

Changes of soil enzyme activities under different tillage practices in the Chinese Loess Plateau

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ABSTRACT

The effects of middle term (7 years) consistent tillage practices on the catalase (CAT), urease (URE) and invertase (INV) activities were investigated during the whole winter wheat growing period on a loess soil in Luoyang (east edge of the Chinese Loess Plateau, Henan province, China). Field plots, set up in 1999, included following tillage practices: subsoiling with mulch (SS), no-till with mulch (NT), reduced tillage (RT), and a conventional control (CT). A clear redistribution of soil organic carbon (SOC) and total nitrogen (TN) was found along the slope in RT and CT, however, no difference was observed between studied enzyme activities along different slope positions. SS had higher winter wheat yield than other treatments, which was attributed to the increased soil water content and improvement of soil fertility. Changes in soil temperature and soil moisture content influenced the magnitude of the enzyme activities, but not the ranking of the different treatments during most of the season. SS consistently had higher enzyme activities compared to other treatments. This indicated that seasonal fluctuations did not obscure effects associated with soil tillage practices and enzyme activities could reflect the effects of conversion of soil tillage practices on soil quality. Time within the growing season had a clear impact upon the enzyme activities. Comparatively higher enzyme activities were observed in the stages with vigorous vegetative growth of winter wheat than in stages with productive growth.

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1. Introduction

Soil quality is defined as 'the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health' (Doran and Parkin, 1994). Soil quality is the result of the interaction between chemical, physical and biological soil properties (Karlen et al., 2001), and therefore these three types of properties should be taken into account when evaluating soil quality.

Soil organic matter plays a crucial part in all aspects of soil quality (soil structure, soil water relations, chemical fertility and biodiversity) and therefore is a key indicator for the integrated evaluation of soil quality (Tiessen et al., 1994; Carter, 2002). However, soil organic matter changes only very slowly and therefore shorter term changes in soil quality are often assessed using specific fractions of soil organic matter such as particulate

organic matter or biologically active components of soil organic matter, including microbial biomass and enzyme activities.

Soil enzymes occupy a pivotal role in catalysing reactions associated with organic matter decomposition and nutrient cycling. It is considered as a valuable tool for assessing the effect of different cropping systems on organic matter dynamics and transformation processes in soils (Bandick and Dick, 1999), therefore, it might be a valuable indicator for a soil's ability to function or bounce back after disturbance (resistance and resilience).

Enzyme activities have been indicated as soil properties suitable for use in the evaluation of the degree of alteration of soils in both natural and agroecosystems (Trasar-Cepeda et al., 2000). Some research has already suggested the positive effects of conservation tillage practices on soil enzyme activities under semi-arid Mediterranean and temperate climate (Kandeler et al., 1999; Riffaldi et al., 2002), and in subtropical soils (Roldán et al., 2005a, 2005b).

Enzyme activities vary seasonally and depend on soil chemical, physical and biological characteristics (Niemi et al., 2005). Therefore, in most cases, single enzyme assays may not be representative of the overall microbial community activity and do not take into account seasonal changes and inherent differences in enzyme activity; consequently, sound information on actual

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phenomena could not be obtained (Bandick and Dick, 1999; Nannipieri et al., 2002; Roldán et al., 2005a, 2005b).

Season and crop differentially influence correlation among enzymes and between enzymes and physico-chemical factors (Aon et al., 2001). However, a wide range of enzymes has not been systematically investigated for their potential to reflect short- and long-term soil management effects in relation to soil quality. Virtually little information exists on the impact of conversion of conventional tillage (CT) to conservation tillage on soil enzyme activities in the dryland agroecosystems of the Chinese Loess Plateau.

Conservation tillage and stubble retention practices are being introduced as options to fight erosion and improve yields (and income) in the Loess Plateau of China and these practices are rapidly being adopted in the last decade (Wang, 2006; Cai et al., 2006). It is estimated that there are now over 1 million ha under conservation tillage in farmer's fields in the dryland of China (McGarry, 2005).

We hypothesized that soil under different tillage practices and residual management would have effects on soil properties over a period of 7 years, consequently, different enzyme activities were expected. Furthermore, we wanted to investigate which environmental factors, such as soil moisture content, temperature, and factors such as the stage of crop development might change the ranking of enzyme activities throughout the growing period. To this end, we monitored enzyme activities under different tillage practices throughout the whole winter wheat growing period (from September 2005 to June 2006) and determined the extent of their response to long-term different tillage practices and residue management in the sloping farmland of the Chinese Loess Plateau. Soil temperature and moisture content together with some chemical parameters were also investigated in order to understand the seasonal variation of soil enzyme activities after 7 years sustained use of different tillage practices.

Criteria for choosing enzyme assays were based on their importance in nutrient cycling and organic matter decomposition and the simplicity of the assay. Catalase splits hydrogen peroxide into molecular oxygen and water and keeps cells from damage caused by reactive oxygen species. All aerobic and most of the facultative anaerobic bacteria contain catalase. It acts mainly at the intracellular level, but it can be catalytic outside of microbial cells in association with soil organic matter and/or can be adsorbed to clay minerals. Urea is the most common fertilizer used in dryland farming in our study area. Urease is involved in the hydrolysis of urea-type substrates and its activity is crucial in the transformation of urea fertilizer. Its origin is basically microbial and its activity is extracellular (Yao et al., 2006). Invertase catalyses the hydrolysis of sucrose to D-glucose and D-fructose, and is widely distributed in micro-organisms. It plays a critical role in releasing low molecular weight sugars that are important as energy sources for micro-organisms. Because the three selected enzymes play a key role in C and N cycling in soils, the activities of these enzymes can provide a potential tool to evaluate the long-term changes in organic carbon and nitrogen pools as related to fallow tillage management.

2. Materials and methods

2.1. Site description

In order to study the impact of the conversion of conventional tillage to conservation tillage, an experimental station was set up in 1999 in Songzhuang Village, 25 km north from the city of Luoyang (Henan province; 113.0° East longitude, 34.5° North latitude), in the eastern part of the Chinese Loess Plateau. Different tillage practices were applied from 1999 onwards consistently.

The experimental site was previously conventionally tilled for more than 30 years. In this region, the quaternary loess accumulated to around 50–100 m thick. It has a loose and porous structure. The soil in the study area was a silt loam soil and classified as Inceptisol according to Soil Taxonomy. Major mineral species are quartz, mica, feldspar and chlorite, accounting for about 88–92% of the total mineral fraction. The basic soil properties were analyzed before the set up of the experimental plots. The basic soil properties that were analyzed to assess plot homogeneity were those from which we anticipated an important influence on soil quality parameters and crop performance, namely soil texture, CaCO₃, soil organic carbon (SOC), and total nitrogen (TN). Standard deviations on the measured soil properties showed that the selected part of the field was indeed homogenous (Table 1), and therefore the different treatments could be laid out as single plots. Statistical analysis of the effects of different soil management practices could therefore be done using replicated samples from single plots (Zhang et al., 2006; Jin et al., 2008).

2.2. Experimental design and layout

The plots were laid out on a 'gullied hill' without replicates. 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 was 90 m long and 3 m wide. The slope of the plots, which were located along the same contour line, was 9%.

Treatments were conventional tillage, no-till with mulch (NT), reduced tillage (RT), and subsoiling with mulch (SS). On CT, NT, RT and SS, winter wheat (*Triticum aestivum* L.) was grown and the different tillage practices were applied from 1999 onward.

Under CT, 10–15 cm of stubble remained after harvest (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 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 performed around October 5. Under NT, 30 cm of stubble 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 performed. Under SS, 25–35 cm of stubble remained on the field after harvest (May 25–June 1). Around July 1, subsoiling was performed to 30–35 cm depth at 60 cm intervals. Between September 25 and October 5,

Table 1
Soil characteristics at the experimental station in Songzhuang (Henan province) ($n = 6$).

Profile	Depth (m)	0–2 μm (g/kg)	2–50 μm (g/kg)	50–2000 μm (g/kg)	Texture ^a	CaCO ₃ (g/kg)	SOC (g/kg)	TN (g/kg)	BK (mg/m ³)	pH (KCl)
A ₀	0.00–0.02	143	748	109	Silt loam	113 (3)	6.942 (0.271)	1.124 (0.18)	1.350 (0.041)	7.7 (0.1)
A _p	0.02–0.40	141	743	116	Silt loam	129 (5)	4.810 (0.123)	0.955 (0.11)	1.350 (0.027)	7.8 (0.0)
B ₁	0.40–0.60	138	745	117	Silt loam	142 (0)	2.859 (0.050)	0.732 (0.09)	1.383 (0.019)	7.7 (0.1)
B ₂	0.60–0.85	148	736	116	Silt loam	146 (2)	2.501 (0.033)	0.431 (0.20)	1.374 (0.021)	7.8 (0.1)
C	0.85–1.30	140	745	115	Silt loam	135 (1)	2.001 (0.019)	0.402 (0.08)	1.414 (0.011)	7.9 (0.0)

SOC, soil organic carbon; TN, total nitrogen; BK, bulk density. Values between brackets indicate standard deviation.

^a USDA textural classification.

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

Fertilizer was applied at local application levels, namely 150 kg N ha⁻¹ (urea) and 90 kg P₂O₅ ha⁻¹ (superphosphate) in each year. Insect control was achieved by applying 1125 ml omethoate (C₅H₁₂NO₄PS) ha⁻¹.

2.3. Soil sampling and analysis

Soil samples were collected at different stages during the 2005–2006 winter wheat growing season, namely before sowing (September 29), before winter (November 15), during winter (December 25), jointing (March, 26), anthesis (April, 9), filling (May, 2) and at maturity (May, 27). Soil samples were taken with a soil auger to a depth of 10 cm. Soil samples were taken between rows to avoid rhizosphere zone for each sampling time. Three replicate cores from the upper and lower parts of each plot were taken separately for each plot. The soil was sieved on a 2 mm mesh and stored at 4 °C until biochemical analysis. At the last sampling occasion, subsamples were air dried for the chemical analyses. The analyses of the total soil nitrogen (TN) for each plot were done using an automatic Kjeldahl distillation–titration unit (Foss, Sweden). Organic carbon (SOC) analyses were based on the method of Walkley and Black (1934). For the soil bulk density, only three replicates were taken for each plot without considering the different position on the slope.

Catalase activity was assessed based on the rates of recovery of hydrogen peroxide. Two grams air-dried soil with 40 ml distilled water and 5 ml 0.3% H₂O₂, was shaken for 20 min (shaking velocity was 150 rpm) and filtered (Whatman 2 V) immediately. The filtrate was titrated with 0.1 mol l⁻¹ KMnO₄ in the presence of sulphuric acid and the results were expressed as μmol KMnO₄ g⁻¹ h⁻¹. For urease activity, moist soil (5 g) was incubated for 2 h at 37 °C with 2.5 ml urea solution and 20 ml borate buffer. At the end of the incubation, 50 ml of 1 M KCl solution was added and the soil suspension was shaken for 30 min. Ammonium was measured at 690 nm with a spectrophotometer (UV 330). Urease activity was expressed as the NH₄⁺ released in the hydrolysis reaction and expressed as mg NH₄⁺-N 100 g⁻¹ soil, 24 h⁻¹. For measuring invertase activities, 5 g of air-dried soil was incubated for 24 h at 37 °C with 15 ml 8% sucrose, 5 ml phosphate buffer at pH 5.5 and 0.1 ml toluene. The glucose released by invertase was then reacted with 3,5-dinitrosalicylic acid and 3-aminonitrosalicylic acid, and was measured at 578 nm (UV 330). Invertase activity was expressed as mg glucose g⁻¹ soil h⁻¹ (Guan, 1986). The catalase, urease and invertase enzyme activities will further be abbreviated as CAT, URE and INV, respectively.

Soil water content was recorded at regular times 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. 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 and possible soil moisture content difference along the slope. Precipitation was measured by a tipping-bucket rain gauge connected to a nearby weather station (Environmental Measurement Limited, UK). Soil temperature was monitored by a Taylor[®] soil thermometer at three depths (0, 5 and 15 cm). Each plot was equipped with one set of thermometers in the middle of the plots.

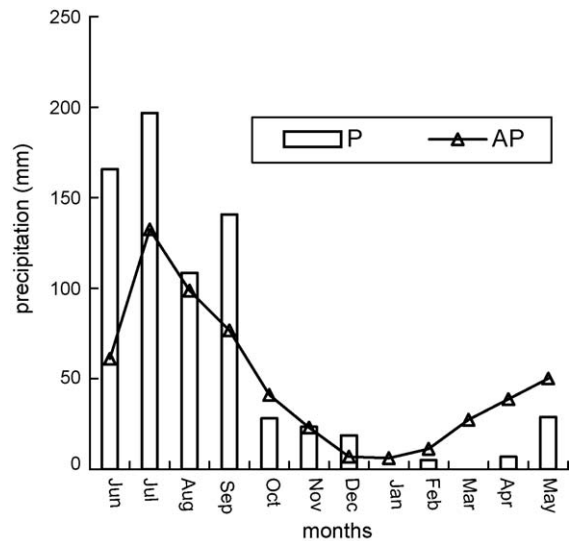


Fig. 1. Monthly precipitation (P) during the cropping season in 2005–2006 and average precipitation of the last 30 years (AP).

2.4. Climate

The climate of the region is classified as continental temperate, with hot, wet summers and cold, dry winters. During the period 1970–2006, the minimum temperature was –23.5 °C and the maximum 43.7 °C. The annual potential evaporation during this period was estimated to vary between 1262 and 1852 mm. Rainfall is 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. The total precipitation for the 2005–2006 cropping year (from June 2005 to June 2006) was 719 mm, which was 136 mm higher than the long-term average (Fig. 1). However, the distribution of rainfall was extremely uneven. The precipitation during the fallow months (from June to September of 2005) was as high as 624 mm accounting for 86.8% of total rainfall in the cropping year, while the precipitation during the growing period was only 95 mm, which was 110 mm less than in a normal year, causing a long dry spell lasting from January to the end of May.

2.5. Statistical analysis

Analysis of variance (ANOVA) was used to detect the treatment-effects on measured variables, and least significant difference (LSD) was used to compare means of measured enzyme activities, soil organic carbon and total nitrogen ($P < 0.05$). When comparing the tillage effects on soil chemical properties, the average value of downslope and upslope was used. Statistical procedures were carried out with the software package SPSS 10.0 for Windows (SPSS Inc., 2001).

3. Results

3.1. Tillage effects on enzyme activities

There were no significant differences in enzyme activities between the soils sampled at upslope and downslope positions of each plot at all sampling time (data not shown); therefore, only the average values for each plot at every sampling time are used. In general, all the studied enzymes showed a significant seasonal variation under all tillage treatments (Fig. 2) ($P < 0.05$). The catalase activities ranged from 3.06 to 6.90 ml KMnO₄ g⁻¹ h⁻¹. It

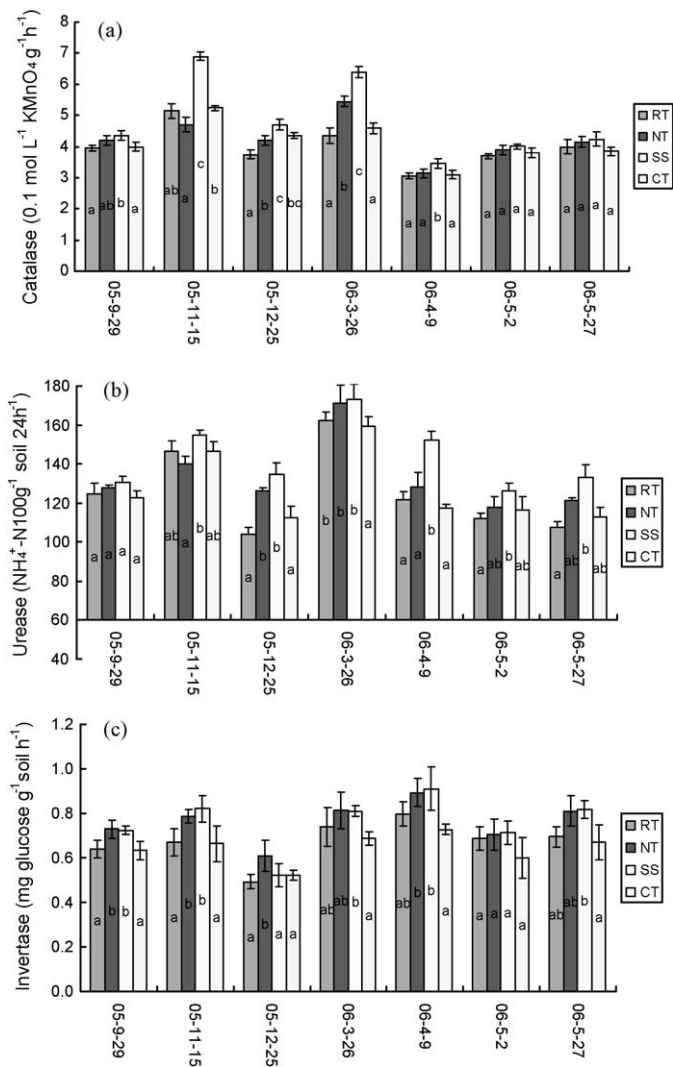


Fig. 2. Temporal change of catalase activities (a), urease (b) and invertase (c) during the winter wheat growing season under different tillage practices.

increased from sowing and reached its maximum before winter, then decreased in the winter time, reached a second peak value at the jointing stage, then dropped to a minimum in the anthesis stage and then continuously increased until maturity. The urease activities varied from 104 to 173 mg $\text{NH}_4^+\text{-N } 100 \text{ g}^{-1}$ soil and the highest URE was observed before winter and at jointing stages and the lowest URE was during winter, filling and maturity stages. The lowest INV appeared during winter whereas the peak value occurred in the stage of anthesis for all treatments.

Tillage practices had significant effects on enzyme activities ($P < 0.05$) during most of the growing season (Fig. 2). CAT under SS was higher than under CT, RT and NT in all stages, and this difference was significant before winter and in jointing and anthesis ($P < 0.05$). CAT was not statistically different for RT, NT and CT at all times except before winter and at jointing (Fig. 2a). No statistical difference in CAT was observed at filling and maturity stages between all treatments.

There were no significant differences in URE before sowing between different tillage practices, while during the growing period of winter wheat, URE under SS was significantly higher (Fig. 2b). NT had the lowest URE before winter but URE became significantly larger afterwards compared to CT and RT.

INV under NT and SS was generally significantly higher than that under CT and RT throughout the study period (Fig. 2c). There

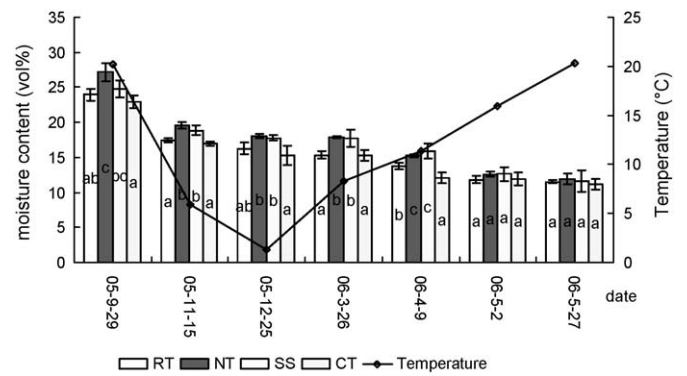


Fig. 3. Temporal change of soil water content and soil temperature during the winter wheat growing season in the different soil layers under different tillage practices.

was no statistical difference between SS and NT and between CT and RT throughout the growing season.

3.2. Soil moisture and temperature

Conservation tillage practices (NT and SS) had a noticeable positive effect on soil moisture content (Fig. 3). Comparisons of soil moisture at different depths revealed that the soil under CT and RT tended to be dryer than under NT and SS throughout the whole cropping season. The seasonal variation of soil moisture during the growing period was high under all tillage practices. For all treatments, the highest moisture content was observed at the end of September and it decreased strongly till the onset of winter, then it remained almost constant until jointing, and then decreased slightly again. In the stage of filling and maturity, soil moisture content was close to permanent wilting point (12.1%) due to the unusually long dry spell.

On the whole, the effect of different tillage practices and mulching on the soil temperature was small. The difference between warmest and coldest temperature during the growing season (from end of September to end of May) ranged from 19.0 to 19.8 °C at 0–10 cm depth. The soil temperature was the highest before sowing and at maturity (around 20 °C).

3.3. Organic carbon, total nitrogen and bulk density

Changes in frequency and intensity of tillage practices did not alter total nitrogen content and soil organic carbon of surface soil and its distribution along the slope in 2002 compared to that in 1999 (data not shown). However, a pronounced change of TN and SOC and its distribution along the slope was observed after 7 years consecutive tillage practices (Table 2). The NT and SS treatments increased the SOC by 4.4% and 2.5% respectively and TN contents

Table 2

The total nitrogen (TN) and soil organic carbon (SOC) contents in 0–10 cm under different tillage practices at the experimental station in Songzhuang (Henan province) in June 2006.

Treatment	TN (mg/ha)		SOC (mg/ha)	
	Lower	Upper	Lower	Upper
RT	1.228 (0.053) ^a	1.123 (0.067) ^a	14.62 (0.68) ^{ab}	13.65 (0.61) ^a
NT	1.382 (0.015) ^b	1.326 (0.016) ^b	14.79 (0.46) ^b	14.71 (0.45) ^a
SS	1.386 (0.018) ^b	1.352 (0.049) ^b	14.71 (0.26) ^b	14.26 (0.24) ^a
CT	1.308 (0.028) ^a	1.195 (0.029) ^a	14.52 (0.46) ^a	13.74 (0.90) ^a

Values between brackets indicate standard deviation. RT, reduced tillage; NT, no-till with mulch; SS, subsoiling with mulch; CT, conventional tillage. Average values in the same row followed by the same letter are not significantly different according to Student–Newman–Keuls test ($\alpha = 0.05$).

Table 3
Winter wheat yields of different treatments.

Year	RT	NT	SS	CT
1999–2000	3690 (52) ^a	3856 (166) ^a	4593 (272) ^b	4218 (225) ^{ab}
2000–2001	4047 (129) ^{ab}	4107 (62) ^{ab}	4246 (142) ^b	3922 (116) ^a
2001–2002	4473 (235) ^a	4897 (233) ^{ab}	5478 (366) ^b	5169 (472) ^{ab}
2002–2003	4347 (312) ^{ab}	4778 (168) ^{bc}	4857 (88) ^c	4019 (142) ^a
2003–2004	4109 (100) ^a	4270 (190) ^{ab}	4559 (268) ^b	4347 (145) ^{ab}
2004–2005	4574 (215) ^a	5292 (243) ^b	5245 (164) ^b	4801 (77) ^{ab}
2005–2006	5166 (193) ^a	5383 (64) ^b	5378 (64) ^b	5171 (55) ^a
Mean	4344	4655	4908	4521

Values between brackets indicate standard error; average values in the same row followed by the same letter are not significantly different according to Student–Newman–Keuls test ($\alpha = 0.05$). RT, reduced tillage; NT, no-till with mulch; SS, subsoiling with mulch; CT, conventional tillage.

by around 8% for both, while the adoption of RT did not change SOC and TN compared to CT. For the CT and RT, TN and SOC were larger in the lower part of the slope. The difference between upper and lower part was around 0.1 mg ha⁻¹ in TN for both, and 0.95 and 0.78 mg ha⁻¹ in SOC for CT and RT, respectively.

Changes in frequency and intensity of tillage practices altered the soil bulk density (ρ_b) in the 0–10 cm depth. NT had the highest ρ_b (1.561 ± 0.024 mg m⁻³), followed by SS (1.467 ± 0.039 mg m⁻³), but the difference was not statistically significant compared to CT (1.359 ± 0.081 mg m⁻³). The RT and CT had similar values of ρ_b .

3.4. Yield

The winter wheat yield was significantly affected by different tillage practices ($P < 0.05$) for all years (Table 3). In general, the highest yield was found in SS, which was statistically higher than CT. Weather conditions in the growing season appear to play an important role in the success of no-till systems. Compared to CT, yield under NT was increased significantly in 2002–2003 corresponding to a low precipitation during the fallow time (291.8 mm), whereas the yield was not significantly different between NT and CT in 2001–2002 and 2003–2004 corresponding to high precipitation years. Yield under NT in the last 2 years of our study was the highest of all treatments. Under RT, on average for all years, a decrease of 2% of yield was observed compared to CT.

4. Discussion

The redistribution of TN and SOC along the slope mainly resulted from soil erosion (Jin et al., 2008). Although a clear redistribution of TN and SOC along the slope was observed in the RT and CT plots, the enzyme activities at different positions of each plot did not show differences at any of the sampling times. This lack of differences can not be ascribed to interactions with different moisture contents or temperatures at different slope positions, since no significant differences in moisture content between slope positions were observed, and because temperature is not expected to differ between slope positions. Taking the variation of SOC and TN between the upslope and downslope positions into account, the enzyme activities did not respond to the spatial variation of soil chemical properties within a same plot sensitively. This finding contradicts earlier observations showing a strong dependence of enzyme activities on SOC (Degens et al., 2000; Kandeler et al., 2001). However, Gianfreda et al. (2005) investigated the activities of a range of enzymes using cultivated and non-cultivated soils from various parts of Europe and found that a high SOC does not necessarily reflect corresponding increases of enzymatic activities. In the present study, the lack of differences in enzyme activities at different slope positions might also be partially due to the sampling methods for the enzyme activities determination. Since

only three replicates were taken at each position in order to avoid excessive disturbance of the plots, there was only one degree of freedom and consequently, finding significant differences in enzyme activities in ANOVA was not evident.

Higher activities in the stages with vigorous vegetative growth (such as jointing stage and before winter) than in stages with productive growth (such as filling and maturity stages) of winter wheat for the three studied enzymes were observed for all plots, which indicates that the development of plant growth may have large impact on enzyme activities. This is in agreement with the findings of Niemi et al. (2005). Here, season had clear effects on the magnitude of differences in enzyme activities, but did not change the ranking of the enzyme activities in most seasons and SS had significantly higher enzyme activities in most cases. The higher URE and CAT in CT in November compared to NT could perhaps be partially explained by a flush of microbial activity directly after the tillage practice and straw incorporation as a result of an increase in substrate and oxygen availability (Kladivko, 2001). This effect was, however, only temporary and enzyme activities fell back to lower levels again at subsequent sampling stages.

The consistent ranking of enzyme activities between different soil management practices demonstrates that the activities of these enzymes could be a potential indicator for the effects of change in tillage on soil functioning and soil quality. The consistent higher enzyme activities in SS indeed coincided with higher productivity. Also the 7 years' different soil tillage practices and residue management had caused clear differences in soil chemical properties and soil bulk densities. The generally higher enzyme activities in SS mainly resulted from the larger water availability in the conservational plot rather than the better soil fertilities. NT and SS maintain residues near the soil surface, minimize soil disturbance and increase soil water storage (Table 3). The returning of straw into the field was also helpful to enhance enzyme production (Sun et al., 2003; Gianfreda et al., 2005).

Water is the most important factor affecting the yield of winter wheat in the Chinese Loess Plateau. The data of the water balance in our previous study has shown that although soil tillage practices had smaller influence on the magnitude of the water balance components than did variation in precipitation, small influences of the applied soil management practices on water conservation during the fallow period can greatly affect winter wheat yield (Jin et al., 2008). SS was the best practice in terms of water conservation, and hence more water will be available to the winter wheat in the growing period (Fig. 3). The reduction of yields under RT seems to be due to its poor performance in terms of water conservation.

Although water availability is the main yield-determining factor in the study region, it can be expected that in high precipitation years, such as in the fallow time of 2003 (830 mm rainfall in the fallow time), the effect of different tillage practices on the yield was determined to a larger extent by the difference in soil fertility because water was not the primary limiting factor. Although differences in yield between different treatments became smaller, the ranking of the different treatments did not change and SS still had significantly higher yield, which indicates that the effect of tillage on yield is more than a mere water conservation effect.

Even though NT had a comparable soil and water conservation effect to SS, the positive effect of NT on yield and enzyme activities was not as pronounced as with SS. The higher bulk density could account for this difference. Microbial numbers and enzyme activities were shown to be negatively and linearly related to soil bulk density (Li et al., 2002). SS loosens the soil and results in a lower bulk density than NT, and as a consequence, increases the soil aeration. Our results also showed sampling should be avoided during the winter time. The low soil temperature (0 °C) can dramatically suppress INV and mask the differentiation between

different treatments in winter time, as supported by ANOVA results.

The unexpected rapid decline of CAT activities in anthesis might result from the applications of omethoate, which severely depressed CAT in soil (Fig. 2). Protection against insects (mainly budworm) in the cultivars was applied in the anthesis stages when pest attacks are most likely to happen, by applying omethoate at a concentration of 35 mg l^{-1} . But it seems that the omethoate application had a negligible effect on the INV and URE activities.

Our study shows that throughout the wheat-growing season soil enzyme activities responded to tillage, residue management and sampling time. Because at the same time soil temperature and moisture content were monitored, an integrated and more complete perspective was obtained on dynamics of soil enzyme activities. It must be noted that our samples were taken over one growing period only, and the possibility of variation in seasonality from 1 year to the next exists. Comparison of climatic data from this year with averages from the past 30 years indicated that the precipitation during the growing period stage was unexpectedly low (95 mm) and not fully representative of typical seasonal changes in this climate. However, based on water balance calculations on the same site, the water content in the later stages of the growing period did not differ much among different years because the precipitation during the growing period of winter wheat always is much less than the water requirement of winter wheat (Jin et al., 2008). In this sense, the influence of seasonal variation from 1 year to the next is probably limited, especially in the later stages of the growing season.

5. Conclusion

Consistent differences in enzyme activities were observed between different tillage practices. These differences were most pronounced between subsoiling at the one hand and conventional and reduced tillage at the other hand.

Season had a clear impact upon the selected enzyme activities. The majority of the enzyme activities were higher in the stages with vigorous vegetative growth than in stages with productive growth. Although the magnitude of differences in enzyme activities between different treatments was not equal at different sampling dates, the effects of different soil management practices on soil enzyme activities were detectable in a consistent manner in samples from the majority of seasons.

Our study showed that changes in tillage practices resulted in important differences in yield, while all factors other than tillage were kept constant for all treatments. This is a strong indication for improved overall soil quality (as also substantiated by e.g. the changes in water storage in these soils). Enzyme activities followed this general trend in increased yield, and therefore seem to be valuable as indicators of overall changes in soil quality.

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