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Dual plastic film and straw mulching boosts wheat productivity and soil quality under the El Nino in semiarid Kenya

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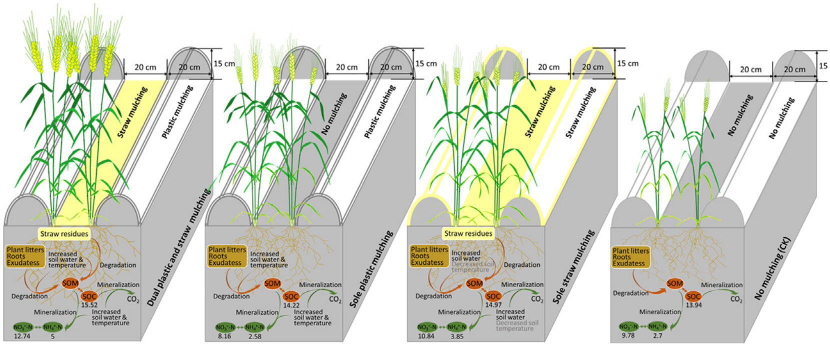
HIGHLIGHTS

- Dual plastic film and straw mulching was explored in semiarid SSA under El Nino.
- It improved crop productivity and soil hydro-thermal status across four seasons.
- It significantly improved soil C and N stocks following four growing seasons.
- It led to the highest economic profitability among all treatments in all seasons.
- Dual mulching proved to be a sustainable farming management in SSA under El Nino.

GRAPHICAL ABSTRACT



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ABSTRACT

The extreme climate events such as El Nino seriously threaten crop production and agro-ecological sustainability because of the aggravated environmental stresses worldwide, particularly in sub-Saharan Africa. To address this issue, we investigated the effects of dual plastic film and straw mulching in ridge-furrow (RF) system on wheat productivity, soil carbon and nitrogen stocks in a semiarid area in Kenya from 2015 to 2017. The experimental site represents a typical semiarid continental monsoon climate, and soil type is chromic vertisols. Field experiment with randomized block design consisted of six RF treatments as follows: 1) dual black plastic film and straw mulching (RFbS), 2) dual transparent plastic film and straw mulching (RFtS), 3) sole black plastic film mulching (RFb), 4) sole transparent plastic mulching RF (RFt), 5) sole straw mulching (RFS) and 6) no mulching (CK). The results indicated that seasonal dynamics of rainfall and air temperature fit in with the weather type of El Nino over four growing seasons. RFbS, RFtS, RFb and RFt significantly increased soil water storage (SWS), topsoil temperature, aboveground biomass, grain yield and water use efficiency across four growing seasons ($p < 0.05$) as compared with CK. Among all the treatments, RFbS and RFtS achieved the greatest SWS, AgB, grain yield and WUE, owing to improved soil hydro-thermal status in both treatments. Critically, RFbS and RFtS significantly improved soil organic carbon and total nitrogen, soil bulk density and the C:N ratio following four growing seasons, comparing with other treatments ($p < 0.05$). Besides, RFbS and RFtS gave the highest economic returns among all treatments. For the first time, we found that dual plastic film and straw mulching could serve as a sustainable land management to boost wheat productivity and improve soil quality under El Nino in semiarid areas of SSA.

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1. Introduction

In sub-Saharan Africa (SSA), agricultural production encounters a range of challenges and limiting factors, including inadequate rainfall, infertile soil and land degradation (Sanchez, 2002; Vohland and Barry, 2009; Thierfelder et al., 2018). Another challenge threatening agricultural production is extreme climate event such as El Nino (Stige et al., 2006; Van Ittersum et al., 2016; Guan et al., 2017; Tumushabe, 2018). Particularly, the El Nino event frequently takes place in the region of SSA, and brings huge risk to the productivity and sustainability of the local farming system because of the aggravated environmental stresses (Stige et al., 2006; Guan et al., 2017).

To meet the above challenges, appropriate agronomic measures are urgently needed for improving agricultural production stability. Over last decade, ridge and furrow (RF) with plastic mulching, an innovative micro-field rainwater harvesting system, has displayed substantial potential to increase crop yield, water use efficiency (WUE) and farmers' livelihood all over the world (Sharma et al., 2011; Ruidisch et al., 2013; Liu et al., 2014; Munoz et al., 2015; J.Y. Wang et al.,2016; Mo et al., 2017). It has shown great advantages at the field scale, such as decreasing surface evaporation, improving rainwater conservation, enhancing soil water infiltration, suppressing weed growth and reducing soil erosion (Jia et al., 2006; Ghosh et al., 2006; Ramakrishna et al., 2006; Zhou et al., 2012).

The effects of plastic mulching on soil organic carbon (SOC) have been found to be variable, including the positive (Jia et al., 2006; Mo et al., 2017), neutral (Liu et al., 2014) and negative (Li et al., 2004; Zhou et al., 2012) effects. The balance of SOC between the inputs from plant organic sources and the losses by microbial decomposition may be partly responsible for the variability in these studies. It is generally accepted that the mineralization of SOC can be accelerated via enhancing microbial activity, due to the improved soil temperature and moisture under the condition of plastic mulching (Li et al., 2004; Jia et al., 2006; Zhou et al., 2012). In most cases, the enhanced mineralization cannot be balanced by the augmented inputs. Therefore, plastic film mulching may negatively affect the SOC pool and further aggravate the productivity and sustainability of the cropping system (Li et al., 2004; Zhou et al., 2012; Y.P. Wang et al., 2016). However, this trend is so far indefinite since plastic mulching effects on the SOC pool are frequently affected by the extreme climatic event such as El Nino.

As one of the measures of conservation agriculture, crop residue retention has been used in some areas of SSA (Fowler and Rockstrom, 2001; Nyamangara et al., 2013; Ndah et al., 2015; Thierfelder et al., 2018). It can help increase SOC, conserve soil water and improve soil structure as compared to conventional tillage practice that frequently results in soil erosion and degradation (Nyssen et al., 2011; Nyamangara et al., 2013; Lee and Thierfelder, 2017). To some extent, sole crop straw mulching can result in yield benefits, which is more pronounced in normal or dry years (Pittelkow et al., 2015). However, this sort of yield effects has been found to be variable in some regions (Giller et al., 2009). In addition, retention of mulch is bound to pose competition with fodder for livestock in smallholder farming systems in SSA (Giller et al., 2009; Ndah et al., 2015).

The application of sole plastic film and straw mulching has been practiced all over the world such as East Asia (Li et al., 2004; Zhou et al., 2012; Ruidisch et al., 2013), South Asia (Sharma et al., 2011; Ram et al., 2013), North America (Diazperez and Batal, 2002; Lenka and Lal, 2013), Europe (Stagnari et al., 2014; Munoz et al., 2015) and SSA (Giller et al., 2009; J.Y. Wang et al., 2016; Mo et al., 2017). Sustainable agriculture managements including soil, nutrient, and water management should be capable of boosting crop productivity and hence leading to a profitable farming strategy, while without compromising land degradation (Tilman et al., 2002; Perkins et al., 2011; Dallimer et al., 2018; Hammad et al., 2018). On one hand, plastic film can increase crop yield and WUE in the semiarid areas. On the other hand, it may cause the loss of SOC and the excessive consumption of available nitrogen particularly under the condition of no input of plant organic source (Li et al., 2004; Zhou et al., 2012; Y.P. Wang et al., 2016). In recent decade, dual plastic film and straw mulching in ridge and furrow system has been tested in northwest China, showing that it can increase crop yield and water productivity (Gao et al., 2009; Li et al., 2013; Chen et al., 2015; Liu et al., 2017). This sort of dual mulching can efficiently prevent rainwater loss through runoff and surface evaporation, increase soil water storage, and improve soil thermal balance (Li et al., 2013; Chen et al., 2015). Also, the dual mulching system is beneficial for enhancing and stabilizing crop production (Liu et al., 2017) and nitrogen use efficiency (Gao et al., 2009). However, it is unclear whether it can positively affect soil carbon and nitrogen stocks under the scenario of El Nino in the semiarid agro-ecosystems of SSA.

In this study, field experiment was conducted in four growing seasons at a typical semiarid site of Kenya to investigate if dual plastic film and straw mulching would provide a novel solution to address the above issue under the El Nino in SSA. The objectives of this study are: 1) to evaluate the responses of wheat yield performance, economic returns, soil water storage and topsoil temperature to dual plastic film and straw mulching, in comparison with sole plastic mulching, sole crop straw mulching and no mulching (CK); 2) to investigate the dynamics of soil carbon and nitrogen stocks in various mulching managements across four growing seasons; 3) to identify an innovative and sustainable agricultural strategy to address food security and cope with the El Nino event in the typical semiarid SSA such as Kenya.

2. Materials and methods

2.1. Study site

The field experiment was conducted from November 2015 to July 2017 (four growing seasons) at Jomo Kenyatta University of Agriculture and Technology (01° 05′ S, 37° 00′ E; altitude 1530 m) in Juja, Kenya (Fig. 1). The site represents typical semiarid continental monsoon climate type, with average annual temperature, annual precipitation and potential evaporation of 19.8 °C, 675.8 and 1650.5 mm respectively. Weather data were obtained from the Juja Meteorological Station (established in 2009, next to the experimental field). The time-course dynamics of semimonthly precipitation and daily average air temperature across the testing years and the past nine years are shown in Fig. 2. Local precipitation is mainly distributed in two distinct rainy seasons, i.e. long and short rainy seasons. Long rainy season generally covers from mid-March to mid-July, and is characterized as lesser inter-annual precipitation variability and lower average air temperature. Short rainy season is generally featured by higher precipitation variability and air temperature, ranging from October to December (Peter and Moses, 2016; Mo et al., 2017). Local aridity index (evaporation/precipitation) (Ponce et al., 2000) is from 2.2 to 3.5 (2009–2017). The soil type belongs to chromic vertisols (Soil Survey Staff, 2003). A brief description of soil characteristics at the depth of 0–30 cm is shown in Table 1.

2.2. Experimental design

The experiment was conducted in a randomized block design with three replicates for each treatment. Each block was composed of five mulching managements with ridge and furrow (RF) and no mulching with RF (CK). Mulching treatments included as follows: 1) furrows mulched with wheat straw and ridges mulched with black plastic film (RFbS), 2) furrows mulched with wheat straw and ridges mulched with transparent plastic film (RFtS), 3) furrows unmulched and ridges mulched with black plastic film (RFb), 4) furrows unmulched and ridges mulched with transparent plastic film (RFt) and 5) furrows and ridges both mulched with wheat straw (RFS). No mulching in RF was used as the control group (CK). The ridge and furrow with mulching system (RFM) was established manually by use of spade, with the ridges (20 cm wide and 15 cm high) and furrows (20 cm wide) being arranged

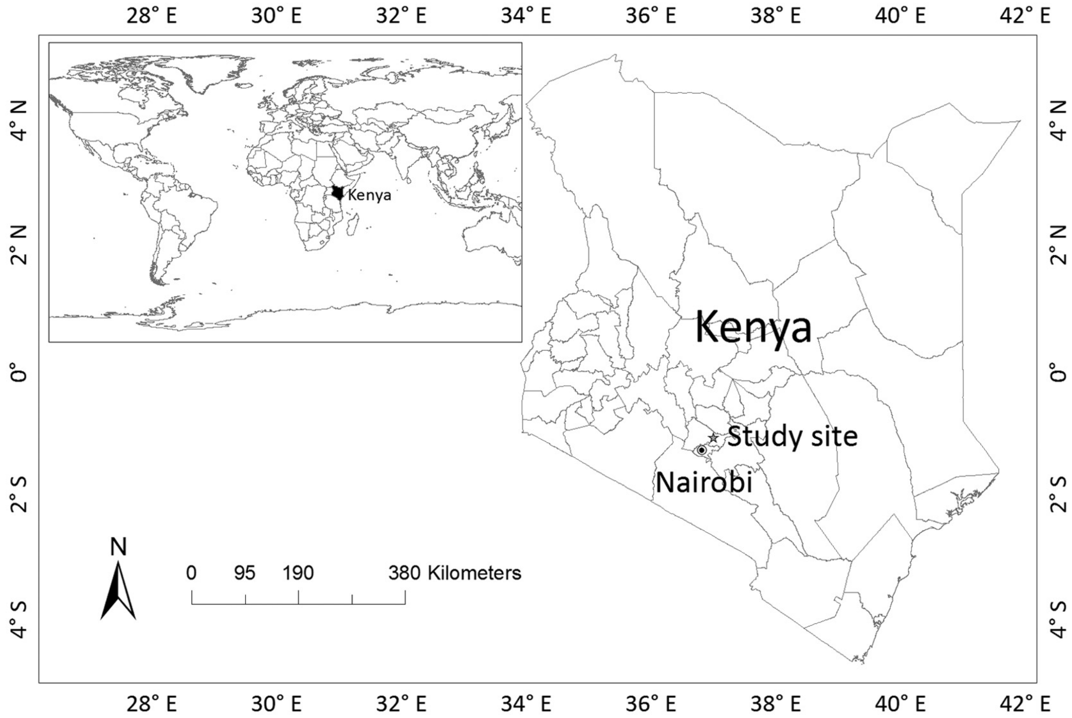

Fig. 1. Geographical map of the study site in Kenya.

alternatively. In RFM system, rainwater was collected at the surface of ridges and stored into the planting zone within furrows. Dried wheat straw was applied manually at the rate of 6000 kg ha^{-1} in RFS, and 3333.3 kg ha^{-1} in RFbS and RFtS during the four growing seasons, respectively.

In Kenya, fertilization was conventionally carried out at low rates for wheat production. In present study, urea for nitrogen, triple superphosphate for phosphorus and potash for potassium were applied at the rates of 40 kg N ha^{-1}, 20 kg P_2O_5 ha^{-1} and 20 kg K_2O ha^{-1}, respectively. Urea was split-applied with 50% at pre-plant and 50% at the jointing stage respectively. Superphosphate and potassium were broadcast applied before sowing. The field was plowed at a depth of 30 cm, and then harrowed and subdivided into three blocks. There were six managements that were replicated in each of the three blocks

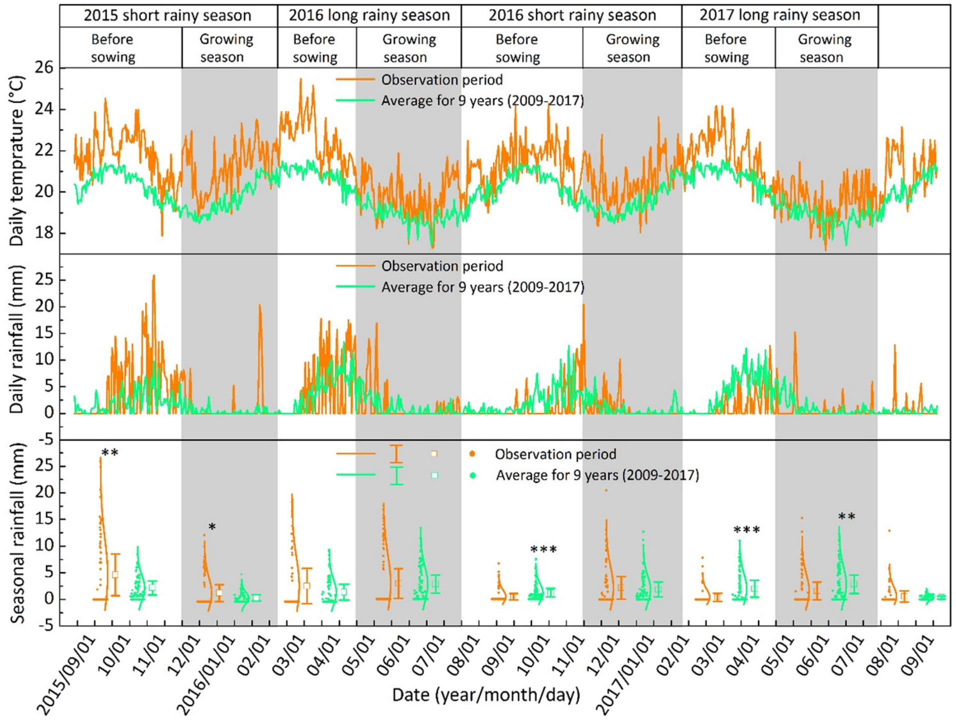

Fig. 2. The difference of rainfall and air temperature among observation period and the average value for recent 9 years (2009–2017) at experimental site. The shaded parts represent wheat growing season in 2015-short, 2016-long, 2016-short and 2017-long rainy season, respectively. The hanging bars represent standard deviation of the rainfall. *, ** and *** mean significant differences at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

Table 1
Soil properties (0–30 cm) of the experimental field before the start of experiment.

SOC ($g\ kg^{-1}$)	STN ($g\ kg^{-1}$)	STP ($g\ kg^{-1}$)	NO_3^--N ($mg\ kg^{-1}$)	NH_4^+-N ($mg\ kg^{-1}$)	AP ($mg\ kg^{-1}$)	Field capacity (%)	Wilting point (%)	pH	BD ($g\ cm^{-3}$)	Soil particle size		
										Clay (%)	Silt (%)	Sand (%)
14.45	0.77	0.20	10.77	0.20	6.97	29.50	9.60	6.36	1.45	58.30	25.20	29.50

Note: SOC, soil organic carbon; STN, soil total nitrogen; STP, soil total phosphorus; NO_3^--N, nitrate nitrogen; NH_4^+-N, ammonium nitrogen; AP, available phosphorus; BD, soil bulk density.

before sowing giving a total of 18 plots. Each plot area was 5 m × 5 m, being surrounded by the ridges to prevent surface runoff. The ridges and furrows in each plot were constructed in the first growing season and repaired in the subsequent growing seasons.

During four growing seasons, local wheat (*Triticum aestivum* L.) cv. *DUMA* was seeded (seed rate, 200 kg ha^{-1}) in two rows of 20 cm spacing in the furrows on 16 November 2015, 16 April 2016, 1 November 2016 and 16 April 2017. At the maturity stage, all plants were manually harvested with a sickle on 8 February 2016, 16 July 2016, 25 January 2017 and 13 July 2017, respectively. After harvesting, plastic residues were completely cleared by hand from all plots. Ridges and furrows were kept clear of weeds to avoid any influence on soil and water conservation over the fallow period. Throughout each growing season, weeds were removed by hand. Insecticide (imidacloprid) and fungicide (diniconazole) were separately sprayed to control aphids and rust at the beginning of the booting stage.

2.3. Measurements and methods

2.3.1. Soil sampling and analysis

Before sowing and after harvesting, three soil samples at 0–30 cm depth in each plot were taken randomly in the furrows and then thoroughly mixed for laboratory determination. Fresh subsamples were passed through a 2 mm sieve and stored at 4 °C before the determinations of NO_3^--N and NH_4^+-N contents. Air-dried subsamples were ground and sieved at 2 mm and 0.25 mm for the measurement of soil pH, SOC, and soil total nitrogen contents (STN), in which gravel (>2 mm) was weighed and discarded. Additionally, three undisturbed core samples at 15 cm depth in each plot were collected using cutting rings (100 cm^3) for determination of soil bulk density (BD). For every plot, other soil samples at 20 cm increment down to the depth of 140 cm were taken at five growing stages for soil moisture determination. Soil water content (SWC) was determined gravimetrically by weight loss after drying at 105 °C for 24 h. Soil water storage (SWS, mm) was calculated from SMC (J.Y Wang et al., 2016; Mo et al., 2016). Across four seasons, soil temperature was measured and recorded at the 10 cm depth with RC-5 instrument (Elitech, Co., Ltd., Jiangsu, China).

Soil samples with the particle diameter of <2 mm were used to measure the soil particle size (clay, silt and sand) on a laser particle size analyzer S3500 (Microtrac Inc., Florida, USA). Soil BD was determined by calculating the ratio of soil mass to a total volume of the core (g cm^{-3}) after oven-drying to a constant weight at 105 °C for 24 h (Finn et al., 2015). Saturation water holding at field water capacity (at 0.033 MPa) and at permanent wilting point (at 1.5 MPa) was determined using the centrifugation method, respectively (Ghorbani et al., 2017). Soil pH was quantified in a suspension of air-dried soil and 0.01 M $CaCl_2$ water (1:2, w/v) with pH meter (Russenes et al., 2016). The content of SOC was detected by dichromate redox titration (Gregorich and Carter, 2007). STN content was determined by micro-Kjeldahl digestion and titrated the distillate with 0.01 M H_2SO_4 (Gregorich and Carter, 2007). Soil mineral-N was extracted from fresh soil using 50 mL 2 M KCl (Rowell, 1994). The contents of NO_3^--N and NH_4^+-N in the extracts were measured colorimetrically in a continuous flow auto-analyzer San^{++} (Skalar Inc., Holland).

2.3.2. Grain yield, aboveground biomass and water use efficiency

Wheat samples at harvest were taken at three randomly located areas of 1 m^2, to measure grain yield and total aboveground biomass (AgB). In addition, evapotranspiration (ET, mm) was calculated using the following formula (J.Y. Wang et al., 2016; Mo et al., 2016):

$$ET = R + \Delta SWS$$

R was the total amount of rainfall during the growing season, ΔSWS (mm) is the difference in SWS (0–120 cm) between the beginning and the end of each growing season.

Thereafter, the water use efficiency (WUE, kg ha^{-1} mm^{-1}) regarding yield (WUE_Y) and aboveground biomass (WUE_B) was calculated as follows:

$$WUE_Y = Y/ET$$

$$WUE_B = B/ET$$

where Y is grain yield, B is aboveground biomass.

2.3.3. Expenses

Major inputs in our study were composed of labor and materials. Labor input included land preparation, RFM making, field managements (i.e. plastic removal, weeding and spraying insecticides and so on), sowing and harvesting. The calculations were performed in light of local currency (Kenyan shilling, Ksh) to convert to the US dollar (100 Ksh = 1 US$). Local farmers were employed to undertake labor work, and the labor cost was 4 US dollars per farmer per workday according to local wage standards. Plastic and wheat straw materials, commercial seeds, fertilizers and pesticides were the major material inputs. According to the local market price at the time of this study, the output was evaluated based on 0.6 US dollars per kilogram for grain yield, and 0.03 for hay biomass, respectively. Finally, net income per treatment was determined by calculating the difference between output and input values, and the benefits-cost ratio according to the outputs divided by inputs.

2.4. Statistical analysis

Wheat yield, AgB, WUE, economic benefits, rainfall, air temperature, and soil physicochemical properties were analyzed using one-way ANOVA followed by Tukey-B ($p < 0.05$) multiple comparison test after homogeneity of variances. We used a two-way ANOVA ($p < 0.05$) to test for the main effects of mulching management, growing season and their interactions on wheat yield, AgB, WUE, and soil BD, pH, SWS, soil temperature, SOC and nitrogen. Pearson correlation coefficients ($p < 0.05$) were used to assess the significance of the interrelationships of soil characteristics, and the significance among soil characteristics, yield, AgB, WUE and HI ($n = 72$). All statistical analyses were performed with SPSS 20.0 (IBM Co., USA) software. Data was visualized in Origin pro 8.0 software (OriginLab, USA).

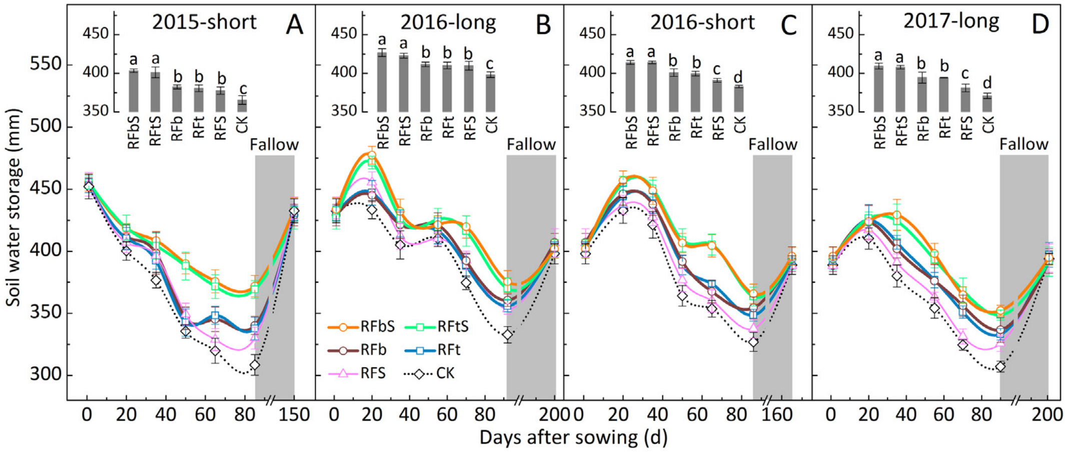

Fig. 3. Effects of different treatments on the soil water storage (SWS) at 0–140 cm layer over four growing seasons of 2015-short (A), 2016-long (B), 2016-short (C) and 2017-long (D) rainy seasons. The bar figure shows the average SWS at each growing season. The line figure provides the SWS dynamics at each growing season. The shaded parts represent fallow period. The same lowercase letter shows that there is no significant difference at $p < 0.05$ according to Tukey-B test.

3. Results

3.1. Dynamics of rainfall and air temperature in the studied period

According to the meteorological data, the dynamics of rainfall and air temperature at the study site showed high variability and deviation as affected by regional El Nino event. The rainfall amount within the four growing seasons accounted for 26.6%, 61.5%, 85.2% and 67.5% of the total amount of semi-annual rainfall respectively. The respective percentage of pre-sowing rainfall was 73.4%, 38.5%, 14.8% and 22.1% in the 2015-short, 2016-long, 2016-short and 2017-long rainy seasons respectively (Fig. 2). Compared with the multi-year value (2009–2017), the rainfall amounts in pre-sowing and growing season were significantly increased in 2015 short rainy season but decreased in 2017 long rainy season (Fig. 2). There were non-significant differences in 2016 long rainy season (Fig. 2). In 2016 short rainy season, the rainfall in pre-sowing was lower than the multi-year value, and there was no difference in the growing season (Fig. 2). Therefore, the above four seasons were defined as wet, normal, dry and severe dry seasons respectively, showing a distinct feature of extreme climate event under the El Nino.

The short rainy seasons of 2015 and 2016 were identified as hot type, with mean daily air temperature of 21.3 °C and 21 °C, respectively. The long rainy seasons of 2016 and 2017 turned to be relatively warm, with mean temperature of 20.8 °C and 20.5 °C, respectively. In comparison with multi-year average value, the air temperature was increased by 1.5 °C, 1.21 °C, 1.03 °C and 0.97 °C in the 2015-short, 2016-long, 2016-short and 2017-long rainy seasons, respectively. Importantly, the variability of air temperature was distinctly higher in each growing season than that of the multi-year average value (Fig. 2).

3.2. Dynamics of soil moisture and temperature in response to the RFM system

RFM system resulted in significant improvement in SWS throughout the four growing seasons (Fig. 3). The dynamics of SWS followed a similar trend in the four growing seasons among the treatments (Fig. 3). Within each growing season, the SWS in all treatments increased firstly to the maximum value at the tillering stage and then started to decrease till the harvesting stage in the 2016-long, 2016-short and 2017-long rainy season (Fig. 3B–D) respectively, except for a continued decrease in the 2015-short rainy season (Fig. 3A). There were no differences in the initial value of SWS among the treatments in each season ($p > 0.05$, Fig. 3). At the middle and later growth stages, significant difference in SWS was observed among the treatments in the four seasons ($p < 0.001$, Fig. 3). For average SWS, there were no differences between RFbS and RFtS, and between RFS and RFt over four growing seasons ($p > 0.05$, Fig. 3). Average SWS declined significantly in the sequences

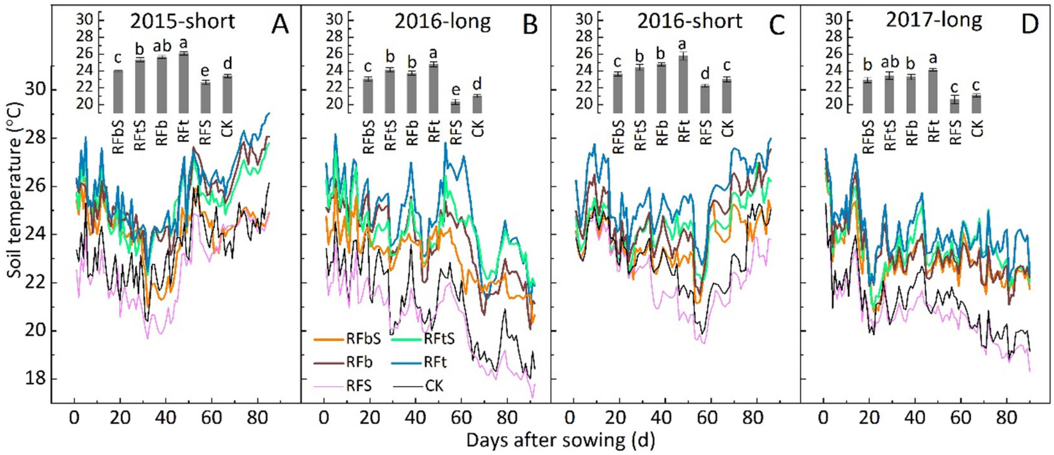

Fig. 4. Effects of different treatments on the daily soil temperature (ST) in 10 cm soil depth over four growing seasons of 2015-short (A), 2016-long (B), 2016-short (C) and 2017-long (D) rainy seasons. The bar figure shows the average ST at each growing season. The line figure provides the ST dynamics at each growing season. The same lowercase letter shows that there is no significant difference at $p < 0.05$ according to Tukey-B test.

of RFbS ≈ RFtS > RFb ≈ RFt ≈ RFS > CK in the former two growing seasons and RFbS ≈ RFtS > RFb ≈ RFt > RFS > CK in the latter two growing seasons, respectively ($p < 0.05$, Fig. 3).

RFM treatments significantly modified topsoil temperature (10 cm depth) across the four growing seasons ($p < 0.001$, Fig. 4). Daily topsoil temperature firstly decreased and then increased in the short rainy seasons with prolonged day length. Yet in the long rainy seasons, it kept decreasing with time (Fig. 4). The topsoil temperature in the short rainy seasons was generally higher than that in long rainy seasons. For all the four growing seasons, RFbS, RFtS RFb and RFt significantly increased the average temperatures, while RFS turned to lower the temperature, compared with CK ($p < 0.05$, Fig. 4). The treatments of transparent plastic film mulching (RFt and RFtS) always resulted in higher soil temperatures than those of black plastic film mulching (RFb and RFbS) did (Fig. 4). Plastic film mulching (RFb and RFt) brought about higher soil temperatures than dual plastic film and straw mulching (RFbS and RFtS) did (Fig. 4).

3.3. Dynamics of soil BD, pH, SOC and nitrogen

Soil BD and pH were significantly dependent on mulching management (Table 2). Comparing with other treatments, RFbS, RFtS and RFS treatments significantly promoted soil pH, yet decreased BD simultaneously (Fig. 6G, H).

The respective basal values of SOC, STN and C:N ratio and other soil properties (Fig. 5, Table S1) had no significant differences among treatments in the four growing seasons ($p > 0.05$). SOC content was significantly affected by mulching managements and interactions with the growing season (Table 2). Also, STN content and C:N ratio were significantly affected by mulching managements and growing season (Table 2). In the former two growing seasons, the contents of SOC and STN were of no significant differences among the treatments (Fig. 5A, B), except that RFb and RFt resulted in significantly higher STN content than RFS and CK did (Fig. 5B). On the other hand, the contents of SOC and STN in RFbS, RFtS and RFS treatments kept increasing across four growing seasons, but those of RFb, RFt and CK were observed to have a slight decrease before the 2016-short rainy season (Fig. 5A, B). Regardless of treatments, C:N ratio remained a decreasing trend over four growing seasons (Fig. 5C). In particular, the C:N ratio in RFbS and RFtS was maintained at relatively high level, and showed significant differences from that of RFb and RFt in the latter two growing seasons (Fig. 5C).

At the end of four growing seasons, RFbS, RFtS, RFS, RFb and RFt increased SOC content by 11.4%, 11.2%, 7.4%, 2.3% and 1.2% respectively, compared with CK (Fig. 6A). The highest STN content was observed in RFbS and RFtS, which was significantly higher than that of CK, but not significant different from that of RFb, RFt and RFS (Fig. 6B). There existed significant positive correlations between SOC and STN contents ($p < 0.001$, Table 3). The C:N ratio in RFbS and RFtS was significantly greater than that of RFb and RFt ($p < 0.05$), but not different from that of the other treatments (Fig. 6C).

The contents of mineral-N, NO_3^--N and NH_4^+-N were significantly affected by the mulching managements, growing season and their interactions (Table 2). Following four growing seasons, the above three parameters in RFbS and RFtS were significantly greater than those of the other treatments (Fig. 6D-F). There existed a strong positive correlation between NO_3^--N and NH_4^+-N contents ($p < 0.001$, Table 3). The contents of SOC, NO_3^--N and NH_4^+-N, and the C:N ratio were positively correlated with soil pH ($p < 0.05$) and negatively correlated with the BD ($p < 0.05$, Table 3).

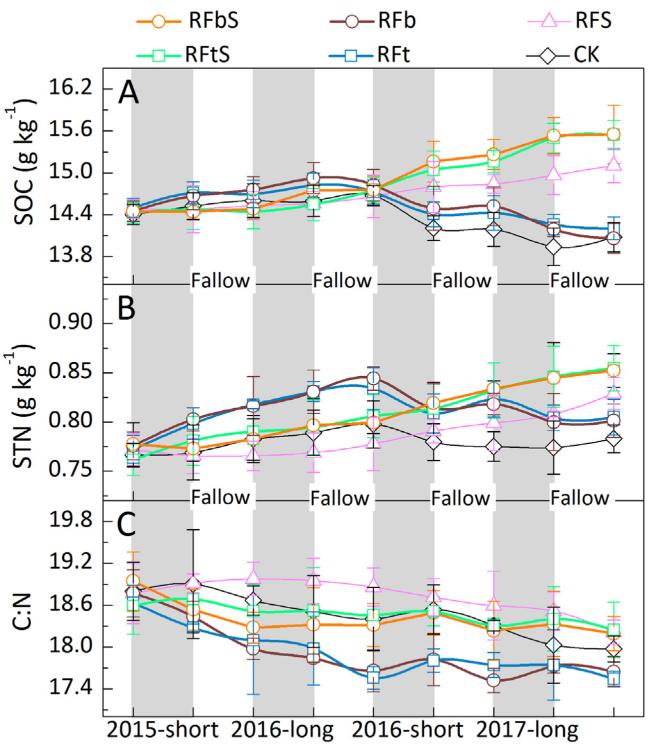

Fig. 5. Dynamics of the soil organic carbon (SOC) (A), soil total nitrogen (STN) (B) and C:N ratio (C) in the 0–30 cm soil layer in different treatments over four growing seasons. The shaded parts represent wheat growing season.

3.4. Wheat yield, growth and WUE

Wheat yield, AgB, WUE and harvest index (HI) were significantly affected by the mulching managements, growing season and their interactions ($p < 0.001$, Table 4). In most cases, there was no difference in wheat yield, AgB, WUE and HI between RFbS and RFtS, and between RFb and RFt across the four growing seasons. As a whole, grain yield, AgB and WUE in RFbS and RFtS were significantly greater than those of RFb and RFt, followed by RFS and the lowest in CK ($p < 0.05$, Table 4). RFbS, RFtS and RFb in 2015-short rainy season, RFbS, RFtS, RFb and RFt in 2016-long rainy season and RFbS, RFtS and RFt in 2017-long rainy season achieved significantly greater HI than RFS did ($p < 0.05$, Table 4).

Regardless of the growing season, grain yield, AgB, WUE and HI were significantly greater in five RFM treatments than those of CK treatment ($p < 0.05$, Table 4). There were significant correlations among grain

Table 2
ANOVA of the effects of mulching management (MM), growing season (GS) and their interaction on SOC, nitrogen, soil pH, BD, SWS and ST.

ANOVA	SOC	TN	C:N	Mineral-N	NO_3^--N	NH_4^+-N	pH	BD	SWS	ST
MM	12.48^{***}	7.72^{***}	9.28^{***}	81.86^{***}	43.32^{***}	71.58^{***}	4.50^{**}	9.98^{***}	118.83^{***}	309.95^{***}
GS	2.06	6.11^{**}	5.13^{**}	253.77^{***}	84.61^{***}	449.82^{***}	0.06	0.26	263.67^{***}	192.26^{***}
MM × GS	7.78^{***}	1.85	0.60	81.20^{***}	45.19^{***}	69.06^{***}	0.82	0.82	1.37	4.56

Note: *, ** and *** mean significant differences at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. SOC, soil organic carbon; STN, soil total nitrogen; C:N, the ratio of SOC to STN; Mineral-N, mineral nitrogen; NO_3^--N, nitrate nitrogen; NH_4^+-N, ammonium nitrogen; BD, soil bulk density; SWS, soil water storage; ST, soil temperature.

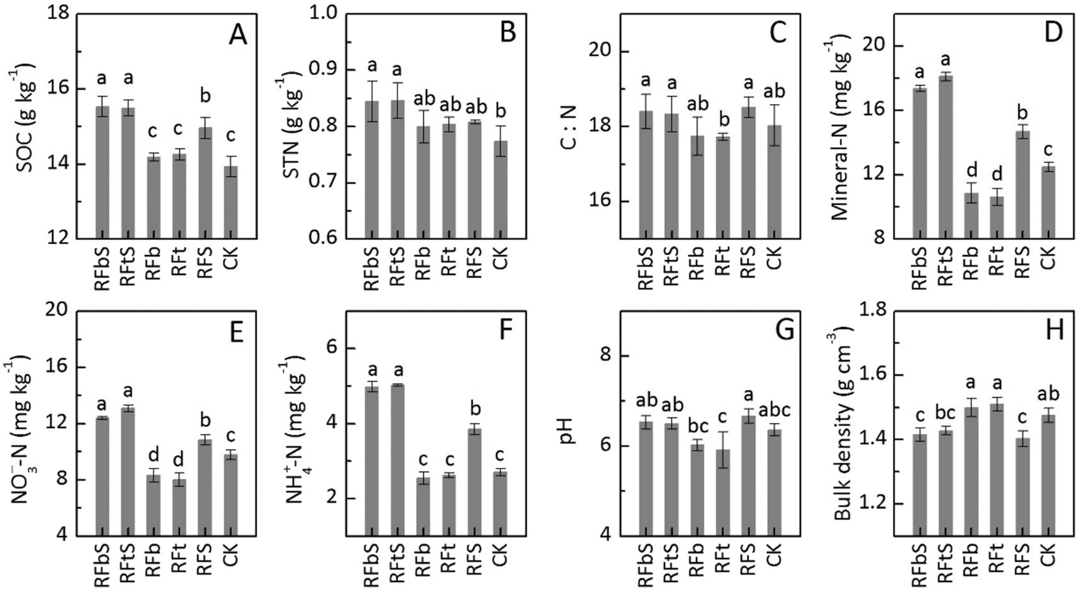

Fig. 6. Dynamics of SOC (A), STN (B), C:N (C), Mineral-N (D), NO_3^--N (E), NH_4^+-N (F), soil pH (G) and bulk density (H) in different treatments after four growing seasons in the experimental site. The same lowercase letter shows that there is no significant difference at $p < 0.05$ according to Tukey-B test. SOC, soil organic carbon; STN, soil total nitrogen; C:N, the ratio of SOC to STN; Mineral-N, mineral nitrogen; NO_3^--N, nitrate nitrogen; NH_4^+-N, ammonium nitrogen.

yield, AgB, WUE_Y, WUE_B and HI ($p < 0.001$, Table S2). Grain yield, AgB, WUE_Y and WUE_B showed positive correlations with SOC, STN, NO_3^--N, NH_4^+-N, SWS and soil temperature, respectively (Table S3). HI was significantly positively associated with NO_3^--N, NH_4^+-N, SMS and soil temperature respectively.

3.5. Economic returns

The labor input in RFbS or RFtS (same input for both), RFb or RFt (same input for both), and RFS were 76.9%, 61.5%, and 30.8% greater than that of CK respectively, but the labor cost for controlling weeds was lowered by 450%, 175% and 266.7% respectively, in comparison with CK (Table 5). The amount of straw material for mulching in RFbS or RFtS was reduced by 80%, compared with that of RFS (Table 5). To sum up, total input in RFbS or RFtS, RFb or RFt, and RFS was increased by 46.6%, 26.7% and 29.4% respectively, compared with that of CK (Table 5). On the other hand, total output was highest in RFbS or RFtS, followed by RFb or RFt, then by RFS, and the lowest was in CK. Consequently, the net income in RFbS and RFtS was significantly greater than that of the other treatments across four growing seasons (Table 5). Additionally, the ratio of output to input in RFbS, RFtS, RFb and RFt was significantly higher than that of RFS and CK, respectively (Table 5).

4. Discussion

4.1. Responses of soil water and temperature to mulching managements under El Nino

According to existing knowledge, the increased air temperature, excessive rainfall and seasonal drought are typical characteristics of the El Nino phenomenon (extreme climate events) (Stige et al., 2006). In this study, most of the growing seasons fell within the weather pattern of El Nino. Across four growing seasons, there were significant influences on the spatial-temporal dynamics of soil moisture and topsoil temperature under the El Nino. Plastic mulching with ridge and furrow (RF) was effective in rainwater harvesting even under light rainfall event in the semiarid agricultural ecosystems (Li et al., 2004; J.Y. Wang et al., 2016; Mo et al., 2016). Crop straw mulching help to reduce surface evaporation and increase soil water infiltration rate. Incorporation of straw into the soil after decomposition improves soil water holding capacity by increasing soil surface roughness and porosity (Fowler and Rockstrom, 2001). In this study, RFbS, RFtS, RFb, RFt and RFS treatments significantly increased SWS than CK did (Fig. 3), which was consistent with the results by previous studies (Gao et al., 2009; Li et al., 2013; J.Y. Wang et al., 2016; Mo et al., 2017). Over the latter two seasons, RFb and RFt were observed to achieve greater SWS than RFS, showing that plastic mulching was more efficient in the aspect of soil water storage than straw mulching, particularly in dry seasons.

Table 3
Pearson correlations between soil properties at the end of four growing seasons.

	SOC	STN	C:N	NO_3^--N	NH_4^+-N	pH	BD	SWS
STN	0.695^{***}							
C:N	ns	-0.647^{***}						
NO_3^--N	0.636^{***}	0.358^{**}	ns					
NH_4^+-N	0.482^{***}	ns	0.32^{**}	0.879^{***}				
pH	0.301^{**}	ns	0.366^{**}	0.32^{**}	0.306^{**}			
BD	-0.408^{**}	ns	-0.402^{***}	-0.403^{***}	-0.348^{**}	-0.419^{***}		
SWS	0.287^{*}	ns	ns	0.49^{***}	0.544^{***}	ns	ns	
ST	ns	0.244^{*}	-0.325^{**}	ns	0.29^{*}	-0.269^{*}	0.252^{*}	ns

Note: *, ** and *** mean significant differences at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively, and ns indicates no significant difference (n = 72). SOC, soil organic carbon; TN, soil total nitrogen; C:N, the ratio of carbon to nitrogen; NO_3^--N, nitrate nitrogen; NH_4^+-N, ammonium nitrogen; BD, soil bulk density; SWS, soil water storage; ST, soil temperature.

Table 4
Wheat yield, aboveground biomass (AgB), water use efficiency (WUE) and harvest index (HI) under different treatments across four growing seasons.

Growing season	Treatments	Yield (kg ha^{-1})	Biomass (kg ha^{-1})	WUE$_Y$ (kg ha^{-1} mm^{-1})	WUE$_Y$ (kg ha^{-1} mm^{-1})	Harvest index
2015 short rainy season	RFbS	3639.6 a	9837.1 a	15.8 a	42.7 a	0.370 ab
	RFtS	3560.4 ab	9744.7 a	15.3 a	41.8 a	0.365 ab
	RFb	3370.6 b	8971.5 b	13.0 b	34.5 b	0.376 a
	RFt	2974.3 c	8394.0 bc	11.4 c	32.1 b	0.355 bc
	RFS	2751.6 c	8025.1 c	10.2 d	29.6 c	0.343 c
	CK	2032.9 d	6466.3 d	7.0 d	22.3 d	0.314 d
	Mean	3054.9 AB	8573.1 B	12.1 AB	33.8 AB	0.354 A
2016 long rainy season	RFbS	4260.9 a	12,502.0 a	13.0 a	38.2 a	0.341 a
	RFtS	4320.7 a	12,533.2 a	13.3 a	38.5 a	0.345 a
	RFb	3529.9 b	10,762.6 b	10.5 b	31.9 b	0.328 ab
	RFt	3661 b	11,093.0 b	10.7 b	32.3 b	0.330 ab
	RFS	2833.9 c	9103.1 c	8.1 c	26.0 c	0.312 c
	CK	2086.3 d	6879.7 d	5.7 d	18.7 d	0.304 c
	Mean	3448.8 A	10,478.9 A	10.2 B	30.9 B	0.327 BC
2016 short rainy season	RFbS	4305.8 a	12,274.8 a	19.4 a	55.4 a	0.351 a
	RFtS	4120.4 a	11,802.6 a	18.4 a	52.7 a	0.349 a
	RFb	3310.8 b	9596.5 b	13.9 b	40.3 b	0.345 a
	RFt	3134.3 bc	8739.1 bc	13.0 b	36.4 bc	0.359 a
	RFS	2824.3 c	8336.6 c	11.1 c	32.8 c	0.339 a
	CK	2078.7 d	6815.0 d	8.1 d	26.6 d	0.305 b
	Mean	3295.7 AB	9594.1 AB	14.0 A	40.7 A	0.341 AB
2017 long rainy season	RFbS	3364.2 a	9931.3 a	15.0 a	44.2 a	0.339 ab
	RFtS	3489.0 a	10,027.1 a	15.4 a	44.2 a	0.348 a
	RFb	2781.0 b	8468.9 b	11.7 b	35.6 b	0.328 b
	RFt	2890.6 b	8562.1 b	12.0 b	35.6 b	0.338 ab
	RFS	2150.0 c	7572.2 b	8.8 c	31.1 b	0.284 c
	CK	1492.5 d	5798.5 c	5.7 d	22.0 c	0.258 d
	Mean	2694.5 B	8393.3 B	11.4 AB	35.4 AB	0.316C
ANOVA	MM	351***	162.4***	512.2***	257.5***	83.9***
	GS	99.9***	74.5***	156.1***	86.9***	68.7***
	MM × GS	4.7***	4.1***	6.2***	4.5***	5.7***

Note: Means within a column followed by the same lowercase letter and capital letter show that there is no significant difference at 0.05 levels under different mulching managements (MM) and different growing seasons (GS) according to Tukey-B multiple range test, respectively. *** means significant differences at $p < 0.001$.

Dual plastic film and straw mulching (RFbS and RFtS) resulted in greater SWS than other treatments did across four growing seasons (Fig. 3). Therefore, it can be argued that dual mulching can lead to improvement effects on soil water conservation (Gao et al., 2009; Li et al., 2013; Chen et al., 2015; Liu et al., 2017). This was mainly because plastic film on the ridges helps collect rainwater that flows into the

Table 5
Economic benefits affected by different treatments across four growing seasons in the experimental site. (Unit: US\$ ha^{-1}).

Growing seasons	Treatments	Labor input			Material input			Total input	Output		Total output	Net income	Output/input
		RFM making	Weeds control	Seeding, harvesting, disease control	Plastic sheets	Straw	Seeds, fertilizers, pesticides		Grain yield	Straw yield			
2015 short rainy season	RFbS	184	16	120	126.7	100	192	738.7	2183.7	185.9	2369.7	1631.0 a	3.2 ab
	RFtS	184	16	120	126.7	100	192	738.7	2136.2	185.5	2321.8	1583.1 a	3.1 b
	RFb	168	32	120	126.7	0	192	638.7	2022.3	168.0	2190.4	1551.7 a	3.4 ab
	RFt	168	32	120	126.7	0	192	638.7	1784.6	162.6	1947.1	1308.4 b	3.0 b
	RFS	136	24	120	0	180	192	652.0	1651.0	125.2	1776.2	1124.2 c	2.7 c
	CK	104	88	120	0	0	192	504.0	1219.7	133.0	1352.7	848.7 d	2.7 c
2016 long rainy season	RFbS	184	16	120	126.7	100	192	738.7	2556.5	247.2	2803.8	2065.1 a	3.8 a
	RFtS	184	16	120	126.7	100	192	738.7	2592.4	246.4	2838.8	2100.1 a	3.8 a
	RFb	168	32	120	126.7	0	192	638.7	2118.0	217.0	2334.9	1696.2 b	3.7 a
	RFt	168	32	120	126.7	0	192	638.7	2196.6	223.0	2419.6	1780.9 b	3.8 a
	RFS	136	24	120	0	180	192	652.0	1700.3	188.1	1888.4	1236.4 c	2.9 b
	CK	104	88	120	0	0	192	504.0	1251.8	143.8	1395.6	891.6 d	2.8 b
2016 short rainy season	RFbS	184	16	120	126.7	100	192	738.7	2583.5	239.1	2822.5	2083.8 a	3.8 a
	RFtS	184	16	120	126.7	100	192	738.7	2472.2	230.5	2702.7	1964.0 a	3.7 ab
	RFb	168	32	120	126.7	0	192	638.7	1986.5	188.6	2175.1	1536.4 b	3.4 bc
	RFt	168	32	120	126.7	0	192	638.7	1880.6	168.1	2048.7	1410.0 bc	3.2 c
	RFS	136	24	120	0	180	192	652.0	1694.6	165.4	1859.9	1207.9 c	2.9 d
	CK	104	88	120	0	0	192	504.0	1247.2	142.1	1389.3	885.3 d	2.8 d
2017 long rainy season	RFbS	184	16	120	126.7	100	192	738.7	2018.5	197.0	2215.5	1476.8 a	3.0 a
	RFtS	184	16	120	126.7	100	192	738.7	2093.4	196.1	2289.6	1550.9 a	3.1 a
	RFb	168	32	120	126.7	0	192	638.7	1668.6	170.6	1839.2	1200.5 b	2.9 a
	RFt	168	32	120	126.7	0	192	638.7	1734.4	170.1	1904.5	1265.8 b	3.0 a
	RFS	136	24	120	0	180	192	652.0	1290.0	162.7	1452.7	800.7 c	2.2 b
	CK	104	88	120	0	0	192	504.0	895.5	129.2	1024.7	520.7 d	2.0 b

Note: Means within a column followed by the same lowercase letter show that there is no significant difference at 0.05 levels.

furrows and also reduce soil surface evaporation. On the other hand, straw mulching in the furrows was helpful in improving water infiltration and soil water storage capacity (Li et al., 2013; Liu et al., 2017).

Previous studies showed that transparent plastic film mulching evidently increased soil temperature (Mo et al., 2016; Qin et al., 2018), which is consistent with our results where the soil temperature in RFt was higher than that of other treatments in all growing seasons (Fig. 4). Soil temperature under black plastic mulching (RFb and RFbS) was lower than that of transparent plastic film mulching (RFt and RFtS), but higher than that of no mulching (CK) in the four seasons (Fig. 4). This phenomenon can be explained by the following reasons. Firstly, black plastic film can absorb most of the solar radiation to reduce topsoil temperature (Moreno and Moreno, 2008; Olivera et al., 2014). Secondly, plastic film mulching can prevent water exchange between surface soil and atmosphere and thus reduce heat fluxes for better heat preservation. However, crop straw mulching turned to reduce soil temperature in semiarid tropical areas (Fowler and Rockstrom, 2001; Mo et al., 2016) and in the temperate regions such as the Loess Plateau (Gao et al., 2009; Gan et al., 2013; Liu et al., 2017).

In the present study, soil temperature in dual plastic film and straw mulching (RFbS and RFtS) was significantly lower than that of sole plastic mulching (Fig. 4), which was consistent with the results of other studies (Li et al., 2013; Liu et al., 2017). A direct reason was that straw covering on soil surface produced higher albedo and lower thermal conductivity, and consequently reduced the magnitude of temperature increase in the tropical climate condition (Horton et al., 1996). However, dual mulching exerted positive impact on soil temperature than RFS and CK did.

4.2. Responses of soil pH and BD to mulching managements under the El Nino

Some studies reported that there frequently existed a significant decrease in soil pH under plastic mulching field (Liu et al., 2012; Gu et al., 2018), the reason may be that plastic film mulching enhanced soil N mineralization, released more H^+ ions into the soil and accordingly increase soil acidity (Wang et al., 2017). Also, more NO_3^--N was released partly owing to soil leaching, which helps increase root exudates and thereby decrease soil pH under the increased soil temperature and moisture (Zhao et al., 2014; Yu et al., 2016). In this study, RFb and RFt to some extent decreased soil pH, compared with CK (Fig. 6G). In addition, the retention of crop residues played an important role for the redistribution of alkalinity in the soil. As presented in the above, the pH tended to increase under straw retention, which was also found in a previous study (Butterly et al., 2013).

Plastic mulching was responsible for the increase in soil BD (Zhang et al., 2008), while straw covering turned to decline it (Zhang et al., 2008; Niu et al., 2016; Ranaivoson et al., 2017). Higher soil organic matter resulted in lower bulk density, since it help improve soil structure and properties, and ultimately promoted flocculation of clay minerals (Zhang et al., 2014). Theoretically, the high SOC level should frequently result from the addition of crop straw. In our study, the highest SOC concentration was observed in the dual plastic film and straw mulching treatments (RFbS and RFtS), thereafter causing the decrease in soil BD.

4.3. The effects of mulching managements on SOC under the El Nino

SOC is a critical environmental indicator for maintaining the soil nutrient pool and improving nutrient availability (Li et al., 2004; Zhao et al., 2009). Previous studies suggested that SOC was increased under plastic mulching with RF in semiarid temperate (Jia et al., 2006) and semiarid tropical regions (Mo et al., 2017), which resulted from increased plant litter, roots residues and exudates in soil. However, the low SOC in plastic mulching was also reported in some studies (Li et al., 2004; Zhou et al., 2012). This outcome was principal that film mulching improved soil hydrothermal status in relatively drier site, and finally enhanced the decomposition of soil organic matter by soil microorganisms. Conventionally, the change of SOC pool was frequently made as a result of the inputs from plant-derived resources and the losses by microbial decomposition. Our results showed that the SOC content in RFb and RFt slightly increased in the former two seasons, but greatly declined in the latter two seasons (Fig. 5A), and was even lower than that of CK at the end of four growing seasons (Fig. 6A). Under the plastic mulching condition, intrinsic soil organic matter and supplemental root residues were effective to restore the SOC stock at the former growing seasons. Yet the inputs of organic matter were not likely to be balanced by the increased deposition of SOC caused by microbial decomposition at the latter growing seasons. Additionally, our observations indicated that the SOC in RFS was greater than CK after four growing seasons (Fig. 6A), which was consistent with the results of other studies (Zhao et al., 2009; Liu et al., 2017).

Importantly, dual plastic film and straw mulching (RFbS and RFtS) achieved a sustained increase in SOC (Fig. 5A), and the content of SOC in dual mulching was significantly greater than that of other treatments after four growing seasons (Fig. 6A). Plastic mulching helps to improve soil water and thermal status, which would be beneficial to enhance the mineralization of soil organic matter and accordingly increase the SOC level in the dual mulching treatments. Meanwhile, crop straw inputs acted as an effective carbon resource to help produce more soil organic matter. Besides, soil C:N ratio is another key parameter to evaluate the decomposition rate of organic matter. Low C:N ratio was frequently generated as a result of accelerated decomposition, and vice versa (Finn et al., 2015; Mo et al., 2017). Over four growing seasons, RFb and RFt indeed maintained the lowest C:N ratio, in comparison with other treatments (Fig. 5C, Fig. 6C). This phenomenon was also observed in a previous study (Jia et al., 2006). Particularly, soil C:N ratio in RFbS and RFtS was significantly greater than that of RFb and RFt over the latter two seasons (Fig. 5C, Fig. 6C). This was common because cereal residues contained a wide ratio of carbon to nitrogen and their decomposition would enable temporary nitrogen immobilization into soil organic matter (Ranaivoson et al., 2017). Therefore, dual plastic film and straw mulching played a critical role in enhancing and optimizing soil carbon stock in semiarid Kenya under the scenario of El Nino.

4.4. The effects of mulching managements on soil nitrogen stock under the El Nino

Previous studies suggested that plastic film mulching had little effects on STN content (Zhou et al., 2012; Luo et al., 2015). A possible explanation was that the accumulation of STN in soil was generally a slow process (Fan et al., 2014), especially in the soil of poor nitrogen in the semiarid areas (Zhou et al., 2012). Nevertheless, Jia et al. (2006) reported that the STN content was higher in the plastic mulched treatments than that of non-mulched ones. In the present study, the STN content was significantly affected by mulching management and growing season (Table 2). It started to increase at first and then decreased with the prolonged mulching time in RFb and RFt. At the initial stage of plastic mulching, soil nitrogen mineralization was enhanced, providing more available nitrogen for the uptake and utilization by plants. At the later stage, the STN would be lowered significantly and depleted under long-term plastic mulching (Li et al., 2004; Gao et al., 2009). Some other evidence showed that plastic film mulching substantially enhanced soil nutrients mineralization and improved soil nitrogen availability due to the improvement of soil hydrothermal conditions (Gao et al., 2009; Zhou et al., 2012; Gu et al., 2018).

The soil mineral-N content significantly decreased in RFb and RFt at the end of four growing seasons, compared with that of CK (Fig. 6D–F). Existing studies suggested that plastic film mulching improved microbial activity and biomass by increasing soil temperature, which was likely to enhance the competition for available nutrients among microbes (Li et al., 2004; Zhou et al., 2012). In the latter two growing seasons, the increasing SOC consumption under the plastic mulching (Fig. 5A) accounted for the reduction in mineral-N, which was mostly released from the mineralization of soil organic matter (Duxbury et al., 1991; Lal, 2004). In this case, crop straw mulching was likely to increase STN content and its availability (Gao et al., 2009; Ranaivoson et al., 2017). This mainly resulted from extra nutrient input, improved soil conditions (Kahlon et al., 2013; Liu et al., 2017) and the reduction in soil erosion (Niu et al., 2016; Ranaivoson et al., 2017).

According to our observations, the highest STN and mineral-N contents occurred in the RFbS and RFtS treatments (Fig. 6B, D–F). Dual plastic film and straw mulching appeared to positively affect soil nitrogen stock due to crop straw application. Also, SOC had significant positive correlations with total and available nitrogen (Table 3). Therefore, SOC proved to be of great importance in maintaining the pool of soil nutrients and improving nutrient availability (Lal, 2004). Taken together, increased SOC was mechanically linked with improved soil nitrogen content and its availability under dual plastic film and straw mulching.

4.5. Responses of wheat yield, growth and WUE to mulching managements under the El Nino

As presented in the above, wheat grain yield, AgB, WUE and HI were significantly promoted by RFM system in semiarid Kenya, and this trend was also observed in other semi-arid areas (Gao et al., 2009; Liu et al., 2012; J.Y. Wang et al., 2016). Also, straw mulching can increase wheat yield and improve plant growth and development in semiarid tropical (J.Y. Wang et al., 2016) and temperate ecosystems (Baumhardt and Jones, 2002; Huang et al., 2005; Zhang et al., 2009). However, some other studies suggested that short-term yield effects of straw mulching have been found to be negative (Chen et al., 2007) or neutral (Gao et al., 2009; Liu et al., 2017). This outcome was most likely as a result of low temperature (Fig. 4), since the relatively cool environment was not conducive to seed germination, seedling growth, leaf photosynthesis and dry matter accumulation (Hurry et al., 1995; Ball et al., 1997).

The highest wheat yield, AgB, WUE and HI appeared in RFbS and RFtS treatments. Dual plastic film and straw mulching displayed a clear advantage in improving plant grow and yield formation, owing to improved soil hydro-thermal conditions (Gao et al., 2009; Li et al., 2013; Chen et al., 2015; Liu et al., 2017; Liang et al., 2018). On the other hand, the above outcome mechanically resulted from enhanced soil carbon storage and improved nitrogen availability (Figs. 5, 6), suggesting that dual mulching proved to be an effective solution to meet the challenges caused by the El Nino.

4.6. Economic returns and environmental effects

Economic profitability is a critical social-economic evaluation index for land users to assess whether to adopt a certain farming system under climate change in SSA (Dallimer et al., 2018). While the total inputs were higher in RFM treatments than CK (Table 5), their labor inputs into weed control turned to be lower than CK, because both plastic film and straw mulch were effective in suppressing weed growth and infestation (Ramakrishna et al., 2006). Conventionally, crop straw resource is mainly used for livestock industry since it can result in greater economic benefits than its utilization as residue retention (also used as mulching material) to improve soil fertility in Africa (Chauhan et al., 2012; Naudin et al., 2015). In this study, the amount of crop straw input in RFbS or RFtS was lowered by 44.4%, in comparison with that of RFS (Table 5). This demonstrated that dual plastic film and straw mulching help save crop straw resource in the mixed crop and livestock farming systems in SSA. Totally, the highest net income and ratio of output to input occurred in the dual mulching system, which was also observed in other studies (Li et al., 2013; Liang et al., 2018). In conclusion, the dual mulching system achieved relatively high economic benefits mainly owing to the higher grain yield and AgB in the semiarid SSA (Table 4).

Numerous researches show that plastic film mulching is not environmentally sustainable, because plastic residue accumulated in the soil alters soil physical and hydraulic properties, reduces soil nutrient availability, and decreases soil enzyme activity and microbial diversity (J. Wang et al., 2016; Gao et al., 2019; Wang et al., 2020). In our study, dual plastic film mulching and straw mulching reduced the use of polyethylene film in comparison with full plastic film mulched ridge and furrow, which alleviates the potential of plastic pollution of agricultural systems in SSA. However, it cannot be overlooked that the study focusing on the effects of plastic film pollution on field crop productivity and ecological environment of cropland, and evaluating degradation of biodegradable plastic films in our future efforts.

5. Conclusions

Dual plastic film and straw mulching in RF system improved wheat productivity, WUE, SOC, and nutrient availability under the circumstances of rainfall deficits and surpluses (El Nino) in semiarid Kenya. Moreover, economic profitability was significantly improved by this feasible and efficient strategy, which may act as a determinant for local farmers to accept and adopt this integrated farming practice. In addition, dual plastic film and straw mulching help reduce the amount of plastic film usage and alleviate potential pollution of plastic residues. It can produce more new straw biomass and reduce crop straw consumption, which was beneficial to local livestock development. Taken together, our findings demonstrated that the dual plastic film and straw mulching in RF system proved to be an innovative and sustainable agronomic measure to address food insecurity and adapt to the El Nino in the semiarid fragile agro-ecosystems of SSA.

CRediT authorship contribution statement

Chong-Liang Luo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Xiao-Feng Zhang:** Data curation, Investigation, Software, Writing - original draft. **Hai-Xia Duan:** Formal analysis, Methodology, Software, Visualization, Writing - review & editing. **David M. Mburu:** Investigation, Resources, Writing - review & editing. **Hong-Xu Ren:** Investigation, Resources, Writing - review & editing. **Levis Kavagi:** Investigation, Resources, Writing - review & editing. **Run-Zi Dai:** Data curation. **You-Cai Xiong:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139808.

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