at the different sites, even though the potential water holding capacity at those sites differs widely.

Root penetration in Pullman soils varies with plant species. Sunflower and wheat roots have grown into and used water from the calcic horizon at Bushland. In contrast, sorghum generally uses water from only the upper 4 feet of soil at Bushland, thus not fully using all available water because depth to the calcic horizon is more than 4 feet. Therefore, even though there are differences in water holding capacity and depth to calcic horizon at the different sites, the management required (for example, irrigation frequency) to obtain similar results with a given amount of water may be nearly identical at the sites, at least for crops that do not root deeply. The rate of water application, however, may need to be varied because of differences in infiltration rates. Crops that root deeply, tolerate stress, and deplete soil water to lower values would require irrigation less often than crops that root less deeply, are sensitive to stress, and fail to extract all the available water. A marked difference in extent of water extraction by sunflower and grain sorghum at the same depths of Pullman soil was found by W. C. Johnson (unpublished data, Bushland, Texas). When these crops were grown on adjacent fallowed plots, sunflower depleted the soil water supply more thoroughly than grain sorghum at all depths.

### Water Application

The low water infiltration rate into Pullman soil allows the use of long irrigation furrows (Fig. 11) with little deep percolation of water. Even when settings are changed only once daily, deep percolation generally is slight. However, unless cutback flow rates are used, tailwater runoff may be high. Some of this water can be recycled through tailwater recovery systems (Fig. 13), but the extra pumping adds to production costs.

Pumping costs also are high for sprinkler systems (Fig. 14) because of the extra head required to pressurize the system. However, labor requirements for sprinkler systems, such as center-pivot systems, are lower than for furrow-irrigation systems. Also, the water can be applied with sprinklers at rates comparable to infiltration rates. In an ideally designed sprinkler system, the water should be applied at a rate slightly less than the infiltration rate. This minimizes the potential for water collecting on the surface and, therefore, water losses by runoff.

High-pressure sprinkler systems simultaneously apply water over a relatively large area, thus minimizing runoff problems. These systems, however, are energy intensive and may result in high evaporative losses of water from the falling droplets or fine spray. Low-pressure sprinklers require less energy, but apply water over a smaller area. Evaporative losses of water should be lower, but runoff losses could be higher unless special provisions are made to reduce runoff. Lyle (1979) controlled runoff and used water efficiently with a low-pressure, precision-water-application system used in conjunction with furrow dikes (Fig. 15). Booms, with attached nozzles, can be added at right angles to the main frame of the sprinkler system, thus applying water to a larger area at the same time.

### Water Infiltration Variation

Based on the data in Table 6, there was about a two-fold variation among the different sites in total water infiltration at 10 minutes and infiltration rates at different times. This variation was significantly related to various horizon and profile characteristics, as previously discussed. However, total water infiltration and infiltration rates varied considerably also among measurements made at some sites. Such variation suggests that localized compaction and possibly soil cracking may be affecting infiltration and that water behavior on a given field in the vicinity of our sampling sites may be considerably different from that indicated by the data in Table 6.

Where infiltration is much lower than expected, a compacted zone such as a plow pan may have developed in the soil. Deeper than normal plowing or chiseling while the soil is relatively dry is a possible remedy for overcoming infiltration problems associated with compacted soil layers. Another possible remedy is the use of reduced- or no-tillage cropping systems, which minimize soil compaction because of less traffic across the field, increase infiltration because of surface protection afforded by crop residues, and improve soil conditions because of decaying plant roots. Excessive infiltration normally is not a problem on Pullman soil. Based on our measurements, large variations in infiltration are possible at all sites on Pullman soil.

*Fig. 13. A tail water recovery system showing a reservoir to collect tail water runoff and a pump to return the water to the field (USDA — Soil Conservation Service photo).*

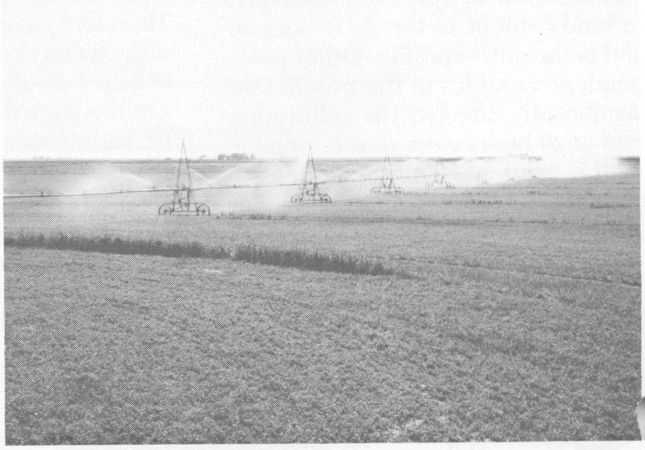

*Fig. 14. Irrigating alfalfa in Parmer County, Texas, with a high-pressure, center pivot sprinkler system (USDA — Soil Conservation Service photo).*

*Fig. 15. Experimental low pressure sprinkler being used on a furrow-blocked field (Photo provided by W. M. Lyle, TAES).*

*Fig. 16. Conservation bench terraces on Pullman soil at Bushland, Texas. Note the uniform distribution of runoff water collected on the leveled bench portion of the terrace system.*

### Crop Sequences

Wheat, grain sorghum, corn, cotton, sunflower, sugar beets, alfalfa, and some vegetable crops such as potatoes (*Solanum tuberosum*) and onions (*Allium cepa*) are adaptable and widely grown throughout some part or the entire area of Pullman soils. Whether the crops are grown continuously or in various rotations depends on such factors as crop prices; water availability; fertilizer cost and availability; weed, insect, and disease problems; and the producers' preferences. When irrigated crops that do not root deeply are grown continuously, some water generally moves beyond the depth of plant rooting and, therefore, reduces water use efficiency for crop production. Unless a deep-rooted crop is subsequently grown, this water may be lost for crop production unless it eventually reaches the aquifer from which it could be pumped again.

Water losses due to deep percolation can be minimized by growing deep-rooted crops in rotation with shallower-rooted crops. The effectiveness of deep-rooted crops for extracting water from deep in the profiles is enhanced when these crops are grown without irrigation or with a limited amount of irrigation. In either case, however, adequate water must be available throughout the profile so that root growth is not restricted by a dry zone of soil.

With water available to a 6-foot depth of Pullman soil at Bushland, dryland grain sorghum used water mainly to a 3-foot depth and only a slight amount from the fourth foot of soil in some years (Unger and Wiese, 1979). In contrast, wheat on dryland used water to a 6-foot depth (Johnson and Davis, 1980), sunflower with limited irrigation used water to a 10-foot depth (Unger, 1978a), and alfalfa used water to a 15-foot depth (Mathers et al., 1975) of Pullman soil when water was available to these depths.

### Tillage and Cropping Practices

Concern regarding the steady decline of the water level in the Ogallala Aquifer, which supplies water for irrigation of Pullman soils, has caused emphasis on conservation of irrigation water and increased the emphasis on conservation and use of precipitation for crop production.

Under dryland conditions, more water from precipitation was conserved and grain yields were higher where stubble mulch tillage rather than one way disk tillage was used in continuous wheat or wheat-fallow cropping systems (Johnson and Davis, 1972). Other practices that have conserved water and increased crop yields on dryland are conservation bench (Fig. 16) and level bench terraces (Jones, 1975; Jones and Hauser, 1975); narrow benches, narrow conservation benches, and large contour furrows (Jones, 1981); and furrow blocking (Clark and Hudspeth, 1976) (Fig. 17). These practices retained potential runoff water

*Fig. 17. Water retained on a furrow-blocked field on Pullman soil (Photo provided by O. R. Jones, USDA-ARS).*

where it fell or retained it on a portion of the field, thus increasing the amount of water available for crop use. Little benefit was obtained with respect to reduced evaporation because the residues produced by dryland crops generally were not adequate to reduce evaporation greatly, even when all residues were maintained on the surface in no-tillage systems (Army et al., 1961; Wiese and Army, 1958; Wiese et al., 1960, 1967).

In contrast to the lack of response to surface residues for increasing water storage from precipitation in no-tillage systems on dryland, major increases in water storage were obtained when residues from irrigated wheat (Fig. 18) were managed on the surface with no-tillage compared with when residues were worked into soil with tillage (Musick et al., 1977; Unger et al., 1971; Unger and Wiese, 1979). The extra stored water decreased the amount of irrigation water needed for irrigated grain sorghum (Musick et al., 1977) and increased the yields of dryland grain sorghum (Unger and Wiese, 1979) (Fig. 19). In a controlled residue-level study, water storage during fallow and subsequent grain sorghum yields increased as surface residues (wheat) increased from 0 to about 11,000 pounds per acre (Unger, 1978b). Dryland wheat often yields only about 1,500 to 2,500 pounds of residue per acre at Bushland. In contrast, irrigated wheat often yields 4,000 to 6,000 pounds of residue per acre and amounts of 10,000 or more pounds per acre have been obtained in some years (Unger, 1977; Unger et al., 1971).

*Fig. 18. Irrigated wheat produces large amounts of residue that can be managed for soil and water conservation (USDA — Soil Conservation Service photo).*

The residue amounts produced by irrigated wheat are in the range that substantially increased water storage and grain sorghum yields (Unger, 1978b). Therefore, residues from crops such as irrigated wheat are a resource that can be managed to increase water use efficiency for crop production on Pullman soil.

The benefits from surface residues result from greater total infiltration and less evaporation of water. Because of the greater water storage capacity of the deeper profiles at Sites 1 and 3 than that of the shallower profiles at Sites 4, 5, and 7, response to surface residues at Sites 4, 5, and 7 may be less than at Sites 1 and 3. With shallower profiles, the soil is more readily filled with water to the calcic horizon, especially where initial water infiltration rates are higher, as at Sites 4, 5, and 7. The greater response to surface residues at a deep site (Site 3) as compared with that at a shallower site near Lubbock was verified by Baumhardt (1980), who compared the effects of disk and no-tillage after wheat on water storage during fallow and subsequent growth and yield of grain sorghum. Because rainfall essentially filled the shallow profile with water with both tillage methods near Lubbock, sorghum yields were not significantly different because of tillage. At Bushland (near Site 3), no-tillage significantly increased grain yields of sorghum over yields with disk tillage when the sorghum was not irrigated. With irrigation, sorghum yields were similar with both tillage treatments.

A benefit from lower evaporation with surface residues is the prolonged time that the surface layer remains wet enough to influence seed germination beneficially. Whereas rapid decreases in surface soil water content because of evaporation may cause poor germination on relatively smooth bare soils, the slower evaporation on mulched soils may result in favorable germination of crops.

*Fig. 19. Grain sorghum planted in standing wheat stubble by the no-tillage method (USDA — Soil Conservation Service photo).*

## Ranching and Livestock Production

Ranching and livestock production are important agricultural enterprises on the High Plains. Native grassland on Pullman soils covers about 1.5 million acres, or 40 percent of the total land area. Most ranches are cow-calf operations, though stocker steers make up a significant percentage of many herds (Fig. 20). Usually, these stocker cattle are placed in nearby feedlots for finishing.

On many ranches, the forage produced on rangeland is supplemented by crop stubble and small grain. In winter, the native forage is often supplemented with protein concentrate. Creep feeding of calves and yearlings to increase market weight is practiced on some ranches.

The native vegetation in many parts of the area has been greatly depleted by continued excessive use. Much of the acreage that was once open grassland is now covered with brush, weeds, or cactus (Fig. 21). Forage production now may be less than half the original production. Productivity of range can be increased by using management practices that are effective for specific kinds of soils and range sites.

Where climate and topography

are similar, differences in the kind and amount of climax vegetation produced on rangeland are related closely to the kind of soil. Effective management is based on the relationships among soils, vegetation, and water.

The typical vegetation and the expected percentage of each species in the composition of the climax plant community on a typical clay loam range site are given in Table 8. The potential total annual production of vegetation in favorable, normal, and unfavorable years is shown in the footnote for the table.

In addition to knowledge of soil properties and the climax plant community, range management requires an evaluation of the present condition of the range vegetation in relation to its production potential. Range condition on a particular range site is determined by comparing the present plant community with the climax plant community for the site. The more closely the existing community resembles the climax community, the better the range condition (Fig. 22). The objective in range management generally is to control grazing so that plants growing on a site are similar in type and percentage composition to the climax plant community for that site. Such management generally results in the maximum production of vegetation, conservation of water, and control of erosion. Sometimes, however, a range condition somewhat below the climax meets grazing needs, provides desirable wildlife habitat, and protects soil and water resources.

The major management concern on most rangeland is to control grazing so that the types and percentages of plants that make up the climax plant community can become reestablished. Controlling brush and minimizing soil erosion by wind are also important management concerns. If sound range management based on soil information and rangeland inventories is applied, the potential is good for increasing the productivity of rangelands.

*Fig. 20. Cattle on native-grass rangeland on Pullman soil (USDA — Soil Conservation Service photo).*

*Fig. 21. Rangeland in poor (left of fence) and excellent condition (right) on Pullman soil. Consistent overuse has resulted in more Cholla cactus and small mesquite becoming established in the pasture at the left (USDA — Soil Conservation Service photo).*

TABLE 8. TYPICAL VEGETATION AND POTENTIAL PRODUCTION[1] ON A PULLMAN CLAY LOAM RANGE SITE

| Plant name | | |
|---|---|---|
| Common | Scientific | %[2] |
| Blue grama | *Bouteloua gracilis* | 40 |
| Buffalograss | *Buchloe dactyloides* | 25 |
| Sideoats grama | *Bouteloua curtipendula* | 5 |
| Western wheatgrass | *Agropyron smithii* | 5 |
| Vine-mesquite | *Panicum obtusum* | 5 |
| Silver bluestem | *Andropogon saccharoides* | 5 |
| Tobosa | *Hilaria mutica* | 5 |
| Other perennial grasses | --- | 5 |
| Perennial forbs | --- | 5 |

[1] Potential production of air-dry vegetation is 2,000 pounds/acre in a favorable year, 1,500 in a normal year, and 1,000 in an unfavorable year.

[2] Percentages refer to the expected proportion of each species in the total annual production on an air-dry basis.

*Fig. 22. A range in excellent condition on Pullman soil in Swisher County, Texas. About 95 percent of the vegetation is blue grama grass and about 5 percent buffalograss (USDA — Soil Conservation Service photo).*

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