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Traffic and tillage effects on runoff and soil loss on the Loess Plateau of northern China

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Abstract. This paper reports the outcome of 5 years of field plot runoff monitoring, 2 years of water erosion measurement, and a rainfall simulation experiment on moderately sloping farmland on the loess plateau of north-west China. The objective was to test different conservation tillage systems compared with the control treatment, conventional mouldboard plough practice (CK). Tillage, residue cover, and compaction effects were assessed in terms of runoff and soil erosion.

Results from the runoff plots showed that conservation tillage, with more residue cover, less compaction, and less soil disturbance, could substantially reduce runoff and soil erosion compared with the control. No tillage with residue cover and no compaction produced the least runoff and soil erosion. Compared with the control, it reduced runoff and soil erosion by about 40% and 80%, respectively. At the start of the experiment, residue cover appeared to be the most important factor affecting soil and water conservation, particularly when antecedent soil moisture was limited. With the accumulation of tractor wheeling effects over the course of the experiment, soil compaction appeared to become a more important factor affecting runoff.

Rainfall simulation was then used to assess the effect of non-inverting surface tillage and different levels of residue cover and wheel compaction on infiltration and runoff. This confirmed that wheel compaction effects could be greater than those of tillage and residue cover, at least under the 82.5 mm/h rainfall rate produced by the simulator. The wheeling effect was particularly large when the treatment was applied to wet soil, and severe even after wheeling by small tractors.

Additional keywords: conservation tillage, runoff, rainfall simulation, water erosion, residue cover, surface tillage, compaction, controlled traffic.

Introduction

Soil and water loss are among the most important environmental problems of dryland farming on the Loess Plateau in north-west China, where surface runoff is the main driver of soil erosion (Wang and Shao 1998). The landscape and soils in these areas, mostly in the provinces along the Yellow River including Shanxi, Shaanxi, South Gansu, and Inner Mongolia, are typically sloping and divided by gullies of different size. The soils are highly susceptible to rainfall erosion and the Soil Survey Office of Shouyang County (where this work was carried out) estimated in 1983 that average annual erosion was approximately 20 t/ha. Rainfall distribution in these areas is highly variable, both within and between years. Most rainfall occurs between July and September as high-intensity storms, which often result in soil and water erosion (Wang and Shao 1998; Jiao *et al*. 1999). The long history of excessive tillage, bare fallow, and exploitative management systems has made this erosion problem even worse (Gao and Li 2003).

The cropping system in these areas is normally a single crop/year monoculture of maize or wheat. In higher altitude, more northern areas, spring crops (usually maize) are planted in April (spring) and harvested in September or early October (autumn). In the southern parts, winter wheat is the most common crop, planted in September (autumn) and harvested in June (summer). The uneven distribution of rainfall and its misalignment with the cropping season often result in soil moisture stress in the early stage of maize growth, and throughout the wheat-growing season. Soil storage of limited rainfall is therefore critical to agricultural production on the loess plateau.

Practices which improve water use efficiency and natural resource management by reducing runoff and erosion are of great importance to this area, so conservation tillage, providing more residue cover and less soil disturbance, has received considerable attention. Since their original use in American ‘Dust Bowl’ areas, several decades of development have demonstrated that conservation tillage (CT) systems are a

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valuable means of reducing erosion by both water and wind (Conservation Technology Information Center 1996; Uri *et al.* 1998). These systems reduce soil disturbance and retain crop residues to protect the soil surface from sealing. They usually increase infiltration, reduce compaction and are sometimes associated with an increase in soil carbon (Myers and Wagger 1996; Holland 2004). The effectiveness of conservation tillage in loess soils has been demonstrated in Europe (Kwaad *et al.* 1998; Basic *et al.* 2004).

Conservation farming systems in North America, Australia, and Europe operate over comparatively large areas with large equipment and substantial herbicide inputs. These are inappropriate in scale, sophistication, and cost for the small land areas (mostly <0.4 ha per family), infrastructure, and economy of rural production in China where, for instance, common small (15–45 kW) tractor hydraulic systems have difficulty lifting a 5-row disc-type seeder. There are also major differences in climate, soil, crops, and farming practice. An ongoing research program by the Conservation Tillage Research Centre of China Agricultural University (CAU), has addressed these problems in the northern provinces since 1992. This program has developed conservation tillage technology and planting/fertiliser placement equipment appropriate to Chinese conditions, and systems based on this equipment have been shown to improve yield and environmental protection on the Loess Plateau (Gao and Li 2003; Li *et al.* 2007*a*).

Conservation tillage demonstration areas are now in operation in many places in China, but better data on the water retention and erosion control advantages of CT are still required for a comprehensive evaluation of this practice. This applies particularly to the Loess Plateau, where a great deal of research has already been completed on landscape, soil property, and rainfall effects under CT (Wang and Shao 1998; Wu *et al.* 1998; Jiao *et al.* 1999). Landscape management, stubble, and vegetation cover effects on soil and water conservation have been studied at a watershed scale by Shen *et al.* (1998); Wang *et al.* (1999), and Liang (1997), but greater understanding of the underlying factors such as compaction, tillage, and residue cover is still required.

Tillage and crop residue effects are commonly compared in soil conservation research, but soil compaction by farm equipment is considered less often, despite evidence that wheel compaction has increased runoff and reduced yields from high-clay content Vertosols in Australia (Li *et al.* 2001; Tullberg *et al.* 2001; McHugh *et al.* 2003). Compaction of cropping areas can be avoided by controlled traffic farming, which has been applied over extensive areas in Australia (Tullberg *et al.* 2007). The value of controlling traffic is frequently questioned by agronomists and farmers, particularly when considering other soils and cropping systems using smaller tractors and equipment (as in China). A preliminary assessment of controlled traffic in China demonstrated useful effects on soil bulk density, moisture content, crop performance, and equipment power requirements (Wang *et al.* 2005). The present work was designed to provide further information on wheel traffic in relation to other conservation tillage effects using small- to middle-sized machinery.

Runoff from different tillage and traffic treatments was monitored for 5 years (1998–2002), and water erosion for 2 years, to elucidate the relative impact of residue cover, tillage, and wheel compaction. This work was designed to complement replicated field trials investigating soil and crop performance effects of similar treatments, some of which have been reported by Bai *et al.* (2008) and Chen *et al.* (2008). Field runoff plots were used in the major experiment reported here, and replicated supporting information was provided using a portable rainfall simulator.

Materials and methods

Site description

The study area in Shanxi province is typical of dryland farming on the loess plateau and has been intensively cultivated for many centuries. The work was carried out at Jingshang (113°12′E, 37°45′N, altitude 1000–1200 m) in Shouyang County (Fig. 1). The climate is described as temperate continental with dry cold winters and warm summers which include the wet season. Length of frost-free season is about 120–140 days per year with annual average temperature of 7.3°C.

Crop growth occurs between April and September, but moisture is often limiting early in the growing season. Annual pan evaporation is 1675 mm, but mean annual rainfall is only 518.3 mm, varying from 812.2 to 235.5 mm in the past 22 years. Rainfall distribution within years is also highly variable, with most (62.9%) occurring between July and September. High-intensity storms (40–60 mm/day) are quite frequent (Wang and Shao 1998), and water erosion is an important problem. Almost 60% of the total farmland in this area is seriously eroded, and average water erosion has been estimated at about 20 t/ha.year (Soil Survey Office of Shouyang County 1983).

Soil type at the Shouyang site is Chestnut–Cinnamon Loess soil, low in organic matter and slightly alkaline. According to the FAO-UNESCO soil map (FAO-UNESCO 1974) the soil type is a Chromic Cambisol. Soils of the Loess plateau are generally described as porous and homogenous to considerable depth with

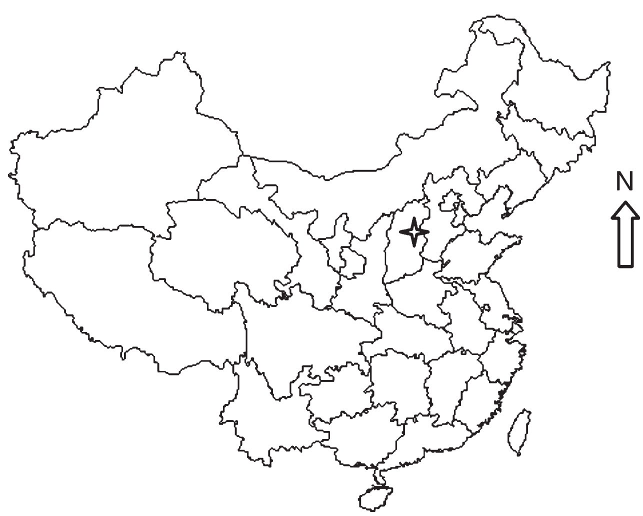

Fig. 1. Location of the experimental site (✧) in Shanxi province, China. (113°12′E, 37°45′N, altitude 1000–1200 m).

limited variability across fields. The physical and chemical properties of the topsoils on the field runoff plots, which have been used for maize monoculture with traditional tillage over many years, and rainfall simulation plots, which have a history of 5 years no-till spring maize monoculture, are shown in Table 1.

Experimental design

Average slope of the field runoff plots was 5%, which is typical of this area. The plots were subject to natural rainfall, each of 20 m length, 5.6 m width, and hydrologically defined by bunds to ensure no flow of water or sediment onto or between plots. In all but the mouldboard plough plot, all tractor operations were carried out in 2 passes of 2.8-m-wide equipment using a medium tractor with rear tyres approximately 0.32 cm in width, so about 75% of plot area was unaffected by tractor wheels, unless deliberately compacted.

The following treatments were chosen to provide information on residue cover, tillage, and compaction effects: no tillage with residue cover and no compaction (NTCN); no tillage with residue cover and compacted by tractor after autumn harvesting (NTCC); no tillage with no cover and compacted by a tractor after autumn harvesting (NTNC); surface tillage with residue cover and no compaction (STCN); surface tillage with no residue cover and no compaction (STNN); and the control was traditional mouldboard ploughing without residue cover (CK). Replication was not feasible given the costs of instrumentation and installation, together with the difficulty of finding sites providing an adequate area of uniform slope with provision for safe disposal of runoff water, together with reasonable access. Ongoing monitoring was also a serious issue at such a distance from the major research base, so while automated measurements (e.g. rainfall, runoff) continued for 5 years, those demanding on-site attendance (i.e. sediment) were monitored for only the first 2 seasons.

Surface tillage was carried out with shallow (0.05–0.08 m) minimum-inversion sweeps. Compaction treatments were intended to simulate annual machinery operation effects by wheeling the whole plot area using 6 passes of a medium (3.6 t, 2 WD) tractor, leaving adjacent rear wheel tyre marks. In the first years of the project, control plots were tilled to approximately 0.15 m depth by an animal-drawn single-furrow mouldboard plough, but animals were replaced by a small (18 kW) tractor in 2000. Maize monoculture was practiced before and throughout the experiment, with planting in mid-April and harvesting in late September. All crop residue (4–5 t/ha) was retained on the residue cover plots (NTCN, NTCC, STCN), providing an average of 70% cover. For the non-covered treatments (STNN, NTNC, CK), all residue was removed from the field after harvesting, which is the traditional practice.

The rainfall simulation experiments were carried out to provide additional information on the impact of different levels of residue cover and wheel compaction. Three levels of residue cover rate, 0% (NTCN 0), 30% (NTCN 30), and 70% (NTCN 70), were used with NTCN. Three levels of wheel compaction were used with the same level of residue cover (70%) used in the runoff plots. Three levels compaction were produced using a non-wheeled treatment (NTCN 70) and soil treated with adjacent rear wheel passes with either a small tractor [ST 70, total weight 1.2 t, front tyre size 4.5–16 (inches), inflation pressure 200 kPa, rear tyre size 9.5–24, inflation pressure 110 kPa] or with the medium tractor used in the runoff plots [MT 70, total weight 3.6 t, front tyre size 6.5–20 (inches), inflation pressure approx. 180 kPa, rear tyre size 12–38, inflation pressure 120 kPa].

The rainfall simulation tests were carried out in a nearby plot with a history of 5 years of no-till spring maize monoculture. This area was slightly flatter, but basic soil properties were similar to those of the field runoff plots (Table 1). The greater surface layer bulk density and organic matter levels in these plots probably reflect the relatively recent change to no-tillage cropping. The soil bulk density and moisture profile of the rainfall simulation plot at the time of compaction is presented in Table 2.

Each run of the rainfall simulator covered 2 treatment subplots (0.75 m by 2 m each). Two simulation runs were done with each treatment, to provide 4 sets of replicate values. The data were analysed using the SPSS analytical software package calculating means, standard deviations (s.d.), and standard errors (s.e.) for each treatment and using ANOVA to assess the significance of differences between treatments. When ANOVA indicated a significant *F*-value, multiple comparisons of mean values were performed by the least significant difference method (l.s.d.).

Instrumentation and procedures

Each runoff plot was equipped with a tipping bucket/tip logging monitoring system. The tipping bucket is an over-centre device, which tips after accepting a calibrated volume of water. Tipping was sensed using a proximity switch, and the time recorded and stored by a battery-powered data logger. Rainfall was also recorded by logging tipping-bucket pluviometers, so rainfall and runoff information could be retrieved from the loggers using a laptop computer with appropriate software. The equipment, procedures, and the DATALOG program for manipulating data have been described by Ciesiolka *et al.* (1995).

Table 1. Soil properties of field runoff plots and rainfall simulation plots

Site	Bulk density (g/cm^3)	Soil texture	Saturated water content (v/v %)	Field capacity (v/v %)	Organic matter (g/kg)	Avail. N (mg/kg)	Avail. P (mg/kg)	pH
Field runoff plots	1.18	SL[A]	55.5	30.3	7.86	74.87	6.96	8.0
Rainfall simulation	1.40	SL[B]	56.0	33.8	8.69	70.45	5.36	7.9

[A]Sandy Loam, <0.002 mm particles 10.9%, 0.002–0.02 mm particle 11.5%, 2–0.02 mm particle 77.6%.
[B]Sandy Loam, <0.002 mm particles 8.4%, 0.002–0.02 mm particle 15.4%, 2–0.02 mm particle 76.2%.

Table 2. Soil bulk density and moisture content before wheeling treatment of rainfall simulation plots

Depth (m)	Bulk density (g/cm^3)	Gravimetric water content (g/g %)	Volumetric water content (v/v %)
0.10	1.40	17.6	24.61
0.20	1.55	15.4	23.82
0.30	1.60	10.9	17.39
0.40	1.44	9.3	13.45
0.50	1.40	9.9	13.82

At the lower end of each plot, water and sediment were collected in a concrete catchbox where part of the sediment (the 'bed load') was deposited. The remaining water and sediment (the 'suspended load') flowed via a slotted collecting manifold to the tipping bucket runoff measuring device, mounted in a 1.5-m-deep pit connected to a water disposal system. A small sample of runoff was continuously withdrawn and collected for sediment concentration measurement, via a PVC pipe with slots exposed to flow from the tipping bucket. Total loss of suspended sediment was calculated by multiplying average concentration by the total volume of runoff. Measurements were taken only through the summer rainy season (between 1 June and 20 October) because significant rainfall events outside this period are rare.

The rainfall simulator used flat fan nozzles oscillating so their spray pattern swept to and fro across 2 adjacent plots 2 m by 0.75 m within the support frame, as described by Loch (1996). Rainfall energy and intensity could be adjusted via nozzle size selection, water pressure, and spray sweep rates. Calibrated rainfall intensity was 82.5 mm/h in these tests. Runoff from each plot was collected simultaneously into 2 containers, via collector trays and a vacuum suction system. Starting times for rainfall and runoff were recorded, and volume scales on the collection containers read at 5-min intervals until the runoff rate was almost constant.

Soil properties of the experimental sites were measured by sampling the surface 0–0.2 m layer of each plot for organic matter, available N and P, and particle distribution. Soil organic matter (SOM) was determined by dry combustion, and N and P were determined using the methods developed by Wells and Williams (1996). Soil samples were fully dispersed for the particle size distribution analysis to determine the soil texture. Undisturbed soil cores for bulk density, soil porosity, field capacity, and soil water content were obtained from different depths of soil layers of each treatment. The samples were weighed wet, dried at 105°C for 48 h, and weighed again to determine bulk density and soil water content.

Results

Field plot results

Annual runoff

Annual wet-season runoff for all runoff plot treatments, together with annual wet season (1 June and 20 October) rainfall and cumulative values over the 5 years of the experiment, are presented in Table 3. Rainfall of relatively low intensity occurred in 1998, 2000, and 2002, resulting in little or no runoff, but substantial runoff occurred in 1999 and 2001.

A much greater proportion of rainfall became runoff in 1999 despite the relatively small rainfall, and this can be attributed to high-intensity storms on 17 and 18 August. Similar events occurred in 2001 when almost 300 mm fell between late June and late August, with storms on 24 and 27 July, and between August 6 and 10. The duration, intensity, and amount of daily rainfall of runoff-producing rainfall events (>10 mm) in 1999 is presented in Table 4.

The event of 18 August is illustrated in Fig. 2 and Table 5. This event produced 44 mm total rainfall with a peak rainfall rate of 114.9 mm/h, and I_{60} (the greatest rainfall in one 60-min period) of 38.6 mm, or 88% of the total event rainfall. It would be classified as a strong erosion-producing storm, according to Jiao *et al*. (1999). Frequency distribution analysis of daily rainfall at Shouyang between 1967 and 1999 showed that erosive rainfall events of >40 mm/day occurred 39 times in 33 years, mainly during the months of July and August.

Table 3. Annual wet season runoff (mm) from 1998 to 2002, and wet season rainfall (mm)

Treatments	1998	1999	2000	2001	2002	Cumulative runoff (5 year)
NTCN	1	19	0	67	5	92
NTCC	0	30	0	123	5	158
NTNC	8	58	0	201	9	276
CK	3	40	1	105	8	157
STCN	1	24	0	89	6	120
STNN	6	46	1	122	11	186
Rainfall	225	274	240	392	289	

Table 4. Rainfall characteristics (1 June–20 Oct. 1999)

I_{15}, I_{30}, I_{60}: the greatest rainfall in one 15-, 30-, and 60-min period

Date	Rain start time	Duration (min)	Rain (mm)	I_{15}	I_{30} (mm)	I_{60}	>30 mm/h Rain (mm)	>30 mm/h Duration (min)	Peak rate (mm/h)
14 June	15:34	702	16.54	2.05	2.84	3.20			10.71
4 July	10:45	537	21.22	1.60	2.75	4.24			16.23
8 Aug.	2:26	370	25.79	9.46	14.20	17.48	8.37	12	63.59
17 Aug.	2:53	294	39.75	13.37	16.15	18.19	21.57	26	76.15
18 Aug.	18:56	176	43.95	25.47	33.11	38.62	33.86	25	114.94
19 Aug.	2:22	221	13.84						
30 Sept.	16:28	408	29.57	7.58	11.59	15.18	6.87	12	39.26

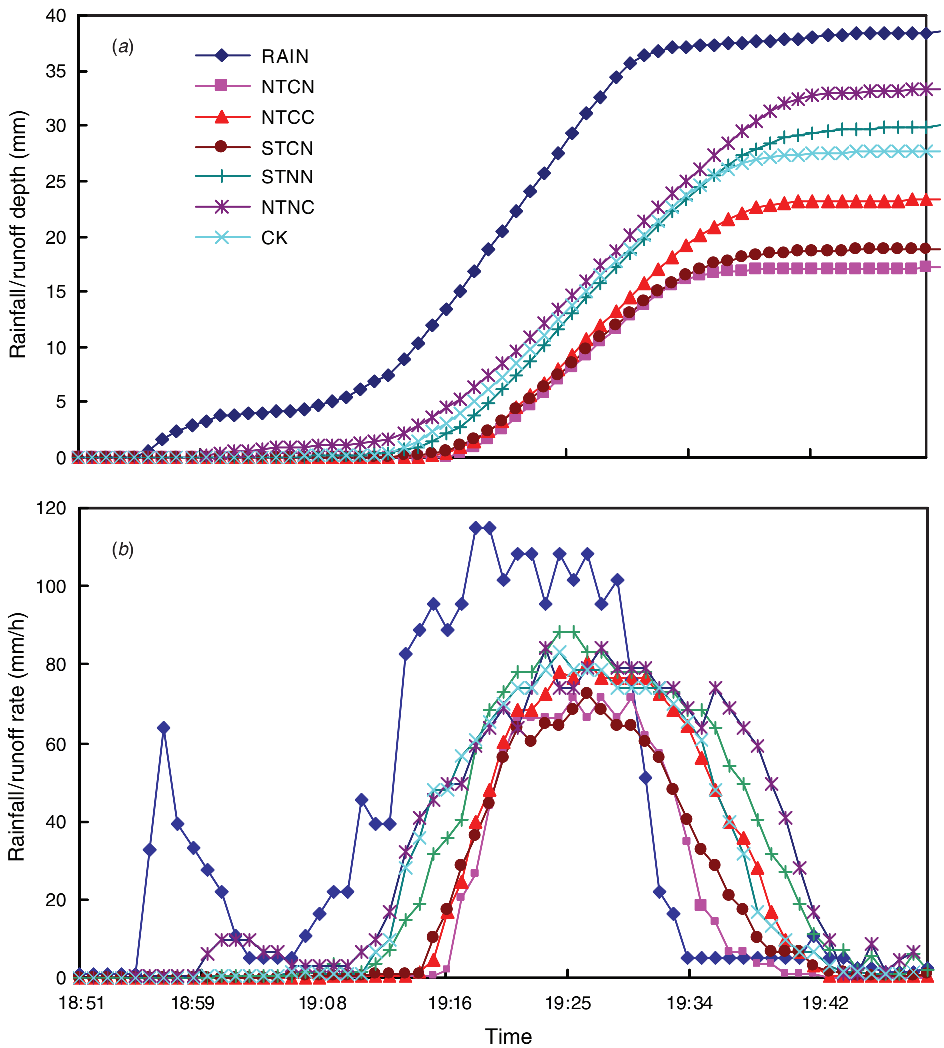

Fig. 2. (*a*) Cumulative runoff and (*b*) runoff rate for the major event (44 mm) of 18 August 1999.

Table 5. Rainfall and runoff characteristics for the major event of 18 August 1999

Treatments	Event total (mm)	Time to runoff	Peak runoff rate (mm/h)	Time to peak runoff rate
Rainfall	43.9	18:56	114.9	19:14
NTCN	17.2	19:18	71.3	19:26
NTCC	23.6	19:16	80.8	19:25
NTNC	34.6	19:01	84.5	19:24
CK	28.2	19:11	83.5	19:26
STCN	19.2	19:16	72.6	19:27
STNN	31.1	19:12	88.1	19:24

Events of >50 mm/day occurred 15 times, and events of >100 mm/day occurred twice.

Annual soil loss

Soil loss was monitored throughout the wet seasons of 1998 and 1999, and the data are summarised in Table 6 and Fig. 3. Under the well-distributed, low intensity rainfall of 1998, soil loss was very small from all treatments. Soil losses were much larger in 1999, as a result of the greater runoff from the 2 intense rainfall events, but losses in these conditions were much smaller from treatments providing greater residue cover and reduced soil compaction.

The treatment NTCN reduced soil loss to 1.5 t/ha, 80% less than that of the mouldboard plough (control) treatment CK. Soil loss was also relatively small (2.3 t/ha) from STCN, but without residue cover (STNN), losses were much greater (10.2 t/ha). NTCC plots lost 3.8 t/ha, but the greatest soil loss, 11.3 t/ha, occurred from NTNC plots. Soil loss from this plot was considerably greater than that from the traditional mouldboard plough treatment.

Rainfall simulator results

Rainfall simulator test results are illustrated in Fig. 4 as infiltration rate *v.* rainfall time. The means and l.s.d. analysis

Table 6. Soil loss from runoff plots, 1998 and 1999
C, Average sediment concentration (g/L)

Treatment	C (g/L)	Runoff (mm)	Suspended load[A] (g)	Bedload[A] (g)	Total soil loss (t/ha)
			1998		
NTCN	0.070	1	7	450	0
NTCC	0.240	0	10	1140	0.1
NTNC	0.580	8	543	2306	0.3
CK	0.720	3	255	1500	0.2
STCN	0.002	1	0	795	0.1
STNN	1.180	6	771	1480	0.2
			1999		
NTCN	7.407	19	15 672	569	1.5
NTCC	12.0	30	40 710	1387	3.8
NTNC	19.310	58	124 294	2627	11.3
CK	18.033	40	80 343	1918	7.3
STCN	9.0	24	24 192	1327	2.3
STNN	22.0	46	112 186	1786	10.2

[A]Plot area 112 m^2.

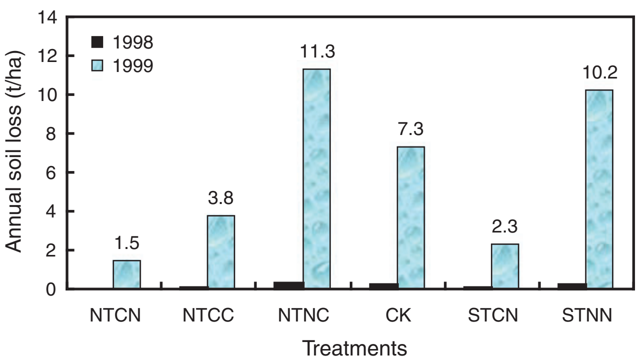

Fig. 3. Treatment effects on annual soil loss in 1998 and 1999.

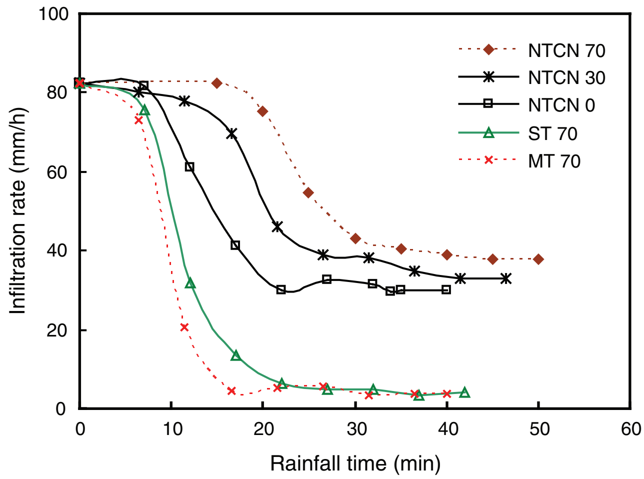

Fig. 4. Residue cover and compaction effects on infiltration rate (mm/h) under simulated rainfall. Rates of surface cover were 0 (NTCN 0), 30% (NTCN 30), and 70% (NTCN 70) on no-till and non-wheeled soil conditions. Compaction levels at 70% cover were created by wheeling the soil with a small (ST 70) and a medium (MT 70) tractor.

Table 7. Treatment effects on runoff, infiltration, time to runoff, and steady infiltration rate after 40 min of simulated rainfall (55 mm)
Within a column, means followed by the same letter are not significantly different at $P = 0.05$. s.d., Standard deviation; s.e., standard error

Treatments	Total runoff (mm)	Total infiltration (mm)	Time to runoff (min)	Steady infiltration rate (mm/h)
MT 70	48.46e	6.54a	4.8a	5.40a
ST 70	43.10d	11.90b	6.3a	5.52a
NTCN 70	13.79a	41.21e	14.7c	38.23c
NTCN 30	18.41b	36.59d	11.5b	33.43bc
NTCN 0	25.87c	29.13c	5.3a	32.25b
s.d.(total)	13.88	13.88	4.18	15.05
s.e.(total)	3.18	3.18	0.96	3.45

for time to runoff, steady infiltration rate, total runoff, and infiltration after 40 min rainfall are presented in Table 7. These data illustrate large effects of compaction and residue cover. Non-compacted soil with 70% residue cover had the least runoff, greatest infiltration rate, and was the last to produce runoff.

Rainfall simulation data from wheel compaction treatments demonstrated large and significant effects. Total runoff, total infiltration, time to runoff, and steady infiltration rate of residue-covered soil wheeled by the medium (3.6 t) tractor was 350%, 15%, 33%, and 15%, respectively, of that from non-wheeled residue-covered soil (NTCN 70), and the effects of wheeling with the small (1.8 t) tractor were only slightly less. Data from non-compacted soil illustrate the significant effects of residue protection of the soil surface. Total runoff, total infiltration, time to runoff, and steady infiltration rate of non-compacted, unprotected soil (NTCN 0) was 190%, 70%, 36%, and 85%, respectively, of that from 70% residue covered soil (NTCN 70). Values from 30% residue covered soil fell about midway between these two.

Bulk density profiles taken after the compaction treatment, illustrated in Fig. 5, suggest that the impact of the 1.8-t and 3.6-t tractors did not extend below 0.15 and 0.25 m, respectively.

Discussion

This experiment was established as part of a China/Australia cooperative program investigating tillage, residue, and wheel traffic effects in dryland farming, so results presented here can usefully be compared with those from other experiments in the same program. Some other experiments in China (Bai *et al.* 2008; Chen *et al.* 2008) were concerned with crop and soil property effects of varying tillage and wheel traffic compaction treatments. While caution is always necessary when considering non-replicated field plot experiments, in this case confidence in the general validity of the field plot runoff results can be improved by reference to the results of nearby, replicated rainfall simulator tests, as well as those from other experiments in the same program.

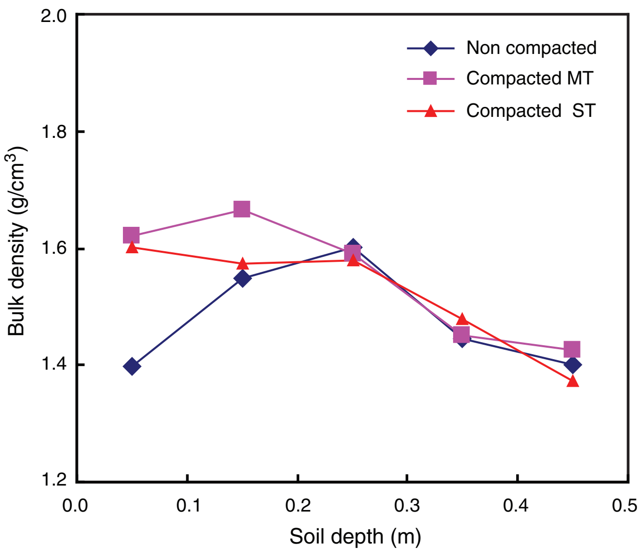

Fig. 5. Wheel compaction effects on soil bulk density for rainfall simulation tests. Surface soil volumetric water content was 24.6%, which is 73% of field capacity. Compaction levels were created by wheeling the soil with a small (ST) and a medium (MT) tractor.

Runoff plot results presented here indicate that the different tillage and compaction treatments produced large effects on water loss by surface runoff. Similar patterns can be discerned in most years, but runoff from the more intense storms of 1999 and 2001 dominate the results. Cumulative runoff values over 5 years show that, compared with the traditional plough tillage, residue-covered, non-compacted no-till was the best treatment, generating 41% less runoff. Shallow tillage alone increased runoff by 30%, and wheel compaction alone increased runoff by 72%, compared with the best treatment. Without residue protection, shallow tillage of non-compacted soil increased runoff by >100%, and but no-till with wheel compaction increased runoff by 200%.

Rainfall simulator results confirm that residue-protected, non-compacted soil produced the least runoff, and that soil compaction by farm equipment wheels increased runoff to a greater extent than removing 70% residue cover. Reporting similar, from replicated field plot experiments in Australia, Li *et al*. (2007*b*) also found that residue-covered, non-compacted zero tillage was the best treatment, with a mean annual runoff level 47% less than that of chisel-tilled, compacted soil. Tillage increased runoff by a mean value of 19% and wheel compaction increased runoff by a mean value of 56%, but residue was never totally removed from the Australian field plots treatments.

Non-replicated soil loss data follow a similar pattern to runoff. Soil losses were large in a year with intense storms (1999), but much less in the more moderate conditions of 1998. Compared with the traditional plough treatment, soil loss from residue-covered, non-compacted, non-tilled soil was 80% less. Soil loss was 68% less when this treatment was shallow-tilled, and 50% less when it was compacted. Worst soil losses occurred from non-tilled, compacted soil without residue protection (55% greater than ploughed treatment) and surface-tilled soil without residue cover or compaction (40% greater).

Within this limited dataset, soil losses appear to be directly related to runoff. Suspended load concentrations from the bare soil treatments appeared to be consistently greater than those from the treatments with residue cover, but there were no noticeable differences in the bedload/runoff ratio for any treatment. The relatively smaller suspended load soil loss from NTNC was the only exception to consistent relationships between soil loss components and runoff. This exception might be explained in terms of surface soil properties and rapid sealing but the possibility of experimental error (monitoring system problems) cannot be excluded in a non-replicated trial.

Associated work on conservation tillage effects on loess by Li *et al*. (2007*a*) demonstrated that the percentage of water-stable aggregates (>2 mm) was doubled in non-tilled (*v*. tilled) soil. The greater proportion of larger, stable aggregates in NTNC (compared with the tilled treatments) could account for this apparent inconsistency. Aggregate distribution and stability data were not recorded in this experiment, which focused on treatments expected to substantially reduce erosion. In retrospect, these data would have been useful.

It is interesting to note that over the 5 early years of this experiment, the impact of wheel compaction treatments appeared to increase, and the effect of residue appeared to decrease. In 1999, for instance, runoff from non-compacted NTCN was 38% less than compacted NTCC, but by 2001 this difference was 83%. Runoff of the residue-covered STCN was 47% less than that of unprotected STNN, but by 2001, this difference was 27%. Greater runoff from wheeled treatments over time could be a product of accumulating wheel compaction damage over the seasons, and perhaps because the initial wheel compaction treatment was applied in a dry autumn (1998).

Rainfall simulator results reported here also illustrate the importance of the compaction effects produced by the wheels of farm equipment, compared with the well-known effect of residue. Runoff from 70% residue-protected soil compacted by tractors was 2–3 times greater than runoff from unwheeled soil, but the difference between the effect of 1.8-t and 3.6-t tractors was small. This probably reflects relatively small differences in tyre pressure and surface bulk density produced by the 2 tractors. Bulk density change produced by the larger tractor was greater at 0.15 m depth, where the effects might be more persistent.

Results from this work generally correspond with those found elsewhere. Zhao *et al*. (2007), for instance, reported significant no tillage and residue cover effects (reducing runoff and soil loss by 34% and 62%, respectively) from rainfall simulation experiments in the drier western loess areas of Gansu province, and Liang (1997) showed the effectiveness of cover in protecting the loess soil in Shaanxi.

Avoiding compaction, increasing residue cover, and eliminating tillage can be achieved together in controlled traffic zero tillage systems with maximum residue retention. In the water-limited, heavily eroded environment of the Loess Plateau, these systems might be expected to improve crop yields and reduce erosion, enhancing productivity, sustainability, or both. The productivity effect has been investigated by Chen *et al*. (2008), who demonstrated a mean yield increase of 10.8%

from controlled traffic, residue-protected treatments (compared with ploughed treatments). An 8% reduction in runoff (expressed as a percentage of rainfall) can be seen when a similar comparison is made within the present dataset, suggesting that runoff reduction is an important mechanism of yield increase from controlled traffic systems. He *et al.* (2008) have also used permanent raised bed systems to reduce tillage and compaction, and to increase grain and biomass production.

Conclusions

Runoff plot experiments were used as part of a program to identify best management practices for the sloping farmland of the Loess Plateau of north China. Field runoff plot results were consistent with those of nearby replicated rainfall simulation experiments. On this basis it is reasonable to conclude that:

- Infiltration will be increased and runoff reduced by avoiding wheel-induced soil compaction, maintaining maximum residue cover, and minimising tillage in maize production systems in this environment. In most cases, soil loss appeared to be directly related to runoff.
- The positive effects of avoiding compaction, even by relatively light equipment, were greater than the effects of 70% residue cover, which were, in turn, greater than those of avoiding soil disturbance.
- Compaction effects of small-scale farm equipment on loess in China appear to be of the same order of magnitude as the effects of large-scale farm equipment on Vertosols in Australia, at least in terms of their impact on runoff.

Practical soil management systems to achieve minimum runoff and soil loss will require control of field traffic with minimal removal of crop residues and zero or minimum tillage. Permanent bed systems appear to be the most attractive way of combining these characteristics in a system appropriate to this environment.

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