Fall Straw Incorporation with Plastic Film Cover Increases Corn Yield and Water Use Efficiency Under a Semi-Arid Climate

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Abstract

Corn straw incorporation in soil has been regarded as an environment-friendly approach for straw utilization. However, the straw incorporation has been a challenge under a cold and dry climate due to a slow decomposition. This field study was to use a novel approach to incorporate corn straw into soil during fall season with plastic film cover, in an effort to enhance the straw degradation. Two-year field experiments were conducted in Northeast China to investigate the effects of four treatments: including 1) straw incorporation with film cover; 2) straw incorporation only; 3) film cover only; and 4) control, on soil properties and corn growth. Soils and corn plants were collected during the growing season and analyzed for soil temperature and moisture, straw degradation, corn biomass, grain yield, and water use efficiency. Results indicated that straw incorporation with film cover increased grain yield by 53% as compared to straw incorporation only and by 102% to control, but did not significantly differ from film cover only. The straw decomposition under film cover was 20% faster, significantly higher than that of the straw incorporation only treatment. In all cases, soil water content before planting, corn water uptake, and corn water use efficiency under straw incorporation with film cover were significantly higher than straw incorporation only and control, but did not significantly differ from film cover only. Surface film cover resulted in 10-day earlier corn tasseling in compared to treatments without film cover. This field study demonstrated that straw incorporation with film cover would enhance straw degradation in soil, improve soil properties, and increase corn yield and water use efficiency, which could be potentially used as the sustainable soil management practice in Northeast China.

Introduction

Corn (*Zea mays* L.) is one of the most important crops in China. It was estimated that 31% of corn grains was produced in the northeast region (Dong et al., 2017). This also led to the production of large amounts of corn straws. According to statistics, the production of corn straw in the northeast China reached 98 million tons in 2015. As a common agricultural practice, most corn stalks produced are burned in field. However, the burning of crop residues would emit harmful substances, including particulate matter (PM), volatile organic compounds, greenhouse gases or other toxics, to atmosphere, which is contributing to air pollution and threatening human health. (Subramanian, 2014; Chen et al., 2017; Liu et al., 2019). In an effort to reduce air pollution and protect human health, Chinese government has officially banned the direct straw burning, which was implemented in April 2014 (Hong et al., 2016). Therefore, it is an urgent need to develop environment-friend and low-costly techniques for the straw utilizations (Qu et al., 2012).

Five common utilizations for crop residues included the uses as energy, fertilizer, feed, industrial raw material, and base material (Li et al., 2018). Among such utilizations, many technologies have been developed for corn straws, such as direct-combustion for power generation (Wang et al., 2018), briquette fuel processing (Zhang et al., 2019), production of biochar (Wang et al., 2019), syngas (Hu et al., 2019), butanol and pulp (Xia et al., 2019), biomass films (Li et al., 2019), rigid polyurethane composite foams (Jiang et al., 2020), special animal feeds, etc. However, straw return into soil still remains as the most common utilization in China. Estimated 32% of the total straws produced were returned to soil annually (Bi et al., 2008), and this number is increasing recently.

Returning straws to soil has been considered as a sustainable, low-cost practice that enhances carbon sequestration, increases soil organic matter and improves soil health. The degradation of straws in soil is usually involved in microbial activity, which requires certain temperature, moisture and other environmental conditions. However, in Northeast China, the practice of straw return to soil has become a challenge due to the cold and dry winter, which limits microbial activity in soil and straw degradation processes. It is therefore critical to develop effective practices to overcome the constraints on straw decomposition caused by the cold and dry climate in Northeast China to promote straw incorporation strategies.

Plastic film cover on soil surface was confirmed as an effective practice in Northeast China that reduced soil water evaporation and increased soil water content and temperature during earlier spring, consequently yielding significantly higher corn grain and water use efficiency. Jin et al. (2018) used an *in situ* ^{13}C-tracing technique and confirmed that plastic film cover enhanced the decomposition of corn straw in soil. The ridge-furrow with polyethylene film cover and straw incorporation in loess soils showed improved soil organic carbon stocks, water storage, grain yields, and higher water use efficiency in compared to the ridge-furrow with film cover only. The ridge–furrow plastic film cover combined with straw ditch burying was reported to improve soil hydrothermal conditions, accelerated straw decomposition, and enhanced crop growth and yields in the loess, relatively dry region of northwestern China (Li et al., 2020).

Despite various benefits of plastic film cover with straw incorporation during growing season, the effects of fall film cover with straw incorporation on straw decomposition, soil properties, corn yield and water use efficiency were little elucidated and still largely unknown. We hypothesized that fall straw incorporation combined with film cover would improve soil water availability and temperature, consequently promoting straw degradation, improving soil health, and increasing corn water use efficiency and grain yield under the semi-arid climate of Northeast China. The objectives of this field study were to investigate the impacts of fall straw incorporation with film cover on soil properties and straw degradation and quantify corn growth, yield and water use efficiency in Northeast China.

2. Materials And Methods

2.1 Site description

Field plot experiments were located at the National Agricultural Experimental Station in Fuxin, Liaoning Province, Northeast China (121.70N, 42.11E, 213 m altitude)(Figure.1. The climate of the site is classified as cold, dry winter and hot summer in the Köppen-Geiger classification, with annual mean temperature of 8.2 ^{o}C, annual rainfall amount of 504.9 mm (429 mm in April-September growing season), annual potential evaporation of 1050 mm, and annual frost-free days of 175. Soil was a calcic cinnamon sandy loam (60.6% sand, 20.5% silt, 18.9% clay), with a bulk density averaged at 1.55 g cm^{-3}, organic matter of 11.6 g kg^{-1}, total nitrogen (N), phosphorus (P), potassium (K) of 0.64, 0.66, and 2.46 g kg^{-1}, and available N, P, and K of 72.6, 136, and 62.2 mg kg^{-1} (20 cm topsoil).

Weather data during the experimental period (October 2015- September 2017) were measured with an automatic weather station (WS-STD1, Delta-T, UK) near the site (Figure. 2). The precipitation during the fallow season (October to May) was 118.7 mm in 2015–2016 and 53.1 mm in 2016–2017. The precipitation during the growing season (May to September) was 441 mm in 2016 and 300 mm in 2017. The pan evaporation during the fallow season was similar for two years at an average of 530 mm.

2.2 Experimental design

Field experiments were conducted from October 2015 to September 2017 for two crop growing seasons. The experimental plots were 50-m^2 size (10 by 5 m) arranged as a randomized complete block design with four treatments and three replicates per treatment. Four treatments included: 1) fall plastic film cover only following corn harvest (AM), 2) fall corn straw incorporation (20 cm topsoil) followed by film cover after harvest (AMS), 3) fall corn straw incorporation following harvest without file cover (S), and 4) control without corn straw and film cover (N). Each plot was separated by brick walls (10-cm high above soil surface) to eliminate the surface runoff across plots.

In fall season (October) after corn harvest, the plots were ploughed at 30-cm depth by a tractor, and rows prepared at spacing of 50-cm apart. Corn straws were chopped into 3–5 cm long pieces and incorporated into soil at 10–30 cm depth manually at a rate of 9000 kg ha^{-1}. Fertilizers were applied in AM and AMS plots before film cover in fall and in S and N plots in spring before corn planting at the rate of 522 kg ha^{-1} of ureophil (46% N), 1250 kg ha^{-1} of superphosphate (12% P_2O_5) and 147 kg ha^{-1} of potassium sulfate (51% K_2O). Herbicide (acetochlor) was applied in AM and AMS plots before film cover in fall and in S and N plots in spring before corn planting. The local-produced white plastic film (100-cm wide, 0.01-mm thick) was used to cover the two rows, and 10-cm film at each side was buried into soil, with a soil coverage ratio of 80%. In spring season (early May), corns (Zhengdan 958) were planted at 33-cm intervals in the rows, with a planting density of 6 plants m^{-2}. Plots were irrigated at 60 mm water after corn planting in spring of 2017 only due to the spring drought, but no additional irrigation was provided during other experimental periods. Other field management practices were the same as local farmers. Each year, corn grains and biomass were harvested in late September, and the film covers from previous year were removed.

2.3 Sampling and measurement

2.3.1 Soil water content and temperature

Soil water contents were measured at 3–5 week intervals during the growing season. A 1-m soil core was collected using a soil auger from the center of each plot between two rows (2016: May 6, June 28, July 27, August 17, September 28; 2017: May 2, June 18, July 17, August 15, September 28) and cut into 10-

cm increments. The samples were oven-dried at 105 ^{o}C for 48 h and weighed for measurement of soil gravimetric water content. Soil volumetric water content was calculated by multiplying the gravimetric water content with soil bulk density. Soil water storage in the root zone was calculated by adding soil water contents over 1-m depths.

Soil temperature was hourly measured and recorded by the sensors of Decagon-5TM (Decagon, EC-TM, USA) during the period from October 1, 2015 to September 28, 2017. The sensors were placed at 5 cm soil depth between two rows at the center of each plot.

2.3.2 Straw decomposition

The corn straw decomposition in soil was measured using the nylon mesh bag method. In AMS and S treatment plots, 120 nylon mesh bags (15 cm long and wide, 1 mm bore diameter), containing 30 g air-dried corn straw of each, were buried in none-planting rows on October 1 in 2015 and 2017 respectively. Three bags were monthly collected from each plot during the growing season. The straws in each bag was rinsed with water and oven-dried at 70°C to constant weight and determined for straw decomposition rate.

2.3.3 Yield and dry matter

Corn grain yield was measured at harvest on September 28 of 2016 and 2017 in the 6-m^2 sampling area (3 by 2 m) at the center of each plot. The grains of collected 10 plants were air-dried to 14% water content and measured for ear density (ear m^{-2}, ear per plant x plant density), kernels per ear and 1000-kernel weight.

Corn above-ground dry matter in each plot was determined by randomly harvesting 3 plants in a 2-m^2 sampling area during the growing season (2016: June 2, June 28, July 27, August 17; 2017: May 24, June 18, July 17, August 15) and a 6-m^2 area at harvest (September 28 in 2016 and 2017). Each sampling area was at least 1 m apart from previous sampling areas to avoid the gap effects. The plant samples were separated into stems, leaves and grains and oven-dried at 80 ^{o}C for 48 h to constant weight and weighed. Harvest index (HI) was calculated as grain yield divided by total dry matter.

2.4 Data analysis and statistics

Water use (WU, mm) during the growing season and the fallow period, including evaporation from bare soil and transpiration by crop, was calculated using a simplified soil water balance equation as listed in Eq. 1, because water deep percolation and capillary rise are often limited in semi-arid region and were ignored in water balance calculation due to low rainfall and deep water table (Allen et al., 1998; Angus and van Herwaarden, 2001; Chen et al., 2015; Moiwo and Tao, 2015

$$WU = P + \triangle SW \quad (1)$$

where P (mm) was rainfall amounts and $\triangle SW$ the change of soil water storage within the 100 cm root zone between planting and harvest.

Water use efficiency (*WUE*, g m^{-2} mm^{-1}) was calculated as grain yield or biomass divided by total water use during the growing season as shown in Eq. 2:

$$WUE = Y/WU \quad (2)$$

where Y (g m^{-2}) was grain yield or dry matter and WU (mm) the water use in growing season.

Straw decomposition rate was calculated as Eq. 3:

$$\text{Straw decomposition rate}(\%) = (M_0 - M_t) \times 100\% \,/\, M_0 \quad (3)$$

where M_0 was the initial dry straw added (g); M_t the dry straw remaining at time *t (d).*

Analysis of variance (ANOVA) was performed on yield, dry matter, harvest index, temperature, WU and WUE using SPSS 18.0 (IBM, USA). Least significant differences were used to separate treatment means and treatment-year interactions at the 5% significance level.

3 Results

3.1 Grain yield

The average of two-year grain yield in AMS was 11.3 t ha^{-1}, 53% higher than that in S and 102% higher than in N, but not significantly different with AM ($P < 0.05$; Table 1). The interactions between year and treatment were not significant. The number of kernels per ear in AMS and AM was similar, but 36% higher than in S and 87% higher than in N. The greater kernels per ear in AMS and AM were attributed to longer ears and larger ear diameter (Table 1). The two-year average of 1000-kernel weight in AMS was 8% higher than in S and 12% higher than in N, but not significantly different with AM ($P < 0.05$; Table 1). The ear density (number of ears per unit area) was slightly greater in N and S than in AMS and AM. The treatment effects on kernels per ear and kernel weight did not interact across year.

Table 1
Corn grain yield and yield components among treatments in 2016 and 2017.

Year	Treatment	Ear density	Ear length	Ear diameter	Kernels per ear	1000-kernel weight	Harvest Index	Grain yield
		ears m^{-2}	cm	mm	Kernels ear^{-1}	g	g g^{-1}	t ha^{-1}
2016	N	8.6 a	13.5 a	42.2 c	335 c	340 c	0.41 a	7.4 c
	S	6.4 b	15.9 a	46.7 b	481 b	358 b	0.43 a	8.9 b
	AM	6.2 b	17.5 a	50.2 a	559 a	375 a	0.40 a	12.8 a
	AMS	6.2 b	16.9 a	52.1 a	559 a	380 a	0.40 a	13.3 a
	SE	0.42	0.43	0.91	19.5	3.09	0.013	0.43
2017	N	6.6 a	13.1 b	37.7 c	235 c	308 c	0.42 a	3.8 c
	S	7.6 a	13.1 b	42.2 b	298 b	319 b	0.44 a	5.9 b
	AM	6.0 b	15.7 a	46.5 a	520 a	339 a	0.45 a	8.7 a
	AMS	6.0 b	15.9 a	45.0 a	505 a	348 a	0.47 a	9.4 a
	SE	0.33	0.57	0.99	23.7	2.94	0.032	0.41
Mean	N	7.6 a	13.4 b	37.7 c	285 c	324 c	0.42 a	5.6 c
	S	7.0 a	14.6 b	42.2 b	390 b	338 b	0.44 a	7.4 b
	AM	6.1 b	16.7 a	46.5 a	539 a	357 a	0.42 a	10.8 a
	AMS	6.1 b	16.3 a	45.0 a	532 a	364 a	0.44 a	11.3 a
	SE	0.33	0.39	0.99	13.1	8.05	0.018	0.87
P	Treatment	0.428	0.053	0.010	0.034	0.001	0.497	0.001
	Year	0.678	0.064	0.007	0.055	0.000	0.035	0.001
	Treatment*Year	0.035	0.609	0.770	0.099	0.693	0.869	0.581

Same small letter indicates no significant difference between treatments in the same year at the 5% level. N is no film mulch and no straw incorporation control, S is straw incorporation in autumn, AM is autumn mulching, i.e. applying the film cover in autumn, and AMS is straw incorporation combined with autumn mulching, i.e. applying the film cover on the basis of straw incorporation in autumn.

3.2 Dry matter and harvest index

Dry matters in AMS and AM were significantly higher than in S and N for both years ($P < 0.05$), There was no significant difference between AMS and AM. The dry matter during the later growing season (after tasseling) was significantly higher in S than in N (Fig. 3). Harvest index was not significantly different among treatments (Table 1).

3.3 Soil temperature

The average of soil temperature at 5-cm depth in AMS was 2.5 ^{o}C higher than in S and 2.4 ^{o}C higher than in N during the winter season, and 4.1 ^{o}C higher than in S and 3.6 ^{o}C higher than in N at the planting time, while there was no significant difference between AMS and AM. During the early growing season (emergence to 6-full leaves), soil temperature at 5-cm depth showed no difference between AM and AMS, but both film treatments (AMS and AM) had an averaged 2.8 ^{o}C higher soil temperature than S and 2.5 higher than N (Fig. 4). After 55 to 61 days, there was no significant difference in soil temperature among treatments for both years.

3.4 Daily water use and water availability

The average of daily water use (DWU) in AMS was 0.14 mm d^{-1} lower than in S and 0.25 mm d^{-1} lower than in N, but not significant different with AM during the fallow season (Table 2), which resulted in significantly higher soil water content in AMS and AM in the 0-100 soil at the early growing season, as compared to S and N (Fig. 5a, 5d). During the early growing stage (planting to V6), the average of DWU in AMS was 1 mm d^{-1} lower than S and 1.35 mm d^{-1} lower than N, but not significantly different with AM (Table 2). At the tasseling stage, soil water content in AMS and AM were greater than those in N and S (Fig. 5b, 5e), while at the harvest, there was no significant difference ($P > 0.05$) among treatments for both years (Fig. 5c, 5f). Results showed that soil water under film cover treatments provided a greater water availability or supply during the tasseling and harvest period. During the grain filling stage (R3 to harvest), the average of DWU in AMS was 1.08 mm d^{-1} higher than in S and 1.26 mm d^{-1} higher than in N, but showed no significant difference with AM (Table 2), which supported higher kernel weights measured in AMS and AM (Table 1).

Table 2

Daily water use (mm d^{-1}) at the fallow and corn growing seasons among treatments in 2015–2016 and 2016–2017 periods.

Season	Treatment	Fallow season (from previous autumn till sowing[1])	Maize growing season	
			Seedling period (From sowing to V6[2])	Grain filling period (From R3 to harvest[3])
		mm d^{-1}	mm d^{-1}	mm d^{-1}
2015/2016	N	0.76 a	2.91 a	1.84 b
	S	0.71 b	2.40 a	2.12 b
	AM	0.54 c	1.19 b	3.15 a
	AMS	0.54 c	1.02 c	3.63 a
	SE	0.011	0.381	0.208
2016/2017	N	0.47 a	2.17 a	1.49 c
	S	0.29 b	1.98 a	1.59 b
	AM	0.21 b	1.44 b	2.02 a
	AMS	0.18 b	1.37 b	2.22 a
	SE	0.042	0.057	0.049
Mean	N	0.61 a	2.54 a	1.67 c
	S	0.50 b	2.19 b	1.85 b
	AM	0.37 c	1.31 c	2.59 a
	AMS	0.36 c	1.19 c	2.93 a
	SE	0.081	0.204	0.229
P	Treatment	0.022	0.083	0.090
	Year	0.001	0.631	0.040
	Treatment*Year	0.194	0.183	0.036

Same small letter indicates no significant difference between treatments in the same year at the 5% level.

N is no film mulch and no straw incorporation, S is straw incorporation, AM is autumn mulching, and AMS is straw incorporation combined with autumn mulching.

[1]The fallow period is from 1 October in previous year to maize sowing, i.e. May 6 in 2015/2016 and 2

May in 2016/2017.
[2]V6 refers to the six leaves growth stage, i.e. 27 days after sowing (DAS) in 2016 and 36 DAS in 2017.
[3]R3 refers to the milk stage, i.e. 104 DAS in 2016 and 106 in 2017. The harvesting time is 146 DAS in 2016 and 150 DAS in 2017.

3.5 Water uptake and use efficiency

The water uptake in AMS and AM were 409 mm and 404mm, respectively, during the growing season, which were slightly higher than 390 mm in S and 358 mm in N. The water use during the winter period (primarily evaporative loss) was 78 mm in AMS and 81 mm in AM, which was significantly lower than 109 mm in S and 133 mm in N ($P < 0.05$; Table 3).

Table 3
Total water use (WU) and water use efficiency for grain yield (WUE_Y) and above-aground dry matter (WUE_B) among four treatments during 2015–2016 and 2016–2017 periods.

Year	Treatment	WU during fallow period[1]	Soil water content at sowing time	WU during growing season	Final dry matter	WUE_Y	WUE_B
		mm	mm	mm	kg m^{-2}	g m^{-2} mm^{-1}	g m^{-2} mm^{-1}
2015/2016	N	166 a	189 b	460 c	1.84 c	1.62 b	3.99 b
	S	156 b	199 b	476 b	2.11 b	1.87 b	4.42 b
	AM	117 c	238 a	489 a	3.20 a	2.63 a	6.55 a
	AMS	119 c	236 a	491 a	3.33 a	2.70 a	6.77 a
	SE	2.3	10.3	2.0	0.088	0.087	0.338
2016/2017	N	100 a	124 c	256 c	0.92 c	1.49 c	3.59 c
	S	61 b	170 b	304 b	1.35 b	1.95 b	4.42 b
	AM	45 b	201 a	319 a	1.98 a	2.71 a	6.18 a
	AMS	38 b	199 a	327 a	2.02 a	2.86 a	6.16 a
	SE	9.0	9.0	4.8	0.103	0.103	0.569
Mean	N	133 a	156 c	358 c	1.38 c	1.55 c	3.79 c
	S	109 b	185 b	390 b	1.73 b	1.91 b	4.42 b

Same small letter indicates no significant difference between treatments in the same year at the 5% level.

N is no film mulch and no straw incorporation, S is straw incorporation, AM is autumn mulching, and AMS is straw incorporation combined with autumn mulching.

[1]The fallow period is from 1 October in the previous year to maize sowing, i.e. May 6 in 2016 and 2 May in 2017.

	AM	81 c	220 a	404 a	2.59 a	2.67 a	6.37 a
	AMS	78 c	218 a	409 a	2.67 a	2.78 a	6.46 a
	SE	18.1	11.4	39.8	0.263	0.065	0.311
P	Treatment	0.021	0.028	0.076	0.013	0.002	0.001
	Year	0.001	0.013	0.000	0.004	0.502	0.074
	Treatment*Year	0.195	0.289	0.001	0.438	0.497	0.930

Same small letter indicates no significant difference between treatments in the same year at the 5% level.

N is no film mulch and no straw incorporation, S is straw incorporation, AM is autumn mulching, and AMS is straw incorporation combined with autumn mulching.

[1]The fallow period is from 1 October in the previous year to maize sowing, i.e. May 6 in 2016 and 2 May in 2017.

Grain WUE (WUE_Y) of AMS was 46% higher than of S and 79% higher than of N, but showed no significant difference with AM across two seasons. Biomass WUE (WUE_B) in AMS was 48% higher than in S and 70% higher than in N, but did not significantly differ with AM across two seasons (Table 3). The interactions between treatment and year for both WUE_Y and WUE_B were not significantly different (Table 3).

3.6 Straw decomposition rate

In general, the decomposition rate of corn straw in AMS treatment was averaged 80% (Fig. 6a), which was 20% higher than that in S treatment. There was no significant difference measured between two years (Fig. 6b).

4 Discussion

Plastic film cover was reported to improve water availability and soil temperature (Tian et al., 2003; Han et al., 2014; Liu et al., 2014b). Previous studies also showed that corn grain yield could be increased by plastic film cover during winter and early spring season in the arid or semi-arid region of China (Wang et al., 2016; Zhang et al., 2019), while the advantage of straw returning to field was only recognized for the improvement of soil moisture and temperature (Cai et al., 2018;). In this field study, straw incorporation combined with plastic film cover in winter not only improved soil water availability and soil temperature, but significantly increased corn yield in compared with straw incorporation only and no-film control, especially in context of 1000-kernel weight. Higher soil temperature and soil moisture content in early spring would promote corn growth and enhance dry matter accumulation by increased kernel number per ear and improved corn transpiration and grain filling, consequently increasing the 1000-kernel weight and grain yield (Zhang et al., 2019). Even though this two-year experiment showed that straw incorporation combined with plastic film cover in winter had the same treatment effect on corn yield as plastic film cover, it is believed that straw incorporation combined with plastic film cover would have a greater long-term benefit to corn yield than plastic film cover or straw incorporation alone, because of enhanced straw decomposition and improved soil properties and health (Jin et al., 2018).

Plastic film cover was an effective practice to increase topsoil temperature and soil water content in winter and early spring (Wang et al., 2015), which resulted from high net radiation gain and greenhouse effect. In this study, both AMS and AM treatments showed increased soil temperature at 5-cm depth during the winter and early spring season, which would promote seed germination and seedling establishment, especially in a cool spring. In addition, straw incorporation practice could benefit from and promoted by plastic film cover in northern China, because it was found that straw decomposition rate under plastic film was higher than that without plastic film, which was attributed to increased soil temperature and improved soil moisture condition.

The treatments of both AMS and AM on corn yield or yield components were more effective in the relatively dry year of 2017 than in the normal year of 2016, suggesting that film cover treatment would help mitigate the adverse impact of climate change.

Corn water use between film cover and bare soil was dependent on not only total water consumption, but also relative portion of transpiration and evaporation. In this study, both AMS and AM treatments reduced soil water loss through surface evaporation during winter season, which contributed not only to good soil moisture condition for corn emergence and seedling establishment, but also to higher transpiration for grain filling. Data indicated that soil limited moisture for straw decomposition could be alleviated by plastic film cover in winter (Cai et al., 2018).

Scenario of future climate change indicated an increased variability of precipitation pattern in northern China. An increase in the frequency and severity of droughts has already been documented in various locations in Northeast China (Xu et al., 2013; Song et al., 2014; Yu et al., 2014). Such climate change would further aggravate drought (Li et al., 2015). This climate change will cause a serious challenge for sustainable agriculture and straw incorporation practice. Straw incorporation combined with fall plastic film cover could be useful to mitigate climate risks by retaining soil water and alleviating cold stress and enhance the efficiency of straw returning practice to soil. Plastic film cover has also shown effective to reduce greenhouse gas emissions (An et al., 2015), and plastic film cover with straw incorporation was recommended as an effective approach to mitigate greenhouse effects and increase soil carbon sequestration (Gao et al., 2017). In addition, a long-term use of plastic film cover could lead to deterioration of soil health, while straw incorporation practice combined with film cover could improve soil properties and mitigate health soil degradation. Therefore, the implementation of straw incorporation combined with fall film cover could be an environmental-sound, cost-effective strategy for straw utilization and sustainable agriculture production.

The effectiveness of fall film cover after straw incorporation has been confirmed to reduce soil water evaporative losses and increase water availability for plant growth. Thus straw incorporation combined with film cover in fall could be a useful practice that may sustain corn production and alleviate regional environmental issues caused by crop residues. In a long run, such practice would also provide a valuable tool for solving the issue of soil health and fertility decline caused by continuous plastic film cover practice.

When crops are harvested, old plastic film needs to be removed to prevent the accumulation in soil, which may damage soil quality and root penetration and affect crop yield (Liu et al., 2014a). Removed plastic film has to be disposed of properly. However, in current practice, film residues are often left in field or burned by farmers, causing potential environmental pollution. Biodegradable film that can be degraded gradually by radiation and/or soil microorganisms may be a promising alternative to retain the advantages and overcome shortcomings of conventional plastic films (Briassoulis, 2006; Scarascia-Mugnozza et al., 2004, Gu et al., 2017). Therefore, straw incorporation practice that is combined with biodegradable film cover is urgently needed in the northeastern region of China.

5 Conclusions

Results of this study showed that fall straw incorporation combined with plastic film cover and only plastic film cover had the same effect on increasing the grain yield and water use efficiency of corn. Straw incorporation combined with plastic film cover significantly reduced soil water evaporative loss during the winter season and increased soil water content in early growing season in compared with the treatments without film cover. Soil temperature at 5-cm depth in early spring increased by an average of 4.1 ^{o}C when soil was covered by film during winter season. Straw incorporation combined with plastic film cover retained more water and improved water availability in soil, which resulted in higher corn dry matter production and grain yield. The grain yield of the straw incorporation combined with plastic film cover increased by 53% and water use efficiency by 45% as compared with only straw incorporation, and 102% and 79%, respectively, in compared without the cover. In addition, film cover would enhance the decomposition of straw incorporated into soil, because of improved soil temperature and moisture during winter. Even though data showed no significant difference between AMS and AM treatments, corn grain yield trended to be slightly higher in 2017 than 2016. With continued straw return to soil in long-term, higher corn yield is expected because of carbon sequestration and improved soil health. Therefore, the implementation of straw incorporating practice with fall film cover would be highly recommended as an environmental-sound practice for sustaining soil health and crop production in northern China.

Declarations

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Figures

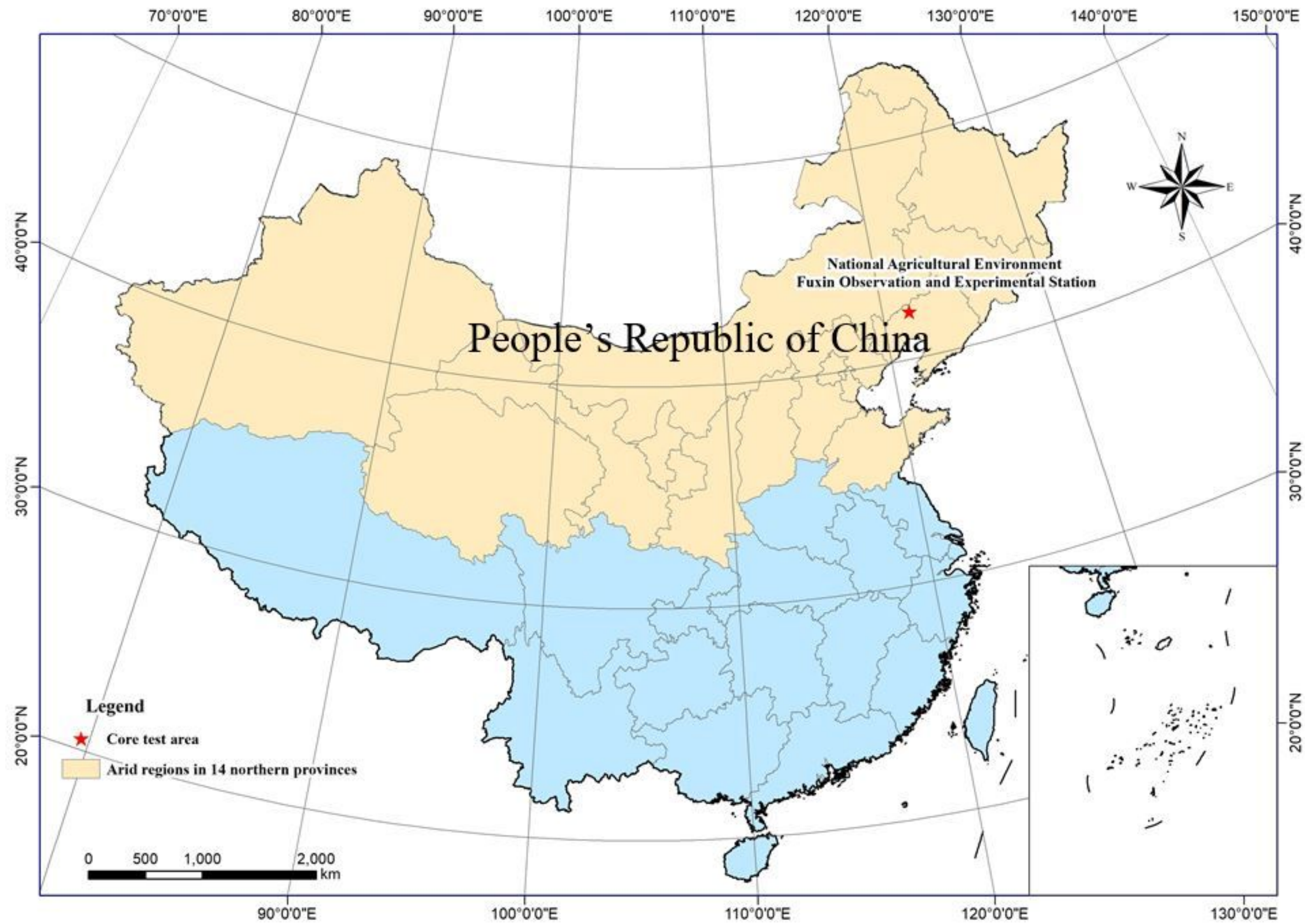

Figure 1

Location of the experimental site (red pentacle)

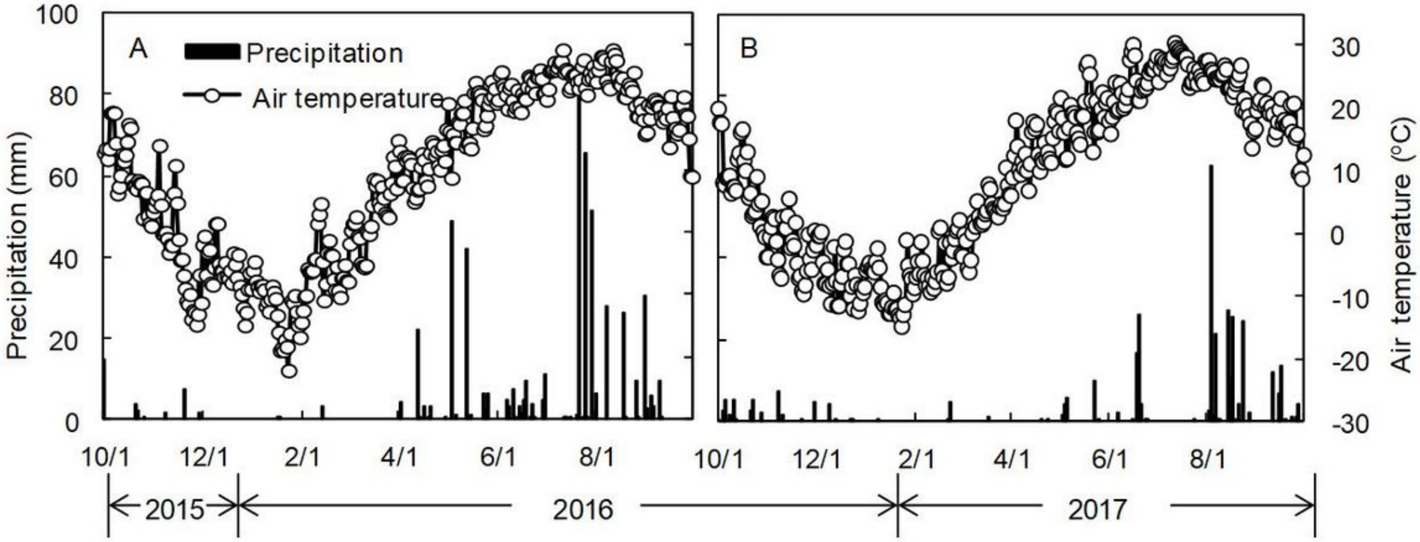

Figure 2

Daily precipitation and air temperature near the experimental site during the period of 2015-2016 (A), and 2016-2017 (B).

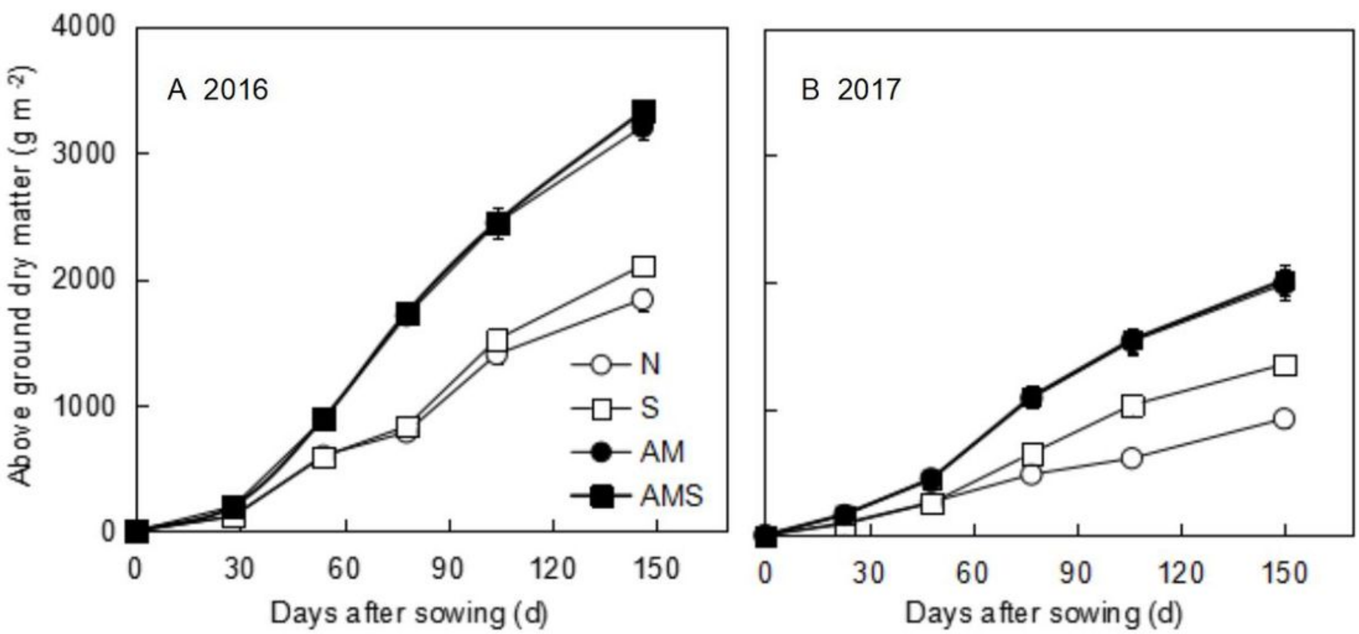

Figure 3

Dynamics of above-ground dry matter of corn in the treatments of straw incorporation combined with fall film mulch (AMS), fall film cover only (AM), straw incorporation only (S) and control (no film and no straw added, N) in 2016 and 2017.

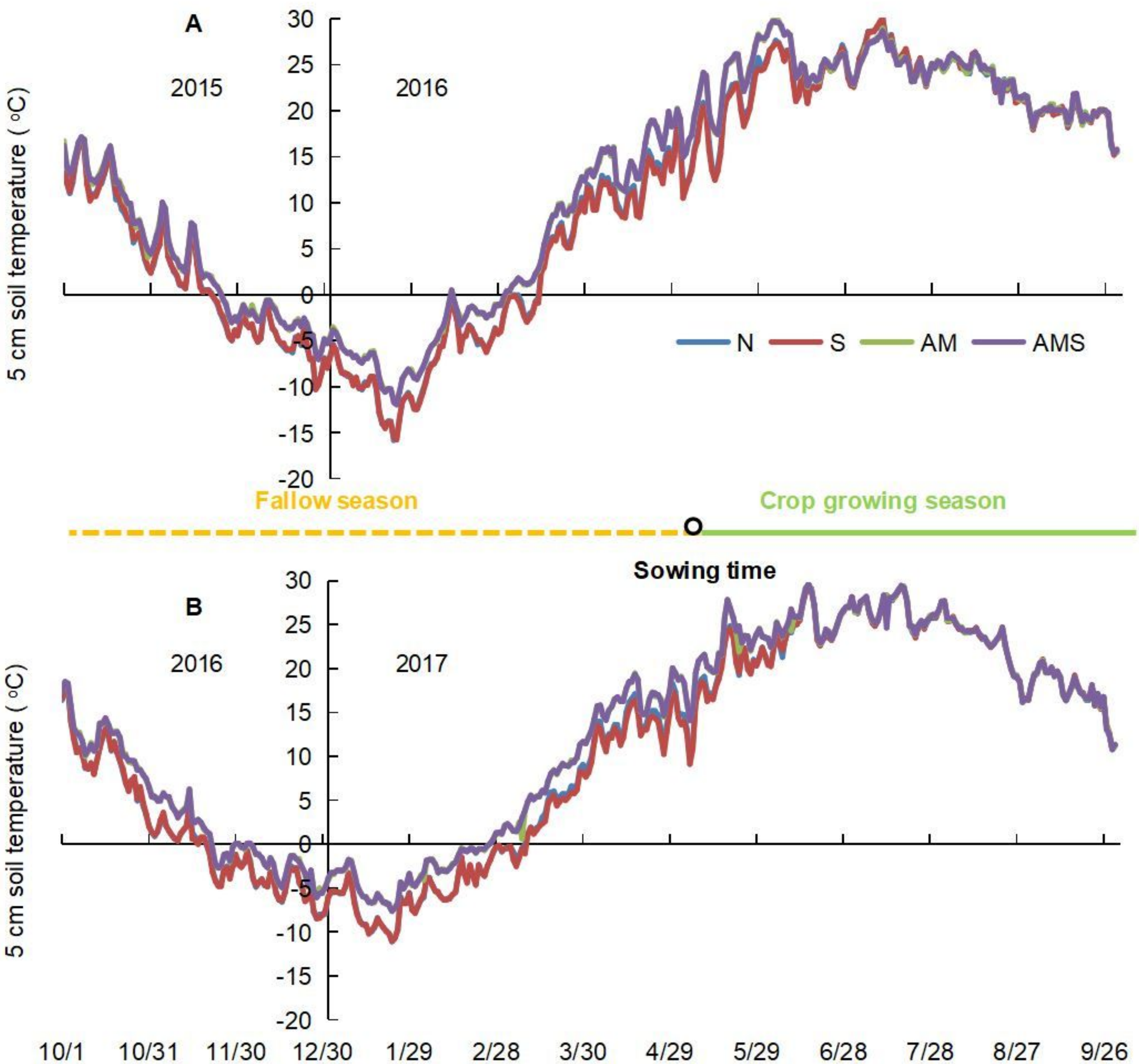

Figure 4

Comparison of soil temperature at 5-cm depth among treatments in 2015-2016 (A) and 2016-2017 (B).

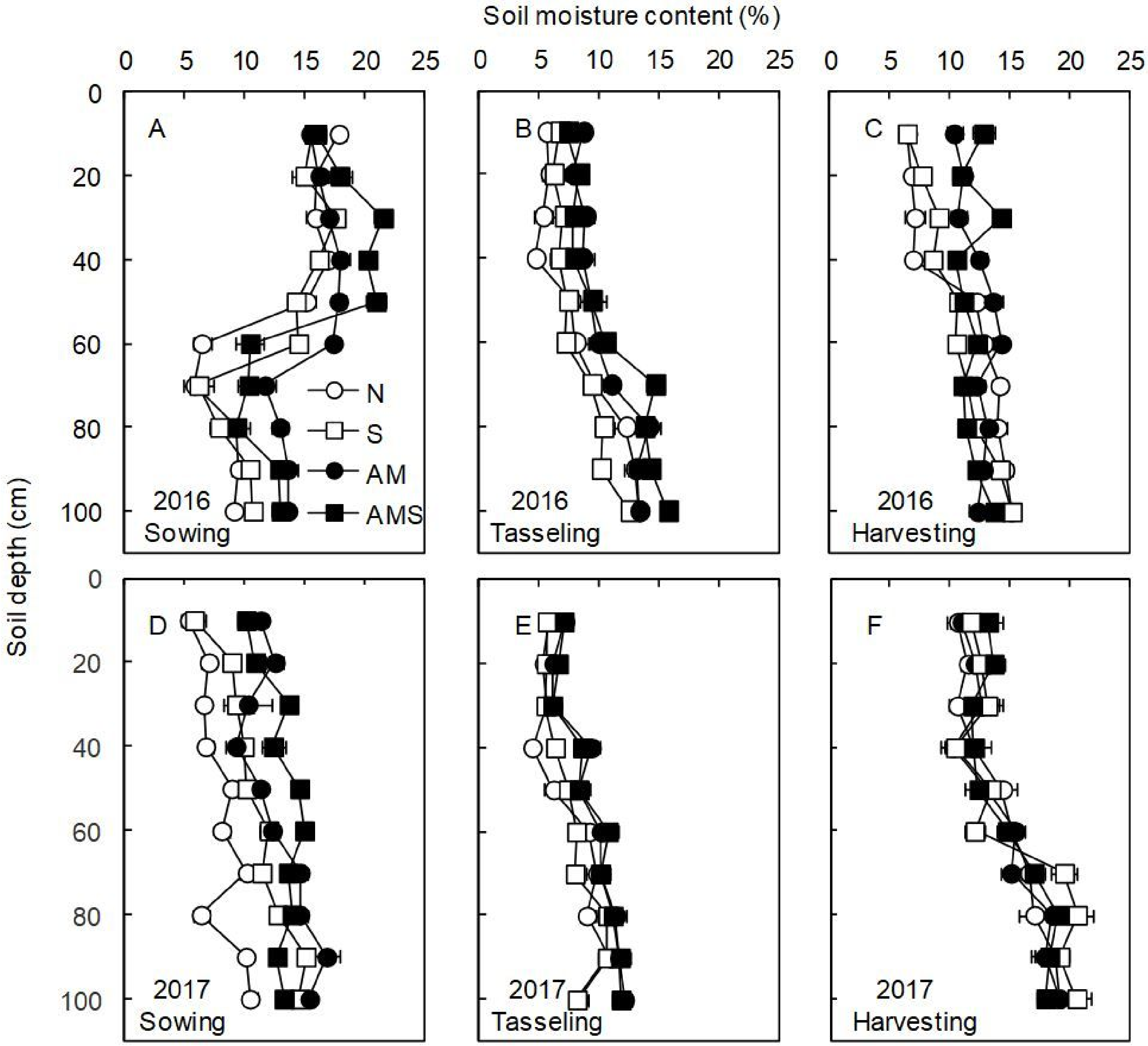

Figure 5

Distribution of soil moisture content within 100 cm soil profile among treatments at various corn growth stages in 2016 (A-C) and 2017 (D-F).

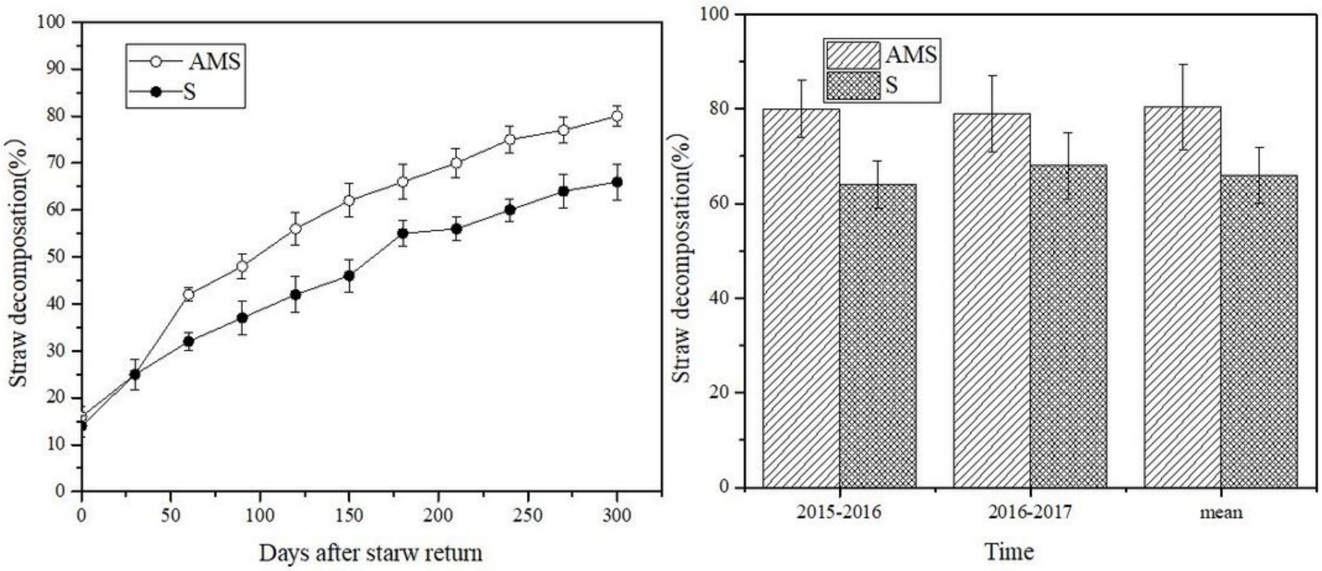

Figure 6

(a) Decomposition rate of corn straw in treatments of AMS and S during two growth seasons. (b) Average straw decomposition across each growing season. Points represent average straw decomposition and bars as standard deviations.