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Effect of straw and plastic film management under contrasting tillage practices on the physical properties of an erodible loess soil

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Abstract

The current cropping system of excessive tillage and stubble removal in the northwestern Loess Plateau of China is clearly unsustainable. A better understanding of tillage and surface cover management on surface soil structure is vital for the development of effective soil conservation practices in the long term. Changes in surface soil structure and hydraulic properties were measured after 4 years of straw and plastic film management under contrasting tillage practices (no tillage vs. conventional tillage) in a silt loam soil (Los Orthic Entisol) which had been under conventional management for hundred of years in the northwestern Loess Plateau, China. Surface soil (0–10 cm) under no tillage with straw cover had the highest water stability of macro-aggregates (>250 μm) and the highest saturated hydraulic conductivity. Compared with straw cover, plastic film cover did not change macro-aggregate stability and the soil had the lowest saturated hydraulic conductivity (K_{sat}) but the highest % <50 μm soil particles. Significant correlation was found between water stable macro-aggregates and soil organic carbon content, indication the importance of the latter on soil structural development. No tillage on its own (without straw cover) was not sufficient to improve structural stability probably due to lack of organic carbon input. While use of plastic film cover might lead to short term yield increases, results indicated that it did little to improve soil physical fertility. On the other hand, no tillage with straw cover management should lead to long-term improvement of physical quality of this structurally fragile soil.

Keywords: Water stable aggregates; Sorptivity; Pore continuity; Organic carbon; Bulk density; Saturated hydraulic conductivity

1. Introduction

Soil degradation as a result of inappropriate tillage practice and stubble management is a worldwide problem. Under cropping, semi-arid lands are especially susceptible to decline in soil organic matter (SOM) because of inherent low and erratic yield. Removing crop residues for feed and/or fuel exacerbates SOM loss. Bare fallowing is practised extensively to increase water storage and stabilize crop yield, but it accelerates C and N loss from soil (Campbell et al., 1995).

In the northwestern Loess Plateau, China, the dominant soils used for cropping are loess soils which

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are notorious for their susceptibility to erosion (Wang and Shao, 2001). The average annual precipitation is 391 mm and evaporation is 1531 mm. The rainfall pattern is highly variable with >60% of annual rainfall occurring in the summer months (July to September). Ability to store this rainfall in the soil for later use by crop is therefore an important feature of agriculture in the region (Deng et al., 1998). Traditionally, soil is cultivated 3–5 times, including ploughing and harrowing after harvest and prior to the sowing of the next crop in March, to increase soil infiltration and moisture storage. Furthermore, nearly all crop residues were removed from land after harvest. Wu et al. (1999) pointed out that the excessive cultivation and stubble removal depleted soil organic matter and exposed the soil to erosion risks. Fu et al. (2000) observed average and maximum rates of soil erosion were 150 and 390 t/ha on the Loess Plateau. Severe erosion of topsoil is resulting in loss and degradation of arable land and heavy siltation of the river systems.

As a way to reverse the low and erratic crop yield of the region, plastic film mulching has recently been used in a ridge-and-furrow system to increase soil water retention and soil temperature and to control weed growth in the region (Zhang and Ma, 1994; Li et al., 2004). Considerable crop yield increases but occasionally yield reduction have been reported using this practice (Li et al., 2004). Furthermore, Li et al. (2003, 2005) reported that plastic film cover had almost no effect on the soil water storage in 2 m soil depth, and had a very high risk of crusting if heavy rainfall events occurred before spring wheat emergence. Under such system, risk of erosion is still high and the long-term effect of such practice on soil quality is little known.

Conservation tillage, the combination of reduced cultivation and stubble retention, has been shown to be effective in improving soil structure, reducing soil erosion and can result in sustainable increases in crop productivity in many parts of the world (Campbell et al., 1995; Fang et al., 2003). However, the effectiveness of such management system on the Loess Plateau has not been documented. While it has been speculated that use of plastic film cover does little to improve soil structure, little information is available on the use of straw as compared to the plastic film cover under different tillage practices on the soil physical properties of these structurally fragile and highly erodible soils. Such information helps to develop long-term farming systems that not only increase crop production but are also effective in increasing long term sustainability particularly in the protection of soil resources.

The objective of the present research was to compare the impact of straw and plastic film cover under contrasting tillage practices on soil organic carbon, aggregate stability and their consequent effects on hydraulic conductivity of a loess soil in northwestern Loess Plateau of China.

2. Materials and methods

2.1. Soil description and experimental design

A tillage/rotation farming system experiment was established in summer 2001 at the Dingxi Research Station of Gansu Agricultural University, located at Dingxi (N 35°27′45″, E 104°44′43″), China. The site had been under continuous cropping with conventional tillage for hundred of years and typical of the region, its crop yield was low and highly variable (Nolan et al., in press). The soil at the site was a Huangmian soil (Soil Taxonomy: Los Orthic Entisol, according to Chinese Soil Taxonomy *Revised Proposal*) with pH 8.3, $CaCO_3$ 133.8 g/kg, total N 0.50 g/kg and soil particle size distribution of >0.05 mm = 7.1%, 0.05–0.002 mm = 63.0% and <0.002 mm = 29.9%.

The experiment had a fully phased factorial design with two tillage treatments (no tillage vs. conventional tillage) and three soil cover treatments (no cover, straw cover and plastic film), replicated four times (Table 1). There were two rotational sequences with field pea – spring wheat – filed pea as phase 1 and spring wheat – field pea – spring wheat as phase 2. The previous crop prior to experiment was Flax (*Linum usitatissimum* L.). There were 48 plots in total. The plot size was 20 m × 4 m.

The conventional tillage treatment was three cultivations after harvest in succession to about 20, 10 and 5 cm depth, followed by 2 harrowings after the last cultivation but before the ground became frozen.

For the soil cover treatments, in the plastic film cover treatment, plastic film was laid out in 0.4 m wide strips over the ridge and the edges were covered by soil, forming a furrow between two ridges. Crop was sown in

Table 1
Summary of tillage and cover treatments under investigation

Treatments	Cover	Tillage
1	No cover	No tillage
2	No cover	Conventional tillage
3	Straw cover	No tillage
4	Straw cover	Conventional tillage
5	Plastic film cover	No tillage
6	Plastic film cover	Conventional tillage

the furrow in pair rows in 10 cm apart. Thus, the row spaces between crops were 0.4 and 0.1 m, alternatively, with average row space as 0.25 m. The ridge-and-furrow system was rebuilt after last cultivation each year for the conventional tillage treatment, while the ridge-and-furrow system was built only once in 2001 for the no tillage treatment and remained unchanged for the duration of the experiment. For the straw cover treatments, all the straw from previous crops was brought back to the original plot immediately after threshing in August. However, chopped wheat straw (6.8 t/ha) was used in all straw cover treatments when experiment started in 2001. The straw on the conventional tillage treatment plots (conventional tillage with straw treatment, Table 1) was incorporated into the soil by subsequent cultivation operations.

2.2. Soil sampling and sample preparation

Soil samples for soil organic carbon and soil structural stability measurements were taken in March 2005 before sowing, 4 years after the field experiment commenced. Six soil samples (10 cm × 10 cm × 5 cm) were randomly taken using a narrow spade from each plot at two depths (0–5 and 5–10 cm). Soil samples from each depth of each plot were then bulked to form one composite sample for each depth. For the plastic film cover treatment, samples were taken in the furrows. Soil samples were air-dried at 36 °C. Roots and large pieces of litter were removed from the soil samples before air drying.

2.2.1. Organic carbon

Sub-samples of soil from all the plots of the field experiment were taken and ground to pass through 0.5 mm sieve and organic carbon was determined by Walkley and Black method (Walkley and Black, 1934). All the measurements were triplicated.

2.2.2. Aggregate stability by wet sieving

Sub-samples of soils from all the plots were gently crushed to pass a 10 mm sieve in air-dried state and stored at 36 °C. About 30 g of the air-dried soil was weighed and wet sieved by hand through a set of two sieves (2000 and 250 μm apertures) to obtain 4 size fraction: (1) >2000 μm, (2) 2000–250 μm, (3) 250–50 μm and (4) <0.05 μm. Before sieving commenced, the soil sample was moistened by capillarity by place them on a filter paper at the upper sieve (2000 μm) for 5 min. The water volume was then raised inside the water tank to wet the filter paper and, consequently the soil. The filter paper was removed and the sample was then sieved under water by gently moving the sieves 3 cm vertically 60 times over period of 2 min through water contained in a cylindrical container. The <50 μm fraction was determined by pipette method (Chan et al., 2002) after sieving and the soil suspension in the container was shaken end-over-end 10 times. Material remaining on each sieve was transferred to an Al container and dried at 105 °C. All the measurements were triplicated.

2.2.3. Bulk density

The soil bulk density in the 0–5 cm depth was determined using the core method (McIntyre, 1974). The bulk of stainless ring was 200 cm^3. Three core samples were collected at random in each plot in March 2005 before sowing and August 2005 after harvest at the same time as the hydraulic conductivity measurements.

2.2.4. Saturated hydraulic conductivity

Soil saturated hydraulic conductivity (K_{sat}) was determined in March and August 2005 (before sowing and after harvesting, respectively) using a disc (disc diameter was 20 cm) permeameter (White et al., 1992), replicated three times in each plot. The water used in K_{sat} measurement was rain water collected in nearby rainfall cellars. Before measurement, all the plant and litter materials on soil surface were removed carefully without disturbing the soil surface structure from a randomly selected area (20 cm × 30 cm in the furrow for the plastic film treatments, and 30 cm × 30 cm for the other treatments). The value of sorptivity (S_o) was determined from the slope of beginning portion of a cumulative infiltration versus $\sqrt{t}$ plot, and K_{sat} was also calculated from the field data following the method of Geering (1995).

2.3. Statistical analyses

All data were analyzed by two-way analyses of variance using a 2 × 3 factorial model in Genstat 9.1 (Lawes Agricultural Trust, 2006). The treatment means were compared using least significant differences for the main effects as well as their interactions. Unless otherwise stated, differences were significant at $P \leq 0.05$.

3. Results

3.1. Soil organic carbon

Tillage and soil cover had a significant effect on soil organic carbon concentration (SOC) in both soil layers

Table 2
Soil organic carbon (g/kg) under different tillage and cover treatments 3 years after treatments imposed

Soil depth	Tillage	No cover	Straw cover	Plastic film cover	Mean
0–5 (cm)	No tillage	8.80	9.85	8.91	9.19
	Conventional tillage	8.10	9.00	8.56	8.55
Mean		8.45	9.43	8.74	–
		$lsd_{tillage} = 0.23$; $lsd_{cover} = 0.28$			
5–10 (cm)	No tillage	8.62	8.81	8.52	8.65
	Conventional tillage	8.18	8.67	8.21	8.35
Mean		8.40	8.74	8.37	–
		$lsd_{tillage} = 0.20$; $lsd_{cover} = 0.23$			

(0–5 and 5–10 cm) 3 years after treatments were imposed (Table 2), except for no tillage × soil cover interaction. Averaged over cover treatments, soil organic carbon was significantly higher for the no tillage treatments than those on the conventional tillage treatment in both 0–5 and 5–10 cm soil layers. Mean (over tillage treatments) soil carbon concentrations under straw cover were significantly higher than those with no cover and plastic film cover in the 0–5 and 5–10 cm soil layers (Table 2). For the plastic film cover treatment, mean SOC (over tillage) was similar to no cover in 5–10 cm and only slightly higher than the no cover in the 0–5 cm layer. Therefore, the no tillage and straw cover treatment had the highest SOC throughout the 0–10 cm depth amongst the other treatments.

3.2. Water stable soil aggregates

Percent of water stable macro-aggregate (>2000 or >250 μm) of soil for all treatments was low (<2% or <10%) reflecting the structural fragility of the soil which had been conventionally managed for hundred of years. For both 0–5 and 5–10 cm soil layers, both tillage and soil cover but not their interaction had significant effects on soil macro-aggregates stability (>250 μm) (Fig. 1). Mean percent soil water-stable macro-aggregates (>250 μm) of no tillage soil was respectively 2.7%

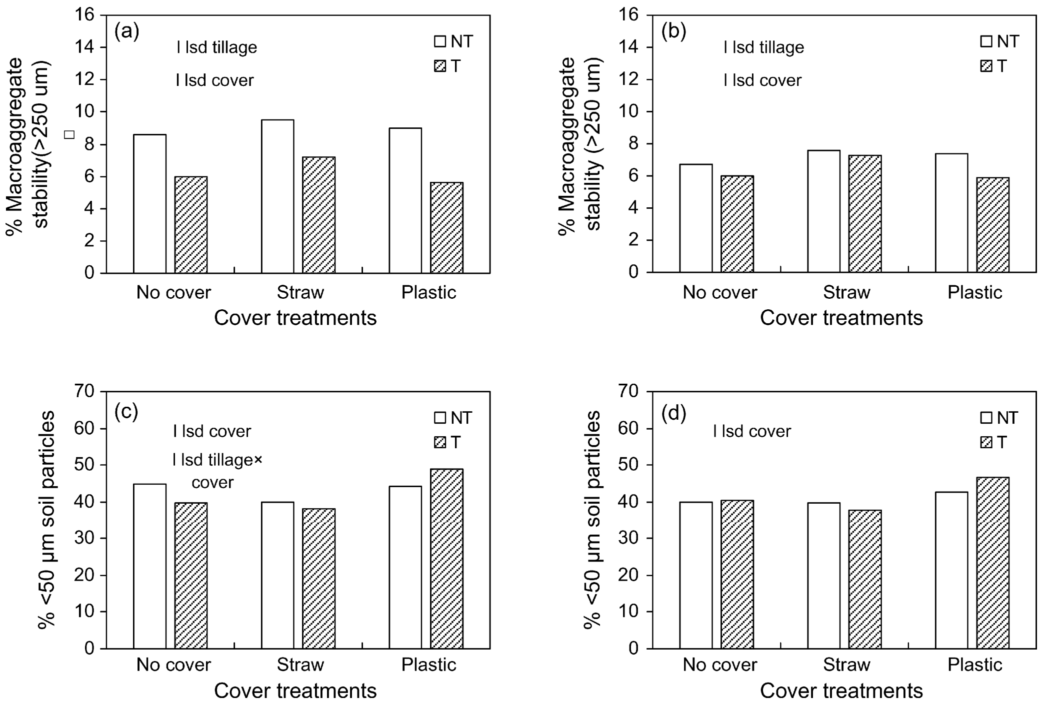

Fig. 1. Water stability aggregation of soils under different tillage and cover treatments (macro-aggregate stability (a) 0–5 cm, (b) 5–10 cm; % <50 μm soil particles (c) 0–5 cm, (d) 5–10 cm).

and 0.8% higher than those of conventional tillage soil in 0–5 and 5–10 cm layers. Soils under plastic film and no cover had similar macro-aggregates stability, both significantly lower than those under straw cover. Correlation analyses indicated that there was significant relationship between SOC and the >250 μm aggregates fraction in 0–5 cm ($r = 0.62^*$, $n = 12$) and 5–10 cm ($r = 0.81^*$, $n = 12$) soil depths.

Tillage and plastic cover and their interaction significantly reduced percent 250–50 μm soil particles (data not showed). For percent <50 μm soil particles, there was significant cover effect and tillage × cover interaction but no significant tillage effect in 0–5 cm soil layer (Fig. 1). Under no tillage, percent <50 μm soil particles was similar amongst the different treatments (mean = 42.9%). However, under conventional tillage, percent <50 μm soil particles of soil under plastic film cover was significantly higher than those under no cover and straw cover (48.8%). For 5–10 cm soil layer, only cover effect had a significant effect on percent <50 μm soil particles in that soil under plastic cover had the highest value for both tillage practices, significantly higher than those of no cover and straw cover, the latter of which were similar.

3.3. Soil bulk density

In the beginning of the 2005 season before sowing, bulk density results indicated significant tillage and cover effects as well as tillage × cover interaction in soil bulk density 0–5 cm soil layer. Bulk density was the highest with plastic film cover under both tillage treatments. On the other hand, the bulk density under straw cover was the lowest under both no tillage and conventional tillage (Table 3a). At the end of the season after harvest in August 2005, there were no significant difference in soil bulk density amongst all the different tillage and soil cover treatments (averaged 1.22 Mg/m^3, Table 3b).

3.4. Sorptivity and saturated hydraulic conductivity

Sorptivity (S_o) was similar for all the tillage and cover treatments in the beginning of the season in March 2005 (Table 3a). However, there was significant cover and tillage × cover interaction in hydraulic conductivity (K_{sat}). K_{sat} was the lowest under no tillage with plastic film cover, and was the highest under no tillage with straw cover (Table 3a). K_{sat} of the latter was 1.8 times of the former (67.1 mm/h vs. 37.2 mm/h).

At the end of season, there were significant cover effect and tillage × cover interaction for S_o and significant tillage and cover effect as well as significant tillage × cover interaction for K_{sat}. Both S_o and K_{sat} were the lowest under no tillage with plastic film cover and the highest under no tillage with straw cover (Table 3b). Comparing results of straw cover for different tillage treatments, both S_o and K_{sat} were

Table 3
Bulk density, sorptivity and saturated hydraulic conductivity (K_{sat}) of soil under different tillage and cover treatments measured in (a) March 2005 and (b) August 2005

Index	Tillage	No cover	Straw cover	Plastic film cover
(a)				
Bulk density (Mg/m^3)	No tillage	1.18	1.12	1.21
	Conventional tillage	1.10	1.06	1.22
		$lsd_{tillage} = 0.03$; $lsd_{cover} = 0.04$; $lsd_{tillage \times cover} = 0.05$		
Sorptivity (mm/min$^{1/2}$)	No tillage	4.2	4.8	3.7
	Conventional tillage	4.8	5.1	4.1
		No difference between treatments		
K_{sat} (mm/h)	No tillage	48.1	67.1	37.2
	Conventional tillage	51.2	57.2	51.2
		$lsd_{cover} = 6.7$; $lsd_{tillage \times cover} = 9.5$		
(b)				
Bulk density (Mg/m^3)	No tillage	1.21	1.19	1.24
	Conventional tillage	1.22	1.20	1.21
		No difference between treatments		
Sorptivity (mm/min$^{1/2}$)	No tillage	4.9	6.2	2.5
	Conventional tillage	4.5	3.3	3.6
		$lsd_{cover} = 1.04$; $lsd_{cover \times tillage} = 1.48$		
K_{sat} (mm/h)	No tillage	45.1	72.2	41.1
	Conventional tillage	51.2	44.8	41.7
		$lsd_{tillage} = 6.5$; $lsd_{cover} = 8.0$; $lsd_{tillage \times cover} = 10.2$		

significantly lower under conventional tillage when compared to that of no tillage. There was poor correlation between soil hydraulic conductivity and total porosity across all treatments and sampling times ($r = 0.258$, $n = 96$) indicating the importance of conducting macroporosity rather than just total porosity on soil hydraulic properties.

4. Discussion

Our results clearly indicate that under no tillage, surface soil with straw cover had significantly higher SOC, macro-aggregate water stability and saturated hydraulic conductivity than that under plastic film cover. In the latter case, magnitudes of these soil quality parameters were similar or even lower (as in the case of K_{sat} in March 2005) than those with no cover. Differences in macro-aggregate stability and hydraulic conductivity between straw and plastic film cover were not detected under conventional tillage because of the well documented deleterious effect of cultivation on accelerating breakdown of SOC as well as physical disruption of soil structure and pore continuity due to cultivation (e.g. Tisdall and Oades, 1982; Chan and Mead, 1989). The significant correlation between SOC and macro-aggregate stability highlights the importance of SOC in promoting structural stability of this structurally fragile soil. The significant lower SOC and macro-aggregate stability found in the no tillage and no cover soil compared to no tillage and straw cover soil was therefore at least partly due to the lower SOC input caused by the removal of straw. The significantly inferior physical qualities found in soil under plastic film compared to straw cover can also be partly attributed to lower organic carbon input.

Xie et al. (2005) reported that spring wheat under plastic film resulted in higher water use efficiency, higher crop yield and income in the semi-arid areas of northwestern Loess Plateau. Since the 1990s, plastic film cover as a rainfall harvesting technique has been applied widely in the northwestern Loess Plateau. However, results from this research clearly indicate the ineffectiveness or even adverse effect of plastic film cover on soil structure and soil physical properties. The significantly higher bulk density and lower K_{sat} found under plastic cover compared to straw cover and even no straw cover treatment provide clear evidence. Of particular concern was the significantly higher percent <50 μm soil particles found under plastic cover compared to straw and no straw cover. The cause of the increase is not clear but could be result of increased soil structural breakdown and erosion occurring in the furrow positions during rainfall events as a consequence of increased runoff from the surrounding plastic film-covered ridges. High percent <50 μm soil particles has been significantly related to poor soil structure and high soil strength (Young and Mullins, 1991; Chan, 1995). Therefore, significantly higher percentage of <50 μm soil particles found under plastic film cover treatment in the present case could be the underlying cause of the observed high bulk density and low K_{sat}. Li et al. (2005) observed severe crusting formed in the furrows of plastic film cover plots which seriously reduced spring wheat emergence. Furthermore, the resulting low K_{sat} found under plastic film cover can easily cause increased runoff under heavy rain, especially during fallowing period, i.e. August to September in the region. Storing rainfall in the soil in autumn for later use is a crucial for rainfed agriculture in the semi-arid area. Our SOC results indicated soil under plastic film while similar or slightly higher than those under no cover, were significantly lower than those under straw cover. Li et al. (2004) suggested that SOC may be exhausted with plastic film mulching over the long term due to accelerated decomposition of organic matter under the prevailing conditions of higher soil temperature and moisture, implying concerns over the long-term structure and fertility of these soils. Despite of the short term yield increases, plastic film cover is not a long-term solution in managing this soil.

The significant improvements in SOC, soil structure and hydraulic properties observed in this fragile loess soil (SOC < 5 g/kg, Wu et al., 2003) in the northwestern Loess Plateau which had been conventionally cultivated for hundred of years clearly demonstrate the effectiveness of no tillage and straw cover management practice. Because of higher surface soil stability and protective actions by straw cover, no tillage treatment with straw cover had the highest K_{sat} although bulk density was similar to or even higher than the other treatments. The latter was observed in March 2005 sampling when bulk density under no tillage and straw cover was significantly higher than that under conventional tillage and straw (1.12 Mg/m^3 vs. 1.06 Mg/m^3) (Table 3). The higher K_{sat} under no tillage and straw cover reflects the better development of continuous macroporosity under this treatment. Findeling et al. (2003), in a 4-year study, showed that K_{sat} increased linearly with increasing rates of straw cover on a sandy loam. Zhang et al. (2007) reported that the infiltration rate under no tillage treatment with stubble retention was 3.7 times higher than that of conventional tillage with stubble burnt under 100 mm/h simulated rainfall after 24 years of no-till practice on a red earth in Wagga

Wagga, Australia. Our results provide evidence that no tillage with stubble retention practice is an effective management technique for improving soil physical quality of this fragile soil in the long term.

5. Conclusion

Results from the present study demonstrated the beneficial effects of no tillage with straw cover on soil structural stability and hydraulic conductivity. These beneficial effects were evident after 4 years of treatment in a soil which had been conventionally managed for hundred of years. In contrast, significant deterioration in soil physical quality particularly reduction in hydraulic conductivities but increased in breakdown of soil aggregates to $<50\ \mu m$ under plastic film cover. The latter is therefore not a long-term solution from the soil conservation point of view.

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