Effects of different management practices on the soil–water balance and crop yield for improved dryland farming in the Chinese Loess Plateau

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Abstract

Field experiments were carried out to study the effects of different soil management practices on the water balance, precipitation use efficiency (PUE), and crop yield (i.e. winter wheat and peanut) on a loess soil near Luoyang (east edge of the Chinese Loess Plateau, Henan Province, China). Field plots were set up in 1999 including following soil management practices: subsoiling with mulch (SS), no-till with mulch (NT), reduced tillage (RT), two crops per year (i.e. winter wheat and peanut, TC), and a conventional tillage control (CT). The field plots were equipped to monitor all components of the soil–water balance except evapotranspiration, which was computed by solving the water balance equation. The results showed that although soil management had smaller influence on the magnitude of the water balance components than did precipitation variations, small influences of the applied soil management practices on water conservation during the fallow period can greatly affect winter wheat yield. SS increased consistently precipitation storage efficiency (PSE) and PUE over the 5 years compared to CT except during the wettest year. NT also had a noticeable effect on postharvest water storage during the fallow period; however, the influence on yield of NT depended on the amount of precipitation. TC lowered the winter wheat yield mainly due to the unfavorable soil moisture conditions after growing peanut in summer; however, the harvested peanut gained an extra profit for the local farmer. No matter which kind of soil management practices was adapted, PSE never exceeded 41.6%, which was primarily attributed to high evapotranspiration. From data of five consecutive agricultural years between 2000 and 2005, it could be concluded that SS resulted in the highest PSE, PUE and crop yield. TC also showed promising results considering the economic value of the second crop. NT performed slightly less as SS. CT gave intermediate results, whereas RT was the worst alternative.

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Abbreviations: CT, conventional tillage; *D*, drainage; ET, evapotranspiration; *I*, irrigation; *L_i*, lateral inflow; *L_o*, lateral outflow; NT, no tillage; OC, organic carbon; *P*, precipitation; *P_f*, precipitation during fallow period; *P_g*, precipitation during growing period; PSE, precipitation storage efficiency; *R*, runoff; RT, reduced tillage; *S*, water storage; *S_i*, water storage in the beginning of the crop year; *S_o*, water storage at the time of winter wheat sowing; *S_e*, water storage at the end of the crop year; SS, subsoiling; TC, two-crop rotation; PUE, precipitation use efficiency

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1. Introduction

Satisfactory crop production under semi-humid conditions will have a major impact on maintaining the economic viability of the major crop production area of the Chinese Loess Plateau. Limited crop available water and soil erosion are major factors constraining agricultural production in this area. Luk and Huang (1991) estimated the average erosion rate of cultivated land in the Chinese Loess Plateau at 60 tonnes ha⁻¹ year⁻¹. Inappropriate conventional farming practices were identified as the main causes for land degradation (Wang et al., 2006). These include practices such as intensive ploughing and the routine removal of crop residues, which are the primary factors leading to soil erosion. Farmers therefore need to manage their resources and adopt appropriate tillage practices without removing residues in order to effectively store and use the limited amount of precipitation for crop production and to control soil erosion.

In the Loess Plateau of China, winter wheat (*Triticum aestivum* L.) is the most commonly grown crop and occupies 44% of the cultivated area. However, wheat productivity is seriously curtailed by water shortage and nutrient deficiency as a result of severe water loss and soil erosion. Since rainwater is the sole water resource for dryland farming in the Loess Plateau, rainfed crop production thus depends strongly on both the amount and distribution of rain, and efficient capture and retention of precipitation is essential to maximize crop growth. The Chinese Loess Plateau is governed by a continental monsoon temperate climate. The rainfall often is not only inadequate but also, over 60% of annual precipitation occurs in the 3 months between July and September in the form of storms. Winter wheat (*T. aestivum* L.) in the Loess Plateau is harvested at the end of May and sown in late September. Therefore, uneven distribution of rainfall and the high evaporative demand result in an unbalance between the crop water requirements and the water supply, leading to water stress and decrease in grain yield.

The conventional tillage methods in the Chinese Loess Plateau are based on the principle that all crop residues are removed from the fields before a new crop is sown or planted in a fine, loose and smooth soil (Cai et al., 2006). The rationale behind this practice is that: weeds are well controlled and the sowing or planting operation can be done efficiently; however, the conventional farming practices are very far from being sustainable and environmentally compatible. The intensive ploughing and little use of crop residue

exacerbate soil, water and nutrient losses in conventional tillage resulting in decreases in water availability, soil fertility and eventually declining crop production. The detrimental effects of drought can be modified to some extent through management options such as conservation tillage (i.e. zero tillage or reduced tillage with mulch) and by sowing early in the season. The management of soil through conservation tillage changes affects the storage of water and evaporation, and thus has a beneficial effect on conservation of rain water and on crop production (Gao et al., 1991; Cai and Wang, 2002; Huang et al., 2003; Wang et al., 2003; Huang et al., 2005; Lenssen et al., 2007). Zero tillage (Wang et al., 2006), rotations with short-season legumes (such as peanut or maize; Cornelis et al., 2004), and stubble retention (Fabrizzi et al., 2005) are being introduced as options to combat erosion and improve yields (and income) in the Loess Plateau of China and these practices are rapidly being adopted. It is estimated that over 1 million ha of farmland is now under conservation tillage in the drylands of China (McGarry, 2005). However, the productivity in the Loess Plateau still tends to be very low (Li, 2004). Therefore, continued efforts are needed in dryland agriculture research in order to feed the rapidly growing population. At present, few studies have investigated the effects of various management practices on water conservation, water use and crop production with long term consecutive results in the Loess Plateau (Huang and Zhong, 2003). Furthermore, few works have been carried out to explore the possibility of changing the cropping system.

In order to develop guidelines for farmers and/or decision makers to adopt sustainable crop production, potential soil management practices under various conditions must be evaluated in terms of their effect on water conservation and yield, and on soil and nutrient losses. The objective of this study was therefore to evaluate four different soil management practices vis-à-vis conventional tillage in terms of water conservation, water use and crop yield, in the eastern part of the Chinese Loess Plateau. This paper reports results from the study period 2000–2005.

2. Materials and methods

2.1. Experimental design

An experimental station aimed specifically at monitoring the impact of the conversion of conventional to conservation tillage, was set up in 1999 near the city of Luoyang (Henan province; 113.0° East longitude,

Table 1
Soil characteristics at the experimental station near Luoyang (Henan Province)

Depth (m)	0–2 μm (g kg^{-1})	2–50 μm (g kg^{-1})	50–2000 μm (g kg^{-1})	CaCO_3 (g kg^{-1})	OC (g kg^{-1})	pH (KCl)
0.00–0.02	143	748	109	113	6.5	7.7
0.02–0.30	141	743	116	129	4.5	7.8
0.30–0.60	138	745	117	142	2.0	7.7
0.60–0.85	148	736	116	146	2.5	7.8
0.85–1.30	140	745	115	135	2.0	7.9

34.5° North latitude), in the eastern part of the Chinese Loess Plateau. In this region, the Quaternary loess has a thickness varying from 50 to 100 m. It has a loose and porous structure with high hydraulic conductivity. The soil in the study area was a silt loam soil and classified as Inceptisol according to Soil Taxonomy.

The experimental site was previously conventionally tilled for more than 30 years and the basic soil properties were analyzed before the setup of the experimental plots, as shown in Table 1. Since the entire experimental site was homogenous from a soil physical, soil chemical and topographical point of view, the different treatments could be laid out as single plots, which reduces the total size of the experimental site and hence the variability. Statistical analysis of the effects of different soil management practices can therefore be done using replicated samples from single plots.

Within the experimental site, two series of plots were laid out; one series was kept under natural rainfall, whereas the other series was used specially for rainfall simulation tests (see Schiettecatte et al., 2005). In the current study, we will consider the plots which were under natural rainfall conditions only. Per tillage practice, one 30 m $\times$ 3 m plot was established. The slope degree of the plots, which were located along the same contour line and 1 m apart, was 9%. Each plot was equipped with three 2-m long access tubes for water-content readings, i.e. at the upslope, midslope and downslope part of the plot, which enabled monitoring

soil–water content at selected depths. All plots further contained a set of 8 tensiometers installed in two rows at a inter and intra row distance of 10 cm at depths of 10, 20, 30, 40, 50, 70, 90 and 120 cm. One plot was equipped with 4 additional sets of 8 tensiometers to determine possible lateral subsurface flow. At the downslope bottom of each plot, a flume with automatic discharge gauge and a collector drum were installed.

Six replicate cores from each plot were taken randomly for organic carbon (OC) analyses using Walkley and Black (1934) method and for soil bulk density in early of August, 2005 for each plot (Table 2). Changes in frequency and intensity of tillage practices altered the bulk density in the 0–40 cm layer. NT had the highest bulk density, followed by SS, but the difference was not statistically significant compared to CT. However, the influence of tillage on bulk density in the layer 40–60 cm was not as pronounced as in the surface layer. The RT, CT and TC had similar bulk density throughout the soil profile. The SS and NT increased soil OC, but again did not reach statistical significance compared to CT. There was no difference of OC between the other treatments. Tillage had negligible effects on the OC in the 30–60 cm soil layer.

During the period 1970–1999, the minimum temperature was -23.5°C and the maximum 43.7°C . The annual potential evaporation was estimated to vary between 1262 and 1852 mm. The average air humidity was 65%. The annual precipitation in the

Table 2
Bulk density and organic carbon under different soil management practices in 2005 ($n = 6$)

Depth (cm)	RT	NT	TC	SS	CT
Bulk density (Mg m^{-3})					
0–20	1.355 (0.089) ^a	1.531 (0.024)	1.358 (0.048)	1.467 (0.039)	1.359 (0.061)
20–40	1.364 (0.071)	1.503 (0.032)	1.369 (0.053)	1.445 (0.027)	1.367 (0.062)
40–60	1.467 (0.038)	1.472 (0.031)	1.483 (0.041)	1.489 (0.041)	1.494 (0.031)
OC (g kg^{-1})					
0–10	7.622 (1.031)	9.200 (0.438)	7.660 (0.215)	9.440 (0.790)	7.862 (0.604)
10–20	6.449 (0.588)	6.382 (0.493)	6.596 (0.307)	7.051 (0.490)	7.054 (0.250)
20–30	5.078 (1.021)	5.700 (0.129)	5.396 (0.143)	5.625 (0.551)	5.494 (0.893)
30–60	2.918 (0.563)	3.011 (0.420)	3.002 (0.715)	2.846 (0.665)	3.104 (0.512)

^a Values between brackets indicate standard error.

Table 3

Monthly precipitation, precipitation during fallow period (P_f), precipitation during growing period (P_g) and total precipitation during the growing year in Songzhuang (Henan Province)

Growing year	Precipitation (mm)												P_f	P_g	Total
	June	July	August	September	October	November	December	January	February	March	April	May			
2000–2001	52	156	215	164	77	23	6	34	18	3	21	6	548	196	744
2001–2002	98	239	23	42	52	3	30	6	2	40	37	170	365	364	729
2002–2003	74	70	56	92	50	1	25	7	22	30	28	66	292	283	575
2003–2004	143	236	240	210	123	45	15	2	31	8	11	118	830	306	1136
2004–2005	166	197	109	141	28	23	19	0	5	0	7	29	624	95	719
1970–1999	61	133	99	77	41	23	7	6	11	28	39	50	369	205	575

area varied from 550 to 864 mm. Rainfall is, however, not evenly distributed throughout the year. High rain intensities and frequent rainstorms typically occur in summer (June–September), whereas in general, the winter months (December–February) are the driest. Table 3 shows the monthly precipitation data from the Menjing County Metrological station which is 5 km away from the research base during the study period 2000–2005 and the average monthly values during the period 1970–1999. The total precipitation per agricultural year showed a great variability in the Chinese Loess Plateau from 2000 to 2005. The total precipitation in the 2003–2004 agricultural year was much higher than average and amounted to 1136 mm, which was the highest record over the last 40 years. The lowest total precipitation, 575 mm, was observed in 2002–2003, which however was equal to the average over the period 1970–1999. The distribution of monthly precipitation was also uneven. Monthly precipitation was highest in July 2001 (239 mm), but unexpectedly low in the following months (with 23 mm in August 2001 and 42 mm in September 2001).

2.2. Tillage practices

Five tillage practices were applied: conventional tillage (CT), no till (NT), reduced tillage (RT), subsoiling (SS) and a two-crop rotation per year (TC). On CT, RT, NT and SS, winter wheat (*T. aestivum* L.) was monocultivated, whereas on TC, peanut (*Arachis hypogaea* L.) was grown prior to sowing of winter wheat.

The five practices can be described as follows.

Conventional tillage (CT). Ten to fifteen centimetres long stubble remains on the field after harvest (25 May–1 June). Straw and ears are removed from the plot at harvest. In the first week of July, the soil is ploughed and turned to a 20 cm depth. Around 1 October, just before sowing, the soil is ploughed again and turned to a 20 cm

depth, while at the same time the fertilizer is incorporated, followed by harrowing (seed bed preparation, 5–8 cm). Sowing of winter wheat is done around 5 October.

Reduced tillage (RT). Ten to fifteen centimetres long stubble remains on the field after harvest (25 May–1 June). Straw and ears are removed from the plot at harvest. Around 15 July, deep ploughing (25–30 cm) combined with harrowing (5–8 cm) is done. Winter wheat is sown around 5 October. This practice thus involves only one ploughing operation instead of two as under CT.

No tillage (NT). Thirty centimetres tall stubble remains on the field after harvest (25 May–1 June) and straw is returned to the field after threshing. Between 25 September and 5 October, direct sowing with fertilizer application is done by hand.

Subsoiling (SS). Twenty-five to thirty-five centimetres tall stubble remains on the field after harvest (25 May–1 June). Around 1 July, subsoiling is performed till 30–35 cm depth at 60 cm intervals. Between 25 September and 5 October, direct sowing with fertilizer application is done by hand.

Two-crop rotation (TC). Ten to fifteen centimetres long stubble remains on the field after harvest of winter wheat (25 May–1 June). Peanut is directly sown at the beginning of June and each pit is supplied with a limited amount of water to ensure its germination. No fertilization is applied. After harvest of peanuts (23 September), the soil is ploughed to 20 cm depth, while at the same time the fertilizer is incorporated, followed by harrowing (seed bed preparation, 5–8 cm depth). Sowing of winter wheat is done around 5 October.

Yearly fertilizer application rates for each plot were 150 kg N ha⁻¹ and 90 kg P₂O₅ ha⁻¹. Protection against insects (mainly budworm) in the cultivars was applied in the elongation or anthesis stages of winter wheat by applying 1125 ml omethoate (C₅H₁₂NO₄PS) ha⁻¹ at a concentration of 35 µg L⁻¹.

2.3. Soil water balance

The water balance in the rootzone over a given period Δt is given by

$$\Delta S = P + I - ET - R - D + L_i - L_o \quad (1)$$

where ΔS is the change in soil–water storage in the rootzone (i.e. between the soil surface and maximum rooting depth), P the precipitation, I the applied irrigation water, ET the evapotranspiration (or evaporation in case of a bare soil), R the surface runoff, D the capillary rise (if negative) or drainage (if positive) at the maximum rooting depth, and L_i and L_o are the lateral inflow and outflow, respectively. All components are expressed in units of length (mm).

There is no irrigation in the dryland of the Loess Plateau. However, on the TC plot, each pit was supplied with a limited amount of water to ensure germination of peanuts. To determine lateral inflow and outflow, one plot (the CT plot) was equipped with five sets of tensiometers installed at downslope intervals of 5 m. The computed equipotential lines on CT plot and on the rainfall simulation plots showed, however, that L_i and L_o were negligibly small during the complete measuring campaign.

Changes in soil–water storage were quantified from soil–water content profiles which were obtained using a Trime[®] Tube Probe (Imko, Germany) which is a modified TDR probe especially designed for water content profiling. It was calibrated both in the laboratory and on the field prior to the water balance experiment. Soil–water content was recorded at regular times at depths of 10, 20, 30, 40, 50, 70, 90, 120 and 160 cm. The tube probe consists of a cylindrical PVC body which has four spring-mounted aluminium plates as TDR wave guides on opposite sides. The two plates on each side have a total length of 18 cm, which corresponds to the length of the sphere of influence of the probe. Experiments in a loamy sand (with clay content of 5.7%, silt content of 8.3%, sand content of 86.0%, organic carbon content of 2.0% and a bulk density of 1.5 Mg m^{-3}) have shown that the diameter of the sphere of influence is 11 to 15 cm depending on the water content. It was further shown that the influence of temperature was negligible. Per depth and access tube, water content was measured in three replicates by rotating the tube probe over an angle of 60° . Since per plot, three access tubes were installed, nine water content values were recorded per depth and time, and the arithmetic mean was taken.

Precipitation was measured by a tipping-bucket rain gauge connected to a nearby weather station. Runoff

was monitored automatically using RBC flumes with pressure transducers connected to a datalogger (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands). Total runoff was also determined from the total volume of water collected in the drums after each rain event. Drainage and capillary rise were determined at a depth of 105 cm from tensiometer readings and soil–water content measurements at 90 and 120 cm using the Buckingham–Darcy equation:

$$D = q \Delta t = -K(\bar{\theta}) \frac{d\bar{H}}{dz} \Delta t \quad (2)$$

where $K(\theta)$ is the hydraulic conductivity corresponding to the (volumetric) soil water content θ , dH/dz the hydraulic-head gradient, and the overbars denote time-averaged values. The hydraulic conductivity was computed using the Mualem–van Genuchten equation (Mualem, 1976; Van Genuchten, 1980). Saturated hydraulic conductivity was measured in the field with a tension infiltrometer (Soil Measurement Systems, Tucson, AR, USA) using Wooding's equation in combination with Gardner's equation. The Van Genuchten (1980) parameters were obtained by non-linear regression to water retention data. Soil–water retention curves were determined on 100-cm^3 undisturbed soil cores using tension tables (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) and pressure chambers (Soilmoisture Equipment, Santa Barbara, CA, USA). The computed hydraulic conductivity values were cross-checked with hydraulic conductivity data obtained from the plane-of-zero-flux method (Maesschalck et al., 1984), which allows calculating the drainage component D as the difference in soil–water storage between the plane of zero flux (if present) and a given depth below for those cases in which the actual rooting depth does not exceed the plane of zero flux. The presence of a zero flux plane could be deduced from monitoring hydraulic potential with tensiometers installed at depths of 10, 20, 30, 40, 50, 70, 90, and 120 cm. All tensiometers were connected to mercury manometers which were shaded against direct sunlight. The results shown by Cornelis et al. (2004) indicated that at the experimental site the drainage component at 105 cm was negligible. Therefore, the soil–water balance equation could be simplified as

$$\Delta S = P - ET - R \quad (3)$$

where soil–water storage S was calculated between the soil surface and a depth of 160 cm using the trapeze rule, allowing to compute the evolution of evapotranspiration with time for the different treatments.

2.4. Efficiency of soil management practice in terms of water conservation

The soil management regime affects both the storage of precipitation water and its use by the crops. Since precipitation is the sole water supply in the rainfed area of the Loess Plateau, we expressed the efficiency of the soil management practice in terms of precipitation storage efficiency (PSE) and precipitation use efficiency (PUE). PSE (Leng and Han, 1996; Tanaka and Anderson, 1997) was calculated as the change in soil water storage within the 0–160 cm depth soil profile during the fallow period divided by precipitation during the fallow period. Note that in case of the two-crop system, the ‘fallow’ period coincides with the peanut growing period.

PUE (Le Houerou, 1984) was determined as the ratio of crop production (grain yield, kg ha^{-1}) to effective precipitation (mm) during the whole crop growing season (including the fallow period and the winter wheat growing period), or yield (kg) per cubic metre of effective precipitation. Effective precipitation is the amount of rainfall that can be used by the plant and

equals total precipitation P less runoff R (Maesschalck et al., 1984). For each plot, yield was determined in three replicates, and is the dry mass of nuts and seeds of peanut and winter wheat, respectively, harvested from $1.2 \text{ m} \times 3 \text{ m}$ large subplots.

3. Results

3.1. Rainfall distribution

Table 3 shows for the five agricultural years (i.e. from 1 June till 31 May) under study the precipitation during the growing period of winter wheat, P_g (mm), i.e. from sowing time around 1 October to harvest time around 1 June of the next year, as well as during the fallow period, P_f (mm), which corresponds to the rest of the agricultural year. As can be observed, both P_g and P_f showed a large variation. For instance, P_f of 2002–2003 was very low (292 mm) compared to the exceptional high values of P_f in the consecutive year (830 mm). P_f was lower than average (for the period 1970–1999) in 2002–2003 only. On the other hand, P_g of 2001–2002 was more than three times (364 mm) that of 2004–2005

Table 4

Components of the soil–water balance for the different tillage practices for the five agricultural years under study ($n = 3$)

Agricultural year	Tillage practice	S_i (mm)	S_o (mm)	S_e (mm)	Fallow period			Growing period		
					ΔS (mm)	R (mm)	ET (mm)	ΔS (mm)	R (mm)	ET (mm)
2000–2001	RT	262	314	241	52	7	429	–72	0	328
	NT	268	415	245	147	4	382	–170	0	380
	TC	264	320	254	56	4	479	–66	0	270
	SS	262	415	251	153	5	384	–164	0	366
	CT	262	378	240	126	8	384	–139	0	364
2001–2002	RT	241	317	291	76	4	336	–26	0	341
	NT	245	398	292	152	1	276	–106	0	407
	TC	254	276	283	22	3	388	7	0	311
	SS	251	394	279	143	1	278	–115	0	423
	CT	240	362	276	123	6	283	–86	0	405
2002–2003	RT	291	312	279	21	0	271	–32	0	316
	NT	292	352	295	60	0	232	–57	0	341
	TC	283	282	273	0	0	292	–9	0	293
	SS	279	337	284	58	0	234	–53	0	337
	CT	276	312	271	36	0	256	–41	0	324
2003–2004	RT	279	547	294	268	11	551	–253	0	559
	NT	295	575	310	281	2	547	–266	0	572
	TC	273	576	303	303	3	524	–274	0	580
	SS	284	574	297	291	1	539	–277	0	584
	CT	271	572	289	301	14	515	–282	0	589
2004–2005	RT	294	446	233	152	17	455	–214	0	309
	NT	310	485	236	175	2	447	–249	0	344
	TC	303	418	247	116	13	495	–171	0	266
	SS	297	482	243	185	2	437	–239	0	334
	CT	289	433	235	143	16	465	–198	0	293

(95 mm) which suffered from a long dry spell lasting from January to the end of May. The years 2000–2001 and 2004–2005 had a P_g lower than average.

3.2. Runoff, change in soil–water storage and evapotranspiration

The different components of the field soil–water balance for the five soil management practices within the five agricultural years under study are given in Table 4. The results indicate that NT and SS had a beneficial effect on runoff reduction from the second year on. Application of RT had a negative impact on runoff reduction compared to conventional tillage.

Fig. 1 shows for the five tillage practices the cumulative change in soil–water storage over a depth of 160 cm as a function of time for the five agricultural years under study. The water storage is expressed as cumulative water storage which was set to zero on the first day of each growing year). Since each plot received the same amount of precipitation, the evolution in cumulative S reflects the difference in R and ET . In general, conservation tillage practices (NT and SS) have a noticeable effect on S , but much less than did variations in P . At the end of the fallow period of each growing season—the fallow period lasts from day 1 to around day 125—the highest cumulative S was observed in NT and SS, followed by CT, except in years 2003–2004, in which TC

Fig. 1. Evolution of cumulative soil–water storage S with time for the different tillage practices for the five agricultural years under study. Day 1 corresponds to 1 June, which is the first day of the fallow period (and of the winter wheat growing season). Winter wheat is sown at around 3 October day 125, except in year 2003–2004, in which winter wheat sowing was postponed with 20 days.

and CT showed the highest cumulative S (respectively, 303 and 301 mm) (see also Table 3). This can be explained by the exceptional high precipitation during the fallow period P_f of 2003–2004. Whereas S was still highest in SS and NT around day 40, it became highest in TC and CT towards the end of the fallow period. This is due to ploughing before seeding winter wheat in case of TC and CT, which improved the infiltration of the rainwater. At the end of the fallow period, unexpected consecutive rainy days with low rainfall intensities were observed, which also reduced the risk of runoff. In general, the RT practice showed a somewhat lower cumulative S compared to CT due to the soil surface being bare during the fallow time. The lowest cumulative S in the TC rotation for all years except 2003–2004, was due to the extra water consumption by peanut ().

During the growing period of winter wheat (from around day 125 to 365), a reversed picture was found. Higher reductions in S were observed for the conservation tillage practices NT and SS compared to CT, except in 2003–2004, in which CT showed the highest S reduction (–282 mm). In all years, S at the end of the growing season (S_e) was similar irrespective of the adapted tillage practice and rotation system. The difference in S at the end of the growing period between the treatments ranged from 13 mm in 2000–2001 to 24 mm in 2002–2003. However, the variation in S at the end of the growing period among different years was high. This can be mainly attributed to the precipitation in the late winter wheat season stage, which was exceptionally low in 2004–2005 and high in 2003–2004. The difference between S at the beginning of the winter wheat growing season (day 125) and S at the beginning of the fallow time (day 1) ranged from 0 mm for CT in 2002–2003 to 303 mm for SS in 2003–2004. For all treatments the highest S reductions were observed in 2004–2005. This was due to the extremely low precipitation during the growing period ($P_g = 95$ mm), with ΔS for the complete winter wheat growing season (days 0–365) ranging from –55 mm for TC to –74 mm for NT. The lowest cumulative reduction in water storage at the end of growing season was observed for all tillage practices in 2001–2002, ranging between –28 mm for SS and –50 mm for RT. This can be mainly explained by the high precipitation during the 2001–2002 growing period (364 mm). Conventional tillage resulted in all years in an intermediate cumulative reduction in S during the growing period of winter wheat. The total soil–water storage during its fallow period was 13.8% greater with SS and 11.7% greater with NT treatment than with CT. In all but the years with a relative wet fallow period, i.e.

2003–2004 and 2004–2005, RT was much less efficient in storing water compared to CT.

The evolution of cumulative evapotranspiration with time is plotted in Fig. 2. At the end of the fallow period, the loss of water by evaporation was lowest in SS and NT, followed by CT and RT, except in 2003–2004 which had an exceptional wet fallow period. Due to transpiration of peanuts, ET in TC was for all but the years 2003–2004 highest. For all practices, larger variations were observed between the years. Total ET during the fallow period ranged from 232 mm for SS in 2002–2003 to 551 mm for RT in 2003–2004, or when calculated on a daily basis, ET rates varied between, respectively, 1.7 and 4.4 mm day^{–1}. Due to the exceptional high rains in 2003–2004, those rates could be close to potential because of probably optimal soil water conditions.

When considering ET during the winter wheat growing period, highest increases (steepest curves), indicating highest root water uptake and hence crop activity, were observed for SS and NT, followed by CT, except again for 2003–2004. This was most manifest in 2002–2003 which received the lowest amounts of rainfall during the fallow period. Also here, yearly variations are most apparent, varying from around 571 mm for SS and NT in 2002–2003 to 1122 mm for SS in 2003–2004, or in ET rates between, respectively, 1.6 and 3.1 mm day^{–1}.

3.3. Effect of tillage on water conservation and precipitation use efficiency

The effectiveness of the tillage practices in storing rainwater relative to the amount of rainfall during the fallow period, expressed in terms of PSE, in yield and use of effective rainfall, expressed as PUE, is summarised in Table 5 for the five agricultural years under study. Tillage practices significantly influenced PSE. It was greatest for SS and NT, followed by CT, except in 2003–2004 in which precipitation was extremely high (830 mm). In 2004–2005, which also had a wet fallow period (624 mm), the differences between NT and CT were minimal, but SS showed a somewhat higher PSE value. The differences between SS and NT on the one hand, and CT on the other were most pronounced in 2001–2002 and 2002–2003, which suffered from a relatively dry fallow period with only 365 mm and 292 mm of rain. Overall, less than 42% of P_f was stored in the soil. Given the relatively low runoff amounts, this means that more than 58% of P_f was lost by evaporation.

In general, winter wheat yields were highest with SS, except in 2004–2005 where SS was second best. CT

Fig. 2. Same as Fig. 1, but with ET as a function of time.

showed the second highest winter wheat yield in 2001–2002 and 2003–2004. In 2000–2001 and 2002–2003, NT resulted in the second highest wheat yields. Significant differences in winter wheat yield between CT on the hand and SS or NT on the other hand were, however, only observed in 2000–2001 and 2002–2003. The agricultural years 2000–2001 had a ‘rich’ fallow period in terms of precipitation ($P_f = 624$ mm), but a relatively dry winter wheat growing period ($P_g = 177$ mm), whereas 2002–2003 had a relatively dry fallow period ($P_f = 292$ mm), followed by a ‘normal’ winter wheat growing period ($P_g = 284$ mm). Yield of winter wheat with RT was lower than with CT in 2001–2002, 2003–2004 and 2004–2005, although

never significant. The rotation of winter wheat with peanut, TC, resulted in lowest winter wheat yields for all the years. This was mainly attributed to the much higher rootzone depletion at the beginning of the winter wheat growing period because of peanut water consumption. However, when considering the total yields of both crops, the TC system resulted in highest values, except in 2001–2002 and 2002–2003. Both years experienced a relatively dry ‘fallow’ period, which in case of TC coincided with the growing period of peanut. In 2001–2002 and 2002–2003, the yield of winter wheat was only, respectively, 68.2 and 54.9% of the winter wheat yield with SS. In the three other years, winter wheat yield of TC ranged from 79.4 to 89.7% compared to that of SS.

Table 5

PSE, yield and PUE for the different tillage practices for the five agricultural years under study

Agricultural year	Tillage practice	PSE (%)	Yield (kg ha ⁻¹)	PUE (kg m ⁻³)
2000–2001	RT	9.5	4047 bc (129)	0.54
	NT	26.8	4107 bc (62)	0.54
	TC	10.2	1191 (84)	
			3662 a (53)	0.49
			4853 x (127)	0.65
	SS	27.9	4246 c (142)	0.57
CT	23.0	3922 ab (116)	0.53	
2001–2002	RT	20.8	4473 b (235)	0.62
	NT	41.6	4897 bc (233)	0.67
	TC	6.0	1044 (102)	
			3737 a (473)	0.51
			4781 x (575)	0.66
	SS	39.2	5478 c (366)	0.75
CT	33.7	5169 bc (472)	0.71	
2002–2003	RT	7.2	4347 bc (312)	0.75
	NT	20.5	4778 cd (168)	0.83
	TC	0	1414 (222)	
			2667 a (73)	0.46
			4081 x (295)	0.71
	SS	19.9	4857 d (88)	0.84
CT	12.3	4019 b (142)	0.70	
2003–2004	RT	32.3	4109 ab (100)	0.36
	NT	33.9	4270 ab (190)	0.38
	TC	36.5	2197 (163)	
			4088 a (46)	0.36
			6285 x (209)	0.55
	SS	35.1	4559 b (268)	0.40
CT	36.3	4347 ab (145)	0.38	
2004–2005	RT	24.4	4574 ab (215)	0.64
	NT	28.0	5292 c (243)	0.74
	TC	18.6	1228 (159)	
			4167 a (327)	0.58
			5395 x (486)	0.75
	SS	29.6	5245 c (164)	0.73
CT	22.7	4801 bc (77)	0.67	

Values between brackets indicate standard error. Average values in the same column followed by the same letter are not significantly different according to Student–Newman–Keuls test ($\alpha = 0.05$); in case of TC, the first line corresponds to peanut yield and the second to winter wheat yield. Values in italics indicate total yield, being the sum of peanut yield and winter wheat yield. In case of TC the values in italics are based on total yield of winter wheat and peanuts. The other values refer to winter wheat yield only.

When comparing the different years, highest winter wheat yields were observed in 2001–2002 and in 2004–2005. Both received relatively high amounts of precipitation during the fallow period (respectively, 548 and 624 mm), and low amounts in the winter wheat growing period (respectively, 196 and 95 mm). It is remarkable that the winter wheat yields in 2003–2004, with its abundant rain in the fallow period, were rather low. Because of the almost saturated water conditions at the end of the fallow period, the sowing time of winter wheat had to be postponed to 28 October, which was 20 days later than normal. The effect of time of sowing on yield has been recognized by Wang (1994) who found

that for each ten days delay in sowing, grain yield was reduced by 150–200 kg ha⁻¹. In addition, soil crusting caused by the heavy rain immediately after sowing severely affected the germination of winter wheat.

With respect to the efficiency in which the effective precipitation was used (PUE), a similar trend as for the winter wheat yield was observed. SS showed highest values, except in the wet 2003–2004, in which NT was best. The differences with CT were significant in all years except 2001–2002 and 2003–2004, which both showed high *P* during the winter wheat growing period. The differences between CT and RT were not significant. Again, TC showed the lowest results for

all years when considering winter wheat yield alone. When, however, accounting for the total yield, including that of peanut, highest values were found for TC except for 2001–2002 and 2002–2003, with their dry ‘fallow’ period. Overall, PUE was by far lowest in the wettest years 2003–2004, and highest in the driest years 2002–2003.

4. Discussion

There is evidence that in the eastern part of the Loess Plateau, a wheat crop needs about 480 mm of water for maximum yield (Wang, 1994). Although the mean annual precipitation is around 580 mm in the Chinese Loess Plateau and exceeds this value, it is mainly concentrated in July, August and September, while the average precipitation in the growing period of winter wheat is 205 mm only. Since the low and variable precipitation during the winter wheat growing period considerably limits rainfed crop yields, increasing water storage within the soil profile is crucial to increase plant available water.

However, due to the combination of low relative humidity, high temperatures, and an uneven distribution of precipitation during the rainy season, soils in the Loess Plateau are generally not filled to field capacity during the fallow period. This was also not the case during our study period, in which matric potentials remained always lower than -34 kPa. More than 60% of the precipitation during the fallow period was lost through evaporation, which indicates the importance of storing water at sowing to supplement the precipitation during the winter wheat growing period for increasing crop production.

Even though the effect of tillage practices on water storage was much lower than did precipitation variations, small influences of the applied tillage practice on water conservation during the fallow period could greatly affect winter wheat yield. Lafond et al. (1996) demonstrated that the improvement in grain yield with conservation practices is directly related to the additional amount of water that is conserved by the tillage practice. The purpose of ploughing the soil in the CT and RT by local farmers after harvesting winter wheat, i.e. in the early stage of the rainy season, is to increase the retention of rainwater. Although it can result in an increased infiltration of water, it will enhance the loss of water by evaporation compared with a residue-covered surface or an undisturbed soil. Since in the CT and RT practice, the soil is also left bare, it further results in higher runoff.

The conservation tillage practices SS and NT had a noticeable effect on postharvest water storage during the fallow period, except during the wettest years. We found that SS was the best practice in terms of water conservation, crop production and effective use of rain water. It resulted in the highest increase in water storage during the fallow period, highest winter wheat yields and highest PUE. Compared with CT, SS resulted, over the 5 years under study, in a PSE, yield and PUE which were, respectively, 16.6, 9.6 and 10.1% higher. This can be explained by the standing stubble and residue mulching (Huang et al., 2005). It not only intercepts significant amounts of precipitation, but also reduces runoff by slowing down the water flowing over the surface by overland flow and protects the soil from direct raindrop impact. It further protects the surface from direct radiation and reduces windspeed, hence reducing evaporation from the soil surface (Hillel, 1998). SS is thus effective to more efficiently save precipitation for crop production. Other field studies in the Loess Plateau also demonstrated that SS had a higher water content during both the wheat growing season and the fallow period, and showed higher yields of winter wheat compared to CT (Liang et al., 2002; Wang et al., 2003). This is also in agreement with results found in diverse regions, including Victoria Australia (Cantero-Martinez et al., 1999), Nebraska USA (Lyon et al., 1998), Texas USA (Baumhardt and Jones, 2002), the northern Great Plain in USA (Lenssen et al., 2007) and on a semi-arid Kenya (Gicheru et al., 2004).

Although slightly less effective than SS, NT also had a pronounced effect on conservation of water. Over the 5 years under study, its PSE, yield and PUE was, respectively, 12.0, 4.9 and 5.8% larger than for CT. Our results on yield under NT are in agreement with Halvorson et al. (2000) who reported differences in wheat yield between CT and NT in specific conditions: in dry years NT was more productive than CT, whilst the reverse was true when rainfall was greater. Even though NT had a comparable effect as SS on water conservation, its yield response was not as clear as SS except in the last year. The somewhat better results that were observed with SS can be attributed to a slightly better infiltration after subsoiling and the breaking up of the continuity of flow paths in the soil (Hillel, 1998). The soil compaction in NT adversely affects soil properties, resulting in a relatively lower PUE compared to SS (Lipiec and Hatano, 2003). However, NT had the highest yield in the last year which could be accounted for by the improved soil physical and chemical conditions after 6 years of consecutive NT practice. According to Franzluebbers (2002), sufficient biological activity will be established, a stable soil

structure will be formed and water infiltration will increase in soils for many years of continuous NT practices. This conclusion was corroborated by the research of [Fabrizzi et al. \(2005\)](#), who found that after 5 years of continuous NT practices, bulk density tended to stabilize. The observed compaction only lasts for a few years. As a consequence, we could expect that continuous NT practice would result in a higher yield response in the coming years.

On the other hand, RT resulted overall in lower PSE, yield and PUE values, being, respectively, 27.4, 3.2 and 2.3% lower than CT. Deep ploughing the soil and harrowing it at around day 45 seemed to increase evaporation in the drier years ([Fig. 2](#)), compared to rather superficially ploughing without harrowing at around day 30 as in CT. It also resulted in higher runoff values during the wetter years, which could be attributed to a lower aggregate stability due to harrowing.

One of the main purposes of fallowing in the Loess Plateau is to increase the storage of water for a subsequent crop. However, no matter which kind of tillage practices was adapted, PSE never exceeded 42%, the rest being slightly lost by runoff, but primarily by evaporation. This indicates that traditional fallow farming utilizes precipitation water inefficient. Cropping systems should be adjusted to precipitation patterns for better soil water use. More intensive cropping with fewer fallow appears to be possible on the drylands of the Loess Plateau. The adoption of peanuts e.g. provides a continuum of crop growth, from the commencement of the rainy season until most of the available moisture is depleted due to crop transpiration. The additional yield of peanut offers a considerable additional income to the local farmer. Our results show that farmers in the Chinese Loess Plateau can optionally include peanut in an annual dryland cropping rotation, in particular when a relatively wet fallow period is predicted. In case of drier fallow periods, we found lower total yields of winter wheat and peanut, compared to the SS and NT. Furthermore, the frequently prevailing drought stress at the sowing time of peanut can severely affect peanut germination and plant establishment, and may cause serious reductions in peanut growth and yield. In order to assure the seed germination, limited water was supplied in our study for TC. As compared to CT, yield and PUE of winter wheat was 17.7 and 19.6% lower for TC. However, when considering the total yield of both winter wheat and peanut, yield and PUE with TC were, respectively, 14.1 and 10.9% higher than with CT. PSE with TC was 44.1% lower than with CT, since a large part of the rainwater was taken up by peanut.

The effects of NT and SS practices were most pronounced during the drier years, although even then, the differences with conventional tillage are not that substantial. However, from a broader and economic viewpoint, conservation tillage has the additional advantage that it needs fewer farming operations, hence reducing the total cost of crop production. It will further reduce the risk on crop failure for years drier than those under study. For other benefits of conservation tillage compared to conventional tillage, the reader is referred to, e.g. [Holland \(2004\)](#).

5. Conclusions

Water is the most limiting factor for crop production in dryland farming in the Chinese Loess Plateau. This study showed that, from a water-conserving perspective, conservation tillage (SS and NT) could be an ecologically sound approach in the drylands of the Loess Plateau. SS practices significantly increased the precipitation storage efficiency and the water use efficiency. Over our study period (2000–2005) SS was the most suitable conservation tillage. Although in general, NT had a less pronounced positive effect on yield, 6 years consecutive NT practice resulted in the highest yield in the last year, which may be an indication that in the longer term, it may be as good an alternative as SS. The two crops system decreased the yield of winter wheat; however, it still showed promising results considering the economic income and the efficient use of rain water. CT gave intermediate results, whereas RT was the worst alternative.

Although tillage practices could influence the magnitude of the water balance components to some extent, a low PSE was observed under all soil management practices. The work underlying this paper showed that cropping systems could be adjusted to precipitation patterns for better soil water use. Hence, a further task for the future is to determine the ideal cropping system at which desirable economic benefits can be maintained. Use of a fallow crop as peanut might be a good choice because of its high economic value and the benefit of legumes in the maintenance of soil organic N ([Van Kessel and Christopher, 2000](#)).

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