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ORIGINAL PAPER

Dynamics of soil organic carbon and soil fertility affected by alfalfa productivity in a semiarid agro-ecosystem

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Abstract We explore the dynamics of soil organic carbon of various forms and its relation with soil fertility in seeded alfalfa grassland established using a field micro-catchment technique to harvest water on the semiarid Loess Plateau in China. Five regimes were set up: (1) conventional flat cultivation without mulch (CK), (2) ridges and furrows were set up alternately on flat land, with 15 cm between each so that the distance between successive ridges (or successive furrows) was 30 cm, and the ridges were mulched with plastic film (M30), (3) similar to M30, but with twice the distance between furrows and ridges (M60), (4) similar to M30, but the ridges were not mulched (B30), (5) similar to M60, but the ridges were not mulched (B60). The increase in alfalfa forage yield in the mulch regimes promotes soil organic carbon (SOC) content, the light fraction of organic carbon (LFOC), the heavy fraction of organic carbon (HFOC) and microbial biomass carbon (MBC). MBC was significantly higher in M30 and M60 than in the other regimes. Significant positive correlation is found between MBC and LFOC ($R=0.89$; $P<0.0001$), and MBC and HFOC ($R=0.82$; $P=0.00016$). At the end of our three-year experiment, the C/N ratio of 10.09 in M60 was significantly ($P<0.005$) higher than the other regimes. Since a lower C/N ratio accelerates SOC decomposition in this region, the higher C/N ratio in M60 could limit mineralization of soil nitrogen, conserving soil nitrogen and SOC. The lower ratio of nitrate and nitrite nitrogen to total nitrogen, of 10.74, in M60 at the end of this experiment than in the other regimes and before sowing supports this point. The correlations of SOC with available P and with the ratio of available P to total P are positive in the dry year of 2001, but negative in the wet year of 2002. This can be explained on the basis that a high forage yield of alfalfa requires more soil available P in the wet years than in the dry years.

Keywords Alfalfa · Loess Plateau · MBC · Ridge and furrow · Semiarid soil fertility · Soil organic carbon

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Introduction

In the semiarid Loess Plateau region of Northwestern China, most soil types derive from calcareous loess (Wu et al. 2003) and are characterized by a low soil organic carbon (SOC) content of about 1%, occasionally reaching 1.5% (Li et al. 1998). Wu et al. (2003) reported that Huangmian soil, when used in cultivation, lost 77% of its SOC within 5 years (0–20 cm). This loss of SOC reduces the fertility of the soil (Jamalam et al. 1998) and may jeopardize future productivity. Changes in SOC also affect the concentration of atmospheric CO_2, which is the principal contributor to global warming (Janzen 1998). Generally, the climate conditions, water and wind erosion are the main reasons for a decline in organic carbon, but management practices are also significant.

In the last 20 years, in the semiarid Loess Plateau region, the crop yield per unit area has greatly increased as a result of new techniques including chemical fertilizer application, plastic film mulching, and rainwater-harvesting techniques (Li et al. 2003). However, new techniques would threaten sustainable land use. The local farmers preferred chemical fertilizer to organic manure (Liu et al. 2000), which created an imbalance between SOC and mineral forms of N and P. In every growing season, large amounts of chemical fertilizer N but very little organic manure is added to the soil. As a result there is positive feedback between the SOC content and the ratio of SOC to total soil nitrogen (C/N ratio) in typical agricultural Loessial soil areas (Song et al. 2003). Heavy application of chemical fertilizers reduces the C/N ratio and accelerates SOC decomposition, so that the C/N ratio is further reduced (Li et al. 2003). In this region, therefore, if farmers placed emphasis on improving the soil water-temperature conditions and the chemical fertilizer input but ignored the organic matter input or management, the C/N ratio would move further from the balance condition. Soil nutrition is a vulnerable area, and the soil would further degenerate (Li et al. 2003). Its maintenance is therefore important.

Conventionally, most crop straws are used as fuel, and farmyard manure is insufficient for agricultural needs. Grass-crop rotation may therefore be the only effective way to maintain and improve soil quality. Buyanovsky and Wagner (1997) reported that if forage legume crops such as timothy and alfalfa are included in rotation, the SOC increases. Conversion of land to permanent cover (grassland restoration) also increases SOC (Mensah et al. 2003).

The SOC is a heterogeneous material that can be separated into a light fraction (LF) and a heavy fraction (HF) by densitometry techniques (Janzen et al. 1992; Gregorich and Ellert 1993). The light fraction organic carbon (LFOC) cycles more rapidly and is more sensitive to agricultural practices than the total SOC or the complicated heavy fraction organic carbon (HFOC) (Christensen 1992; Janzen et al. 1992; Biederbeck et al. 1994; Gregorich et al. 1994). The release of soil nutrients through decomposition of soil organic matter by soil microbes plays an important role in agro-ecosystems (Bonde et al. 1988; Duxbury et al. 1991). Microbes influence soil quality by decomposing and transforming soil nutrients (Bottner 1985; Gupta and Germida 1988; Perfect et al. 1990; Yu et al. 1999). Thus, microbial activity indirectly determines the availability of soil nutrients, from which plants in turn affect the self-maintaining capacity of the soil (McGill et al. 1986; Powlson et al. 1987; Wick et al. 1998). Microbial biomass carbon (MBC) is a standard index of soil microbial activity (Wick et al. 1998). Tillage and other management practices greatly affects soil MBC and SOC (Cater 1986; Zhang et al. 1999). SOC, LFOC, and MBC are frequently measured to evaluate the influence of agricultural management practices on soil quality (Bremer et al. 1994; Gregorich et al. 1994).

Soil water deficits cause reduced alfalfa growth and reduced yields (Lucey and Tesar 1965; Bauder et al. 1987; Sheafer et al. 1998; Grimes et al. 1992). The alfalfa forage yield and water use efficiency is low and is unstable in conventional alfalfa cultivation in the semiarid Loess Plateau region (Yang et al. 2004). We have reported that a field micro-catchment technique for rainfall harvesting with mulching could reduce the establishment time, and increase the forage yield of alfalfa and the water use efficiency (Jia et al. 2006b). We have also reported that this technique can affect the soil nutrient balance (Jia et al. 2006a). The present study looks at: (1) effects of the establishment of alfalfa on MBC, SOC, LFOC and HFOC; (2) the relation between soil organic carbon forms and soil nutrients in various regimes. Our results suggest effective ways of sustaining the SOC and of improving the soil quality.

Materials and methods

Research site

The present field experiment was conducted from April 2001 to October 2003 at the Semiarid Ecosystem Research Station of Lanzhou University on the Loess Plateau (36°02 N, 104°25 E, 2400 m above sea level). The study area is located in Zhonglianchuan in the northern mountainous region of Yuzhong County, Gansu, China. The area has a medium temperate semiarid climate, with an annual mean air temperature of 6.5°C, a maximum temperature of 19.0°C (July), and a minimum of −8.0°C (January). The mean annual precipitation from 1999 to 2003 is 314.1 mm; about 56% of this falls between July and September. The water table is at least 20 m below the soil surface, so that underground water is not available for plant growth. The field site has a rusty colored dark loessial soil (Chinese soil Taxonomy) (Shi et al. 2003). In 2000, before the experiment, the site was planted with spring wheat, with about 220 fallow days before alfalfa was sown in 2001. Precipitation during the growing season (April–October) was 226.5 mm in 2001, 323.4 mm in 2002, and 294.6 mm in 2003.

Experimental setup and management

As part of the water micro-catchment technique, alternating ridges and furrows were set up on the flat land. The ridges acted as the rainfall harvesting zone and the furrows were the planting zone. Five regimes were set up: (1) conventional cultivation in a flat plot without mulch (CK), (2) ridges and furrows were set up alternately on flat land, with 15 cm between each so that the distance between successive ridges (or successive furrows) was 30 cm, and the ridges were mulched with plastic film (M30), (3) similar to M30, but with twice the distance between furrows and ridges (M60), (4) similar to M30, but the ridges were not mulched (B30), (5) similar to M60, but the ridges were not mulched (B60). Individual plots, 10.0 m long and 3.6 m wide, were replicated three times in a randomized complete block design. Before sowing, plastic film (PE film, 1.0 m wide and 0.008 mm thick) was mulched on the ridge surface of M30 and M60, with the edges of the plastic film buried under the soil. The ridge and furrow configuration was maintained after harvesting in 2001 and 2002, and was used in the subsequent growing season. Alfalfa was sown with a seed drill in mid-April 2001. In the 30 cm furrow, two rows were planted, whereas four rows were planted in the 60 cm furrow at a density of 22.5 kg ha^{-1}. In accordance with local practice, di-ammonium phosphate and urea were applied at the sowing depth, prior to sowing, so as to provide 34.5 kg N ha^{-1} and 8.0 kg P ha^{-1}. There was no irrigation, and the plots were weeded by hand. The alfalfa was harvested (cut near the soil surface) once in 2001, on 15 October, and in 2002 and 2003 it was harvested twice, on 15 July and 15 October.

Sampling and measurements

In each alfalfa plot field, 3 soil cores (diameter 8 cm and height 20 cm) of depth 0–20 cm were taken randomly within furrow before sowing or in mid-April, and at the time of the first harvest (mid-July) and the second harvest (mid-October) every alfalfa growing season from 2001 to 2003. Soil nutrients were analyzed using the methods outlined by Nanjing Agriculture University (1996). Organic carbon content was determined using an Elementar Analysensysteme (GmbH VarioEL) at 450°C. Available P was extracted by the Olsen method (Olsen et al. 1954), and total phosphorus content was determined by colorimetric measurement after digestion with $HClO_4$–H_2SO_4. Samples of dry weight 5 g were soaked in 50 ml 2 M KCL, shaken for 1 h, and analyzed with a Fluxion Injection Analyzer (Smith and Scott 1983) for nitrate nitrogen (NO_3-N) and nitrite nitrogen (NO_2-N). In the first 2 years of the experiment period we pre-measured ammonium nitrogen, but no significant difference was found among all the regimes during the alfalfa-growing season. Therefore, in the third year we did not measure the ammonium nitrogen in this paper. A KJ (Kjeldahl) Auto Analyzer (TECATOR Product, Sweden) was used to measure total soil N after digestion with salicylic acid-H_2SO_4.

In 2003, after sampling, soil samples were brought immediately to the laboratory for mixing. About 200 g of mixed fresh soil was stored at 4°C for microbial biomass determination. Soil MBC was determined by the chloroform fumigation extraction method (Voroney et al. 1993). Two aliquots of fresh soil sample were weighed in triplicates, and mixed with 0.5 M K_2SO_4 in the soil: K_2SO_4 ratio 1:2.5. One aliquot of soil sample was shaken on a mechanical shaker for 1 h at 200 rpm, and 1 ml of purified $CHCl_3$ was added to the other soil aliquot in a flask. The flask was sealed and shaken at 200 rpm for 1 h. Both aliquots were filtered and the fumigated aliquot was bubbled with air-free CO_2 for 30 s to remove the $CHCl_3$. After extraction, microbial biomass C was measured by directly determining C in the filtrate using the Elementar Analysensysteme (GmbH VarioEL) at 450°C. All the measurements for each sample were replicated 3 times, and the microbial biomass C and N were calculated by dividing the differences of C and N content in the non-fumigated and the fumigated soil samples by a conversion factor (K_{EC}) of value 0.18 (Voroney et al. 1993).

The LFOC and HOFC of soil samples taken before sowing and at the final harvest time were measured. The density fractionation scheme used for the light fraction (LF) is that described by Gregorich and Ellert (1993). In the fractionation, 25 g of air-dried soil (<2 mm) was shaken with 50 ml of NaI solution of density 1.70 g cm^{-3} for 1 h. After centrifuging, the supernatant was passed trough a Millipore filter and the LF was collected. Soil residue in the centrifuge tube was extracted again with NaI, and the additional LF was collected. The two parts of the LF were combined and the concentration of organic C was measured using the Elementar Analysensysteme (GmbH VarioEL). The soil residue in the centrifuge tube was washed with distilled water 3 times and then freeze-dried. The residue was taken to represent the heavy fraction, and the concentration of organic C in the heavy fraction was measured using the Elementar Analysensysteme (GmbH VarioEL).

Statistical methods

From the SAS package, ANOVA was used to conduct analysis of variance, and REG was used for linear regression.

Results

Soil microbial biomass C, soil organic C and its fraction

Significant differences were found in MBC between the regimes and between the sampling dates in 2003, and there was significant interaction between the regimes and the sampling dates (Table 1). The interaction between these two factors was significant at the three sampling dates. During the growing season, the soil MBC was increasing with the sampling dates. The soil MBC in the mulched regimes (M30 and M60) was always higher than in the others.

Total organic C (TOC), LFOC, and HFOC differed significantly among the regimes (Table 2). After the 3 years of growing seasons, TOC had increased significantly in the mulching regimes (M30 and M60), but decreased significantly in the control (CK) at 0–20 cm soil layer, while in the bare regimes (B30 and B60) the TOC leveled off. The light fraction organic C (LFOC) in all the regimes increased significantly in 2003 over its value before sowing, and the trend of the C concentration in LF in all the regimes was similar to the TOC. The order of LFOC was: M60>M30>B30>B60>CK. The HFOC amounts in all regimes in 2003 were also higher than before sowing, except for CK in which HFOC was not significantly different from at the start of the experiment.

Table 1 Soil MBC (mg kg^{-1} soil) of the topsoil layer of depth 0–20 cm and related analysis of variance in 2003

Date	CK	M30	M60	B30	B60	ANOVA	*P*-Value
15-Apr-03	233.0cC	269.1aC	259.4abC	251.9abcC	243.2bcC	Regimes	0.0001
15-Jul-03	260.6dB	304.4abB	317.3aB	292.1bcB	280.7dcB	Sampling date	0.0001
15-Oct-03	316.0dA	390.8bA	418.8aA	354.9cA	363.0cA	Interaction	0.0020

Values within columns in the same component followed by the same letter (lower case) or within the same row in the same component (upper case) are significantly different at $P<0.05$

CK: conventional cultivation in flat regime without mulch; M30 and M60: plastic mulched ridge with the width of ridge and furrow as 30 cm (M30) or 60 cm (M60); B30 and B60: bare ridge with width of ridge and furrow 30 cm (B30) or 60 cm (B60)

Table 2 Effect of various regimes on soil organic carbon (0–20 cm soil layers) and its different fractions

Date	Regimes	Soil organic carbon (t C ha^{-1})	Light fraction			HFOC (t C ha^{-1})
			Dry matter (g (kg soil)$^{-1}$)	C content (g C (kg soil)$^{-1}$)	LFOC (t C ha^{-1})	
Apr-01	Before sowing	23.840	5.336	63.806	0.818 (3.43)	19.580 (82.13)
Oct-03	CK	22.480	6.605	61.237	0.971 (4.32)	20.822 (92.63)
	M30	25.280	7.590	66.982	1.220 (4.82)	22.489 (88.96)
	M60	26.640	8.728	69.352	1.452 (5.45)	24.549 (92.15)
	B30	24.720	6.575	66.837	1.056 (4.27)	22.623 (91.52)
	B60	24.136	6.611	64.366	1.021 (4.23)	22.101 (91.57)
	LSD	0.822	0.376	2.743	0.079	1.485
	Pr.>F	0.0001	0.0001	0.0005	0.0001	0.0002

CK, M30, M60, B30 and B60 are as described in the Table 1 footnote

Values in brackets are the percentage of total organic carbon represented by each fraction

Significant positive correlation was found between the total forage yield and TOC (P=0.029), and between the total forage yield and LFOC (P=0.0013). There was no significant correlation between forage yield and HFOC.

Relation between soil microbial biomass C and soil nutrients

The soil nutrient content at the beginning and end of the experiment (Table 3) shows that nitrate and nitrite nitrogen and available phosphorus at the end of the experiment were significantly less than before sowing, and the decreases in M30 and M60 were significantly greater than in other regimes. The ratio of nitrate and nitrite nitrogen to total soil nitrogen (NN/TN) and the ratio of available phosphorus to total phosphorus (AP/TP) had the same trend as nitrate and nitrite nitrogen and available phosphorus. In October 2003, M60 had the lowest NN/TN and AP/TP, of 11.81 and 13.27 respectively. The total soil nitrogen in M30 and M60 at the end of the experiment were significantly greater than before sowing. However, the total phosphorus leveled off during the experimental period.

Significant positive correlation of MBC was found with SOC and total N in April and October (Table 4). Negative correlation of MBC was found with nitrate and nitrite nitrogen, NN/TN ratio at three sampling dates, and with available P, and AP/TP ratio in July and October 2003. Significant positive correlation of MBC was found with nitrate and nitrite nitrogen, NN/TN ratio, available P and the ratio of available P to total P using the pooled data for the whole year, but not between MBC and SOC.

There was a significant positive correlation between MBC and LFOC (R=0.89; $P<0.0001$), and MBC and HFOC (R=0.82; P=0.00016), at the last harvest time. No significant correlation was observed between MBC/SOC and soil nutrients in April 2003

Table 3 Effect of various regimes on soil nutrient contents (0–20 cm soil layers) at the beginning and end of the experiment

Date	Regimes	TN (g (kg soil)$^{-1}$)	NN (mg (kg soil)$^{-1}$)	NN/TN	TP (g (kg soil)$^{-1}$)	AP (mg (kg soil)$^{-1}$)	AP/TP
Apr-01	Before sowing	1.08	25.21	23.41	0.63	17.08	27.11
Oct-03	CK	1.08	15.84	14.66	0.63	11.73	18.74
	M30	1.09	13.17	12.03	0.62	9.05	14.52
	M60	1.10	11.81	10.74	0.64	8.44	13.27
	B30	1.08	17.95	16.56	0.62	13.23	21.27
	B60	1.08	17.16	15.83	0.62	14.16	22.91
	LSD	0.006	0.032		0.127	1.483	11.68
	Pr.>F	0.0001	0.0001		0.1523	0.0002	

CK, M30, M60, B30 and B60 are as described in the Table 1 footnote

NN/TN and AP/TP are the ratios of mineral N to total N and of available P to total P, respectively. NN: the sum of nitrate and nitrite nitrogen; TN: total nitrogen; AP: available phosphorus; TP: total phosphorus

Table 4 Correlation coefficient (*R*) and significance level (*P*) between MBC and soil nutrients in 2003

Date	Correlation level	SOC	TN	NN	NN/TN	AP	AP/TP
15 Apr 2003	*R*	0.74601**	0.60269*	−0.5490*	−0.56512*	0.21671	0.1231
	P	0.0014	0.01741	0.03401	0.02815	0.43787	0.66207
15 Jul 2003	*R*	0.16719	0.3628	−0.5470*	−0.55523*	−0.63179*	−0.60482*
	P	0.55146	0.18383	0.03479	0.03167	0.01152	0.01691
15 Oct 2003	*R*	0.87801***	0.82921***	−7.01E-01**	−0.70923**	−0.60662*	−0.58821*
	P	<0.0001	1.32E-04	0.00361	0.00307	0.0165	0.02109
2003	*R*	0.63845***	0.22691	−0.84307***	−0.81467***	−0.69762***	−0.67775***
	P	<0.0001	0.13388	<0.0001	<0.0001	<0.0001	<0.0001

NN/TN and AP/TP are the ratios of nitrate and nitrite nitrogen to total N and of available P to total P, respectively. NN: the sum of nitrate and nitrite nitrogen; TN: total nitrogen; AP: available phosphorus; TP: total phosphorus

*,**,*** mean $P \leqslant 0.05$, $P \leqslant 0.01$, $P \leqslant 0.001$, respectively

(Table 5). A significant negative correlation was found between MBC/SOC and nitrate and nitrite nitrogen, NN/TN ratio, available P, AP/TP ratio in July, whereas a significant positive correlation existed between SOC and total N at that time. Significant negative correlation of MBC/SOC was found with nitrate and nitrite nitrogen and the ratio of nitrate and nitrite nitrogen to total N in October. No significant correlation was observed between MBC/SOC and total P, available P and AP/TP ratio at that time, but there was a significant positive correlation between MBC/SOC and total N at that time. A significant negative correlation is also observed between MBC/SOC and nitrate and nitrite nitrogen, NN/TN ratio, available P and AP/TP ratio using the pooled data for the entire year.

Relation between soil organic C and soil nutrients

A significant positive correlation was found only between SOC and available P, and ratio of available P to total P in 2001 (Table 6). However, there was a significant negative correlation between SOC content and available P, and SOC and the ratio of available P to total P in 2002. A negative correlation was also found between SOC content and nitrate and nitrite nitrogen, and SOC and ratio of nitrate and nitrite nitrogen to total N in 2002 and 2003, but in those years there was a significant positive correlation between SOC content and total N. The significance levels of correlation between SOC content and soil total N, nitrate and nitrite nitrogen, the ratio of nitrate and nitrite nitrogen to total N, total P, available P, and the ratio of available P to total P were respectively P=0.0010, 0.00013, 0.0001, 0.0033, 0.00065 and 0.00029, based on the pooled data for the 3 years (Table 6).

In the 2001 growing season, the C/N ratio decreased in all regimes (Table 7). At the end of this growing season, the C/N ratio in the CK and M60 plots were significantly lower than in the other plots. At the end of the 2002 growing season, the C/N ratio of 8.31 in the B60 plot was significantly higher than in the other plots. At the end of the 2003 growing

Table 5 Correlation coefficient (*R*) and significant level (*P*) between MBC/SOC and soil nutrient contents

Date	Correlation level	TN	NN	NN/TN	TP	AP	AP/TP
15 Apr 2003	*R*	0.1426	−0.399	−0.38075	0.12538	0.13596	0.04209
	P	0.61216	0.14102	0.16148	0.65614	0.62899	0.88161
15 Jul 2003	*R*	0.67681**	−0.6580**	−0.70803**	0.38387	−0.5747*	−0.60069*
	P	0.00559	0.00765	0.00314	0.15778	0.02503	0.01788
15 Oct 2003	*R*	0.60375*	−0.5950*	−0.59773*	0.09188	−0.45227	−0.43355
	P	0.01716	0.01938	0.01861	0.74467	0.09053	0.10642
2003	*R*	0.0143	−0.70383***	−0.66508***	0.23951	−0.7185***	−0.71372***
	P	0.92572	<0.0001	<0.0001	0.11304	<0.0001	<0.0001

NN/TN and AP/TP are the ratios of nitrate and nitrite nitrogen to total N and of available P to total P, respectively. NN: the sum of nitrate and nitrite nitrogen; TN: total nitrogen; AP: available phosphorus; TP: total phosphorus

*,**,*** mean $P \leqslant 0.05$, $P \leqslant 0.01$, $P \leqslant 0.001$, respectively

Table 6 Correlation coefficient (*R*) and significant level (*P*) between SOC and soil nutrient contents

Year	Correlation level	TN	NN	NN/TN	TP	AP	AP/TP
2001	*R*	0.137	0.182	0.173	0.149	0.493***	0.434**
	P	0.369	0.231	0.256	0.328	5.84E-04	0.00289
2002	*R*	0.314*	−0.369*	−0.374*	0.179	−0.369*	−0.390**
	P	0.035	0.013	0.011	0.240	0.0125	0.00813
2003	*R*	0.443**	−0.602***	−0.606***	−0.151	−0.283	−0.247
	P	0.0023	< 0.0001	< 0.0001	0.321	0.0600	0.102
Three years	*R*	0.279**	−0.324***	−0.328***	0.251**	−0.290***	−0.307***
	P	0.00104	1.26E-04	1.02E-04	0.0033	6.47E-04	2.94E-04

NN/TN and AP/TP are the ratios of nitrate and nitrite nitrogen to total N and of available P to total P, respectively. NN: the sum of nitrate and nitrite nitrogen; TN: total nitrogen; AP: available phosphorus; TP: total phosphorus

*,**,*** mean $P \leqslant 0.05$, $P \leqslant 0.01$, $P \leqslant 0.001$, respectively

Table 7 Ratio of organic C to total soil N (C/N ratio) and ratio of organic C to available P (C/P ratio) in the 0–20 cm soil layer with various regimes over the three-year period

Regimes	Apr-01	Jul-01	Oct-01	Apr-02	Jul-02	Oct-02	Apr-03	Jul-03	Oct-03
C/N ratio									
CK	9.22aA	7.34cC	6.75bD	6.43tD	6.46tD	6.73tD	7.53yBC	8.09yB	8.67yA
M30	9.32aAB	8.10abC	8.04aC	7.46rC	7.85rC	7.74sC	9.38wAB	8.89wxB	9.62xA
M60	9.28aB	7.65bcEF	6.93bG	7.23rsFG	6.91stG	7.95rsDE	8.60xC	8.36xCD	10.09wA
B30	9.25aA	8.05abcB	7.91aBC	7.22rsD	7.39rsCD	7.81rsBC	9.13wxA	9.19wA	9.51xA
B60	9.22aA	8.72aBC	8.28aC	7.52rD	7.55rD	8.31rC	8.94wxAB	9.16wAB	9.28xA
C/P ratio									
CK	583.46aBC	544.85bCD	459.94bEF	401.73tF	452.33tEF	505.56uDE	534.94yCD	623.13zB	801.42yA
M30	583.46aDE	561.99bE	602.37aDE	429.88stF	653.43rCD	707.29sC	690.04wC	957.48wB	1165.13xA
M60	583.46aC	460.67cD	531.38abCD	417.18tD	450.72tD	817.75rB	624.00xC	877.58wxB	1326.07wA
B30	583.46aBCD	618.18aBC	542.03abDE	489.14rsE	555.10sCDE	608.29tBCD	648.04wxB	796.07xyA	779.37yA
B60	583.46aC	616.43aBC	563.66aCD	508.31rD	586.22sC	615.00tC	671.66wAB	726.07yzA	711.18yA

Value within columns followed by the same letter (lower case) or within the same row (upper case) differ significantly at $P < 0.05$

season, the C/N ratio increased significantly by 15% for CK and 17% for M60 over the value at the start of this growing season. The highest C/N ratio, of 10.09, was recorded in M60 three years after the mulched ridge and furrow system had been established. This value was significantly higher than any other. At the same time, the lowest C/N ratio occurred in the CK.

The C/P ratio at the end of the 2001 growing season was less in all plots than before sowing (Table 7). At the beginning of the 2002 growing season, C/P in all regimes was less than at the end of the 2001 growing season, but it then increased rapidly in all regimes. At the end of this growing season, the ordering of C/P was M60>M30>B30 (B60)>CK. At the start of the 2003 growing season, C/P in M30 and M60 was less than at the end of the 2002 growing season, but higher in the non-mulched regimes. At the end of the 2003 growing season, C/P in all regimes was significantly higher than before sowing, and was significantly higher in M30 and M60 than in the other regimes.

Discussion

Soil microbial biomass C and soil organic C

Microbial biomass C is a critical attribute of soil organic matter quality, since it provides an indication of a soil's capacity to store and recycle nutrients and energy. As a measure of organic matter quality, it also serves as a sensitive indicator of change and future trends in organic matter level and equilibrium (Gregorich et al. 1994, 1997). Fraser et al. (1996) reported that the MBC content generally increases with time under pasture and decreases with time under arable conditions, due to increased organic matter input under pasture and decreased input and increased decomposition in arable soil. Many reports also find that MBC is positively correlated with the soil organic matter concentration (Jenkinson and Ladd 1981; Smith et al. 1993; Woods and Schuman 1986). Our present results generally agree with those cited above, although the correlation was not observed on 15 July 2003. This is probably because the harvest disturbed the soil and the elimination of cover changed the topsoil temperature, temporarily changing the activity of soil microbes and the soil MBC. The micro-catchment system had a significant effect on MBC, but the effect differed among regimes. In 2003, MBC was higher in the mulched regimes (M30 and M60) than in the others as a result of the higher SOC content.

The light fraction of soil organic matter consists mainly of plant residues, small animals and microorganisms, which may be in various stages of decomposition. This pool of organic matter is important for the turnover of organic matter in agricultural soils because it serves as a readily decomposable substrate for soil microorganisms, and is a short-term reservoir of plant nutrients (Gregorich et al. 1994). In the present study, we found a significant positive correlation between MBC and LFOC. This suggests that the increase in alfalfa residue provided more substrate for microorganisms, causing the increase in MBC. Combined with the positive correlation between MBC and HFOC, this probably implies that the increase in productivity of alfalfa led to the increase in alfalfa residue, in turn increasing the MBC; moreover, through decomposition of the microorganism, the more labile components of soil organic carbon would be converted to stable components, increasing the HFOC. The increase in various components of soil organic carbon clearly increased the SOC content. Therefore, the increase in productivity of alfalfa is mainly responsible for the increase in SOC content.

Factors that may be responsible for the significant increase of SOC and LFOC associated with alfalfa include large amounts of organic materials from alfalfa surface litter, roots, and its exudates, usually greater than that of annual crops that are incorporated into soil and contribute to the increase in SOC and LFOC (Paustian et al. 1997). Moreover, the difference in SOC between alfalfa regimes was mainly responsible for the difference in input of dry matter of the LF, and the difference in forage yield of alfalfa in various regimes resulted in the difference in dry matter of the LF. Table 2 also shows that the increase in forage yield leads to a significant increase in LFOC.

Soil microbial biomass C, soil organic C and soil available nutrients

Li et al. (2004) showed that MBC is negatively correlated with available N and available P in the mulched spring wheat field with plastic film. Our present study finds a similar result in 2003. Li et al. (1998) reported a positive correlation between SOC and available N at different positions from the top of a hill in Loess Plateau soils. This sampling also showed that the available P was unaffected. In the present study, SOC is negatively correlated with mineralized N and with the ratio of mineralized N to total N in the 2002 and 2003 growing seasons. These results show that, although the increase in SOC resulted in an increase in microbial biomass, the increased microorganism activity did not correspondingly promote the mineralization of soil N, P but rather limited it. The explanation is that both microorganisms and the existing plants compete for soil nitrogen. When soil microorganisms become active, they decompose the organic matter and increase their biomass. In the same period, the plants grow rapidly and need much more soil nutrient than before. Competition for nutrients then occurs between plants and soil microorganisms (Li et al. 2004). Moreover, the C/N ratio of alfalfa residue exceeds 12 (Puget and Drinkwater 2001), and is higher than that of soil; the input of material having higher C/N ratio is probably another reason for this phenomenon. At the last harvest, the M60 regime had the highest SOC and C/N ratio, indicating that this regime is more effective in conserving soil nitrogen.

Soil organic C and soil N, P

The ratio of soil organic C to total soil N (C/N) is important in determining the ability of soil microorganisms to assimilate and mineralize N. Chen (1990) and Huang (2000) reported that C/N ratios of 5.6–11.3 enhance the mineralization of soil organic N and significantly increase the microbial biomass C; C/N ratios of 15.3–20.6 rapidly increase the microbial biomass C, and lead to complete decomposition of the soil organic matter, releasing mineralized N; and C/N ratios of 37.1–64.4 do not meet the demand of the microorganisms for N. In the semiarid Loess Plateau region, Song et al. (2003) found that the soil

C/N ratio ranged from 7.7 to 9.0 in a wheat-cultivated field. This is significantly less than 11.3, at which value the decomposition of soil organic matter is accelerated and organic nitrogen runs at the mineralizing level. In this region, therefore, increasing the SOC content and C/N ratio is crucial for improving the soil quality and reducing the N loss. In the present study, the C/N ratio in all regimes declined in the first growing season. Since, the input of organic matter is low as a result of the low productivity and residue of alfalfa in this season, the explanation is probably that the loss in SOC and N was different. Wang et al. (1999) showed that the loss of SOC was significantly higher than that of N in soil erosion; moreover, soil microorganisms would consume SOC for energy (Song et al. 2003). Both of these effects probably reduced the C/N ratio in the first season. Thereafter, more alfalfa residue was incorporated into the soil, increasing the SOC and N content and also the C/N ratio as a result of the higher C/N ratio in alfalfa residue than in local soil, since the C/N ratio of alfalfa is generally above 12 (Puget and Drinkwater 2001). At the end of our three-year experiment, the M60 regime had the highest C/N ratio, of 10.09. It follows that this regime is good at reserving organic N, with the benefit of sustaining the soil.

An examination of the nutrient content at different positions on a hill in the Loess Plateau soils in Northwest China about 2 months after harvesting of the crops indicated that the total P content increases linearly with increased organic matter content (Li et al. 1998). This work also shows that the available P content was unaffected. The present study found that a significant positive correlation of SOC with total P only when the data for the three years were pooled. However, differing correlations of SOC with available P and with the ratio of available P to total P were recorded in different years; the correlation was positive in 2001 but negative in 2002. Since 2001 was a dry year with only 226.5 mm rainfall, and 2002 was a wet year with 323.4 mm rainfall, it follows that in a dry year the increase in SOC would increase the accumulation of available P, and in the wet year the trend is reversed for alfalfa cultivation. A logical explanation is that alfalfa has different demand for available P in years having different precipitation. A wet environment could promote dry matter production in alfalfa (Grimes et al. 1992). Also, a high forage yield of alfalfa will require more soil available P in a wet year than in a dry year.

Conclusion

The increase in alfalfa forage yield in the mulch regimes promotes soil organic carbon (SOC) content, the light fraction of organic carbon (LFOC), the heavy fraction of organic carbon (HFOC) and microbial biomass carbon (MBC). MBC was significantly higher in M30 and M60 than in the other regimes. Significant positive correlation of MBC was found with LFOC and HFOC. At the end of our three-year experiment, the C/N ratio of 10.09 in M60 was significant higher than that of the other regimes. Since a lower C/N ratio accelerates SOC decomposition in this region, the higher C/N ratio in M60 could limit mineralization of soil nitrogen, conserve soil nitrogen and SOC. The lower ratio of nitrate and nitrite nitrogen to total nitrogen, of 10.74, in M60 at the end of this experiment than in the other regimes and before sowing supports this point. The correlations of SOC with available P and with the ratio of available P to total P are positive in the dry year of 2001, but negative in the wet year of 2002. This can be explained on the basis that a high forage yield of alfalfa requires more soil available P in the wet years than in the dry years.

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