Journal of Soil Science and Plant Nutrition
https://doi.org/10.1007/s42729-019-00106-y

ORIGINAL PAPER

An Approach to Improve Soil Quality: a Case Study of Straw Incorporation with a Decomposer Under Full Film-Mulched Ridge-Furrow Tillage on the Semiarid Loess Plateau, China

Feng ke Yang[1,2] · Baolin He[1,2] · Ligong Zhang[3] · Guoping Zhang[1,2] · Yingping Gao[3]

Received: 6 May 2019 / Accepted: 25 September 2019

Abstract
There is limited understanding of the effects of straw incorporation with decomposition agent (refer to decomposer) under full plastic film-mulched ridge-furrow tillage (FM) on straw decomposition rate and soil fertility. A direct field incubation test of straw with and without decomposer (T1 and T2) under FM using the litter bag method and a 3-year field experiment of five treatments including conventional planting (CP, as control), CP with straw incorporation (CP_S), CP with straw incorporation plus decomposer (CP_{SD}), FM with straw incorporation (FM_S), and FM with straw incorporation plus decomposer (FM_{SD}) were conducted in 2014–2016. The results showed that the initial straw N content, indigenous soil nitrogen content, and soil hydrothermal conditions were all remarkably affected by maize straw decomposition, and C and N release regardless of the decomposer. Applying the decomposer resulted in 80.3% decomposition of maize straw, leading to 81.3% of straw C and 83.3% of straw N release into the soil, which were 1.4, 1.1, and 1.06 times than that of CK, respectively. Meanwhile, the FM_{SD} was significantly better in improving soil nutritional conditions, particularly for the tested parameters of soil organic carbon (SOC), soil total nitrogen (TN), available nitrogen (AN), available phosphorus (AP), and available potassium (AK). Importantly, FM_{SD} drove a strong synergistic effect of decomposer and the modified soil hydrothermal conditions in comparison with CP, which led to the significant increase in SOC, TN, TP, AN, AP, and AK by 4.4–8.7%, 5.2–7.5%, 3.0–6.8%, 11.1–12.6%, 3.6–60.5%, and 6.2–54.6%, respectively. Therefore, FM_{SD} is the best model for more efficient and sustainable soil fertility management in semiarid areas in China.

Keywords Straw incorporation into topsoil · Straw decomposer · Soil fertility response · Full plastic film-mulched ridge-furrow tillage · Model

1 Introduction

Agricultural management measurements, such as tillage, straw mulching and incorporation, fertilization, and organic amendments, have played a great role in promoting soil fertility (Su et al. 2006; Diacono and Montemurro 2010; Cong et al. 2012; Laird and Chang 2013; Zhang et al. 2013; Shang et al. 2014; Vega-ávila et al. 2018) and soil productivity (Unger 1978; Blanco-Canqui and Lal 2009; Pan et al. 2009; Liu et al. 2014; Akhtar et al. 2018; Sheidai Karkaj et al. 2019). Particularly, the application of full plastic film-mulched ridge-furrow rainwater harvesting technique (FM) has not only increased soil water content due to the reduced soil evaporation (Li et al. 2016) but also greatly increased crop yield attribute to the increase in soil water content and temperature (Ye and Liu 2012; Gan et al. 2013; El-Sadek and Salem 2015). However, the low soil fertility (Zhang et al. 2016) resulting from intensive cropping negatively impacts on soil productivity in semiarid agroecosystems (Zhang et al. 2013, 2015; Liu et al. 2018).

Recently, a more effective integrated soil quality management pattern of fully plastic film-mulched ridge-furrow tillage with straw incorporation in topsoil (FM_S) replacing FM has

---

Feng ke Yang and Baolin He contributed equally to this work.

✉ Feng ke Yang
yang_fk@163.com

[1] Key Laboratory of High Water Utilization on Dryland of Gansu Province, Lanzhou 730070, China

[2] Institute of Dryland Farming, Gansu Academy of Agricultural Sciences, Lanzhou 730070, China

[3] Agricultural Technology Promotion Center of Zhuanglang County, Zhuanglang 744600, Gansu, China

been widely in use on the Loess Plateau. This technique is more efficient in improving the soil hydrothermal conditions and soil fertility via the synergistic effects of film and straw double mulching, and the additional organic matter from straw C input resulting in replenished soil nutrients and increased crop yields (Wang and Xing 2016; Liu et al. 2018; Yu et al. 2018). However, the slow decomposition rate of incorporated straw (Surekha et al. 2003; Li et al. 2012; Palika et al. 2013) remains to be the main challenge in the successful use of straw as a soil amendment. Many biotic and abiotic factors including the residues of lignin, cellulose, and polyphenol contents; soil moisture and temperature conditions; soil physicochemical properties; C/N ratio; N dose; soil microbial activities; and residue and soil particle size (Marrack and Germany 2004) drastically affect incorporation of straw decomposition (Wang et al. 2014; Zhou et al. 2015; Tang et al. 2016) which result in low soil nutrient availability and fertility (Zhou et al. 2015; Hu et al. 2018). Several studies have shown that the lignin, cellulose, and polyphenol contents, soil moisture, and temperature conditions are most important factors that dominate the decomposition of the incorporated straw; the soil biochemical processes carried out by microorganisms have a significant role in the degradation, transformation, and utilization of plant residue, thus are important regulators of SOM accumulation and nutrient cycling (Potthoff et al. 2008; Esther et al. 2013; Qin et al. 2015).

To hasten the decomposition of the incorporated straw, direct inoculation of straw with a decomposing agent (consisting of a combination of different fungi and bacteria strains) was used. This technique is being promoted in China (Li et al. 2012; Esther et al. 2013). Researchers have reported that the decomposing agent (refer to decomposer hereafter) can effectively accelerate straw decomposition and nutrient release through activating soil microorganisms activities thereby ameliorating the soil nutrient content and their availability, in turn aiding the soil productivity and sustainability in semiarid agroecosystem (Qin et al. 2015; Zhao et al. 2017). Previous studies conducted under short-term anaerobic incubation conditions (Palika et al. 2013; Wang et al. 2016) showed that the mass loss of straw was greater in deep straw incorporation than surface mulching and had substantial influence on the soil organic matter (SOM) and nitrogen (SON) accumulation (Blanco-Canqui and Lal 2009; Tang et al. 2016). However, studies of straw decomposition with and without a decomposer in the topsoil under fully film-mulched ridge-furrow tillage had not yet been systematically investigated.

SOC and soil nourishing nitrogen, phosphorus, and potassium elements are the important soil fertility and quality indicators (Gan et al. 2013) that play a crucial role in nutrient cycling and are often associated with dryland soil fertility (Wu et al. 2004; Xu et al. 2011). There has been an increased effort to develop more reasonable agricultural management practices based on a systematic understanding of the relationships between soil organic amendments and soil quality (Surekha et al. 2003; Huang et al. 2005). FM_S has significantly improved maize (*Zea mays* L.) yields on the Loess Plateau, while soil quality and fertility responses to straw incorporation considerably vary and are site-specific (Wang et al. 2015a; Zhang et al. 2016); thus, their sustainability is not well studied (Xu et al. 2015).

Hence, to investigate the effects of adding decomposer and FM tillage on the decomposition and nutrient releasing pattern, incorporated maize straw rate and the soil quality response are critical. Although there have been many research studies regarding ridge and furrow mulching technique (Wang et al. 2009, 2014; Zhou et al. 2009; Xu et al. 2015; Zhang et al. 2018) and straw decomposition (Palika et al. 2013; Tang et al. 2016), these studies separately investigated these issues, seldom paying attention to the integrated effect on soil fertility. Our purposes were to (1) investigate the effects of integrating FM_S tillage with a straw decomposer on the decomposition of buried straw and the nutrient release and (2) determine the consequences of the soil carbon and nitrogen dynamics and the response of soil fertility in order to update the FM_S system and develop a more efficient alternative pattern of increasing soil fertility and resilience for sustainable crop production on the semiarid Loess Plateau, China.

2 Materials and Methods

2.1 Field Site and Experiment Description

A field study was conducted from 2014 to 2016 at the Zhuanglang Agricultural Station of the Gansu Academy of Agricultural Sciences, Zhuanglang County, Gansu Province, China (106° 05′ 28″ E, 35° 10′ 30″, 1765 m a.s.l.), within a typical semiarid area of the Loess Plateau. The average annual precipitation was 510 mm, with approximately 70% falling from July through September. The average annual evaporation, temperature, and frost-free period were 1310 mm, 7.9 °C, and 145 days, respectively. Interestingly, the annual evaporation capacity (2014–2016) ranged from was 1310, 1307, and 1289 mm whereas the precipitation during the growing season (April 15–September 30) was 321, 520, and 397 mm, respectively. Taking into consideration the precipitation within the growing season, the years 2014, 2015, and 2016 represented a typically dry, wet, and normal year in comparison with the multi-year rainfall data (2000–2016) mean of 391 mm, respectively. The temperature and rainfall during the summer maize growing season during 2014, 2015, and 2016 are shown in Fig. 1. All the weather data were obtained from the nearest local weather station. The soil at the experimental site is classified as loessal soil (Chinese Soil Taxonomy Cooperative Research Group 1995) aligning with Calcaric Cambisols in the FAO soil map of the world (FAO-UNESCO 1990). The

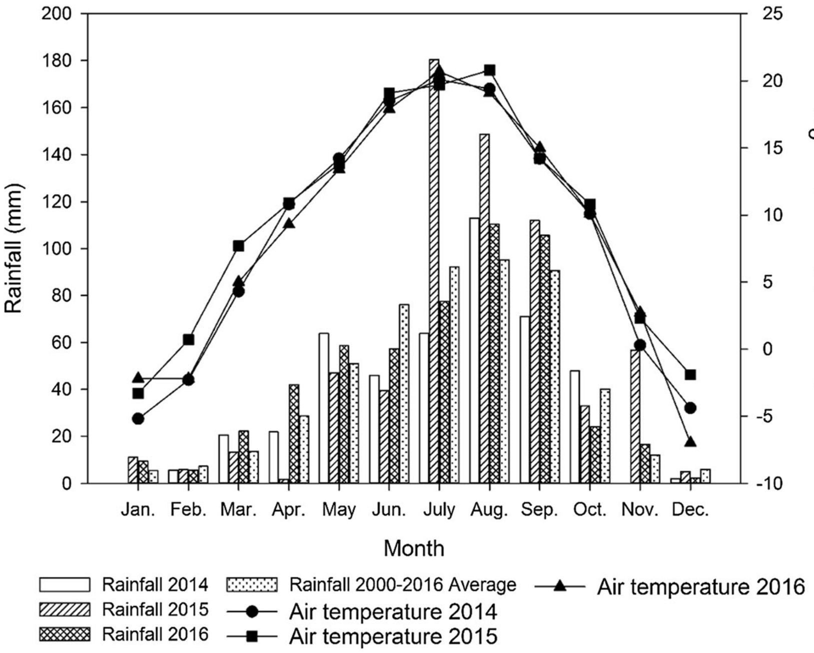

Fig. 1 The annual rainfall and average air temperature during 2014–2016 in the experiment site (Zhuanglang, Gansu, China), which were used to illustrate weather conditions of the experimental site

basal physicochemical characteristics of the 0–20-cm soil layers are listed in Table 1.

2.2 Experimental Design

2.2.1 Straw Decomposition (Litter Bag Study)

Direct field incubation with the buried maize straw test using the nylon mesh bag method (Puttaso et al. 2011) was used to study the characteristics of straw decomposition and straw carbon and nitrogen release dynamics. A commercially produced microbial compound (decomposer; produced by Beijing Jingpu Yuan Bioengineering Co., Ltd) consisting of combination of different fungi and bacteria with effective viable bacteria number exceeding 2×10^{10} g^{-1} was used. The test had two treatments as follows: (1) maize straw with decomposer (T1), 2 kg/1000 kg of straw and (2) maize straw without decomposer (T2). Approximately 100 polyethylene litter bags (25 × 35 cm, 40 mesh) containing 50 g of air-dried maize straw (length of 2–3 cm) were separately buried underneath the top 20-cm soil layer in each FM treatment. Each plot area measured 6 m by 4.4 m. The initial nutrient content of the maize straw was 482.85 g kg^{-1} of total organic carbon (TOC), 5.33 g kg^{-1} of total nitrogen (TN), 1.56 g kg^{-1} of total phosphorus (TP), and 22.40 g kg^{-1} of total potassium (TK), with C/N ratio of 90.60. Five litter bags for each treatment were randomly retrieved at 10, 20, 30, 60, 90, 120, 150, 180, 210, and 240 days after straw burial. In the laboratory, all the extraneous soil particles were carefully removed, followed by the brushing off of the organic matter in the litter bags. The remaining fine particulates were subjected to winnowing agitated by hand in a flat tray to further clear the lighter organic materials. Furthermore, the remaining litter was cleaned using running water, then oven-dried at 85 °C for 6 h. The final dry mass of each bag was accurately weighed and recorded. On the other hand, the straw carbon and nitrogen (total C and N) were estimated using the dichromate oxidation and Kjeldahl methods (Wang et al. 2014) at each sample time, respectively.

Table 1 The basal physicochemical characteristics of the 0–20-cm soil layers at the experimental fields of Zhuanglang Experimental Station, Gansu Province, China in 2014

pH	SOM	TN	TP	TK	AN	AP	AK	BD
8.5	15.70	0.86	0.70	19.5	96.5	15.0	176.6	1.29

SOM soil organic matter (g kg^{-1}), *TN* total nitrogen (g kg^{-1}), *TP* total phosphorus (g kg^{-1}), *TK* total potassium (g kg^{-1}), *AN* available nitrogen (g kg^{-1}), *AP* available phosphorus (mg kg^{-1}), *AK* available potassium (mg kg^{-1}), *BD* soil bulk density (g cm^{-3})

At a specific interval, five soil samples of 0–30 cm in the soil profile were randomly collected using an "S" shape sampling technique before incorporation of organic residue. These were 0, 20, 30, 60, 90, 120, 150, 180, 210, and 240 days after the burial of the litter bags. The soil organic carbon (SOC), nitrogen (SON), soil bulk density (BD), 0–100-cm soil layer water content (W_{100}), and 0–25-cm soil layer temperature (T_{25}) were simultaneously measured at each sampling time. SOC and SON were evaluated from air-dried soil samples (sieved through a 2-mm sieve) using the dichromate oxidation and micro Kjeldahl methods, respectively. The BD was determined using the core cutter method; soil moisture content was determined gravimetrically whereas the soil temperature was measured using geothermometers.

The residual mass rate and decomposition rate of straw during maize straw decomposition process were calculated according to Puttaso et al. (2011) and Wang (2015) as follows:

$$\textit{Straw residual mass rate } (\%) = \frac{M_t}{M_0} \times 100 \tag{1}$$

$$\textit{Straw decomposition rate } (\%) = \frac{(M_0 - M_t)}{M_0} \times 100 \tag{2}$$

where M_0 is the initial straw residue mass, g, and M_t is the straw residue mass at time t, g. The relationship of the maize straw residue rate (%) changes over time was fitted as follows:

$$y = y_0 + \alpha \times \exp^{-\kappa t} \tag{3}$$

where y is the proportion of the maize straw mass at time t count for the initial straw mass, g; κ is the decomposition rate constant calculated using the least-squares method; and y_0 is the asymptote value of y when t is ∞, g.

Straw C and N release to the soil was determined individually as follows:

$$\textit{Carbon released quantities } (\mathrm{g}) = (C_0 \times M_0 - C_t \times M_t) \times 10^{-3} \tag{4}$$

$$\textit{Nitrogen released quantities } (\mathrm{mg}) = \left(N_0 \times M_0 \times 10^{-3} - N_t \times M_t \times 10^{-3}\right) \times 10^{-3} \tag{5}$$

where C_0 and N_0 are the initial straw C and N content, g kg^{-1}; C_t and N_t are the straw C and N content at time t, g kg^{-1}; and M_0 and M_t are the same as in Eqs. 1 and 2. Straw C and N release quantities were fitted as Puttaso et al. (2011) reported as follows:

$$C_t = C_0 \times \left(1 - \exp^{-\kappa_0 t}\right) \tag{6}$$

$$N_t = N_0 \times \left(1 - \exp^{-\kappa_0 t}\right) \tag{7}$$

where C_t and N_t are the straw C and N accumulative mineralization mass, g and mg; C_0 and N_0 are straw C and N mineralization potential, g and mg; k_0 is the constant of the C and N mineralized rate; and t is the straw burial time.

2.2.2 Field Experiment

A field experiment to investigate the effects of FM$_S$ with straw decomposer on soil properties was conducted from 2014 to 2016. A local best maize (*Zea mays* L.) cv. termed as Funong No. 1 was selected. The treatments were laid out in a randomized complete block design with three replications including the following five treatments: (1) conventional planting (CP) or traditional planting, i.e., local farmer's standard way of planting, no plastic film mulching as well as straw retention (CK); (2) CP with straw incorporation and without a decomposer (CP$_S$); (3) CP with straw incorporation and with a decomposer (CP$_{SD}$); (4) full film-mulched ridge-furrow tillage with straw incorporation and without a decomposer (FM$_S$); and (5) full film-mulched ridge-furrow tillage with straw incorporation and with a decomposer (FM$_{SD}$). The FM$_S$ and FM$_{SD}$ plots were implemented by first cutting the air-dried maize straw into a 2–3-cm length segments and evenly scattering them on the soil surface, then uniformly mixed with the top 20–25 cm of soil using a spade. The FM$_S$ and FM$_{SD}$ plots were then set up according to a method previously described by Jiang and Li (2015) in Fig. 2. Approximately 7500 kg ha^{-1} of maize straw and 2 kg of decomposer per 1000 kg of straw were thoroughly mixed and used in the FM$_S$ and FM$_{SD}$ plots, respectively. At the end of each growing season, the plastic residues were completely removed, followed by the establishment of the FM$_S$ and FM$_{SD}$ plots without the incorporation of straw, mainly for the next season. The maize seeds were sown in the furrows at a planting density of approximately 55,000 plants ha^{-1} (an average of approximately 55 cm between rows and 33 cm between two plants in rows) using a handheld device. All the 25 plots were randomly arranged. Weeding and pest control were carried out to maintain the clean plots.

The FM$_S$ and FM$_{SD}$ plots were established approximately 2 or 3 weeks ahead of sowing. The total fertilizer dosages used was based on the recommended rates for maize crop in the area, consisting of 90 kg P_2O_5 and 240 kg N ha^{-1}. The total phosphorus and a third of the nitrogen fertilizer were applied as a basic fertilizer before setting up FM technique, whereas the remaining two thirds of the nitrogen fertilizer was applied through the placement method at a depth of 10 cm in spaces between the plants using a manually operated device during the shooting stage (55–60 DAS) each year. Maize seeds were sown at mid-April and harvested at the end of September at each growing season.

2.2.3 Soil Sampling and Measurement

A total of five soil samples from each plot were taken in an "S" shape at a depth of 0–30-cm soil layer using an auger (5.5-cm inner diameter) before and after maize harvest each year. The soil samples of each plot were manually mixed to a 1-kg composite sample. The samples were sieved through a 2-mm sieve where roots and other debris were removed and cleared. Subsequently, the air-dried samples were processed to determine the soil organic carbon (SOC) and soil total and available nitrogen, phosphorus, and potassium (TN, TP, TK and AN, AP, AK) concentrations as mentioned by Su et al. (2006). Eventually, the soil BD at 0–30-cm depth was determined using a cut

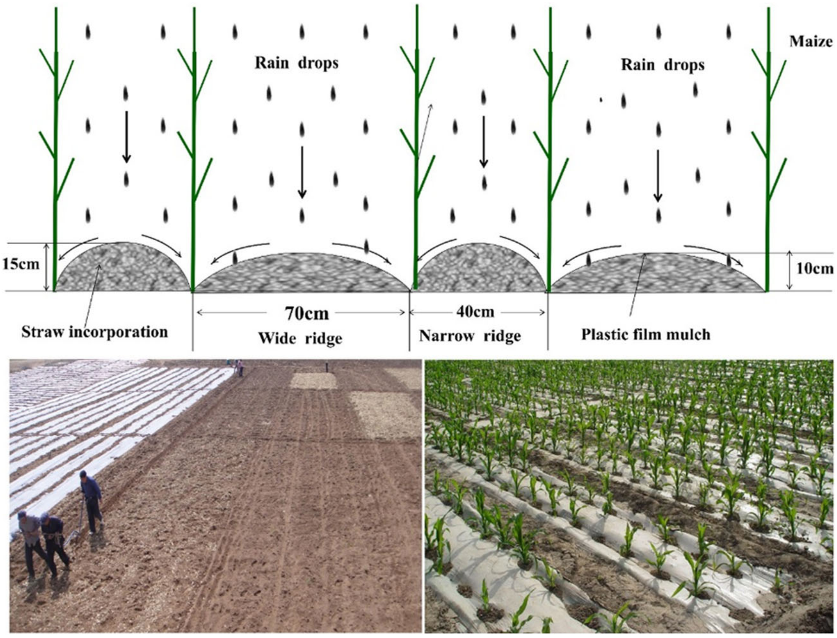

Fig. 2 Diagrammatic sketch of typical film-mulched ridge-furrow with straw incorporation maize cropping system (FM_S) and field layout. It is showing that the FM_S and FM_{SD} plots were implemented by first evenly scattering the 2–3-cm chopped maize straw (with and without decomposer) on the soil surface, buried by plowing, followed by building of the narrow (15 cm high × 40 cm wide) and wide (10 cm high × 70 cm wide) ridges alternatively arranged, with maize seeded in furrows

ring (volume of 100 cm^3) both at the beginning of the field experiment and during October of 2016.

2.3 Statistical Analysis

The significant difference of the buried straw decomposition residue and straw C and N release rate with and without decomposer was compared using a *T*-pair test ($p < 0.05$). The field experiment data were tested via ANOVA using IBM SPSS 19 (IBM Institute Inc., USA), and the significant differences between the treatments were compared based on the least significant difference test (LSD, $p < 0.05$) using mean data values. Importantly, relationships between various soil and residue factors in the straw decomposition and straw carbon and nitrogen release processes were analyzed using Pearson's correlation coefficient. Curve fitting and figures were generated using SigmaPlot 14.0.

3 Results

3.1 Residue Decomposition and Straw C and N Release (Litter Bag Test)

The buried maize straw residue followed an exponential decay pattern, uniformly trending as a fast reduction and then steady gradual reduction with incubation time, regardless of decomposer application. The measured straw mass loss at the end of 240 days of incubation was 80.3% in T1, 11.2% faster than that in T2 (72.2%) and with a statistically significant difference at the $p < 0.05$ level (Fig. 3a). Curve fitting using the first-order kinetic Eq. 3 showed that the constant decomposition rate κ was 0.01365 day^{-1} ($R^2 = 0.9844$, $p < 0.0001$) and 0.0096 day^{-1} ($R^2 = 0.9848$, $p < 0.0001$) with half-lives ($t_{0.5}$) of 73.3 and 104.2 days under T1 and T2 (Fig. 3b), respectively.

The rapid loss of the straw mass consequently resulted in the considerable available carbon and nitrogen released. This release showed a similar trend of a fast release during the first 90 days then a slow release until the end of 240 days of incubation regardless of the decomposer addition (Figs. 4 and 5), but the cumulative quantity released was significantly different ($p < 0.05$) between T1 and T2. Approximately 81.3 and 73.8% of the initial straw C mass were lost, i.e., 19.67 and 17.87 g of straw C were cumulatively released in T1 and T2, respectively. As fitted by Eq. 6, the κ and half-life ($t_{0.5}$) values in T1 and T2 were 0.0195 g day^{-1} ($R^2 = 0.9926^{***}$, $p < 0.0001$) and 51.3 days and 0.0220 g day^{-1} ($R^2 = 0.9892^{***}$, $p < 0.0001$) and 45.5 days, respectively, as indicated in (Fig. 4b).

Simultaneously, about 222.47 and 198.97 mg of straw N accounting for 83.3% and 74.5% of the original straw N were released under T1 and T2 (Fig. 5a), respectively. Furthermore, a curve fitting using Eq. 7 showed that the κ and half-life ($t_{0.5}$) values of straw N release were 0.0134 mg day^{-1} ($R^2 = 0.9821^{***}$, $p < 0.0001$) and 74.6 days under T1 and 0.0142 mg day^{-1} ($R^2 = 0.9050^{***}$, $p < 0.0001$) and 70.4 days under T2 (Fig. 5b).

The overall results showed the rates of buried corn straw initial mass loss and straw C and N release were 1.42, 1.13, and 1.06 times higher under T1 than those under T2, yielding approximately 11.2% more initial mass loss, 10.7% more straw C, and 11.81% more straw N release during the 240 days of direct field incubation.

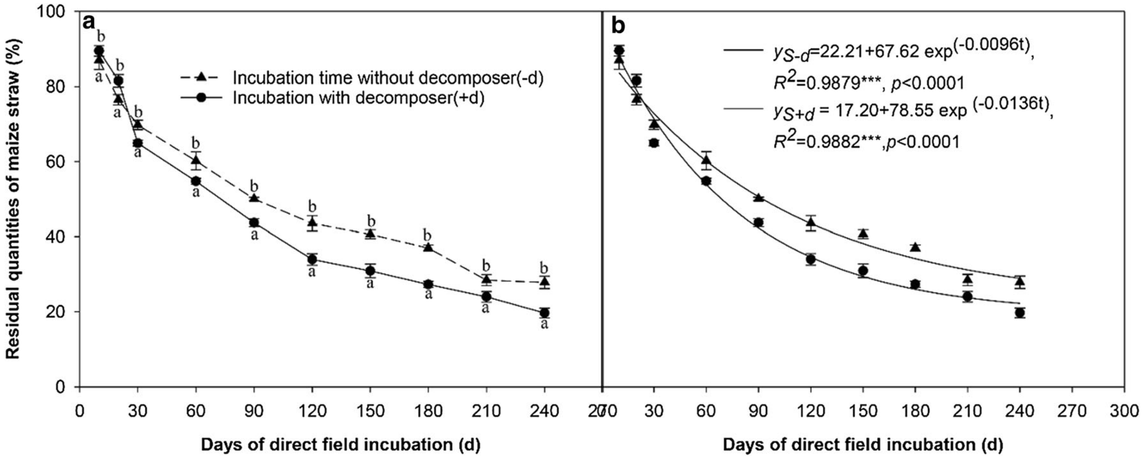

Fig. 3 Initial dry mass remaining (%) of buried maize straw with and without decomposer during the 240 days of direct field incubation test, indicating the proportion of maize straw that degraded with incubation time. **a** Original curve. **b** Fitting curve by using the single exponential decay equation, $y = y_0 + a \times \exp^{-kt}$. – d and + d means with and without decomposer; $y_{S-\mathrm{d}}$ and $y_{S+\mathrm{d}}$ were the straw residue rates under the condition of with and without decomposer with test time, respectively. Error bars represent standard error. The different small letters show a significant difference at $p < 0.05$ level (*T* test)

3.2 Changes in Soil Properties After Straw Incorporation with Decomposer

3.2.1 Soil Bulk Density

The addition of the straw decomposer had no significant effect on soil bulk density (BD), but it greatly decreased as compared with that of the CP. The average soil BD in the 0–30-cm soil layer decreased in all straw incorporation treatments by 4.7%, 3.9%, 2.3%, and 1.6% after 3 years of experiment, corresponding to $\mathrm{FM_{SD}}$, $\mathrm{FM_S}$, $\mathrm{CP_{SD}}$, and $\mathrm{CP_S}$, respectively. The observed trend of BD decline was in the order of $\mathrm{FM_{SD}}$ and $\mathrm{FM_S}$ < $\mathrm{CP_{SD}}$ and $\mathrm{CP_S}$ across the 2014–2016 study period (Table 2).

3.2.2 Soil Organic Matter, Nitrogen, Phosphorus, and Potassium Content

The selected parameters of soil chemical properties were all significantly improved across the three growing seasons, and they were more noticeable for SOC, TN, AN, AP, and AK both in individual test year and in the average years (Table 2). The straw incorporation treatments ($\mathrm{FM_{SD}}$, $\mathrm{FM_S}$, $\mathrm{CP_{SD}}$, and $\mathrm{CP_S}$) were significantly ($p < 0.05$) effective in improving these parameters with $\mathrm{FM_{SD}}$ being the highest and $\mathrm{CP_S}$ recording the lowest with respect to CP. Interestingly, although TP content showed the same trend as that of average SOC, a small effect occurred with the different treatment during different test years with $\mathrm{CP_{SD}}$ having the highest level during 2014 and $\mathrm{FM_{SD}}$

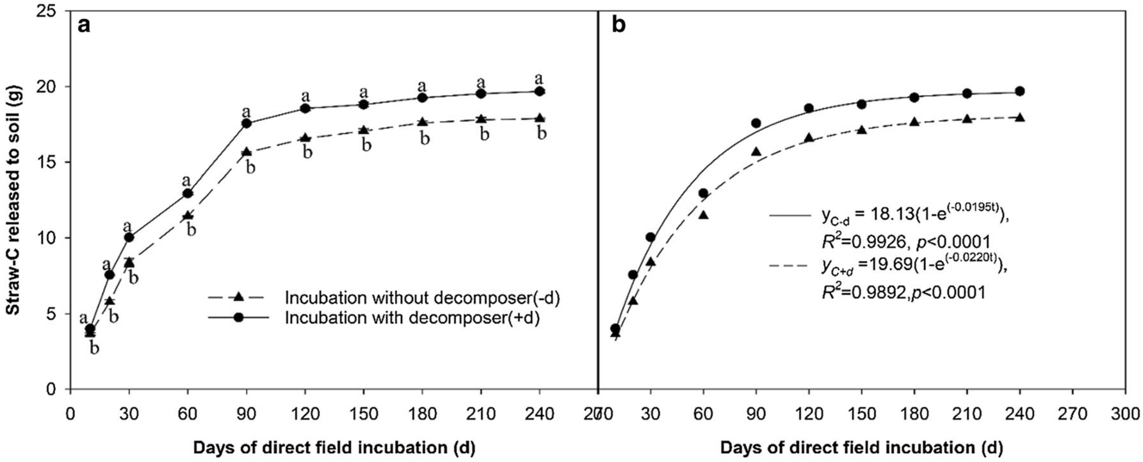

Fig. 4 Cumulative quantities of straw C released during the decomposition process of buried maize straw under different treatments during the 240 days of direct field incubation test. **a** Original curve. **b** Fitting curve he single exponential equation, $C_t = C_0 \times (1 - \exp^{-k0 \times t})$. – d and + d means with and without decomposer; $y_{C-\mathrm{d}}$ and $y_{C+\mathrm{d}}$ were the cumulative quantities of straw carbon released under the different treatments during the test period with test time, respectively. Error bars represent standard error. The different small letters show a significant difference at $p < 0.05$ level (*T* test)

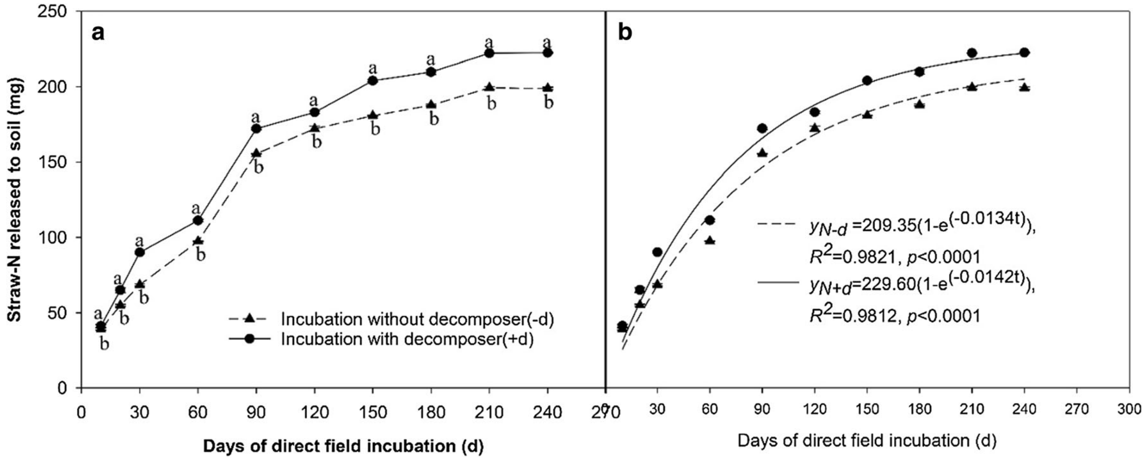

Fig. 5 Cumulative quantities of straw nitrogen released induced by different treatments during the 240 days straw decomposition process. **a** The original curve and **b** the fitting curve by using the single exponential equation, $N_t = N_0 \times (1 - \exp^{-k0 \times t})$. $y_{N-\mathrm{d}}$ and $y_{N+\mathrm{d}}$ were the cumulative quantities of straw carbon released primed by both without and with decomposer during the test period, respectively. Error bars represent standard error. The different small letters show significant difference at $p < 0.05$ level (T test)

higher during 2015 and 2016. In addition, the TK and AN content slightly changed in contrast to the others both within treatments and test years, with FM$_{\mathrm{SD}}$ the highest on average, CP$_{\mathrm{SD}}$ and FM$_{\mathrm{SD}}$ equally high during 2014 and 2015, and FM$_{\mathrm{SD}}$ was the highest during 2016. Furthermore, all the selected soil parameters remarkably improved ($p < 0.05$), in comparison with compared soil nutrient content at the initial stages before tillage (Table 1), i.e., the 3-year average SOC, TN, TP, AN, AP,

Table 2 Soil organic carbon (SOC), soil bulk density (BD), total and available N, P, and K content under different treatments with and without decomposer during the spring corn–growing season in 2014–2016

Year	Treatment	BD	SOC	TN	TP	TK	AN	AP	AK
2014	CP	1.29 (0) a	9.40 (0.1) c	0.87 (0) c	0.69 (0)b	19.61 (0.5) b	101.3 (2.4) c	15.1 (0.4) c	180.98 (4.29) c
	CP$_{\mathrm{S}}$	1.28 (0) ab	9.51 (0.2) bc	0.89 (0) b	0.71 (0) a	20.25 (0.4) a	104.2 (1.3) b	15.4 (0.1) bc	185.05 (1.69) c
	CP$_{\mathrm{SD}}$	1.27 (0) bc	9.63 (0.2) b	0.91 (0)a b	0.72 (0) a	20.17 (0.4) ab	106.8 (1.0) a	15.7 (0.1) b	190.93 (1.77) b
	FM$_{\mathrm{S}}$	1.26 (0) c	9.80 (0.1) a	0.91 (0) a	0.71 (0) a	20.32 (0.1) a	101.0 (0.6) c	23.1 (0.1) a	260.99 (1.52) a
	FM$_{\mathrm{SD}}$	1.26 (0) c	9.86 (0.1) a	0.91 (0) a	0.72 (0) a	20.32 (0.1) a	102.6 (0.6) bc	23.4 (0.1) a	262.55 (1.55) a
2015	CP	1.29 (0) a	9.34 (0.2) c	0.88 (0) c	0.71 (0) c	19.70 (0.2) b	102.4 (1.0) c	15.3 (0.1) b	182.48 (1.74) b
	CP$_{\mathrm{S}}$	1.27 (0) b	9.45 (0.3) b	0.90 (0) c	0.72 (0) b	20.10 (0.2) b	106.6 (1.0) ab	15.3 (0.1) b	186.10 (1.74) b
	CP$_{\mathrm{SD}}$	1.26 (0) c	9.63 (0.1) b	0.92 (0) ab	0.73 (0) ab	20.49 (0.2) a	108.2 (0.3) a	15.5 (0.4) b	189.39 (0.66) b
	FM$_{\mathrm{S}}$	1.25 (0) c	9.92 (0.1) a	0.91 (0) ab	0.73 (0) a	20.39 (0.2) a	104.4 (0.6) c	23.4 (0.2) a	264.04 (1.77) a
	FM$_{\mathrm{SD}}$	1.25 (0) c	9.98 (0.2) a	0.93 (0) a	0.74 (0) a	20.99 (0.8) a	107.0 (3.5) ab	24.2 (1.1) a	271.39 (9.67) a
2016	CP	1.27 (0.2) a	9.45 (0.2) b	0.89 (0) c	0.72 (0) b	20.06 (0.7) b	106.2 (3.3) c	15.4 (0.3) b	185.87 (3.21) b
	CP$_{\mathrm{S}}$	1.25 (0.2) ab	9.63 (0.4) b	0.93 (0) ab	0.74 (0) b	20.90 (0.2) b	110.8 (1.2) b	15.9 (0.2) b	191.25 (2.94) b
	CP$_{\mathrm{SD}}$	1.25 (0.1) b	9.57 (0.4) b	0.90 (0) ab	0.72 (0) b	20.36 (0.9) b	107.6 (4.3) c	15.5 (0.5) b	187.92 (5.70) b
	FM$_{\mathrm{S}}$	1.24 (0.1) b	9.98 (0.2) a	0.93 (0) ab	0.74 (0) ab	20.47 (0.8) ab	114.9 (0.9) ab	23.9 (0.6) a	274.44 (4.30) a
	FM$_{\mathrm{SD}}$	1.23 (0.1) b	10.03 (0.2) a	0.93 (0) a	0.79 (0.1) a	22.76 (2.3) a	116.3 (1.9) a	24.6 (1.1) a	284.88 (13.02) a
2014-2016 Average	CP	1.28 (0) a	9.40 (0.1) c	0.88 (0) c	0.70 (0) b	19.79 (0.3) b	103.3 (1.6) b	15.3 (0.2) b	183.11 (2.27) b
	CP$_{\mathrm{S}}$	1.27 (0) b	9.51 (0) b	0.90 (0) b	0.72 (0) b	20.44 (0.2) ab	107.2 (0.5) a	15.5 (0) b	187.47 (0.74) b
	CP$_{\mathrm{SD}}$	1.26 (0.1) b	9.57 (0.1) b	0.91 (0) ab	0.72 (0) b	20.34 (0.4) b	107.5 (1.3) a	15.5 (0.2) b	189.42 (1.80) b
	FM$_{\mathrm{S}}$	1.25 (0) bc	9.92 (0.1) a	0.91 (0) ab	0.73 (0) b	20.39 (0.2) ab	106.8 (0.4) a	23.5 (0.2) a	266.49 (1.70) a
	FM$_{\mathrm{SD}}$	1.24 (0) c	9.98 (0.2) a	0.92 (0) a	0.75 (0) a	21.36 (1.0) a	108.6 (1.8) a	24.1 (0.7) a	272.94 (7.27)a

Values followed by the same lowercase letter indicate that mean values with standard errors in parentheses of SOM, total and available N, P, and K, and BD are significantly different (at $p < 0.05$) between treatments. Different letters in the same column indicate significant differences ($p < 0.05$)

CP conventional planting, *CP$_S$* conventional planting with straw incorporation, *CP$_{SD}$* conventional planting with straw incorporation plus decomposer (refer to straw cellulose degradable microbial compound), *FM$_S$* fully film-mulched ridge-furrow planting with straw incorporation, *FM$_{SD}$* fully film-mulched ridge-furrow planting with straw incorporation plus decomposer

Table 3 Pearson correlation coefficients (r) relating residue chemical compositions to buried maize straw decomposition and straw C and N release rate during the incubation period

Parameters	Periods (day)	Without decomposer			With decomposer		
		C_S	N_S	C/N$_{\text{straw}}$	C_S	N_S	C/N$_{\text{straw}}$
k_s	30	0.869**	− 0.142	0.755**	0.860**	− 0.058	0.498
	60	0.937**	− 0.457*	0.890**	0.967**	− 0.582**	0.871**
	90	0.870**	0.449*	0.900**	0.886**	0.534**	0.922**
	120	0.891**	0.578**	0.824**	0.926**	0.700**	0.946**
	150	0.906**	0.680**	0.688**	0.943**	0.781**	0.556**
	180	0.923**	0.748**	0.570**	0.951**	0.812**	− 0.035
	210	0.933**	0.780**	0.136	0.956**	0.843**	− 0.237
	240	0.938**	0.790**	− 0.215	0.959**	0.864**	− 0.340*
κ_C	30	0.590*	− 0.720**	0.795**	0.929**	− 0.605*	0.877**
	60	0.837**	− 0.754**	0.920**	0.980**	− 0.725**	0.944**
	90	0.849**	0.411*	0.916**	0.860**	0.450*	0965**
	120	0.866**	0.572**	0.794**	0.911**	0.648**	0.974**
	150	0.883**	0.690**	0.632**	0.931**	0.758**	0.564**
	180	0.906**	0.765**	0.507**	0.941**	0.805**	− 0.047
	210	0.917**	0.801**	0.071	0.946**	0.840**	− 0.254
	240	0.922**	0.814**	− 0.268	0.950**	0.863**	− 0.358*
κ_N	30	0.725**	− 0.719**	0.901**	0.816**	− 0.890**	0.995**
	60	0.862**	− 0.776**	0.950**	0.953**	− 0.878**	0.997**
	90	0.747**	0.215	0.957**	0.769**	0.279	0.990**
	120	0.791**	0.384*	0.890**	0.839**	0.510**	0.991**
	150	0.824**	0.524**	0.761**	0.873**	0.642**	0.637**
	180	0.854**	0.623**	0.647**	0.893**	0.706**	.0044
	210	0.873**	0.680**	0.208	0.906**	0.756**	− 0.170
	240	0.884**	0.708**	− 0.158	0.914**	0.791**	− 0.283*

K_S, K_C, and K_N represent the constant rate of corn straw decomposition and its carbon and nitrogen release; C$_S$, N$_S$, and C/N$_{\text{straw}}$ represent the original corn straw C and N content and its C/N ratio. ** and * indicate significant differences at $p < 0.05$ and $p < 0.01$ levels, individually

AK, and TK content increased by 4.4–8.7%, 5.2–7.5%, 3.0–6.8%, 11.1–12.6%, 3.6–60.5%, 6.2–54.6%, and 4.3–9.5% corresponding to CP$_S$, CP$_{SD}$, FM$_S$, and FM$_{SD}$ treatments, respectively, whereas the differences between the CP and pretreatment value were not significant at $p < 0.05$.

3.3 Relationship Correlating the Straw Decomposition to Straw C and N Release and Soil Physicochemical Properties

3.3.1 Straw Decomposition and Straw C and N Release

Straw decomposition simultaneously released carbon and nitrogen that gradually reduced the C/N ratio, and in turn, it enhanced additional straw degradation and carbon and nitrogen release. The results showed that the initial straw C and N content and straw C/N ratio (C$_S$, N$_S$, and C/N$_{\text{straw}}$) strongly affected the degradation of the maize straw regardless of the decomposer input. During the 240 days of direct field incubation with maize straw, C_S was significantly positively related to the straw residue rate (K_s), and straw C and N release rates (K_C and K_N) both in T1 ($r = 0.769$** to 0.956**) and T2 ($r = 0.590$* to 0.938**).

Our results showed that N_S was highly and positively correlated with K_S, K_C, and K_N ($r = 0.411$* to 0.864**), except where there was a variable relationship during the 30–60 days of incubation ($r = -0.058$ to -0.754**) under T1 and T2. Furthermore, the correlations relating C/N_{straw} to K_s, K_C and K_N were inferior, but high and positive from the beginning through 150–180 days of incubation ($r = 0.498$, 0.507** to 0.995**). However, negative correlations were observed until the end of the study ($r = -0035$ to -0.358*) under T1 and T2 (Table 3). The overall relationships between C_S, N_S, and C/N$_{\text{straw}}$ and K_s, K_C, and K_N were more noticeable and variable under T1 than under T2 as shown in Table 3.

3.3.2 Straw Decomposition and Soil Carbon and Nitrogen Content

The released straw C and N were gradually added into soil, changing the soil carbon and nitrogen content and soil C/N ratio

Table 4 Pearson correlation coefficients (r) relating soil chemical properties, 0–100-cm soil profile water content (W_{100}), and 0–25-cm soil profile temperature (T_{25}) to straw decomposition rates, and straw carbon and nitrogen accumulative release rates in 2016 at the end of the 3-year field study

Parameters	PPeriods (d)	Without decomposer					With decomposer				
		SOC	SON	C/N$_{\text{soil}}$	W_{100}	T_{25}	SOC	SON	C/N$_{\text{soil}}$	W_{100}	T_{25}
κ_s	30	− 0.307	− 0.724**	0.200	0.723**	− 0.641**	− 0.727**	− 0.907**	0.858**	− 0.781**	− 0.529*
	60	− 0.069	− 0.844**	0.615**	0.797**	− 0.850**	− 0.686**	− 0.800**	0.748**	− 0.602**	− 0.713**
	90	0.242	− 0.820**	0.739**	0.844**	− 0.882**	− 0.493*	− 0.826**	0.840**	− 0.566**	− 0.826**
	120	0.332	− 0.841**	0.784**	0.849**	− 0.910**	− 0.583**	− 0.849**	0.840**	0.234	− 0.830**
	150	0.282	− 0.869**	0.820**	0.844**	− 0.918**	− 0.589**	− 0.861**	0.844**	0.452**	− 0.826**
	180	− 0.004	− 0.886**	0.814**	0.386*	− 0.909**	− 0.549**	− 0.867**	0.849**	0.142	− 0.828**
	210	− 0.290	− 0.900**	0.770**	0.290	− 0.887**	− 0.531**	− 0.876**	0.857**	0.128	− 0.731**
	240	− 0.437**	− 0.907**	0.731**	0.342*	− 0.670**	− 0.608**	− 0.890**	0.820**	0.294*	− 0.425**
κ_C	30	− 0.426	− 0.400	−0.191	0.962**	− 0.585*	− 0.868**	− 0.916**	0.776**	− 0.673**	− 0.908**
	60	− 0.067	− 0.787**	0.569**	0.876**	− 0.879**	− 0.739**	− 0.820**	0.741**	− 0.586**	− 0.822**
	90	0.259	− 0.815**	0.740**	0.898**	− 0.909**	− 0.561**	− 0.848**	0.834**	− 0.569**	− 0.889**
	120	0.360	− 0.867**	0.811**	0.883**	− 0.929**	− 0.634**	− 0.865**	0.835**	0.240	− 0.877**
	150	0.295	− 0.893**	0.841**	0.861**	− 0.943**	− 0.628**	− 0.871**	0.837**	0.465**	− 0.861**
	180	− 0.015	− 0.907**	0.826**	0.369*	− 0.925**	− 0.579**	− 0.873**	0.842**	0.138	− 0.855**
	210	− 0.316*	− 0.920**	0.774**	0.267	− 0.894**	− 0.555**	− 0.881**	0.850**	0.124	− 0.749**
	240	− 0.467**	− 0.927**	0.729**	0.323*	− 0.663**	− 0.632**	− 0.894**	0.810**	0.298*	− 0.431**
κ_N	30	− 0.528*	− 0.503	−0.233	0.967**	− 0.714**	− 0.743**	− 0.646**	0.462	− 0.360	− 0.984**
	60	− 0.217	− 0.751**	0.431	0.950**	− 0.864**	− 0.767**	− 0.787**	0.673**	− 0.514*	− 0.928**
	90	0.052	− 0.693**	0.561**	0.957**	− 0.820**	− 0.647**	− 0.834**	0.772**	− 0.534**	− 0.948**
	120	0.177	− 0.746**	0.654**	0.935**	− 0.858**	− 0.700**	− 0.861**	0.796**	0.195	− 0.938**
	150	0.154	− 0.791**	0.712**	0.923**	− 0.874**	− 0.690**	− 0.876**	0.812**	0402*	− 0.927**
	180	− 0.088	− 0.821**	0.721**	0.466**	− 0.873**	− 0.642**	− 0.883**	0.824**	0.122	− 0.921**
	210	− 0.326*	− 0.843**	0.689**	0.370*	− 0.858**	− 0.614**	− 0.891**	0.835**	0.111	− 0.821**
	240	− 0.449**	− 0.856**	0.660**	0.413**	− 0.658**	− 0.671**	− 0.904**	0.799**	0.284*	− 0.496**

SOC, SON, and C/N$_{\text{soil}}$ represent the 0–30-cm soil profile C and N content and soil C/N ratio; W_{100} represents the 0–30-cm soil profile water content; T_{25} represents the 0–25-cm soil profile temperature. ** and * indicate significant differences at $p < 0.05$ and $p < 0.01$ levels, individually

(SOC, SON, and C/N$_{\text{soil}}$). This played a significant role in the decomposition of buried straw resulting in straw C and N release, particularly in the treatment with the decomposer. Generally, during the 240 days of direct field incubation, K_S, K_C, and K_N were significantly negatively related to SOC and SON (r = − 0.493** to − 0.904**) and highly positively related to C/N$_{\text{soil}}$ (r = 0.673** to 0.857**) under T1. Conversely, the situation was more complicated under T2, with SOC being positively related to K_S, K_C, and K_N during the period of 90–150 days (r = 0.052 to 0.369) of incubation and significantly negatively correlated both during the 30–60-day (r = − 0.067 to − 0.528*) and 180–240-day (r = − 0.004 to − 0.467**) period. Meanwhile, SON was highly negatively related to K_S, K_C, and K_N (r = − 0.693** to 0.907**) except for a weak negative relation to K_C (r = − 0.400) and K_N (r = − 0503) during the first 30 days. In addition, C/N$_{\text{soil}}$ was also highly positively related to K_S, K_C, and K_N with the exception of a positive relation to K_S (r = 0.200) and negative relation to K_C (r = − 0.191) during the first 30 days and negatively or positively related to K_N (r = − 0.233 to 0.431) during the 30–60 days (Table 4).

3.3.3 Straw Decomposition and Soil Hydrothermal Conditions

As shown in Table 5, K_S, K_C, and K_N were positively related to the 0–100-cm soil water content (W_{100}) and negatively correlated with the 0–25 soil temperature (T_{25}), whether there was the addition of a decomposer or not; the relationship was more complex during the 240 days of direct field incubation. The results demonstrated that W_{100} was significantly positively correlated with K_S, K_C, and K_N (r = 0.723** to 0.967**) during the 30–150-day period that ended during the 180–210-day period (r = 0267 to 0.369*), then inferior and highly positively correlated with each other (r = 0.342* to 0.413**) again until 240 days under T2. However, it was more controversial under T1, in which the values were significantly negatively related to each other from 30 to 90 days (r = − 0.360 to − 0.781**) ending in 120 days (r = 0.195 to 0.240), highly positively correlated with each other at 150 days (r = 0.402* to 0.465**), positively related to each other from 180 to 210 days (r = 0.11 to 0.142), and then remarkably positively correlated again at the end (r = 0.294* to 0.298*). Additionally, T_{25} was

Table 5 The initial nutrient mass content of test maize straw in using in litter bag study

TOC	TN	TP	TK	C/N
482.85	5.33	1.56	22.40	90.60

TOC total organic carbon (g kg^{-1}), *C/N* maize straw C/N ratio, *TN* total nitrogen (g kg^{-1}), *TP* total phosphorus (g kg^{-1}), *TK* total potassium (g kg^{-1})

significantly negatively correlated with K_S, K_C, and K_N both under T1 ($r = -0.425^{**}$ to -0.948^{**}) and T2 ($R = -0.585^{**}$ to -0.943^{**}). It could be seen that W_{100} and T_{25} were importantly controlled by the maize straw decomposition and straw C and N release.

4 Discussion

4.1 Straw Decomposition and Straw C and N Release as Affected by the Decomposer

Application of straw decomposition agent combined with FM tillage efficiently enhanced straw decomposition and the C and N release rates, which confirming the results of several similar research studies (Wang et al. 2016; Zhao et al. 2017). Our result findings can be explained by the enhanced soil biological activity of the additive decomposer (Zhao et al. 2016; Siczek et al. 2018) and the optimal soil moisture and temperature condition under FM_S tillage (Potthoff et al. 2008; Gan et al. 2013; Liu et al. 2018). Moreover, our results indicated that the fast decomposition period of the buried maize straw lasted for 120 days, with a much lower residual mass rate under T1 than that under T2, which was much longer than the finding in an anaerobic field incubation test of buried wheat straw reported by Wang (2015). This indicates that applying decomposer plus FM tillage favorably facilitates the degradation of buried maize, which is in line with Ali Abro et al. (2011) findings in their incubation study with maize straw. In addition, our results showed that approximately four fifths of the straw mass was lost at the end of the 240-day incubation test in the group that was treated with a decomposer (Fig. 3a). This was higher than the finding of Wang (2015), taking into consideration the difference in the incubation period and soil moisture and temperature. Our findings showed that the straw decomposition rate κ in our experiment was also higher than that found in the previous studies (Wang 2015).

Simultaneously, our results showed that more than four fifths of the straw C and N were released to the soil under the condition of added decomposer during the 240 days of the field incubation. This showed that adding decomposer with FM tillage also was the most favorable technique for straw C and N degradation and release. This contributed to the synergistic effects of enhanced soil microbial activity and modified soil hydrothermal conditions (Zhao et al. 2017; Akhtar et al. 2018). Also, the results indicate that a fast release of straw C and N lasted for 210 days of incubation in the presence of the straw decomposer, but it was longer than that found by Wang (2015) and Ali Abro et al. (2011), mainly because of the difference in the incubation period and the aerobic conditions. Furthermore, our finding on straw decomposition was consistent with the work of Iqbal et al. (2014); the decomposition rate constant (*K*) of straw C and N was more than onefold greater in the case of the straw incorporation with decomposer plus FM tillage; thus, this was an effective means for elevating maize straw decomposition and the straw C and N release rate. However, the decomposition rate was relatively higher, and it contributed to the difference in the soil environment condition and straw particle size in use.

4.2 Soil Fertility Features Changes Caused by Straw Decomposition and Straw C and N Release

Proper management of crop residues is of great importance in soil physical and chemical properties, and when correctly implemented, it improves soil organic matter dynamics and nutrient cycling because of their abundant C, N, P, K, and microelement content (Xu et al. 2011; Wang et al. 2015a). This content can aid in increasing soil fertility (Lou et al. 2011; Wang et al. 2015b; Diochon et al. 2016; Zhang et al. 2016) and enhancing soil productivity (Malhi et al. 2011; Xu et al. 2011; Loke et al. 2012) and sustainability of agricultural ecosystems (Anyanzwa et al. 2010) in dryland farming areas of the Loess Plateau, China.

SOC, TN, TP, TK, AN, AP, AK as well as BD are all the important soil fertility indicators, universally used to assess soil fertility quality induced by changes in agricultural management (Shang et al. 2014; Wang et al. 2015a; Zhang et al. 2015). In our 3-year field study, we found the content of the selected soil fertility parameters all improved, particularly the SOC, TN, AN, AP, and AK content, which was more pronounced in the case of straw incorporation with decomposer plus FM tillage (FM_{SD}). This was partly in line with the findings of Surekha et al. (2003) and Diacono and Montemurro (2010); in their field experiments and publications, they show that crop residue incorporation and organic amendment significantly increased AK, extractable phosphorus, and SOC over the control. This could be a result of the following factors: First, residue incorporation presumably contributes to the rapid replenishing of SOC and NPK content by liberated nutrients that offset or reduce the loss of native soil carbon and nitrogen via the synergistic effects of modified soil hydrothermal conditions and soil organism activity under FM_{SD} (Gan et al. 2013; Thiessen et al. 2013; Qin et al. 2015), indicated by the massive liberation of straw C and N during the buried maize straw incubation test. Second, it may be because more litter and root residues were returned to the soil. The plants grew better in the soil enhanced by the improved hydrothermal and nutritional condition under FM_{SD} (Zhang et al. 2015), as shown in Table 4. The increased phosphorus content is of great importance for crop drought resistance in dryland farming, which is exactly in good agreement with the finding of Jemo et al. (2017), who found that the increases in soil phosphorus availability significantly reduced the damage resulting from adverse water deficits.

Moreover, several studies have indicated that straw application significantly and gradually increases SOM and TN (Wang et al. 2015c) and AN (Zhang et al. 2015) contents both with time and with the increased rate of straw incorporation, suggesting a positive relationship between the straw incorporation rate and SOM and N storage. Loke et al. (2012) indicated that SOM degradation is a scientific problem in semiarid regions because of frequent and intensive soil disturbance, crop residue removal, and climate change. Thus, further study is necessarily required to enhance the decomposition of straw incorporated under a sophisticated environment.

Concomitantly, soil BD was positively significantly influenced by crop straw incorporation (Surekha et al. 2003). The mean soil BD in the 0–30-cm soil layer significantly decreased under all the straw incorporation treatments after 3 years, regardless of whether a decomposer was added or not. This finding was consistent with several other studies (Wang et al. 2015b; Zhang et al. 2015). The significant decrease in BD implies the improvement of the soil structure and is of great importance in a dryland cropping system. The positive effect of straw retention on soil BD has also been reported in several similar results of other studies of the same soil. It was unexpected that straw decomposer (Shang et al. 2014; Wang et al. 2015a; Zhang et al. 2015) had no significant effect on soil bulk density, presumably because of the straw returning rate and the experimental periods, making this desirable for further study.

4.3 Relationship Correlating Straw Decomposition and Straw C and N Release Rate to Soil Fertility Indicators

The straw decomposition, its C and N release rate, and SOC and SON content mutually and positively affect each other. It is well known that straw incorporation is beneficial to the concentration and storage of SOC and SON (Zhang et al. 2015), while nutrient availability in the soil, conversely, influences the straw decomposition rate (Puttaso et al. 2011). Furthermore, SOC and SON responses to straw incorporation widely vary and are site-specific, largely contributing to the complex interactions between the quantity and quality of incorporated straw and native SOC under diverse management practices (Wang 2015). In our study, we found that K_S, K_C, and K_N were significantly negatively correlated with initial SOC and SON, particularly in the presence of a straw decomposer both in the direct field incubation test and in the 3 years of field experiment; this resulted in a considerable amount of liberated straw C and N and high SOC and SON accumulation, probably because of the following reasons: First, addition of a decomposer enhanced the overall soil microbial activities in conjunction with the increased soil hydrothermal conditions under the FM tillage, resulting in rapid decomposition of the buried maize straw thus releasing additional nitrogen that gradually adjusted the straw and soil C/N ratio and favorably facilitated additional straw decomposition and straw C and N release (Li et al. 2006; Jiang and Li 2015; Tang et al. 2016; Liu et al. 2018). Second, the addition of the decomposer might have offset some negative effects caused by the initial straw and soil chemical composition and the unfavorable soil moisture and temperature conditions during the early stages of straw decomposition through the multilateral reaction among them, synergistically enhancing the buried straw decomposition and C and N release, which was similar to the finding in the maize straw incubation reported by Qin et al. (2015). Finally, the released straw C and N were slowly converted into soil carbon and nitrogen that reduced the native SOC and SON lost via crop uptake, increasing soil carbon and nitrogen accumulation and storage (Akhtar et al. 2018).

5 Conclusion

The dryland farming practical pattern of straw incorporation with a decomposer and fully film-mulched ridge-furrow tillage (FM_{SD} treatment) was effectively verified to hasten straw decomposition and C and N release, thereby improving soil nutrient content and availability; this mainly occurred via the synergistic regulation of the soil hydrothermal condition and enhanced soil microbial activity. This pattern may be a more efficient scenario to substitute FM tillage to manage soil quality and fertility in dryland farming, as it could offset the negative effects of both straw incorporation and film mulch in the short term via facilitation of incorporated straw decomposition and nutrient release to improve the soil physicochemical condition and replenish SOM content that is favorable for soil carbon and nitrogen accumulation. This aids in offsetting the loss of the indigenous soil organic C and N pool stimulated by the C and N mineralization and crop uptake, thus alleviating soil degradation and conserving the soil nutrient source and maintaining and improving soil fertility. Therefore, this pattern could be the best dryland farming practice on the Loess Plateau of China, and it could be applied to similar areas. The pattern can be particularly and effectively used for increasing maize production in this area. Lowering the decomposition rate of incorporated straw remains a great challenge in its expanding application, so further research is needed.

Acknowledgments We are grateful to Doctor Xiaomei Yang, of the Soil Physics and Land Management, Wageningen University & Research, for precious language editing advice and to the many staff who are not listed as coauthors but were involved in maintaining the field experiments and collecting the soil samples.

Funding Information This study was funded by the Natural Science Foundation of China (31560137), the Gansu Science & Technology Support Program (1204NKCA108), and the Natural Science Foundation Support Program of Gansu Academy of Agricultural Sciences (2017 GAAS95).

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Akhtar K, Wang WY, Khan A et al (2018) Wheat straw mulching with fertilizer nitrogen: an approach for improving soil water storage and maize crop productivity. Plant, soil environ 64:330–337. https://doi.org/10.17221/96/2018-PSE

Ali Abro S, Tian X, Wang X et al (2011) Decomposition characteristics of maize (Zea mays. L.) straw with different carbon to nitrogen (C/N) ratios under various moisture regimes. African J Biotechnol 10: 10149–10156. https://doi.org/10.5897/AJB10.2261

Anyanzwa H, Okalebo JR, Othieno CO, Bationo A, Waswa BS, Kihara J (2010) Effects of conservation tillage, crop residue and cropping systems on changes in soil organic matter and maize-legume production: a case study in Teso District. Nutr Cycl Agroecosystems 88:39–47. https://doi.org/10.1007/s10705-008-9210-2

Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. CRC Crit Rev Plant Sci 28: 139–163. https://doi.org/10.1080/07352680902776507

Chinese Soil Taxonomy Cooperative Research Group (1995) Chinese soil taxonomy (revised proposal). Institute of Soil Science, Academic Sinica. Chinese Agricultural Science and Technology Press, Beijing

Cong R, Xu M, Wang X, Zhang W, Yang X, Huang S, Wang B (2012) An analysis of soil carbon dynamics in long-term soil fertility trials in China. Nutr Cycl Agroecosystems 93:201–213. https://doi.org/10.1007/s10705-012-9510-4

Diacono M, Montemurro F (2010) Long-term effects of organic amendments on soil fertility. A review To cite this version : Review article Long-term effects of organic amendments on soil fertility. A review. Agron Sustain Dev 30:401–422. https://doi.org/10.1051/agro/2009040

Diochon A, Gregorich EG, Kellman L, Morrison M, Ma BL (2016) Greater soil C inputs accelerate loss of C in cropping systems with low N input. Plant Soil 400:93–105. https://doi.org/10.1007/s11104-015-2718-8

El-Sadek A, Salem E (2015) Impact of ridge–furrow water harvesting system on faba bean (Vicia faba L.) production under rainfed conditions in Matrouh, Egypt. Ann Agric Sci 60:61–66. https://doi.org/10.1016/j.aoas.2015.03.003

Esther QJ, Hong TX and Hui GC (2013) Influence of straw degrading microbial compound on wheat straw decomposition and soil biological properties. African Journal of Microbiology Research 7(28):3597–3605. https://doi.org/10.5897/AJMR2013.5918

FAO-UNESCO (1990) FAO-UNESCO Soil map of the world Revised legend World resources Report 60

Gan Y, Siddique KHM, Turner NC et al (2013) Ridge-furrow mulching systems-an innovative technique for boosting crop productivity in semiarid rain-fed environments. Elsevier

Hu J, Wu J, Qu X (2018) Decomposition characteristics of organic materials and their effects on labile and recalcitrant organic carbon fractions in a semi-arid soil under plastic mulch and drip irrigation. J Arid Land 10:115–128. https://doi.org/10.1007/s40333-017-0035-1

Huang Y, Chen L, Fu B et al (2005) The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects. Agric Water Manag 72:209–222. https://doi.org/10.1016/j.agwat.2004.09.012

Iqbal A, Garnier P, Lashermes G, Recous S (2014) A new equation to simulate the contact between soil and maize residues of different sizes during their decomposition. Biol Fertil Soils 50:645–655. https://doi.org/10.1007/s00374-013-0876-5

Jemo M, Sulieman S, Bekkaoui F, Olomide OAK (2017) Comparative analysis of the combined effects of different water and phosphate levels on growth and biological nitrogen fixation of nine cowpea varieties 8:. doi: https://doi.org/10.3389/fpls.2017.02111

Jiang X, Li XG (2015) Assessing the effects of plastic film fully mulched ridge-furrow on rainwater distribution in soil using dye tracer and simulated rainfall. Soil Tillage Res 152:67–73. https://doi.org/10.1016/j.still.2015.04.002

Laird DA, Chang CW (2013) Long-term impacts of residue harvesting on soil quality. Soil Tillage Res 134:33–40. https://doi.org/10.1016/j.still.2013.07.001

Li X, Li F, Bhupinderpal-Singh et al (2006) Decomposition of maize straw in saline soil. Biol Fertil Soils 42:366–370. https://doi.org/10.1007/s00374-005-0042-9

Li P, Zhang D, Wang X et al (2012) Survival and performance of two cellulose-degrading microbial systems inoculated into wheat straw-amended soil. J Microbiol Biotechnol 22:126–132. https://doi.org/10.4014/jmb.1102.02021

Li C, Wen X, Wan X et al (2016) Towards the highly effective use of precipitation by ridge-furrow with plastic film mulching instead of relying on irrigation resources in a dry semi-humid area. F Crop Res 188:62–73. https://doi.org/10.1016/j.fcr.2016.01.013

Liu E, Teclemariam SG, Yan C et al (2014) Long-term effects of no-tillage management practice on soil organic carbon and its fractions in the northern China. Geoderma 213:379–384. https://doi.org/10.1016/j.geoderma.2013.08.021

Liu G, Zuo Y, Zhang Q, Yang L, Zhao E, Liang L, Tong Y (2018) Ridge-furrow with plastic film and straw mulch increases water availability and wheat production on the Loess Plateau. Sci Rep 8:1–12. https://doi.org/10.1038/s41598-018-24864-4

Loke PF, Kotzé E, du Preez CC (2012) Changes in soil organic matter indices following 32 years of different wheat production management practices in semi-arid South Africa. Nutr Cycl Agroecosystems 94:97–109. https://doi.org/10.1007/s10705-012-9529-6

Lou Y, Xu M, Wang W et al (2011) Return rate of straw residue affects soil organic C sequestration by chemical fertilization. Soil Tillage Res 113:70–73. https://doi.org/10.1016/j.still.2011.01.007

Malhi SS, Nyborg M, Goddard T, Puurveen D (2011) Long-term tillage, straw and N rate effects on quantity and quality of organic C and N in a gray Luvisol soil. Nutr Cycl Agroecosystems 90:1–20. https://doi.org/10.1007/s10705-010-9399-8

Marrack P, Germany KE (2004) Current opinion in immunology editors Frederick alt. Curr Opin Immunol 16:7915–7915. https://doi.org/10.1023/a:1004207219678

Palika S, Veena K, Poonam K (2013) Efficacy of aminocyclopropane-1-carboxylic acid (ACC)-deaminase-producing rhizobacteria in ameliorating water stress in chickpea under axenic conditions. African J Microbiol Res 7:5749–5757. https://doi.org/10.5897/AJMR2013.5918

Pan G, Zhou P, Li Z et al (2009) Combined inorganic/organic fertilization enhances N efficiency and increases rice productivity through organic carbon accumulation in a rice paddy from the tai Lake region, China. Agric Ecosyst Environ 131:274–280. https://doi.org/10.1016/j.agee.2009.01.020

Potthoff M, Dyckmans J, Flessa H, Beese F, Joergensen RG (2008) Decomposition of maize residues after manipulation of colonization and its contribution to the soil microbial biomass. Biol Fertil Soils 44:891–895. https://doi.org/10.1007/s00374-007-0266-y

Puttaso A, Vityakon P, Saenjan P, Trelo-ges V, Cadisch G (2011) Relationship between residue quality, decomposition patterns, and soil organic matter accumulation in a tropical sandy soil after 13 years. Nutr Cycl Agroecosystems 89:159–174. https://doi.org/10.1007/s10705-010-9385-1

Qin T, Jiao L et al (2015) Effects of maize residue and cellulose-decomposing bacteria inocula on soil microbial community, functional diversity, organic fractions, and growth of Malus hupehensis Rehd. Arch Agron Soil Sci 61. https://doi.org/10.1080/03650340.2014.928927

Shang Q, Ling N, Feng X, Yang X, Wu P, Zou J, Shen Q, Guo S (2014) Soil fertility and its significance to crop productivity and sustainability in typical agroecosystem: a summary of long-term fertilizer experiments in China. Plant Soil 381:13–23. https://doi.org/10.1007/s11104-014-2089-6

Sheidai Karkaj E, Sepehry A, Barani H, Motamedi J, Shahbazi F (2019) Establishing a suitable soil quality index for semi-arid rangeland ecosystems in northwest of Iran. J Soil Sci Plant Nutr:1–11. https://doi.org/10.1007/s42729-019-00065-4

Siczek A, Frąc M, Wielbo J, Kidaj D (2018) Benefits of flavonoids and straw mulch application on soil microbial activity in pea rhizosphere. Int J Environ Sci Technol 15:755–764. https://doi.org/10.1007/s13762-017-1434-8

Su YZ, Wang F, Suo DR et al (2006) Long-term effect of fertilizer and manure application on soil-carbon sequestration and soil fertility under the wheat-wheat-maize cropping system in Northwest China. Nutr Cycl Agroecosystems 75:285–295. https://doi.org/10.1007/s10705-006-9034-x

Surekha K, Kumari APP, Reddy MN, Satyanarayana K (2003) Crop residue management to sustain soil fertility and irrigated rice. 145–154

Tang S, Cheng W, Hu R, Guigue J, Kimani SM, Tawaraya K, Xu X (2016) Simulating the effects of soil temperature and moisture in the off-rice season on rice straw decomposition and subsequent CH4production during the growth season in a paddy soil. Biol Fertil Soils 52:739–748. https://doi.org/10.1007/s00374-016-1114-8

Thiessen S, Gleixner G, Wutzler T, Reichstein M (2013) Both priming and temperature sensitivity of soil organic matter decomposition depend on microbial biomass—an incubation study. Soil Biol Biochem 57:739–748. https://doi.org/10.1016/j.soilbio.2012.10.029

Unger PW (1978) Straw-mulch rate effect on soil water storage and Sorghum yield. Soil Sci Soc Am J 42:486–491. https://doi.org/10.2136/sssaj1978.03615995004200030023x

Vega-Ávila, A., Medina, E., Paroldi, H., Toro, M., Baigori, M., & Vázquez, F. (2018). Bioindicators of soil quality of open shrubland and vineyards. Journal of soil science and plant nutrition, (ahead), 0–0. doi:https://doi.org/10.4067/s0718-95162018005003002

Wang J (2015) Characteristic of wheat straw decomposition under aerobic and anaerobic condition in soil. J China Agric Univ 30:161–168

Wang X, Xing Y (2016) Effects of mulching and nitrogen on soil nitrate-N distribution, leaching and nitrogen use efficiency of maize (Zea mays L.). PLoS One 11:1–18. https://doi.org/10.1371/journal.pone.0161612

Wang Y, Xie Z, Malhi SS et al (2009) Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yield in the semi-arid Loess Plateau, China. Agric Water Manag 96:374–382. https://doi.org/10.1016/j.agwat.2008.09.012

Wang YP, Li XG, Hai L et al (2014) Film fully-mulched ridge-furrow cropping affects soil biochemical properties and maize nutrient uptake in a rainfed semi-arid environment. Soil Sci Plant Nutr 60:486–498. https://doi.org/10.1080/00380768.2014.909709

Wang J, Wang X, Xu M, Feng G, Zhang W, Lu C' (2015a) Crop yield and soil organic matter after long-term straw return to soil in China. Nutr Cycl Agroecosystems 102:371–381. https://doi.org/10.1007/s10705-015-9710-9

Wang W, Lai DYF, Wang C et al (2015b) Effects of rice straw incorporation on active soil organic carbon pools in a subtropical paddy field. Soil Tillage Res 152:8–16. https://doi.org/10.1016/j.still.2015.03.011

Wang X, Jia Z, Liang L et al (2015c) Maize straw effects on soil aggregation and other properties in arid land. Soil Tillage Res 153:131–136. https://doi.org/10.1016/j.still.2015.05.001

Wang YP, Li XG, Fu T et al (2016) Multi-site assessment of the effects of plastic-film mulch on the soil organic carbon balance in semiarid areas of China. Agric For Meteorol 228–229:42–51. https://doi.org/10.1016/j.agrformet.2016.06.016

Wu T, Schoenau JJ, Li F et al (2004) Influence of cultivation and fertilization on total organic carbon and carbon fractions in soils from the Loess Plateau of China. Soil Tillage Res 77:59–68. https://doi.org/10.1016/j.still.2003.10.002

Xu M, Lou Y, Sun X et al (2011) Soil organic carbon active fractions as early indicators for total carbon change under straw incorporation. Biol Fertil Soils 47:745–752. https://doi.org/10.1007/s00374-011-0579-8

Xu J, Li C, Liu H et al (2015) The effects of plastic film mulching on maize growth and water use in dry and rainy years in Northeast China. PLoS One 10:1–14. https://doi.org/10.1371/journal.pone.0125781

Ye J, Liu C (2012) Suitability of mulch and ridge-furrow techniques for maize across the precipitation gradient on the Chinese Loess Plateau. J Agric Sci 4:182–190. https://doi.org/10.5539/jas.v4n10p182

Yu YY, Turner NC, Gong YH et al (2018) Benefits and limitations to straw- and plastic-film mulch on maize yield and water use efficiency: a meta-analysis across hydrothermal gradients. Eur J Agron 99:138–147. https://doi.org/10.1016/j.eja.2018.07.005

Zhang F, Chen X, Vitousek P (2013) An experiment for the world. Nature 497:33–35. https://doi.org/10.1038/497033a

Zhang P, Wei T, Li Y et al (2015) Effects of straw incorporation on the stratification of the soil organic C, total N and C:N ratio in a semiarid region of China. Soil Tillage Res 153:28–35. https://doi.org/10.1016/j.still.2015.04.008

Zhang P, Chen X, Wei T et al (2016) Effects of straw incorporation on the soil nutrient contents, enzyme activities, and crop yield in a semiarid region of China. Soil Tillage Res 160:65–72. https://doi.org/10.1016/j.still.2016.02.006

Zhang F, Zhang W, Qi J, Li FM (2018) A regional evaluation of plastic film mulching for improving crop yields on the Loess Plateau of China. Agric For Meteorol 248:458–468. https://doi.org/10.1016/j.agrformet.2017.10.030

Zhao S, Li K, Zhou W et al (2016) Changes in soil microbial community, enzyme activities and organic matter fractions under long-term straw return in north-central China. Agric Ecosyst Environ 216:82–88. https://doi.org/10.1016/j.agee.2015.09.028

Zhao J, Ni T, Xun W, Huang X, Huang Q, Ran W, Shen B, Zhang R, Shen Q (2017) Influence of straw incorporation with and without straw decomposer on soil bacterial community structure and function in a rice-wheat cropping system. Appl Microbiol Biotechnol 101:4761–4773. https://doi.org/10.1007/s00253-017-8170-3

Zhou LM, Li FM, Jin SL, Song Y (2009) How two ridges and the furrow mulched with plastic film affect soil water, soil temperature and yield of maize on the semiarid Loess Plateau of China. F Crop Res 113:41–47. https://doi.org/10.1016/j.fcr.2009.04.005

Zhou Z, Zhang X, Gan Z (2015) Changes in soil organic carbon and nitrogen after 26 years of farmland management on the Loess Plateau of China. J Arid Land 7:806–813. https://doi.org/10.1007/s40333-015-0051-y