Soil management effects on runoff and soil loss from field rainfall simulation

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ABSTRACT

Soil erosion from agricultural lands is a serious problem on the Chinese Loess Plateau. In total, 28 field rainfall simulations were carried on loamy soils under different management practices, namely conventional tillage (CT), no till with mulch (NTM), reduced tillage (RT), subsoiling with mulch (SSM), subsoiling without mulch (SS), and two crops per year (TC), to investigate (i) the effects of different soil management practices on runoff and sediment (ii) the temporal change of runoff discharge rate and sediment concentration under different initial soil moisture conditions (i.e. initially dry soil surface, and wet surface) and rainfall intensity (85 and 170 mm h\textsuperscript{-1}) in the Chinese Loess Plateau. NTM was the best alternative in terms of soil erosion control. SSM reduced soil loss by more than 85% in 2002 compared to CT, and its effects on runoff reduction became more pronounced after 4 years consecutive implementation. SS also reduced considerably the runoff and soil loss, but not as pronounced as SSM. TC resulted in a significant runoff reduction (more than 92%) compared to CT in the initial 'dry' soil, but this effect was strongly reduced in the initial 'wet' soil. Temporal change of runoff discharge rate and sediment concentration showed a large variation between the different treatments. In conclusion, NTM is the most favorable tillage practices in terms of soil and water conservation in the Chinese Loess Plateau. SSM can be regarded as a promising measure to improve soil and water conservation considering its beneficial effect on winter wheat yield.

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1. Introduction

Erosion is one of the main problems that the agricultural sector on the Chinese Loess Plateau is confronted with. The total eroded area of the Loess Plateau is 454,000 km\textsuperscript{2}, of which 337,000 km\textsuperscript{2} is affected by water erosion (YRCC, 2002). The average erosion rate of cultivated land on the Loess Plateau is estimated at 60 ton ha\textsuperscript{-1} year\textsuperscript{-1} (Luk, 1996).

The conventional tillage methods in the Chinese Loess Plateau use moldboard plows and harrows pulled by animals or tractors and 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 of the farmer is that the advantages are clear: weeds are well controlled and the sowing and planting operation can be done effectively. However, the conventional farming practices are very far from being sustainable and environmentally compatible from a soil and water conservation perspective because of the uncovered soil surface during July, August and September, which are characterized by the highest rainfall intensities (more than half of the total annual rainfall occurs during this period), and because of the conventional up and down the slope ploughing (Jin et al., 2003; Zhang et al., 2007).

As a consequence, conventionally tilled winter wheat in the Loess Plateau is now gradually shifting towards conservation tillage because of economic and soil and water quality benefits associated with conservational tillage production (Wei et al., 2000). Several researchers have already indicated that conservation tillage practices reduce soil and nutrient losses considerably (e.g. Mostaghimi et al., 1988; Kisic et al., 2002; Puustinen et al., 2005).

Maintaining a crop residue cover and standing stubble after harvest in conservational tillage are two important factors controlling the intensity and the frequency of overland flow and surface wash erosion. Both runoff and sediment loss decrease exponentially as the percentage of vegetation cover increases (Kosmas et al., 1997). Rainfall
simulation experiments conducted by Mostaghimi et al. (1988) on a silt loam, showed a strong decrease in runoff and soil loss as the residue level of winter rye increased, regardless of the tillage system (no till and conventional till). Surface residues that cover only 20% of the soil surface can already substantially reduce soil loss compared with a bare surface (Johnson and Moldenhauer, 1979), while above 60% of coverage, the bare areas are generally too small and discontinuous to contribute to runoff or erosion at the field scale (Le Bissonnais et al., 2005). Cogo et al. (1984) found that a standing stubble reduced soil erosion by water more than surface roughness did, especially when residue cover was present. Retention of wheat stubble in situ without incorporation (standing stubble in furrows) can minimize erosion and runoff and consequently maximize water infiltration (Mostaghimi et al., 1998).

Our primary objective was to investigate plot-level runoff and soil losses via overland flow by analyzing the temporal change of runoff, sediment concentration, and sediment load in runoff and to determine the magnitude of runoff and sediment under different soil management practices. For the plots where runoff occurred, we focused particularly on the overland flow patterns (e.g., time to initiate runoff, runoff volume, sediment discharge rate, runoff peak flow) at different temporal scales of measurement. These results are needed to select and promote valid tillage alternatives for abating soil erosion and nutrient losses in the Chinese Loess Plateau by introducing improved land management strategies so as to improve yields whilst minimizing soil loss and reducing nutrient inputs.

2. Materials and experimental designs

2.1. Site description

An experimental site aimed specifically at monitoring the impact of converting conventional tillage to conservation tillage was established in Songzhuang Village, 25 km north of the city of Luoyang (Henan Province; 113.0° East longitude, 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 Ustochrept according to Soil Taxonomy (Soil Survey Staff, 2003).

The experimental site was previously conventionally tilled for over 30 years and the basic soil properties were analyzed before the establishment of the experimental plots (Table 1). There was no significant difference between the tested properties (p<0.05). Since the entire experimental site was relatively homogenous in terms of soil physical, chemical and topographic properties, the different treatments could be laid out as single plots which reduced the total size of the experimental site and hence variability. Statistical analysis of the effects of different soil management practices could therefore be conducted using the results from replicated samples in one single plot (Zhang et al., 2006).

Two series of plots were laid out: one series of five plots under natural rainfall (set up in 1999) and another series of four plots was designed specifically for rainfall simulation tests (set up in 2001) on a ‘gullied hill’. Gullied hilly loess consists of rounded hills of considerable height with a high density of steep-sided gullies showing evidence of active erosion. Each plot under simulated rainfall was 15 m long and 1.8 m wide. The slope of the plots, which were located along the same contour line, was 9%.

During 1970–2006 the minimum temperature was ~23.5 °C and the maximum was 43.7 °C. The average annual precipitation during the study period was 580 mm. The annual potential evaporation varied between 1262 and 1852 mm and the average air humidity was 65%. Rainfall was unevenly distributed throughout the year with high rainfall intensities and frequent rainstorms in summer (June–September) and dry winters (December–February).

Table 1

| Soil characteristics in Songzhuang (Henan province) in 2001 (n=6) |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|
| Profile | Depth (m) | 0–2 μm (g kg⁻¹) | 2–50 μm (g kg⁻¹) | 50–2000 μm (g kg⁻¹) | Texture⁴ | CaCO₃ (g kg⁻¹) | Total N (g kg⁻¹) | Bulk density⁵ (Mg m⁻³) | pH (KCl) |
| A₀ | 0.00–0.02 | 143 | 748 | 109 | Silt loam | 113 (3) | 1.124 (0.18) | 1.350 (0.041) | 7.7 (0.1) |
| A₁ | 0.02–0.30 | 141 | 743 | 116 | Silt loam | 129 (5) | 0.955 (0.11) | 1.350 (0.027) | 7.8 (0.0) |
| B₁ | 0.30–0.60 | 138 | 745 | 117 | Silt loam | 142 (0) | 0.732 (0.09) | 1.383 (0.019) | 7.7 (0.1) |

Values between brackets indicate the standard deviation.

⁴ USDA textural classification.

⁵ n = 3.
2.2. Tillage practices

This study was focusing on plots subjected to artificial rainfall. Treatments were conventional tillage (CT), no till with mulch (NTM), reduced tillage (RT), and subsoiling with mulch (SSM). On CT, NTM, RT and SSM, winter wheat (*Triticum aestivum* L.) was grown and the different tillage practices were applied from 2001 onward.

Under CT, a stubble of 10–15 cm remained on the field after harvest of winter wheat (May 25–June 1), but the straw and ears were removed from the plot at harvest. In the first week of July, the soil was ploughed and turned to 20 cm depth. Around October 1, just before sowing of winter wheat, the soil was ploughed again and turned to 20 cm depth while at the same time the fertilizer was incorporated, followed by harrowing (seed bed preparation). Sowing of winter wheat was done around October 5.

Under NTM, a stubble of 30 cm remained on the field after harvest (May 25–June 1) and straw was returned to the field after threshing. Between September 25 and October 5, direct sowing with fertilizer application was done by hand.

Under RT, a stubble of 10–15 cm remained on the field after harvest of winter wheat (May 25–June 1) and the straw was returned to the field after threshing. Around July 15, deep ploughing (25–30 cm) combined with harrowing (5–8 cm) was done. Winter wheat was sown around October 5. This practice thus involved only 1 time ploughing instead of 2 times ploughing under CT.

Under SSM, stubble of 25–35 cm remained on the field after harvest (May 25–June 1) and straw was returned to the field after threshing. Around July 1, subsoiling was performed till 30–35 cm depth at 60 cm intervals. Between September 25 and October 5, direct sowing with fertilizer application was done.

In order to make a comparison with the plots under natural rainfall and to study the effect of mulch on erosion reduction, two new plots, namely subsoiling without mulch (SS) and two crops per year (i.e. winter wheat with peanut (TC)), were set up in 2004.

Under SS, the soil tillage practices were the same as with subsoiling with mulch (SSM), but no winter wheat residues were returned to the field. Under TC, a stubble of 10–15 cm remains on the field after harvest of winter wheat (May 25–June 1). Peanut (*Arachis hypogaea* L.) was directly seeded in the beginning of June and limited water was supplied in each planting pit to ensure the germination of peanut but no fertilizer is applied. After the harvest of peanut (around Sept. 23), the soil was ploughed to 20 cm depth while at the same time the fertilizer was incorporated, followed by harrowing (seed bed preparation). Sowing of winter wheat was done around October 5.

Winter wheat and peanut were sown by hand up and down the slope for all treatments. In order to investigate the environmental impacts of fertilization at local application levels, application rates for each plot were 150 kg N ha$^{-1}$ (urea) and 90 kg P$_{2}$O$_{5}$ ha$^{-1}$ (superphosphate) in each year. Insect control was achieved by applying 1125 ml omethoate (C$_{5}$H$_{12}$NO$_{4}$PS$^{-1}$) ha$^{-1}$.

2.3. Rainfall simulations and sampling

Because of the position of the field plots, rainfall was simulated on two adjacent field plots at the same time (Fig. 2). The rainfall simulator was similar to the one used by Schiettecatte et al. (2005) and consisted of two 15-m long sprinkler booms, each positioned at a height of 1.8 m above the soil surface and at a mutual distance of 1.5 m. On each sprinkler boom, Teejet® TG SS 14 W nozzles were fixed every 1 m and positioned in a triangular configuration.

Each runoff plot was bounded and trenched around to divert upslope runoff water. Runoff from the plot was collected in a trough at the downhill side of the plot, with runoff discharge measured by timed volumetric sampling. Runoff samples were taken when runoff started and then after 2.5, 5, 7.5, 10, 15, 20, 25 and 30 min. Sediment concentration was determined gravimetrically on the runoff samples after oven-drying (at 105 °C). Prior to each rainfall simulation, the incised rill developed in the previous rainfall test was refilled manually to make the temporal replicates as less as possible dependent on the previous simulation.

A total of 28 rainfall simulations were carried out, or six simulations on each of the four plots established in 2001 (Table 2). Four simulations were conducted per plot in 2002 and two in 2005. The simulations were performed in a series of two, first on an initially ‘dry’ soil (with gravimetric water content ranging from 0.087 to 0.295 kg kg$^{-1}$), and then a few days later on the same but now initially ‘wet’ soil (with gravimetric water content ranging from 0.175 to 0.288 kg kg$^{-1}$). The rainfall intensity was 85 and 170 mm h$^{-1}$ which is exceptional during natural rainfall events, but nevertheless can occur in the study area, primarily over short time periods. Rainfall at a high

Fig. 2. A rainfall simulation experiment conducted simultaneously on a no-till plot (left) and on a conventional tillage plot (right).
Table 2

Experimental conditions of field rainfall simulations and runoff and sediment under each rainfall simulation test

<table>
<thead>
<tr>
<th>Date</th>
<th>Plot</th>
<th>w (kg kg(^{-1}))</th>
<th>RI (mm h(^{-1}))</th>
<th>Code of experiment</th>
<th>Percentage cover (%)</th>
<th>Roughness(^a)</th>
<th>Residue status(^b)</th>
<th>Runoff (m(^3) ha(^{-1}))</th>
<th>Sediment (ton ha(^{-1}))</th>
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</tbody>
</table>

CT: convention tillage, NTM: no till with mulch, RT: reduced tillage, SSM: subsoiling with mulch, SS: subsoiling, TC: two crops per year, w: initial gravimetric water content, RI: rainfall intensity.

\(^a\) The classification of roughness is based on Ludwig et al. (1995):
R0: Strongly crusted, or tilled fields, harvested fields with intense compaction.
R1: Sown fields with fine-loosened or moderately crusted seedbeds.
R2: Recently sown fields with a cloddy surface, crusted tilled fields without residues.
R3: Stable-ploughed fields and recently sown fields with a very cloddy surface.
R4: Ploughed fields.

\(^b\) The classification of residue status: 1: standing winter wheat residues; 2: winter wheat residues incorporated into soil; 3: peanut vegetation.

intensity was applied over a longer period in order to ensure a complete consolidation of the soil at the end of the rainfall simulation experiments. Each rainfall simulation lasted for 30 min.

For each experimental plot, the bulk density in the 0–10 cm layer was measured on 100 cm\(^2\) (diameter of 5 cm) soil cores collected five days after the last rainfall simulation test in three replications per plot. Prior to each rainfall simulation, disturbed soil samples were taken at the soil surface in six replicates, in order to determine antecedent soil–water content by oven-drying (at 105 °C). SOC was determined in 2005 in three replications in the upslope and downslope part of the plot to a depth of 40 cm in three layers (0–10 cm, 10–20 cm and 20–40 cm) after the last rainfall simulation. SOC was determined using the method of Walkley and Black (1934).

2.4. Data analysis

The spatial variability in soil texture and SOC observed prior to the experiments was negligible (which was one of the reasons for finally selecting the field for our experiments). Therefore, rather than applying a classical block design which allows accounting for possible effects of spatial variability, the different treatments were, as said, laid out as single plots and statistical analysis of the effects of different soil management practices was conducted using the results from replicated samples in one single plot (Zhang et al., 2006). We believe that, particularly for experiments in which measurements are conducted at given instants (no long term continuous recordings), it is important to account for some variation in environmental factors such as rainfall intensity and antecedent water content, rather than considering spatial variability, which was not existing in our case. Those environmental factors greatly influence the process under study, apart from the management practice. We further believe that performing experiments under different experimental conditions on one plot, made our results more firm than if we would have included more plots, but always with the same rainfall intensity and antecedent water content, at least for the field under consideration. The six rainfall simulations can hence be seen as replicates in time, on which no classical statistical can be performed (because of the range in influencing factors). Mean values and standard deviations are reported for each of the measurements on bulk density and SOC. An analysis of variance (ANOVA) was used to detect the effects of treatments on measured SOC distribution along the slope, and the Least Significant Difference (LSD) was used to test comparisons among treatment means calculated at \( p < 0.05 \). Statistical procedures were carried out with the software package SPSS 10.0 for Windows (SPSS Inc. 2001).

3. Results

3.1. Change of soil bulk density and soil organic carbon

Changes in frequency and intensity of tillage practices altered the soil bulk density \((\rho_b)\) and soil organic carbon (SOC) in the 0–10 cm layer (Table 3). NT had the highest \(\rho_b\), followed by SSM and SS, but the difference was not statistically significant compared to CT. RT, CT and TC had similar \(\rho_b\), SSM and NT increased SOC, but again did not reach statistical significance compared to CT. There was no difference of SOC...
between the other treatments. However, we must notice that TC and SS plots were set up three years later compared to the other plots.

### 3.2. Runoff and soil loss under field simulated rainfall

#### 3.2.1. Amount of runoff sediment (ton ha\(^{-1}\)) under different soil management practices

Table 2 also shows the amount of runoff under the different management practices for the experiments. No runoff occurred with NTM and SSM in 2005, and therefore they were not delineated in the graph (same as hereafter). The results indicated that NTM has a beneficial effect on runoff reduction. SS reduced runoff by 28% compared to CT5 in the initial ‘dry’ soil, but reduced it with 58% in the initial ‘wet’ soil. The runoff reduced by more than 64% under SSM compared to under CT in 2002, whereas, no runoff occurred on SSM in 2005 after four years of consecutive SSM practices. From comparing the runoff in SSM and SS under the same initial soil moisture conditions, it could be concluded that mulch had a significant beneficial effect on runoff reduction in the initial ‘dry’ soil, but this effect was less pronounced in the initial ‘wet’ soil. TC resulted in a pronounced runoff reduction (more than 92%) compared to CT in the initial ‘dry’ soil, but this effect was strongly reduced to 50% in the initial ‘wet’ soil. Application of RT in the initial ‘dry’ soil reduced runoff with 37% in 2002 compared to CT, but this effect diminished during the experiments on fallow, which was carried out in the initial ‘wet’ soil in 2002. In contrast, RT produced 46% and 10% higher runoff in the initial ‘dry’ soil and ‘wet’ soil compared to CT in 2005, respectively.

Both NT and SSM strongly reduced sediment losses (Table 2). Under NT no runoff occurred and consequently no soil was lost. SSM reduced soil loss by more than 85%. SS also reduced considerably the soil loss (46% on the initial ‘dry’ soil and 64% on the initial ‘wet’ soil). RT resulted in a soil loss decrease of 46% to 63% in 2002 compared to CT, while it increased soil loss by 25% in the initial ‘dry’ soil in 2005 and reduced the soil loss by 24% in the initial ‘wet’ soil. TC reduced soil loss by more than 93% in the initial ‘dry’ soil compared to CT, but it only reduced 63% of the sediment loss in the initial ‘wet’ soil.

Generally, three distinct stages in the runoff process could be distinguished (Fig. 3). In stage I, defined as the period from the start of rainfall to the time to runoff initiation (Ti), all rainfall infiltrated and no runoff occurred. Stage II represented the period in which infiltration rapidly declined and runoff started at the same time and increased rapidly. Stage III started with a constant discharge rate (Dc) indicating a constant rate of infiltration.

There was always a delay between the start of the simulated rain and the runoff initiation. For the experiments on the same plot under the same RI, a longer delay was found in the initially ‘dry’ soil compared to the initially ‘wet’ soil. Runoff started always earlier on the RT plot compared to the other plots under RI 170 mm h\(^{-1}\). But runoff was significantly delayed on RT1 compared to CT1. The SSM, SS and TC had a postponed Ti compared to CT.

Comparing the Dc under the same tillage practices, the highest Dc was always observed under RI of 170 mm h\(^{-1}\) in the initially ‘wet’ soil. The Dc in RT and CT under RI of 85 mm h\(^{-1}\) was quite similar, while it differed substantially under RI of 170 mm h\(^{-1}\) at different times. In 2002, the Dc in CT was around 9% higher compared to RT, but in 2005, the Dc in CT was 37% lower in the initially ‘dry’ soil compared to RT. Compared to CT, SSM reduced Dc by 44% on average under RI of 85 mm h\(^{-1}\) and by 49% under RI of 170 mm h\(^{-1}\) in the initially ‘wet’ soil in 2002, whereas SS increased Dc with 3% in the initially ‘dry’ soil and with 11% under RI of 170 mm h\(^{-1}\) in the initially ‘wet’ soil in 2005.

#### Fig. 3. Temporal change of runoff discharge rate (l min\(^{-1}\)) under different soil management practices. The meaning of the different codes per treatment is explained in Table 2.
The temporal change of sediment concentration (Cs) also showed a large variation between the different treatments (Fig. 4). In general, the temporal change of Cs followed two different patterns: (1) Cs increased rapidly immediately after the Ti, followed by a slight decline, and then leveled off, which was found in most cases under RT and CT; (2) Cs reached its peak value at the Ti, then dropped rapidly, and then leveled off as with RT5 and CT5 and with SSM, TC and SS. In generally, under the same management practices, the highest constant Cs was always observed in the initially ‘wet’ soil under the RI of 170 mm h⁻¹. But RT and CT in 2005 had a relatively lower Cs (12.1 and 13.5 g l⁻¹ respectively) compared to Cs under the RI of 85 mm h⁻¹ in 2002. SSM and TC significantly reduced Cs compared to CT. SS also reduced Cs, but less pronounced compared to SSM.

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Under natural rainfall, all the runoff events occurred during the rainfall season from early June to late September. There was a big variation of annual runoff of every plot under different tillage practices (Table 4). No runoff occurred in 2002 because of unusual low rainfall in the summer time. The highest rainfall occurred in 2004 because of the highest amount of precipitation recorded in the last 50 years (around 900 mm during the rainfall season). Application of NTM and SS resulted in the lowest runoff and runoff was reduced by more than 87% compared to CT. TC also had a strong effect on runoff reduction compared to CT. The RT and CT yielded similar results, as expected.

4. Discussion

The negligible runoff and soil loss in no till with mulch (NTM) under simulated rainfall in our study (Table 2) could be attributed to the high permeability of the loess soils in the Loess Plateau on the one hand, and the high percentages of soil surface cover, standing stubble, no disturbance of soil surface and relatively high SOC in NTM and their interaction, on the other. This result was confirmed by the observations in the plots under natural rainfall (Table 4). Ferreras et al. (2000) and Raper et al. (2000) reported that long-term application of NTM might lead to soil compaction and thereby increasing the runoff and decreasing infiltration. Indeed, a significantly higher bulk density with NTM compared to conventional tillage (CT) was found in our study, but no statistical differences in saturated hydraulic conductivity were observed between the different treatments on the same site (Jin et al., 2003). According to Fabrizzi et al. (2005), the observed compaction in no till only lasts for a few years. After many years continuous conservation tillage practices, sufficient biological activity will be established, a stable soil structure will be formed and water infiltration will increase in the soils.

Our results showed that non-inverse tillage could reduce soil erodibility significantly in the initially ‘dry’ soil, when conventionally ploughed topsoils could be very erodible (Table 2). The combination of subsoiling (SS) with mulch (SSM) appeared to be more effective in reducing runoff by 50% and sediment loss by 85% compared to CT in 2002. From comparing the results of Figs. 3 and 4, it could be concluded that SS and SSM had a higher reduction in soil loss than in runoff. This indicates that the reduced runoff and soil loss within a short time after conversion to conservation tillage were not merely due to the temporary protective effect of the residue cover, which was concluded by Freebairn and Wockner (1986). The applied tillage also affected soil erodibility. Schiettecatte et al. (2003) proved that tillage has a supplementary effect on soil erodibility: a lower erodibility value was found in SSM compared to CT. Van Dijk et al. (1996) tested several cropping systems of fodder maize on runoff and soil loss and reported that soil loss is reduced strongly if the soil surface is partially covered with plant residues and soil loss reductions are much higher than reductions in runoff water.

Although subsoiling with mulch (SSM) showed a pronounced soil and water conservation effect in the year 2002, it was not as efficient as NTM, indicating that even a small disturbance of the soil could make the soil more vulnerable to erosion (Table 2). McGregor and Greer (1982) indicated that even when crop residues are left on the

<table>
<thead>
<tr>
<th>Year</th>
<th>RT</th>
<th>NT</th>
<th>TC</th>
<th>SS</th>
<th>CT</th>
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</thead>
<tbody>
<tr>
<td>2001</td>
<td>9.6 (2)</td>
<td>0</td>
<td>2.4 (1)</td>
<td>1.0 (1)</td>
<td>11.5 (3)</td>
</tr>
<tr>
<td>2002</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2003</td>
<td>9.4 (3)</td>
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<td>1.4 (2)</td>
<td>0.3 (1)</td>
<td>13.4 (3)</td>
</tr>
<tr>
<td>2004</td>
<td>17.4 (4)</td>
<td>1.9 (3)</td>
<td>13.7 (3)</td>
<td>2.0 (3)</td>
<td>15.7 (4)</td>
</tr>
<tr>
<td>2005</td>
<td>14.1 (2)</td>
<td>0</td>
<td>2.1 (2)</td>
<td>0</td>
<td>13.7 (2)</td>
</tr>
<tr>
<td>2006</td>
<td>16.3 (2)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15.7 (2)</td>
</tr>
</tbody>
</table>

Values between brackets indicate the number of runoff events.
surface of the tilled soils, they provide less protection against erosion than the accumulated residues from no till systems. However, no runoff and soil loss was observed in SSM in 2005 in contrast to the record in 2002 with the same rainfall intensity. This difference was related to a temporal change of the soil erosion resistance of the surface soil in the SSM plot. Significantly higher soil carbon storage was observed relative to CT after 4 years of consistent SSM practices (Table 3). It is expected that this increase in carbon storage was rather precarious, since it was mainly stored in the top 10-cm soil layer, and consequently could improve the soil permeability (Azooz et al., 1996) and increase the stability and amounts of macro-aggregates (Shepherd et al., 2002; Six et al., 2002), and finally, soil erosion resistance increased. These improvements in surface soil properties influencing erodibility could only occur within a minimum of 3–4 years after the introduction of conservation practices on a loamy soil (Rhoton et al., 2002).

Even though two crops per year (TC) showed a significant runoff and soil loss reduction in the initially ‘dry’ soil due to the high vegetative cover (60%), still small runoff and soil losses occurred (Figs. 3 and 4). Furthermore, this reduction diminished strongly in the initially ‘wet’ soil. We could conclude that in our study mulching with winter wheat straw combined with standing stubble (NTM and SSM) was more effective on soil and water conservation than using a cover crop (TC). The less efficient erosion control of TC is related to the vegetation pattern on the slopes and the application of straight-row farming up and down the slope. Water concentrated into the continuous bare surface with low infiltration rate between rows and routed along the steepest algorithm row, and consequently erosion was more likely to occur. It is noteworthy that Ti (12 min) under TC was significant delayed even in the initially ‘wet’ soil (Fig. 3).

Reduced tillage (RT) did not show an appreciable runoff and soil reduction even though the winter wheat residue was returned to the field after threshing and one tillage practice was cancelled compared to CT. The primary tillage operation at the beginning of July in RT and CT did not significantly affect the saturated hydraulic conductivity, but significantly increased the soil erodibility in comparison to a consolidated soil (Schiettecatte et al., 2005). Actually, soils under RT remain almost bare with a smooth soil surface during summer due to the incorporation of the straw. Consequently, the beneficial effects of standing stubble and mulch on soil and water conservation are therefore lost. If there would not be a protection of vegetation and stabilization by the root systems, the raindrop impact would destroy the porous soil structure and therefore cause a dramatic decrease in soil permeability. The results of laboratory experiments with the same soil also indicated a significant correlation between percolation and surface cover. Schiettecatte et al. (2003) found that the average saturated hydraulic conductivity as measured from rainfall simulations was 2.9 mm h\(^{-1}\) and 5.5 mm h\(^{-1}\) in case of respectively 0 and 50% cover at same site. This proved that surface mulch plus standing residue in the upper soil layer was more effective in reducing soil losses than when they were ploughed into the soil.

The difference in runoff between RT and CT in 2002 was rather surprising. RT had a lower runoff compared to CT (Table 2). Under CT, the ploughing in July was done without harrowing and crushing the large clods causing more roughness, while RT resulted in a smoother bare surface. The lower runoff in RT was therefore opposite to what we expected. Most literatures report that increased roughness causes lower runoff (Ludwig et al., 1995). The only observed benefit from soil surface roughness in terms of soil water conservation was the short delay in runoff initiation in our study.

Comparing the measurements in 2002 and 2005 on the same plots, a large difference between the “replicate” experiments in RT and CT was found (Table 2). Much higher runoff and soil loss was observed in the experiment of 2002, although the exactly same practices were applied resulting in apparently almost identical homogenous erosion plots. The temporary protective effect of a weed cover under RT and CT could be one of the explanations for this variation. One of the purposes of the tillage practices in July in RT and CT is weed control. However, the effects on weed control were limited in some cases due to the high precipitation and temperature in the fallow period. There was considerable weed growth and weed covered around 20% of the soil surface in 2005. However, due to the unexpected lower precipitation in July and August (105 mm), weed growth was severely depressed by drought stress causing a much lower cover percentage (around 5%).

The temporal change in runoff discharge rate could be explained by the temporal variation of soil infiltration. Infiltration experiments conducted by Schiettecatte et al. (2005) on the same soil showed high infiltration rates at the beginning of the water input event, followed by a relatively rapid decline and an asymptotic approach to a near-constant value. Mulching or covering the soil surface with a layer of plant residue in NTM, SSM and TC increases infiltration of water into the soil (Ghawi and Battikhi, 1986) and resulted in a lower runoff discharge rate compared to CT and RT. Schiettecatte et al. (2003) found that the percolation rates on the CT, RT, SS and NTM plot are respectively 10, 18, 52 and 85 mm h\(^{-1}\) under a rainfall intensity of 85 mm h\(^{-1}\) and a steady-state runoff for the same soil. The difference of total runoff discharge on the different initial soil moisture could be explained by the mechanism of runoff generated. On the dry soil, the runoff mainly corresponds to infiltration excess. The experiment on the wet soil surface was carried out a few days after the previous rainfall simulation test. A saturated soil profile can occur and runoff could be caused by infiltration excess runoff as well as by saturation excess runoff (Calvo-Cases et al., 2003). Results on the effect of antecedent soil moisture content on runoff and soil loss were inconsistent. Luk (1985) and Lado et al. (2003) found that increasing antecedent moisture content reduced runoff and soil loss under simulated laboratory rainfall using a soil pan. However, our results contradicted to their observations, which could be explained by the difference of the test soils used. The loess soil in our study had much lower clay content (15%) than the soil used by these authors (higher than 23%). Mamedov et al. (2001, 2002) found that the effect of antecedent moisture on runoff and soil loss was very pronounced in clay soil, while in silt loam soil, the effect was negligible. Another explanation could be the different experimental conditions. For the above-mentioned experiments, the soil structure was completely destroyed with only a shallow soil layer (<5 cm), where no limit for water percolation existed. In contrast, in our experiment, the soil profile was saturated after the previous rainfall test, decreasing water percolation capacity, and consequently producing higher amounts of runoff.

The increase in the Cs after the Ti in RT and CT corresponded to the simultaneously increasing runoff discharge rate (Fig. 3). The increasing runoff discharge enlarged the hydraulic radius of surface flow, enhancing flow velocity and thus transport and detachment capacity. With time, the runoff discharge rate became constant, and hence produced a relatively constant sediment concentration. The highest Cs in the initially ‘wet’ soil in SSM and TC could be partially due to the post effect of previous rainfall simulation, in that in the initially ‘dry’ soil, runoff was negligible. However the high kinetic energy during the previous rainfall test had already broken down many soil aggregates, so that consequently more soil particles were more vulnerable to be transported in the subsequent experiment. In contrast, the high rate of runoff discharge rate in our simulated test on RT and CT transported most of particles off site and consequently had relatively smaller effect on the Cs of the next test. The unusually highest Cs on RT5 and CT5 immediately at the start of runoff could be explained by the post effect of the natural rainfall. There was 48 mm natural rainfall occurring in the 10 days before our experiment without erosion taking place. Natural raindrop detaches soil particles on the bare soil surface so that subsequently they are easier transported by the overland flow. Indeed, before we started
our experiment in 2005, a thin layer of fine particles at the bottom of RT and CT plot was observed. But in 2002, due to the unusually low natural rain in the fallow time, fewer aggregates were broken and transported by natural rain.

The rainfall simulation results were found to compare favorably with natural rainfall, producing much more runoff and sediment in RT and CT, and less runoff and sediment in SSM and NTM (Tables 2 and 4). However, there were runoff events recorded in 2004 on the natural plots with less runoff and sediment in SSM and NTM (Tables 2 and 4). However, natural rainfall, producing much more runoff and sediment in RT and CT, transported by natural rain.


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References


