Reprinted from the *Soil Science Society of America Journal*
Volume 50, No. 3, May–June 1986
677 South Segoe Rd., Madison, WI 53711 USA

Profile Modification and Irrigation Effects on Yield and Water Use of Wheat

HAROLD V. ECK

Profile Modification and Irrigation Effects on Yield and Water Use of Wheat[1]

HAROLD V. ECK[2]

ABSTRACT

Where water is limited, there are continuous searches for management practices that increase water use efficiency (WUE). Profile modification (PM) of Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls) has been shown to increase yield and WUE of grain sorghum [*Sorghum bicolor* (L.) Moench] and alfalfa (*Medicago sativa* L.). We hypothesized that it might increase those of winter wheat (*Triticum aestivum* L.) and, combined with limited irrigation, might further increase water use efficiency. A 4-yr study was conducted on a site on which PM treatments (imposed in 1964) included thorough mixing of the soil profile to 0, 0.9, and 1.5 m with a wheel-type ditching machine. Measurements in 1985 showed that PM still affected infiltration rate, bulk density, and surface elevation of the soil. Irrigation treatments were: (i) fall irrigation only (preplant or preplant + emergence), (ii) fall irrigation plus one spring irrigation, (iii) fall irrigation plus two spring irrigations, and (iv) fall irrigation plus three spring irrigations. Under irrigation Treatment I, compared to yields on unmodified soil, average grain yields were increased 11% by 0.9-m PM and 20% by 1.5-m PM. With Treatment II, average increases were 16 and 25%, respectively, but under treatments III and IV, PM did not affect grain yields. Under irrigation Treatment I, compared to WUE on unmodified soil, WUE for grain production was increased 10% on 0.9-m PM soil and 16% on 1.5-m PM soil. Under Treatment II, the respective increases were 15 and 21%, but with treatments III and IV, PM had little effect on WUE. Profile modification-induced increases in wheat grain yield and WUE were small compared to those obtained with grain sorghum and alfalfa in previous studies. Profile modification of Pullman clay loam is not a feasible practice for wheat production because of limited yield response and high energy requirements to accomplish PM.

***Additional Index Words:* *Triticum aestivum*, yield components, infiltration rate, bulk density, water use efficiency.**

Eck, H.V. 1986. Profile modification and irrigation effects on yield and water use of wheat. Soil Sci. Soc Am. J. 50:724–729.

IN AREAS where the availability of water limits crop yields, there are continuous searches for practices that increase yields without proportionately increasing water use, thus increasing water use efficiency (WUE). Profile modification (PM) of Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls) has been shown to increase yields and WUE of grain sorghum [*Sorghum bicolor* (L.) Moench] (Eck and Taylor, 1969) and alfalfa (*Medicago sativa* L.) (Eck et al., 1977). It has also increased yields of sudangrass (*Sorghum sudanense*), sugarbeets (*Beta vulgaris* L.), soybeans (*Glycine max* L.), and cabbage (*Brassica oleracea*) (Eck and Davis, 1971), but WUE was not measured. I hypothesized that PM of Pullman clay loam would increase yield and WUE of winter wheat (*Triticum aestivum* L.) and in combination with limited irrigation, WUE would be further increased.

Eck and Unger (1985) have presented a review of the literature regarding profile modification. Hence, only that involving wheat as a test crop will be mentioned here. Mech et al. (1967) found that profile modification increased wheat and alfalfa yields on Freeman silt loam (fine-silty, mesic Mollic Haploxeralfs) in eastern Washington and northern Idaho. However, yields were not affected by deep plowing a Palouse silt loam (fine-silty, mixed, mesic Pachic Ultic Haploxerolls), which did not contain a slowly permeable horizon. They did not measure WUE; however, since the research was conducted under nonirrigated conditions, increased yields also effectively increased WUE. Kaddah (1976) chiseled and slip-plowed Rositas loamy fine sand (mixed, hyperthermic Typic Torripsamments) that naturally overlies Imperial silty clay [fine, montmorillonitic (calcareous), hyperthermic Vertic Torrifluvents] at about a 1.0-m depth. Slip plowing in two directions increased wheat yields 1.8 Mg ha^{-1} (from 4.5–6.3 Mg ha^{-1}). Wheat roots penetrated deeper and were more numerous along slip-plow and subsoil channels compared with areas between channels. Hobbs et al. (1961) grew wheat on two "subsoiled" (tillage depth to 0.46–0.66 m with shanked points) soils that had dense subsoils in eastern Kansas. They obtained a significant yield response in only one of five tests. In England, McEwen and Johnston (1979) obtained a 21% increase in wheat yields on a sandy loam soil on which the topsoil had been removed, the subsoil (0.23–0.46 cm) mixed, and the topsoil replaced. The soil had no detectable plowpan.

Winter wheat is a drought tolerant crop that responds to limited irrigation. Schneider et al. (1969) showed that the most critical period for water application was booting through early grain filling. They stated that during crop seasons with normal or above normal precipitation, yields from two or three well-timed spring irrigations will approach those from full irrigation.

The objective of this study was to determine the effects of soil profile modification, irrigation, and profile modification × irrigation interactions on yield, yield components, and water use efficiency of winter wheat.

METHODS AND MATERIALS

The experiment was conducted on Pullman clay loam at the USDA Conservation and Production Research Laboratory, Bushland, TX. A thorough description of the soil has been published (Taylor et al., 1963). The site had been used for previous studies involving grain sorghum (Eck and Taylor, 1969) and alfalfa (Eck et al., 1977). In the present study, winter wheat was grown under four irrigation regimes on three soil PM treatments. The PM treatments (unmodified profile, profile mixed to 0.9 m, and profile mixed to 1.5 m) were imposed in 1964 with a wheel-type ditching machine. The ditching wheel rotated as the machine moved forward; thus, the wheel removed and thoroughly mixed vertical slices of the soil profile. The mixed soil was returned to the ditch with a small bulldozer before the next pass of the ditching machine. Further details of the PM procedure were given by Eck and Taylor (1969). Unger (1970) measured the water relations of PM and unmodified soil in 1967. Water infil-

[1] Contribution from USDA-ARS, P.O. Drawer 10, Bushland, TX 79012. Received 3 June 1985.
[2] Soil Scientist, USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX 79012.

Table 1. Irrigation dates and amounts; planting and harvest dates.

Season	Preplant irrigation		Planting	Fall irrigation		First spring irrigation		Second spring irrigation		Third spring irrigation		Harvest
	Date	mm	Date	Date	mm	Date	mm	Date	mm	Date	mm	Date
1977 to 1978	9/28	178	10/13	--	--	3/23	102	4/21	102	5/18	102	7/5
1978 to 1979	9/14	254	10/10	--	--	4/18	127	5/11	102	--	--	7/5
1979 to 1980	9/27	152	10/12	10/24	127	6/6	102	--	--	--	--	7/1
1980 to 1981	8/22	178	10/16	11/7	102	4/22	127	5/15	102	5/29	102	6/23

tration rates, bulk density, and surface elevations were measured in 1985 and are reported as a part of this study. Irrigation variables were (Treatment I) fall irrigation only (Treatment II), fall irrigation plus one spring irrigation (Treatment III), fall irrigation plus two spring irrigations, and (Treatment IV) fall irrigation plus three spring irrigations. For Treatment I, sufficient water was applied to wet the soil profile to a depth of 1.8 m. This was accomplished by preplant irrigation (1977 and 1978) or by preplant irrigation plus an "emergence" irrigation (1979 and 1980). Statistically, the experiment was treated as a randomized block-split plot design with three replications. Profile modification treatments were main plots and irrigation treatments occupied subplots. For this study, each PM plot (9 by 49 m) was split in half, for two irrigation subplots, 9 by 24.5 m. Plots were leveled and bordered for flood irrigation. Water was applied through gated pipe and measured with a propeller-type line meter.

Spring irrigations were applied when plants on the respective treatments began wilting in mid-afternoon. Treatments II, III, and IV were irrigated at the first spring irrigation, treatments III and IV at the second, and Treatment IV was irrigated at the third spring irrigation. Dates and amounts of seasonal irrigations are given in Table 1.

The plots were sweep-plowed and disked at intervals during the summer of 1977 to destroy the alfalfa grown in the previous study. In subsequent years, the wheat straw was shredded and plots were disked after harvest and during the summer as necessary to control weeds and to incorporate the residues. Plots were releveled and chiseled about 0.2-m deep before preplant irrigations each year.

The wheat variety grown was 'TAM 101'. Planting and harvest dates are given in Table 1. Planting rates (in 0.25-m spaced rows) were 62 kg ha^{-1} in 1977 and 1978 and 50 kg ha^{-1} in 1979 and 1980. No fertilizer was applied for the 1978, 1979, or 1980 crops. There was adequate residual N from alfalfa and adequate residual P from that applied for the alfalfa crop. A blanket application of N (100 kg N ha^{-1} as ammonium sulfate) was applied in early spring, 1981. There were no indications of plant nutrient deficiencies on any treatment at any time during the study.

In the first 3 yr, grain and straw yields were determined by harvesting 0.5- by 21-m swaths through each plot and threshing with a nursery thresher. Straw yield was determined as the difference between total dry matter and grain yield. In 1981, straw yields were obtained by harvesting single square meter samples from each plot and following the procedure used in the other years. Grain yields were obtained by plot combine harvesting 1.5- by 21-m areas from each plot. Harvest indexes (wt of grain/wt of grain + straw) were calculated using field grain weights adjusted to 13% moisture and straw weights. Heads per square meter were obtained by counting numbers of heads in one or more 1-m lengths of row per plot. Test weights were determined by standard procedures.

Soil water was measured by the neutron method. One access tube was installed in each subplot after planting each year. Measurements were taken to 1.8-m depths by 0.30-m increments. They were made after planting, before each irrigation, at harvest, and at other selected times during the growing season. Water use was determined by summing pre-

Table 2. Soil bulk density as affected by depth of profile modification (21 yr after application).

Depth of modification	Sampling depth, m					
	0.15	0.45	0.75	1.05	1.35	1.65
m	Mg m^{-3}					
0	1.41	1.53	1.58	1.60	1.51	1.57
0.9	1.46	1.49	1.49	1.61	1.54	1.57
1.5	1.49	1.46	1.53	1.55	1.53	1.59

cipitation, applied irrigation water, and the difference in soil-water content between the initial and final measurements. Preplant and emergence (fall) irrigations were not included in the water use calculations.

Water use efficiency (WUE) in grain production was determined by dividing grain yields (13% H_2O) by cubic meter of water used.

Water infiltration rates were measured when the soil was at approximate field capacity. Twenty centimeters of water were applied inside 9-m^2 areas and in 2-m wide buffer areas around the test areas. Subsidence rate was measured on the test areas with FW-1 water stage recorders. Soil bulk density was determined from cores (35-mm diam and 63.5-mm long) taken by 0.30-m depth intervals to a depth of 1.65 m. Elevations of plots and adjacent undisturbed areas were measured with an engineer's level. Reported changes are differences in elevations between plots and undisturbed areas.

RESULTS AND DISCUSSION

Infiltration, bulk density, and surface elevation measurements show that these properties were still affected 21 yr after PM. Sustained water infiltration rates, measured in August 1985, were 2.3 mm^{-h}, 9.1 mm^{-h}, and 11.2 mm^{-h} on the unmodified, 0.9-m modified, and 1.5-m modified treatments, respectively. These rates are higher than those measured in 1975 (Eck et al., 1977).

The bulk density data (Table 2) show that soil disturbed by PM 21 yr earlier was less dense than unmodified soil. The bulk densities measured in 1985 are generally higher than those measured earlier (Eck et al., 1977). This may have resulted from differences in methods of measurements or differences in soil-water content when the measurements were made. The 1975 measurements were made on cores taken by jacking a sampler into dry soil horizons horizontally, and the 1985 samples were taken by driving a sampler into wet soil horizons vertically.

Changes in surface elevation induced by profile modification are shown in Fig. 1. Twenty-one years after PM, the disturbed soil volume remained about 2 to 4% greater than before modification.

Temperature and precipitation data for each growing season are given in Table 3. The 1977 to 1978 growing season was rather poor for winter wheat as is indicated by the comparatively low yields even with the adequately irrigated treatments (Table 4). Temperatures were near long-time averages. However, precipitation was much below average until late May when it was more than double the long-time average (Table 3). Plants on irrigation treatments I and II were subjected to severe drought and many tillers senesced before the drought was broken in late May. All irrigation treatments were applied; however, two spring irrigations were adequate to produce maximum yields. Significant precipitation occurred a few days after the third irrigation was applied.

The 1978 to 1979 season was very favorable for wheat production. Average maximum temperatures were below average and precipitation was near or above average in all months except October, April,

Table 3. Summary of October to June precipitation and temperature data for 1977 to 1981 at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX.

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
				1977 to 1978					
Precipitation, mm	7	5	1	6	21	3	17	159	84
Temperature—Max °C	23.1	17.0	12.3	4.8	3.6	15.4	24.6	24.1	29.7
Min °C	5.5	1.4	−5.4	−9.4	−7.4	−1.1	5.7	9.7	14.9
				1978 to 1979					
Precipitation, mm	8	25	4	17	5	30	17	43	80
Temperature—Max °C	21.9	12.2	7.6	1.6	11.6	14.8	20.2	24.1	28.1
Min °C	6.3	1.7	−8.1	−10.9	−5.1	0.1	4.2	8.7	13.6
				1979 to 1980					
Precipitation, mm	46	14	4	19	9	62	21	114	36
Temperature—Max °C	25.2	11.2	11.3	8.2	10.1	13.7	19.3	22.6	33.2
Min °C	5.1	−2.4	−5.2	−5.9	−4.1	−2.6	3.0	8.7	16.3
				1980 to 1981					
Precipitation, mm	27	24	6	1	2	47	15	62	105
Temperature—Max °C	21.9	12.9	13.2	11.6	14.1	15.1	23.6	25.4	32.3
Min °C	4.4	−1.9	−3.4	−5.4	−5.3	0.8	6.7	9.3	16.1
				43-yr Avg					
Precipitation, mm	41	19	13	11	12	19	28	70	74
Temperature—Max °C	23.0	15.7	11.5	9.9	12.5	16.8	22.1	26.2	31.1
Min °C	6.1	−0.7	−4.6	−6.4	−4.2	−1.1	4.4	9.6	14.9

Table 4. Grain yields as affected by irrigation and profile modification.

Modification depths	Irrigation treatments I	II	III	IV	Avg
m			Mg ha⁻¹		
		1978			
0	1.92	1.72	3.53	3.85	2.76
0.9	1.73	1.94	3.39	3.41	2.62
1.5	1.77	2.57	3.36	3.25	2.74
Avg	1.81	2.08	3.43	3.50	
LSD (0.05) Mod = NS Irr = 0.76 Mod × Irr = NS					
		1979			
0	2.97	5.55	6.83	6.50	5.46
0.9	3.64	5.94	6.90	7.50	5.99
1.5	3.98	6.16	6.92	6.85	5.98
Avg	3.53	5.88	6.88	6.95	
LSD (0.05) Mod = 0.53 Irr = 0.43 Mod × Irr =NS					
		1980			
0	4.09	4.71	4.24	4.89	4.48
0.9	4.72	5.13	5.14	5.58	5.14
1.5	4.83	5.48	5.21	5.86	5.34
Avg	4.55	5.11	4.86	5.44	
LSD (0.05) Mod = 0.58 Irr = 0.38 Mod × Irr = NS					
		1981			
0	2.47	3.58	5.37	4.99	4.10
0.9	2.63	5.08	5.37	5.33	4.60
1.5	3.18	5.23	5.74	5.71	4.97
Avg	2.76	4.63	5.49	5.34	
LSD (0.05) Mod = 0.70 Irr = 0.48 Mod × Irr = NS					
		Avg 1978 to 1981			
0	2.86	3.89	4.99	5.06	4.20
0.9	3.18	4.52	5.20	5.46	4.59
1.5	3.44	4.86	5.31	5.42	4.76
Avg	3.16	4.42	5.17	5.31	
LSD (0.05) Mod = 0.30 Irr = 0.24 Mod × Irr = NS					

Table 5. Straw yields as affected by irrigation and profile modification.

Modification depths	Irrigation treatments I	II	III	IV	Avg
m			Mg ha⁻¹		
		1978			
0	3.01	4.69	6.72	8.00	5.61
0.9	3.96	4.24	9.06	7.39	6.16
1.5	2.63	6.77	8.86	8.06	6.58
Avg	3.20	5.23	8.21	7.82	
LSD (0.05) Mod = 1.06 Irr = 1.09 Mod × Irr = 1.50					
		1979			
0	5.00	7.82	10.43	10.46	8.43
0.9	6.03	9.37	11.19	10.44	9.26
1.5	6.58	8.72	10.44	11.59	9.33
Avg	5.87	8.64	10.68	10.83	
LSD (0.05) Mod = 0.79 Irr = 0.72 Mod × Irr = NS					
		1980			
0	5.39	5.76	6.20	5.61	5.49
0.9	6.16	6.47	6.09	7.10	6.45
1.5	7.91	6.66	6.65	8.25	7.37
Avg	6.49	6.30	5.98	6.98	
LSD (0.05) Mod = 0.49 Irr = 0.29 Mod × Irr = 0.70					
		1981			
0	4.04	6.53	6.21	8.20	6.24
0.9	5.03	7.77	7.92	8.19	7.23
1.5	5.69	7.79	8.02	7.24	7.19
Avg	4.92	7.36	7.38	7.88	
LSD (0.05) Mod = 0.77 Irr = 0.56 Mod × Irr = 1.09					
		Avg 1978 to 1981			
0	4.36	6.20	7.14	8.07	6.44
0.9	5.30	6.96	8.57	8.28	7.28
1.5	5.70	7.49	8.49	8.79	7.62
Avg	5.12	6.88	8.07	8.38	
LSD (0.05) Mod = 0.43 Irr = 0.35 Mod × Irr = NS					

and May. Only two of the three spring irrigation treatments were applied. The first irrigation was not required until mid-April and precipitation after the second irrigation (10 May) provided adequate water to maturity. In the 1979 to 1980 season, precipitation was near or above average except approaching physiological maturity in June. Maximum temperatures through May were below long-time averages. After the emergence irrigation in the fall, only one additional irrigation was required. In the 1980 to 1981 season, fall and winter temperatures were below average and spring temperatures were near average. After an emergence irrigation in the fall and above average winter precipitation, the first spring irrigation was applied on 22 April, a second was applied on 15 May, and a third on 29 May. The yield data showed that the third spring irrigation was not necessary for maximum yields. A total of 91 mm of precipitation occurred after the 15 May irrigation and before harvest on 23 June.

Grain yields, straw yields, seasonal water used, and grain WUE are presented in Tables 4 through 7, respectively. Other parameters measured but not reported in detail were harvest index, test weight, plant height, and head density. A statistical summary of irrigation and PM effects on these parameters is given in Table 8.

Irrigation Effects

Spring irrigation increased grain and straw yields in all four seasons as compared to yields with fall irrigation only. For maximum yields, one spring irrigation was required in 1980 while two were required in the other three seasons. Compared to fall irrigation only, grain yield increases from one spring irrigation avg 0.27 Mg ha^{-1} (15%) in 1978, 2.35 Mg ha^{-1} (67%) in 1979, 0.56 Mg ha^{-1} (12%) in 1980, and 1.87 Mg ha^{-1} (68%) in 1981. Two spring irrigations gave yield increases of 1.6 Mg ha^{-1} (89%) in 1978, 3.39 Mg ha^{-1} (96%) in 1979, and 3.39 Mg ha^{-1} (96%) in 1981. Straw

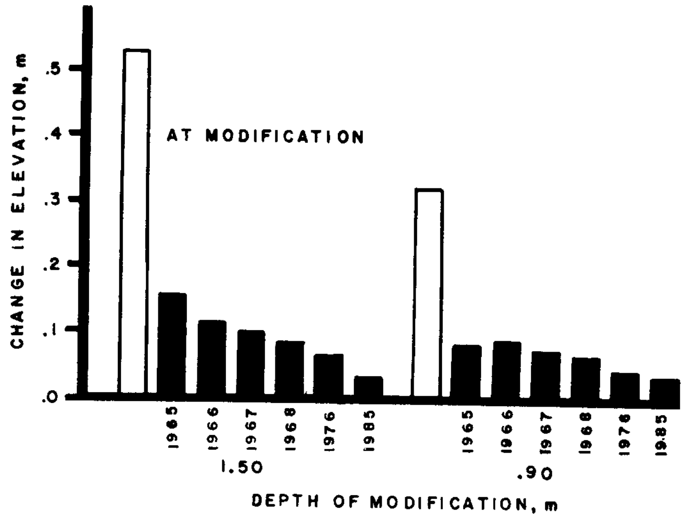

Fig. 1. Changes in plot surface elevation induced by profile modification, subsequent irrigation, leveling, and cropping.

Table 6. Water use as affected by irrigation and profile modification.

Modification depths	Irrigation treatments I	II	III	IV	Avg
m	mm				
		1978			
0	339	364	491	521	429
0.9	297	357	414	609	419
1.5	225	384	547	635	448
Avg	287	368	484	588	
LSD (0.05)	Mod = NS	Irr = 49	Mod × Irr = NS		
		1979			
0	378	533	551	541	501
0.9	362	478	557	548	486
1.5	398	498	605	575	519
Avg	379	503	571	554	
LSD (0.05)	Mod = 28	Irr = 22	Mod × Irr = NS		
		1980			
0	393	415	415	445	417
0.9	444	461	483	492	470
1.5	441	462	466	506	469
Avg	426	446	455	481	
LSD (0.05)	Mod = 45	Irr = NS	Mod × Irr = NS		
		1981			
0	313	473	571	602	490
0.9	320	474	557	626	494
1.5	356	495	520	628	499
Avg	330	481	549	619	
LSD (0.05)	Mod = NS	Irr = 50	Mod × Irr = NS		
		Avg 1978 to 1981			
0	356	446	507	527	459
0.9	356	442	503	569	468
1.5	355	460	535	586	484
Avg	356	449	515	561	
LSD (0.05)	Mod = 24	Irr = 20	Mod × Irr = NS		

Table 7. Water use efficiency as affected by irrigation and profile modification.

Modification depths	Irrigation treatments I	II	III	IV	Avg
m	kg grain:m³				
		1978			
0	0.57	0.47	0.72	0.75	0.63
0.9	0.59	0.55	0.82	0.57	0.63
1.5	0.79	0.67	0.70	0.54	0.67
Avg	0.65	0.56	0.75	0.58	
LSD (0.05)	Mod = NS	Irr = NS	Mod × Irr = 0.17		
		1979			
0	0.78	1.08	1.24	1.20	1.07
0.9	1.01	1.20	1.24	1.37	1.20
1.5	0.94	1.25	1.14	1.19	1.13
Avg	0.91	1.17	1.20	1.25	
LSD (0.05)	Mod = 0.14	Irr = 0.12	Mod × Irr = NS		
		1980			
0	1.04	1.13	1.02	1.25	1.11
0.9	1.06	1.11	1.06	1.13	1.09
1.5	1.09	1.20	1.12	1.16	1.14
Avg	1.06	1.14	1.07	1.18	
LSD (0.05)	No significant differences				
		1981			
0	0.80	0.75	0.93	0.82	0.83
0.9	0.85	1.08	0.96	0.85	0.93
1.5	0.91	1.05	1.10	0.91	0.99
Avg	0.85	0.96	1.00	0.86	
LSD (0.05)	Mod = 0.13	Irr = NS	Mod × Irr = NS		
		Avg 1978 to 1981			
0	0.80	0.86	0.98	1.00	0.91
0.9	0.88	0.99	1.02	0.98	0.97
1.5	0.93	1.04	1.02	0.95	0.99
Avg	0.87	0.96	1.01	0.98	
LSD (0.05)	Mod = 0.08	Irr = 0.07	Mod × Irr = NS		

Table 8. Statistical summary of effects of irrigation and profile modification on yield components.

	1978			1979			1980			1981		
	Irr	Mod	Irr × Mod	Irr	Mod	Irr × Mod	Irr	Mod	Irr × Mod	Irr	Mod	Irr × Mod
Harvest index	NS	NS	NS	NS	NS	NS	**	**	**	NS	NS	NS
Test weight	NS	NS	NS	**	NS	*	**	NS	NS	**	NS	NS
Plant height	--	--	--	**	*	NS	NS	**	NS	**	NS	NS
Heads m²	**	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS

*,** Statistically significant at the 0.05 and 0.01 probability levels, respectively.

yield increases from one spring irrigation avg 2.03 Mg ha^{-1} (63%) in 1978, 2.77 Mg ha^{-1} (47%) in 1979, 0.19 Mg ha^{-1} (3%) in 1980, and 2.44 Mg ha^{-1} (50%) in 1981. Two spring irrigations gave straw yield increases of 4.34 Mg ha^{-1} (135%) in 1978, 4.88 Mg ha^{-1} (83%) in 1979, and 2.71 Mg ha^{-1} (55%) in 1981.

Amounts of water used without spring irrigation (preplant or preplant plus emergence irrigation only) and with one, two, and three spring irrigations avg 356, 453, 532 (3-yr data), and 604 mm (2-yr data). These values compare favorably with those obtained in a 2-yr study by Schneider et al. (1969). They reported 362, 446, 537, and 627 mm of seasonal water use for similar numbers of irrigations. In their study, a fourth irrigation was required for maximum yields, while in ours, two spring irrigations were adequate in 3 of 4 yr and only one irrigation was sufficient in 1 yr. Differences in irrigation needs between the two studies were probably due to differences in timing of irrigations and to differences in prevailing climatic conditions.

Water use efficiency for grain production was significantly affected by spring irrigation only in 1979 when the first spring irrigation increased WUE from 0.91 to 1.17 kg m^{-3}. Average water use efficiencies in the four seasons were as follows: 1978, 0.64; 1979, 1.13; 1980, 1.11; and 1981, 0.92 kg m^{-3}. The low values in 1978 occurred even though water use was relatively low in comparison to that in other years. The low water use efficiencies may have been due to almost two-thirds of the growing season precipitation occurring after 18 May, too late to be fully utilized in grain production.

Spring irrigation increased harvest index slightly (0.39–0.42) in 1980 when only one spring irrigation was applied. Harvest index was not affected by irrigation treatments in other years. Test weights were increased by spring irrigation in all years except 1978; however, increases were small, ranging from 1 to 4%. In 1979 and 1980, the increase was from the first spring irrigation. In 1981, the second spring irrigation was required before maximum test weights were attained. Plant heights were increased by spring irrigation in 1979 and 1981 but were not affected in 1980. In both 1979 and 1981, major increases were from the first spring irrigation. Plant heights were not measured in 1979. Spring irrigation increased heads per square meter in 1978 and 1979 but did not affect them in 1980 and 1981. In 1978, the major increase was from the second spring irrigation but in 1979, it was from the the first.

Profile Modification Effects

Profile modification did not affect grain yields significantly in 1978 but increased them in other years. In 1979 and 1980, major differences were between the 0- and 0.9-m PM treatments. In 1981, the difference between the 0- and 0.9-m treatments was not significant but the difference between the 0- and 1.5-m PM treatment was significant.

Straw yields were significantly increased by PM in all years. In 1979 and 1981, major differences were between the 0- and 0.9-m PM treatments but in 1978 and 1980 there were trends toward greater straw yields with the deep PM treatment.

Profile modification significantly affected water use in 1979 and 1980 but not in the other years. In 1979, less water was used on the 0.9 m than on the 1.5-m PM treatment. The unmodified treatment was intermediate in water use. In 1980, less water was used from the unmodified treatment than from the other two treatments. Differences in water use among modification treatments reflect differences between soil water at the beginning of the season and at harvest, thus differences are small in comparison to the total amounts of water used. Small differences in plot elevation can cause differences in water intake and distribution, thus in measured depletion and use. Greater water use from modified than from unmodified soil such as occurred in 1980 seems more reasonable than the results obtained in 1979. The soil-water data from treatments that received no spring irrigation showed that, in most cases, there was more water depletion from deeper depths on modified than on unmodified soil. During the 1980 cropping season, for instance, 10% of the water depleted from the unmodified treatment plots was extracted from the 1.2- to 1.8-m zone while the comparable figure on the PM treatments was 29%, indicating deeper rooting activity for water extraction.

Since PM reduced soil bulk density (Eck and Unger, 1985), increased water infiltration, rooting depth, and WUE of grain sorghum (Eck and Taylor, 1969), it was logical to hypothesize increased WUE of winter wheat. Although increased WUE was obtained in 2 (1979 and 1981) of 4 yr, the increases were not nearly as large as those obtained with grain sorghum (41.3%). In 1979, with no spring irrigation, the maximum increase in WUE for grain production (29%) was on the 0.9-m PM treatment. In 1981, the maximum increase (14%) was with the 1.5-m PM treatment.

In 1980, without spring irrigation, wheat with the 1.5-m PM treatment produced plants with lower harvest indexes than with other treatments. This resulted from increased straw yields without proportionally increased grain yields with this treatment. Harvest indexes were not affected by PM in other years. Plant heights were increased by PM in 2 of the 3 yr (1979 and 1980) in which they were measured. Test weights and head densities were not affected by PM.

Irrigation × Modification Interactions

There were no significant irrigation × PM interactions in grain yield, water use, or water use efficiency data. However, in 1978, 1980, and 1981, there were significant interactions in the straw yield data. In 1978, the interaction resulted principally from the fact that the treatment that received no spring irrigation yielded less on the 1.5-m PM treatment than on the 0.9-m PM treatment, while with one spring irrigation, the straw yield was considerably higher on the 1.5- than on the 0.9-m PM treatment. There is no ready explanation for this anomoly. In 1980, the data were analyzed as though there were three spring irrigation treatments when only one was applied. Although the three treatments were similar, yields on Treatment IV plots were higher than those on Treatment II and III plots on the modified treatments but not on the unmodified treatment. The interaction apparently resulted from this difference. Since the three treatments were similar, it is concluded that there was no true interaction in this case.

In 1981, with three spring irrigations, the straw yield was lower with the 1.5-m PM treatment than with the 0.9-m PM treatment, while the trend with the other irrigation treatments was towards higher yields with the 1.5-m PM treatment. Again, there is no ready explanation for this anomoly.

The analysis indicated a significant interaction in the 1980 harvest index data. The situation was the same as for the straw yield data in 1980 and the same interpretation applies. The only other significant interaction was in the test weight data for 1979. The interaction resulted from small increases in test weights with increasing depths of PM on treatments I and II and small decreases on treatments III and IV. Since only two spring irrigations were applied, treatments III and IV were similar. The slight increases in test weight with increasing depth of modification may have resulted from the plants extracting slightly more water from PM plots than from unmodified ones during late grain filling, thus allowing more complete filling. Treatments III and IV provided adequate water. There is no apparent explanation for the slight decrease in test weight with depth of PM with those treatments.

With fall irrigation only, average grain yield increases on 0.9- and 1.5-m PM soil (over yields on unmodified soil) were 11 and 20%, respectively. Corresponding WUE increases were 10 and 17%. With fall irrigation plus one spring irrigation, respective yield increases were 16 and 25% and WUE increases were 15 and 22%. With fall irrigation plus two spring irrigations, PM did not affect grain yields and had little effect on WUE.

The advantages of PM for wheat production were small compared to those obtained for grain sorghum and alfalfa in previous studies on the same site. Under limited water (preplant irrigation only), PM to 0.9 and 1.5 m increased grain sorghum yields by 66 and 80%, respectively, and WUE in grain production was increased by 41%. Under adequate irrigation, PM had little effect on grain yields but increased WUE in 2 of 3 yr (Eck and Taylor, 1969). In the alfalfa study, PM increased yields 30% when two irrigations were applied between harvests and 50% with single irrigations between harvests. Increases in WUE were 35% with two irrigations and 57% with single irrigations between harvests (Eck et al., 1977). The lower alfalfa hay yields and lower WUE on unmodified soil were attributed to inadequate penetration and the attendant loss of water to evaporation and to the effects of surface ponding of water after irrigation. In this study with wheat, these factors probably would not be as important because the root zone was fully wetted with preplant or fall irrigations and growing season irrigations were applied when the soil was dry and temperatures were cool enough so that differential penetration and evaporation had little effect.

There were only small changes in physical properties of the PM soil between 1976 and 1985. Water infiltration rates were as rapid or more rapid, differences in bulk densities between PM and unmodified soil had declined but were still present, and surface elevations were still higher on PM than on unmodified plots. These measurements show that changes induced by PM persisted 21 yr after PM. It is believed that improved conditions for plant rooting persisted too. Considering the amounts and cost of energy required for PM and the moderate increases in wheat yields and WUE obtained from the practice, it is concluded that PM is not a feasible practice for wheat production on Pullman clay loam.

REFERENCES

Eck, H.V., and R.G. Davis. 1971. Profile modification and root yield, distribution, and activity. Agron. J. 63:934–937.

Eck, H.V., and H.M. Taylor. 1969. Profile modification of a slowly permeable soil. Soil Sci. Soc. Am. Proc. 33:779–783.

Eck, H.V., and P.W. Unger. 1985. Soil profile modification for increasing crop production. Adv. Soil Sci. 1:65–100.

Eck, H.V., T. Martinez, and G.C. Wilson. 1977. Alfalfa production on a profile-modified slowly permeable soil. Soil Sci. Soc. Am. J. 41:1181–1186.

Hobbs, J.A., R.B. Herring, D.E. Peaslee, W.W. Harris, and G.E. Fairbanks. 1961. Deep tillage effects on soils and crops. Agron. J. 53:313–316.

Kaddah, M.T. 1976. Subsoil chiseling and slip plowing effects on soil properties and wheat grown on a stratified fine sandy soil. Agron. J. 68:36–39.

McEwen, J., and A.E. Johnston. 1979. The effects of subsoiling and deep incorporation of P and K fertilizers on yield and nutrient uptake of barley, potatoes, wheat, and sugarbeet grown in rotation. J. Agric. Sci. 92:695–702.

Mech, S.J., G.M. Horner, L.M. Cox, and E.E. Cary. 1967. Soil profile modification by backhoe mixing and deep plowing. Trans. ASAE 10:775–779.

Schneider, A.D., J.T. Musick, and D.A. Dusek. 1969. Efficient wheat irrigation with limited water. Trans. ASAE 12:23–26.

Unger, P.W. 1970. Water relations of a profile modified slowly permeable soil. Soil Sci. Soc. Am. Proc. 34:492–495.