MATERIALS AND METHODS

A 6-yr tillage management study was conducted from August 1993 to July 1999 at the Washington State University Dryland Research Station at Lind, WA. Annual precipitation averages 244 mm. The Shano silt loam soil is more than 2 m deep with less than 2% slope. The experimental design was a randomized complete block with three tillage treatments replicated four times. Individual plots were 18 by 46 m, which allowed use of commercial-size farm equipment. Wheat and fallow phases of the study were present each year.

Tillage Treatments and Field Operations

The three tillage management treatments were (i) conventional tillage (CT)—standard frequency and timing of tillage operations using implements commonly utilized by growers, (ii) minimum tillage (MT)—standard frequency and timing of tillage operations, but herbicides were substituted for tillage when feasible and a noninversion undercutter V-sweep implement was used for primary spring tillage, and (iii) delayed minimum tillage (DMT)—similar to minimum tillage except primary spring tillage with the undercutter V-sweep was delayed until at least mid May. A complete list of field operations and timing for each treatment throughout the study are shown in Table 1.

With conventional tillage, postharvest tillage was conducted in August of 1993, 1994, and 1995 with overlapping 36-cm-wide V-sweeps on 30-cm spacing at 13-cm depth to kill Russian thistle (*Salsola iberica* Sennen and Pau) by severing the tap root. Russian thistle was not present in August 1996, 1997, and 1998; thus postharvest sweep operations were not required. Plots were chiseled in November, after the surface soil was wetted by fall rains, to a depth of 25 cm with straight-point shanks spaced 60 cm apart to create channels for controlling frozen soil runoff during the winter. In late February, 0.32 kg a.e. ha^{-1} glyphosate herbicide [*N*-(phosphonomethyl) glycine] was applied to control grass weeds. Primary spring tillage was conducted in mid to late March with two passes of a duck-foot cultivator at 13-cm depth with staggered 22-cm-wide blades spaced 18 cm apart with an attached four-bar spring-tooth harrow. After high residue production years, primary spring tillage involved a single pass with a tandem disk with 56-cm-diam. blades to a depth of 13 cm (Table 1). Plots were fertilized with 45 kg ha^{-1} anhydrous NH_3–N in April with a shank applicator and rodweeded three times at 10-cm depth during late spring and summer to control Russian thistle and other broadleaf weeds. Soft white winter wheat (cv. Eltan) was sown in 0.4-m-wide rows in early September all years with a John Deere HZ deep furrow drill (Deere and Co., Moline, IL). Deep-furrow drills are the standard for sowing winter wheat into carryover soil water in summer fallow in the inland Pacific Northwest.

Minimum tillage treatments were sprayed with a nonselective herbicide for postharvest control of Russian thistle instead of tillage in August of 1993, 1994, and 1995, but not in 1996, 1997, and 1998 when Russian thistle were not present (Table 1). In November, the plots were chiseled to depths of 25 to 40 cm with straight-point shanks spaced 120 cm apart (twice the shank spacing of conventional tillage). Chiseling was not conducted in 1996. A rotary shark's tooth subsoiler that caused little residue disturbance and created one 40-cm-deep pit with 4-L capacity every 0.7 m^2 was used in 1997 and 1998 in lieu of chiseling. Glyphosate was applied in late winter followed by primary tillage at 13-cm depth with the undercutter equipped with overlapping 80-cm-wide V-blades spaced 70 cm apart. A rolling harrow was attached behind the undercutter to break up large clods and fill air voids. The plots were rodweeded three times at 10-cm depth during late spring and summer and fertilized with aqua NH_3–N injected between every other row of the John Deere HZ deep furrow drill when sowing winter wheat in early September. Though sowing depth varied each year depending on soil water content, it was always the same for each treatment.

The delayed minimum tillage treatment was identical to the minimum tillage treatment except that (i) plots were not chiseled or rotary subsoiled in 1996, 1997, and 1998; (ii) primary spring tillage was delayed until mid May or early June; and (iii) only two rodweedings were conducted during late spring and summer (Table 1).

To alleviate rough areas and other problems associated

Table 1. Field operations for the three tillage management systems during the six fallow cycles (1993–1999).

Date	Conventional tillage	Minimum tillage	Delayed minimum tillage
Aug.	Sweep—30 cm shank spacing, 36-cm-wide sweeps, 13-cm depth. Sweeping was not conducted in 1996, 1997, and 1998.	Herbicide—0.38 kg a.e. ha^{-1} glyphosate + 0.67 kg a.i. ha^{-1} 2,4-D in 1993; 0.85 kg a.e. ha^{-1} glyphosate 1994 and 1995. Not required in 1996, 1997, and 1998.	Herbicide—0.38 kg a.e. ha^{-1} glyphosate + 0.67 kg a.i. ha^{-1} 2,4-D in 1993; 0.85 kg a.e. ha^{-1} glyphosate 1994 and 1995. Not required in 1996, 1997, and 1998.
Nov.	Chisel—60-cm shank spacing, straight point, 25-cm depth.	Chisel—120-cm shank spacing, straight point, 25–40-cm depth. Not conducted in 1996. Rotary subsoiler, 40-cm depth in 1997 and 1998.	Chisel—120-cm shank spacing, straight point, 25–40-cm depth. Not conducted in 1996, 1997, and 1998.
Feb.	Herbicide—0.32 kg a.e. ha^{-1} glyphosate.	Herbicide—0.32 kg a.e. ha^{-1} glyphosate.	Herbicide—0.32 kg a.e. ha^{-1} glyphosate.
Mar.†‡	Primary tillage—cultivator, overlapping 18-cm-wide sweeps, 13-cm depth + 5-bar spring-tooth harrow (two passes). Tandem disk, 13-cm depth (one pass) in 1997 and 1998.	Primary tillage—undercutter, overlapping 80-cm-wide V-blades, 13-cm depth + rolling harrow.	
Apr.	Anhydrous NH_3–N injection at 45 kg ha^{-1}.		
May	First rodweeding, 10-cm depth.	First rodweeding, 10-cm depth.	Primary tillage—undercutter, overlapping 80-cm-wide V-blades, 13-cm depth + rolling harrow.
June	Second rodweeding, 10-cm depth.	Second rodweeding, 10-cm depth.	First rodweeding, 10-cm depth.
July	Third rodweeding, 10-cm depth.	Third rodweeding, 10-cm depth.	Second rodweeding, 10-cm depth.
Sept.§	Sown to winter wheat at 45 kg ha^{-1}.	Sown to winter wheat at 45 kg ha^{-1} + aqua NH_3–N injection at 45 kg ha^{-1}.	Sown to winter wheat at 45 kg ha^{-1} + aqua NH_3 injection at 45 kg ha^{-1}.

† All treatments sown to hard red spring wheat in March 1995 because winter wheat failed due to dry seed zone conditions in September 1994.

‡ Skew tread to cut and incorporate high quantities of residue in all treatments on 1 March and again on 15 May in 1998.

§ MT and DMT treatments first blind sown in 1997 with just the drill's packer wheels in order to pass through 2000 kg ha^{-1} residue without plugging during actual sowing.

with conducting all tillage operations in the same track, the rodweeder implement was pulled perpendicular or at an angle to plot direction over the entire experimental area whenever weeding was required in all three treatments. All treatments were sown at the same time. Winter wheat stand establishment failed in September 1994 due to insufficient seed zone water and all plots were resown to hard red spring wheat (cv. Butte 86) at 67 kg ha^{-1} in 0.15-m rows with a double-disc drill in March 1995. In-crop broadleaf weeds were sprayed with 0.5 kg a.i. ha^{-1} bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) applied in March (winter wheat) or April (spring wheat) during tillering stage of wheat growth.

Measurements

Water measurements in the 180-cm soil profile were made immediately after grain harvest in late July to early August (beginning of fallow), in March prior to primary tillage, and again in late August to early September just before sowing winter wheat. Soil volumetric water content in the 30- to 180-cm depth was measured in 15-cm increments by neutron attenuation. Volumetric water in the 0-to 30-cm depth was determined from two 15-cm core samples using gravimetric procedures (Gardner, 1986). In addition, volumetric water content in the seed zone was determined in 2-cm increments to a depth of 22 cm just before sowing winter wheat in early September of 1994, 1995, and 1996 using an incremental soil sampler (Pikul et al., 1979). All soil water measurements were obtained from three locations in each plot.

Surface soil cloddiness was determined at the end of the fallow cycle in 1994, 1995, 1996, and 1998 by measuring the diameter of individual soil clods within a 1-m-diam. sampling hoop randomly positioned at three locations in each plot. Wheel tracks were avoided. All clods with diameters ≥5 cm were sorted into 1-cm size increments, and the mass of each size group measured in the field with a battery-powered digital scale. Clod mass was not measured in 1997 because clod structure was dispersed during an intense rain shower. Subsurface soil cloddiness was measured by gently dry sieving 0.01 m^3 of soil from the 0- to 10-cm tillage mulch layer through stacked 5-, 2.5-, and 1.2-cm^2 mesh screens. Clods not passing through each of the three mesh screens were then weighed. Subsurface clod measurements were obtained from the same 1-m-diam. area where surface clods had just been removed, therefore surface clods ≥5 cm in diameter were excluded from subsurface samples. Oriented roughness in all plots was measured soon after sowing in September using the chain method (Saleh, 1993).

Surface residue remaining from the previous crop cycle was measured several times throughout the fallow period by clipping and gathering all aboveground dry matter within a 1-m-diam. hoop. Three samples were always obtained from each plot. Wheat straw and dead Russian thistle plants were separated, placed in paper bags, and allowed to air dry in a low- humidity greenhouse before weighing.

Winter wheat stand establishment was determined by counting individual plants in 1-m row segments 21 d after sowing. Three row segments were selected and marked within each plot prior to emergence of wheat seedlings. Grain yield was determined in mid to late July by harvesting a 6.1-m swath through each 46-m-long plot with a commercial-size combine and auguring grain into a weigh wagon.

Precipitation was recorded at a standard U.S. Weather Bureau shelter located <1 km from the experiment site (Table 2). A frost depth tube (McCool and Molnau, 1984) was installed in undisturbed winter wheat stubble near the weather shelter and freeze–thaw status of the soil was recorded daily throughout the winter.

Analysis of variance was conducted for total soil water content in the 1.8-m profile, seed- zone water content, quantity of surface residue, surface cloddiness, subsurface cloddiness, surface roughness, wheat stand establishment, and grain yield. The procedure used to compare treatment means was Fisher's protected least significant difference. All statistical tests were done at the 0.05 level of significance.

RESULTS AND DISCUSSION

Surface Residue

Residue at the beginning of fallow (just after harvest) ranged from 2200 to 5700 kg ha^{-1} during the 6-yr period, and was lowest after a spring wheat crop (1993-1994 and 1995–1996 fallow cycles, Table 3). Russian thistle produced more dry matter by the time of grain harvest than dry matter for the spring wheat crop. The important contribution of dead Russian thistle plants as residue during fallow after low crop production years in this study has been reported (Schillinger et al., 1999). By using herbicides instead of tillage for postharvest Russian thistle control, and noninversion undercutter V-sweeps for primary spring tillage, significantly greater quantities of surface residue were maintained with MT and DMT when compared with CT on all sampling dates (after the onset of tillage) during all years (Table 3). Retention of sufficient residue for government farm program compliance (>390 kg ha^{-1}) during fallow was not a problem, even with CT, when the previous winter wheat crop produced 4000 kg ha^{-1} or more straw.

Surface Clods, Subsurface Clods, and Roughness

Averaged across years, the mass of surface soil clods ≥5 cm in diameter at time of sowing in September was 20, 37, and 46 Mg ha^{-1} for CT, MT, and DMT, respectively (Fig. 1). The DMT treatment generally resulted in the greatest surface clod mass because the undercutter V-sweep did little mixing or disturbance to the surface soil layer, which was dry when primary spring tillage occurred in mid May to early June. The greater mass of surface clods in 1996 compared with

Table 2. Precipitation during six 13-mo-long fallow cycles compared with the 80-yr average at Lind, WA.

Time period	1993–1994	1994–1995	1995–1996	1996–1997	1997–1998	1998–1999	80-yr avg.
	mm						
August–February	103	190	212	246	164	189	157
March	5	56	10	35	17	13	21
April	26	24	25	25	3	8	18
May	39	8	28	27	38	15	20
June	7	42	12	23	2	13	20
July	5	15	1	21	12	3	8
August	0	6	0	4	8	14	9
13-mo total	185	341	288	381	244	255	253

Table 3. Quantity of surface residue as affected by conventional, minimum, and delayed minimum tillage during the 13-mo-long fallow cycle†. Values in parentheses for 1993–1994 and 1995–1996 fallow cycles are the percentage of total dry biomass comprised of dead Russian thistle plants.

	Conventional	Minimum	Delayed minimum
	kg ha^{-1}		
1993–1994			
5 Sept.	3385a (56%)	3365a (57%)	3340a (55%)
7 Nov.	735b (29%)	3030a (56%)	2905a (52%)
10 May	510c (12%)	1125b (29%)	1570a (38%)
17 Aug.	310b (16%)	875a (31%)	1000a (36%)
1994–1995			
11 Nov.	1970b	2280a	2185a
11 Apr.	670c	1345b	1860a
27 June	595c	1230b	1520a
11 Sept.	570b	1040a	1200a
1995–1996			
12 Sept.	3450a (57%)	3470a (58%)	3610a (59%)
18 Dec.	1125b (34%)	2400a (43%)	2480a (44%)
5 Apr.	625c (17%)	1370b (28%)	1880a (37%)
12 June	560b (16%)	1020a (25%)	1170a (27%)
29 Aug.	435b (15%)	840a (28%)	860a (26%)
1996–1997			
3 Mar.	3460b	5280a	5740a
28 May	1170c	2470b	2730a
5 Sept.	830b	2315a	2270a
1997–1998			
29 Jan.	4155b	5445a	4965a
3 June	1910b	2175a	2130a
2 Sept.	1690b	1890a	1880a
1998–1999			
17 Dec.	2680b	4230a	4005a

† Within-row means followed by a different letter are significantly different at $P < 0.05$.

other years is probably due to extensive and prolonged freezing of the soil during the 1995–1996 winter (data not shown), which generally promotes a more stable clod structure. The skew treader tillage operations in March and May of 1998, to cut and incorporate large quantities of surface residue into shorter lengths, resulted in a major reduction in surface clods compared with other years when the skew treader was not used (Fig. 1). Quantities of blowing dust collected from portable wind tunnel (Pietersma et al., 1996) tests on soils at the Lind Dryland Research Station (Horning et al., 1998), and on the tillage management experiment (K.E. Saxton, 1995, unpublished data), were significantly reduced with increasing levels of residue, clods, and roughness.

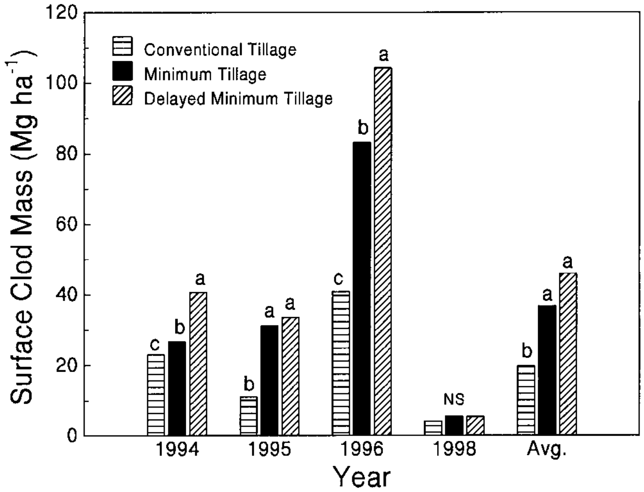

Fig. 1. Mass of surface soil clods 5 cm in diameter or larger at time sowing in early September for 1994, 1995, 1996, 1998, and the 4-yr mean as affected by conventional, minimum, and delayed minimum tillage during fallow. Within years, means followed by a different letter are significantly different at $P < 0.05$. NS = nonsignificant.

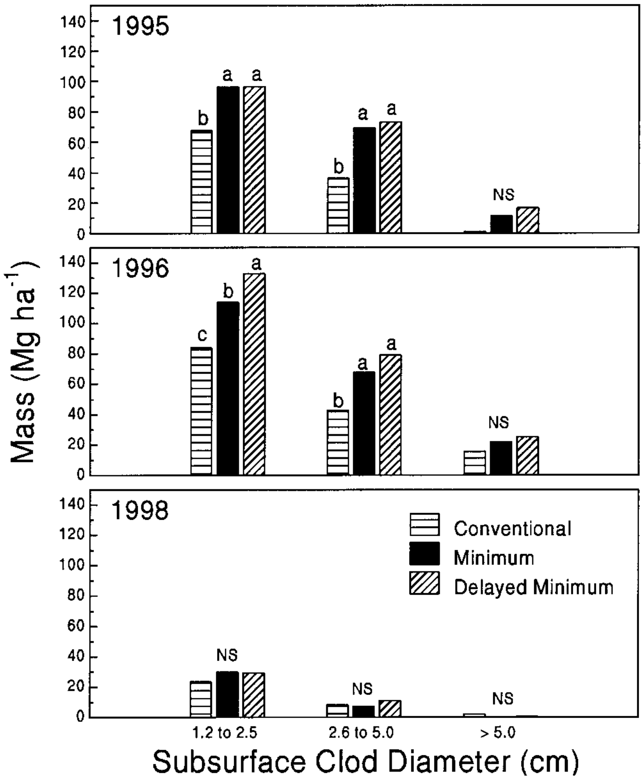

Fig. 2. Subsurface (0–10 cm depth) soil clods in 1995, 1996, and 1998 as affected by conventional, minimum, and delayed minimum tillage during fallow. Within years, means for each subsurface clod size group followed by a different letter are significantly different at $P < 0.05$. NS = nonsignificant.

In the subsurface (0–10 cm) tillage mulch layer, masses of 1.2- to 2.5- and 2.5- to 5.0-cm-diam. clods in 1995 and 1996 were greater in MT and DMT treatments compared with CT, but there were no differences for subsurface clods 5 cm and larger (Fig. 2). Growers feel that finely divided soil aggregates within the subsurface tillage mulch layer are desirable for retarding evaporative water loss from summer fallow; thus there is a perception that CT is required for optimum soil water conservation. Similar to surface clods, the skew treader implement used in 1998 reduced subsurface clod mass compared with previous years and there were no differences in subsurface clods among treatments (Fig. 2).

There were no differences in oriented soil roughness between MT and DMT measured just after sowing winter wheat. Both MT and DMT had rougher surfaces than CT, except in 1998, when there were no differences among treatments (data not shown), presumably due to use of the skew treader on all plots.

Soil Water Content

Figure 3 shows that there was little or no difference in soil water content among treatments immediately after grain harvest (beginning of fallow) during any year. Less than 15 cm of water remained in the 180 cm soil

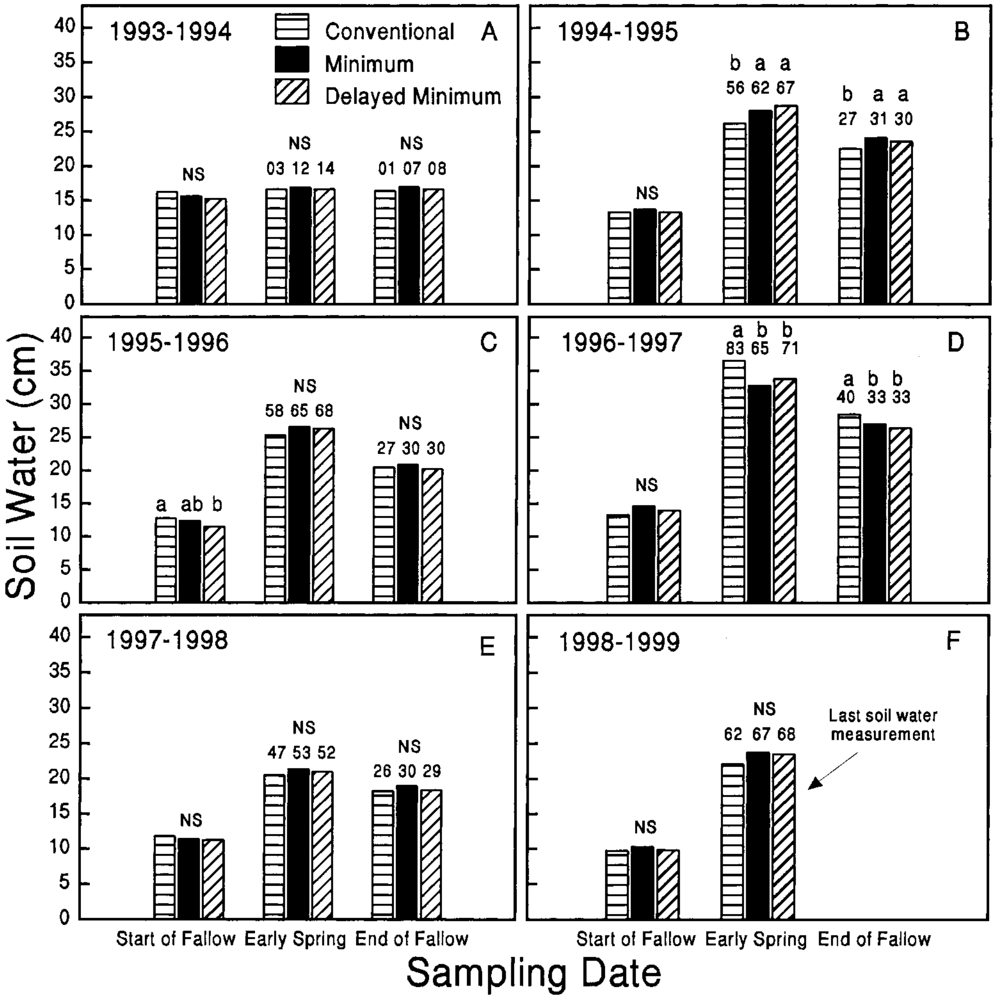

Fig. 3. Soil water content in the 180 cm soil profile during the 6-yr (1993–1999) study period at the beginning of each fallow cycle in early August, in early spring after over-winter soil recharge had occurred, and at the end of the fallow cycle in early September as affected by conventional, minimum, and delayed minimum tillage. Means for each sampling date followed by a different letter are significantly different at $P < 0.05$. Numbers above bars show storage efficiency (SE), i.e., the percentage of precipitation occurring during the fallow cycle which was stored in the soil. NS = nonsignificant.

profile at the beginning of fallow, except in 1993 (Fig. 3a) when 53 mm of rain fell in July after wheat had reached physiological maturity and was no longer extracting soil water.

Precipitation storage efficiency (SE) is defined as the percentage of precipitation occurring during the fallow cycle that is stored in the soil. Over-winter SE (from late July to March) was extremely low (3–14%) in 1993-1994 (Fig. 3a) because (i) water from the 53 mm July rainfall event probably evaporated after beginning-of-fallow soil water measurements were obtained, and (ii) only 103 mm of over-winter precipitation occurred, the least for any year of the study and well below the long-term average (Table 2). Over-winter SE was significantly improved with MT and DMT compared with CT in 1994–1995 (Fig. 3b) when several January and February precipitation events occurred when surface soil was frozen to depths as great as 31 cm (data not shown). The 40-cm-deep channels created by wide-spaced chiseling in MT and DMT probably allowed precipitation to infiltrate into unfrozen soil, whereas infiltration was probably impeded in the CT treatment because the soil was frozen below the 25-cm chiseling depth.

During the 1996–1997 fallow cycle, when no fall chiseling was conducted in the MT and DMT treatments, several winter precipitation events occurred on frozen soil, or on thawed soil overlying a frozen layer, extending as deep as 22 cm (data not shown). The CT treatment stored significantly more water in the soil than MT or DMT (Fig. 3d). This was presumably due to frozen soil restricting water infiltration in nonchiseled soils, while channels in the chiseled soils extended below the depth of frost. The 1995–1996, 1997–1998, and 1998–1999 winters were relatively open and mild, and there were no over-winter SE differences among treatments (Fig. 3c, 3e, and 3f). Averaged across 6 yr, over-winter SE was 51, 54, and 57% for CT, MT, and DMT, respectively. These over-winter SE values are considerably higher (61, 62, and 65% for CT, MT, and DMT, respectively) if 1993–1994 is excluded from the data set.

Water remaining in the soil profile at the end of fallow cycle was always in the same relative ranking among treatments as measured over winter, that is, highest for

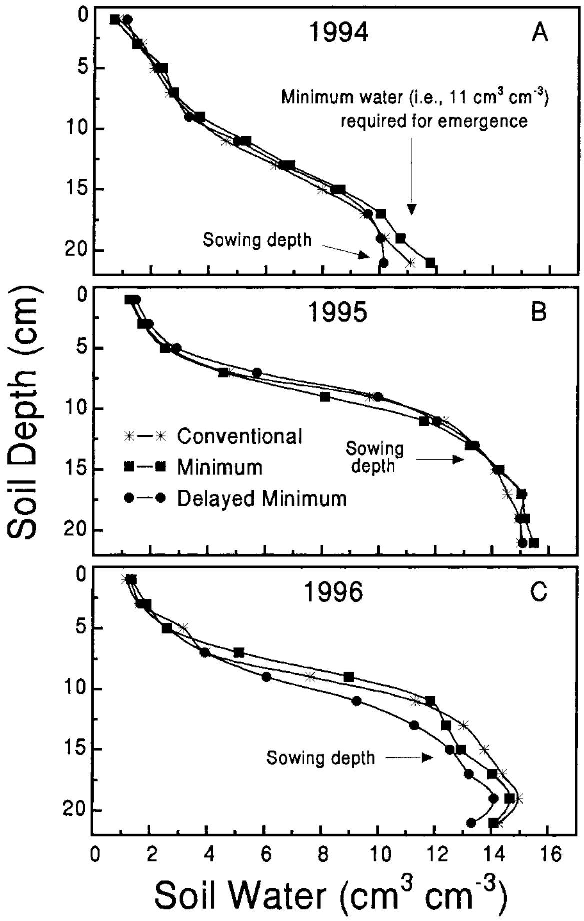

Fig. 4. Seed-zone soil water content at time of sowing in September 1994, 1995, and 1996 as affected by conventional, minimum, and delayed minimum tillage during fallow. There were no water differences among treatments at any depth (0–22 cm) in any year.

MT and DMT in 1995 (Fig. 3b) and for CT in 1997 (Fig. 3d), but not different in the other years (Fig. 3a, 3c, and 3e). The 5-yr mean end-of-fallow SE was 24, 26, and 26% for CT, MT, and DMT, respectively.

There were no differences in seed zone water content among treatments in 1994, 1995, and 1996 (Fig. 4). Sowing of winter wheat was attempted in 1994, but the deep-furrow drill could penetrate no deeper than 20 cm, which was not adequate to reach the minimum soil water content (11 cm^3 cm^{-3}, Fig. 4a) required for emergence from deep sowing conditions on silt loam soils (Lindstrom et al., 1976). Seed zone water content was adequate in 1995 (Fig. 4b) and 1996 (Fig. 4c) as well as in subsequent years (comparative measurements not taken) in all treatments. Many growers feel that it is necessary to create a fine dust mulch on the soil surface to retard evaporative soil water loss from fallow during the summer. These data, however, show that the greater mass of surface clods (Fig. 1) and subsurface clods (Fig. 2) in the MT and DMT treatments did not adversely affect seed zone water content compared with CT.

Stand Establishment and Grain Yield

Winter wheat seedling stand establishment was not affected by tillage treatment, except in 1996, when CT stands were greater than in MT and DMT (data not shown). Differences in 1996 are probably due to the larger quantities of surface clods in MT and DMT compared with CT (Fig. 1), as many seedlings were unable to elongate around clods that rolled into the furrow during sowing. These stand differences in 1996 did not affect grain yield. In 1997, MT and DMT treatments were first blind sown with only the drill's packer wheels in order to pass through 2270 kg ha^{-1} or more surface residue (Table 3) without plugging during actual sowing.

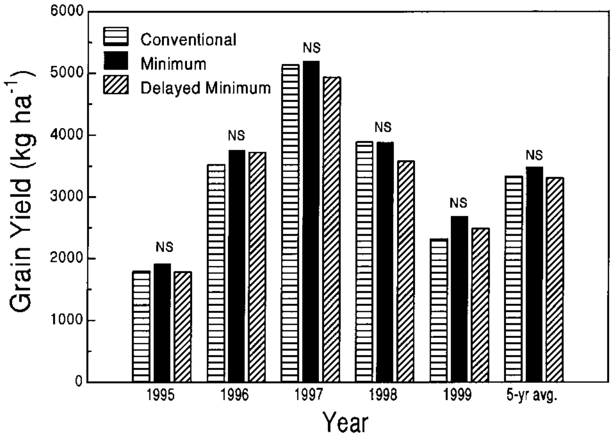

Fig. 5. Yearly and 5-yr mean grain yield of wheat as affected by conventional, minimum, and delayed minimum tillage during the preceding fallow cycle. NS = nonsignificant.

There were no differences in grain yield among treatments during any year or when averaged over 5 yr (Fig. 5). Due to generally favorable precipitation and growing conditions, grain yield averaged across treatments and years in this study was 3500 kg ha^{-1} compared with the long-term (30 yr) average winter wheat grain yield at Lind of 2350 kg ha^{-1}. Janosky (1999), who conducted an economic analysis of this study for the 6-yr period, reported that MT and DMT slightly outperformed the CT system in terms of net returns over total costs.

SUMMARY AND CONCLUSIONS

1. Surface residue retention during fallow was consistently and significantly increased using MT and DMT compared with CT. When wheat straw production was low, the minimum quantity of surface residue (390 kg ha^{-1}) required for highly erodible soils for government farm program compliance could not be achieved or was marginally met using CT, whereas ample surface residue was always present in all years with MT and DMT.
2. On average, twice the surface soil clod mass and a rougher surface was achieved with MT and DMT compared with CT.
3. Chiseling in late fall with straight-point shanks benefitted over-winter precipitation SE in two out of six years when water runoff or snowmelt occurred on frozen soils, but had no effect during open winters when runoff was not a factor. Creating deep tillage channels at wide spacing in late fall with MT and DMT was equal to or greater for over-winter SE than with CT, where chisel shanks

were more closely spaced and operated at a shallower depth. The best option to maximize overwinter water storage with minimal residue disturbance may be to create narrow pits about 40 cm deep with a long-tooth rotary subsoiler, with approximately one pit every 1 m^2.

4. Seed-zone water at the end of fallow (measured 3 yr) was not affected by tillage treatment. This suggests that finely divided soil particles within the tillage mulch may not be as important for retarding evaporative water loss during the summer as previously thought. Rather, creating of an abrupt break between the tilled and nontilled layer with primary spring tillage, which severs capillary channels from the subsoil to the surface, appears to be the dominant factor regulating over-summer evaporative water loss.
5. Delaying primary spring tillage until mid May and beyond had no adverse agronomic affects compared with MT and CT. The late winter application of a nonselective herbicide provided excellent control of downy brome (*Bromus tectorum* L.) and broadleaf weeds until at least 1 May in all years in the DMT treatment. Downy brome, the most problematic grass weed in the region, was well controlled in all tillage treatments during all years of the experiment.
6. Surface residue in excess of 2250 kg ha^{-1} at time of sowing in MT and DMT treatments plugged the deep-furrow drill in 1997. This problem was easily remedied by blind sowing (with only the drill packer wheels) prior to actual sowing. Several implements, such as the coil packer, rotary hoe, and skew treader will bury, align, or otherwise cut straw to allow effective drill operation in heavy residue, but these implements also pulverize soil clods and, therefore, are not recommended in low-residue situations.

In conclusion, conventional tillage during fallow held no agronomic or economic (Janosky, 1999) advantages over MT or DMT in this 6-yr experiment. The CT system had distinct environmental disadvantages, especially when straw production from the preceding wheat crop was <3500 kg ha^{-1}. This research showed that, with judicious use of herbicides, tillage operations during fallow can be effectively reduced from eight (CT) to as few as three (DMT). If MT and DMT fallow management were widely practiced on Shano soils in the Columbia Plateau of eastern Washington, it is reasonable to expect a sharp reduction in wind erosion and suspended dust emissions, with associated benefit to air quality. Minimum tillage and delayed minimum tillage practices, as outlined in this paper, can be implemented by wheat growers with little or no hardship to their livelihood.

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