Soil & Tillage Research 214 (2021) 105171

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Soil organic carbon, total nitrogen, available nutrients, and yield under different straw returning methods

Tiantian Huang [a,1], Ning Yang [a,1], Chen Lu [a], Xiaoliang Qin [a,*], Kadambot H.M. Siddique [b]

[a] College of Agronomy/State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi 712100, China
[b] The UWA Institute of Agriculture and School of Agriculture & Environment, The University of Western Australia, Perth, WA 6001, Australia

ARTICLE INFO

Keywords:
Soil organic carbon
Soil total nitrogen
Soil available nutrients
Crop yield
Straw mulching
Straw burying

ABSTRACT

Straw returning is an important measure for improving soil organic matter, biological activity, and nutrient availability. Straw mulching and straw burying are two methods for returning straw to the soil; however, there is little information to compare their benefits and limitations. This study assessed changes in soil nutrients induced by straw mulching and straw burying using a meta-analysis of straw returning data from 420 publications in China. The results showed that straw burying significantly increased soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), soil total potassium (STK), soil available nitrogen (SAN), soil available phosphorus (SAP), and soil available potassium (SAK) in the surface soil (0–20 cm), with mean effect sizes of 0.126, 0.095, 0.056, 0.053, 0.118, 0.117, 0.138, respectively. Straw mulching increased SOC, STN, STP, SAN, SAP, and SAK in the surface soil, with mean effect sizes of 0.114, 0.079, 0.082, 0.125, 0.152, 0.150, respectively. Straw burying is more conducive to increasing SOC, STN, and STK, while straw mulching is more conducive to increasing SAN, SAP, and SAK. Straw mulching increased soil nutrient contents more than straw burying in areas with mean annual precipitation (MAP) <400 mm, while the reverse was true in areas with MAP> 800 mm. Straw mulching and straw burying both increased crop yield, with mean effect sizes of 0.100 and 0.101, respectively. Straw burying positively correlated with the effect size of yield, SOC, SAP, and SAK, while there were no significant relationships for straw mulching. Long-term straw burying and straw mulching was conducive to increasing crop yields, SOC, and STN. The benefits and limitations of straw mulching and burying on soil fertility and yield vary under different agronomic management, environmental, and edaphic factors.

1. Introduction

The United Nations Department of Economic and Social Affairs predicts that the world's population will reach 9.3 billion by 2050; however, the growth rate of food production will gradually slow, and the gap between food supply and demand will widen (Tian et al., 2021). The increasing pressure to increase crop yields is promoting intensive farming in agro-ecosystems, but conventional intensive tillage operations promote soil nutrients loss (Zalles et al., 2019). The maintenance of soil fertility is essential for sustainable land use (Mäder et al., 2002) and yield production (Li et al., 2021).

Straw returning—a sustainable farming technology (Yang et al., 2020)—can provide sufficient organic matter for microorganism proliferation, and increase the number of microorganisms and enzyme activity (Akhtar et al., 2019a; Su et al., 2020). The mineralization of straw organic matter releases nutrients for crop growth and increases soil nitrogen (N), phosphorus (P), and potassium (K) contents (Ahmed et al., 2020; Bai et al., 2015; Ma et al., 2010). As a large agricultural producing country, China is rich in organic fertilizer resources, with about 1 billion tons of air-dried straw produced each year (Niu and Ju, 2017). In China, the benefits of crop residues have been greatly recognized by scientists and the government (Li et al., 2018), but the utilization rate is low (Liu et al., 2007).

There are two traditional methods of straw returning—covering the soil surface directly with straw (straw mulching) and mixing the straw into soil (straw burying) (Chen et al., 2014). Straw mulching can resist soil erosion from wind and rain and reduce soil nutrient decline (Feng et al., 2014; Tan et al., 2015). Straw burying is generally combined with farming measures, such as plow tillage, rotary tillage, subsoiling tillage, and so on. Some studies have shown that straw mulching has a

---

[*] Corresponding author.
E-mail address: xiaoliangqin2006@163.com (X. Qin).
[1] The first two authors equally contributed to this work.

https://doi.org/10.1016/j.still.2021.105171
Received 20 January 2021; Received in revised form 20 July 2021; Accepted 14 August 2021

significantly lower decomposition rate (by 35 %) than straw burying, and delays the net release of nitrogen (Bradford and Peterson, 2000). In contrast, another study found that straw mulching has significantly higher total mineralization than straw burying; thus, straw mulching could increase SAN (Coppens et al., 2007). These contrasting findings call for a comprehensive nationwide assessment to compare the benefits and limitations of straw mulching and straw burying on soil nutrients.

Mean annual precipitation (MAP) and mean annual temperature (MAT), N application rate (NAR), straw returning amount (SRA), initial soil pH (pH), and soil texture can influence soil microbial and soil enzyme activity, which affects straw decomposition (Akhtar et al., 2019b; Jarvis et al., 1996; Six et al., 2004) and soil nutrient conversion (Dancer et al., 1973; Katyal et al., 1988). NAR and SRA influence the soil C/N ratio (Akhtar et al., 2019b; Döring et al., 2005). The lower the C/N ratio, the faster the decomposition rate, and vice versa (Zhang et al., 2008). Numerous meta-analyses have revealed that straw returning could increase crop yields and soil organic carbon and soil nitrogen storage, but no studies have compared the effects of straw mulching and straw burying under different edaphic, environmental, and agronomic management factors. This information could influence the selection of straw returning method in agricultural systems.

This study collected data from 420 straw returning publications to undertake a meta-analysis to identify the effects of straw mulching and straw burying application on SOC, STN, STP, STK, and soil available nutrients in China. We used regression analysis to study trends in the effect sizes of SOC, STN, and soil available nutrients with experimental duration and the relationship between the effect sizes of SOC, TN, and available nutrients and the effect size of crop yield. This study 1) analyzed differences between the effects of straw mulching and straw burying on soil surface nutrients and crop yields, 2) identified suitable methods of straw returning for different edaphic, environmental, and agronomic management factors, and 3) analyzed the relationship between changes in crop yield and soil surface nutrients under straw mulching and straw burying to provide a scientific basis for returning straw to improve soil fertility in China.

2. Materials and methods

2.1. Data search and collection

We identified ‘straw returning’ or ‘straw mulching,’ and ‘soil nutrients’ as the keywords for our search. We searched the Web of Science (http://apps.webofknowledge.com/) and the China National Knowledge Infrastructure (http://www.cnki.net/) for relevant peer-reviewed journal articles. To avoid any bias, publications were selected according to the following criteria: (1) experiment must be conducted in the field with an actual location in China (greenhouse and laboratory incubation experiments were excluded); (2) must include at least one of the following parameters: crop yield, SOC, STN, STP, STK, SAN, SAP, or SAK; (3) straw returning measures clearly distinguished as straw burying and straw mulching; (4) must include both control (no straw return; CK) and treatments (straw mulching or straw burying); (5) means, standard deviations (or standard errors), and number of replications must be available or can be calculated.

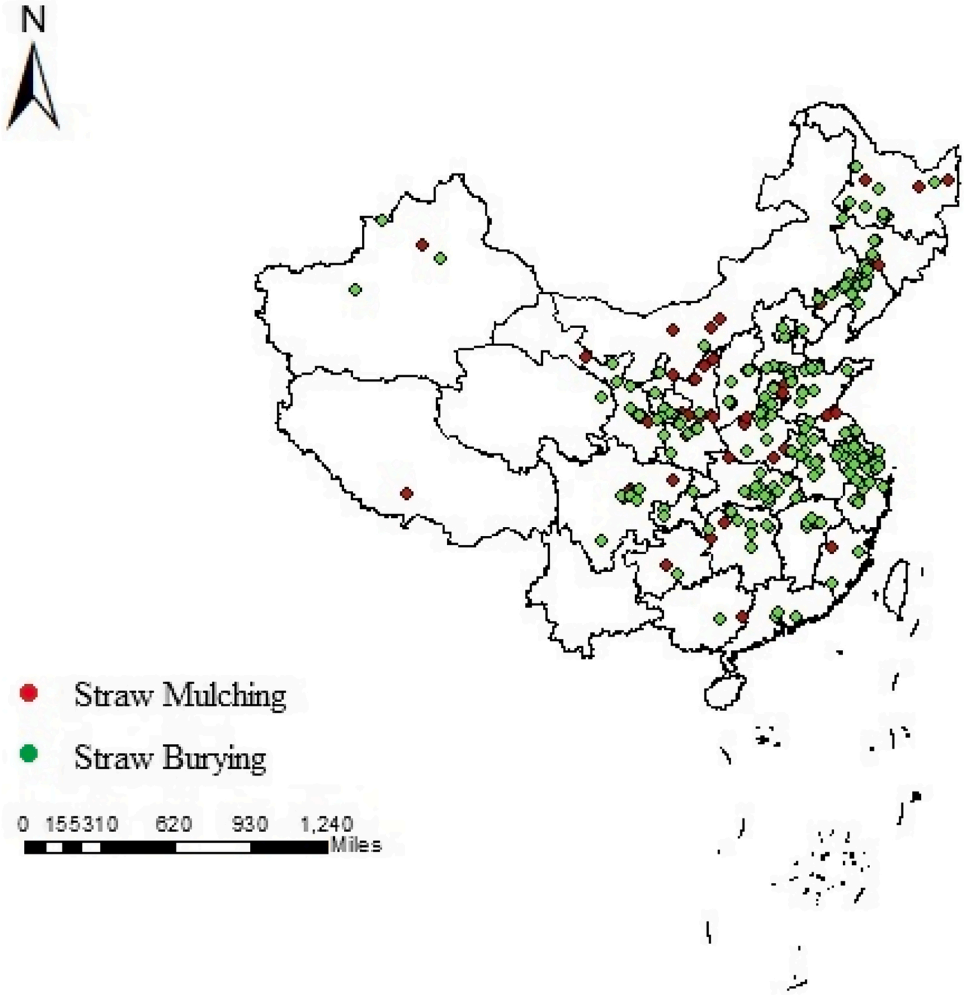

Fig. 1. Location of straw returning experiments used in the meta-analysis of China.

For each selected study, raw data were collected directly from tables and text. If the data appeared in the form of a graph, then GetData software was used to obtain the values. MAP and MAT for each site were extracted from the publication. If no meteorological information was provided, we obtained MAP and MAT from the nearest meteorological station (Chinese meteorological data network, http://data.cma.cn/). If the latitude and longitude of the test site were not provided, we used the Baidu map to determine latitude and longitude coordinates (https://map.baidu.com/). The location of the straw mulching and straw burying experiments used in the meta-analysis are shown in Fig. 1.

From each publication, we extracted information on the test site (location, MAP, MAT, pH, soil texture), agronomic management (NAR, SRA), and experimental duration. The dataset was categorized based on MAP (<400, 400–800, >800 mm), MAT (<7, 7–14, >14 °C), soil texture (loam, clay loam, clay) (International Standard for Soil Texture Classification), pH (acidic, neutral, alkaline), SRA (<4500, 4500–9000, >9000 kg ha^{-1}), NAR (<100, 100–200, >200 kg ha^{-1}), and experimental duration (0–3, 4–10, and >10 years).

Our dataset incorporated data from 420 publications, including 168 on straw mulching and 287 on straw burying. Straw mulching studies included covering the soil surface directly with whole straw/smashed straw, straw burying studies included mixing total straw/smashed straw into the soil at depths ranging from 5 to 40 cm. Straw mulching or burying in selected studies occurred wither after harvesting the previous crop or before planting the subsequent crop. The selected studies provided 6820 measurements of response variables, including 908 for yield, 1506 for SOC, 950 for STN, 390 for STP, 268 for STK, and 2798 for soil available nutrients (Fig. S1).

2.2. *Data analysis*

Where standard deviations (SD) were not reported, we calculated the average coefficient of variation within each dataset and then estimated the missing SD using the following equation (Wang and Shangguan, 2015):

$$SD = \overline{X} \times CV$$

where $\overline{X}$ is the mean of the treatment (straw mulching or straw burying) and the control group (CK, no straw returning).

A meta-analysis was used to analyze the responses of SOC, STN, SAP, SAK, and available nutrients in straw mulching and straw burying treatments using Meta Win 2.1. The effect size (lnR) was used (Hedges et al., 1999):

$$\ln R = \ln\overline{X_t} - \ln\overline{X_c}$$

where $\overline{X_t}$ is the mean value of the experimental group under straw mulching or straw burying, $\overline{X_c}$ is the mean value of the corresponding control treatment (no straw returning)

The variance (V) of lnR is:

$$V(\ln R) = \frac{(S_t)^2}{n(\overline{X_t})^2} + \frac{(S_c)^2}{n(\overline{X_c})^2}$$

where S_t and S_c are the corresponding SDs, and n is the number of replicates in the treatment.

To derive the overall response effect of the treatment group relative to the control group, the mean effect size ($\ln\overline{R}$) was calculated as follows:

$$\ln\overline{R} = \frac{\sum_{i=1}^{k} \ln R_i Wi}{\sum_{i=1}^{k} W_i}$$

$$W_i = \frac{1}{V_i}$$

where W_i is the weight for study i, calculated as the inverse of V(*lnR*) (Curtis and Wang, 1998). Thus, studies with large variance among replicates have smaller weights. $\ln R_i$ is the effect size for study i, k is the number of studies, and $\ln\overline{R}$ is the mean effect size

Means and 95 % confidence intervals (CI) on the estimated effect size were generated using the bootstrapping test. If the 95 % confidence interval values for the effect size of a variable did not overlap zero, then the treatment effects on the variable studied were considered statistically significant. The means of the categorical variables were considered significantly different if their 95 % CIs did not overlap (Xia et al., 2018). We used the statistical software program SPSS for the correlation analysis, Sigmaplot for graphing, and ArcGIS to map experimental locations.

3. Results

3.1. *Effect of straw returning on SOC and STN*

Straw burying increased SOC (mean effect size: 0.126, 95 % CI: 0.122–0.130) significantly more than straw mulching (mean effect size: 0.114, 95 % CI: 0.110–0.119) (Fig. 2), and the effect of straw returning on SOC differed under various edaphic, environmental, and agronomic management factors (Fig. 3A). When MAP was <400 mm, straw mulching had a more significant positive effect on SOC (mean effect size: 0.111, 95 % CI: 0.098–0.122) than straw burying (mean effect size: 0.072, 95 % CI: 0.062–0.083), and the reverse was true when MAP was >800 mm. When MAT was <7 °C, straw returning improved SOC significantly more than when MAT was >7 °C; the effect size of straw burying on SOC significantly decreased with increasing MAT ($P < 0.05$, Table S1). Straw burying (mean effect size: 0.153, 95 % CI: 0.147–0.159) was better than straw mulching (mean effect size: 0.105, 95 % CI: 0.098–0.113) in alkaline soil, while straw mulching (mean effect size: 0.145, 95 % CI: 0.133–0.158) was superior to straw burying (mean effect size: 0.063, 95 % CI: 0.055–0.071) in neutral soil. The SOC of straw mulching increased with increasing SRA ($P < 0.05$), and the SOC of straw burying decreased with increasing NAR ($P < 0.05$,

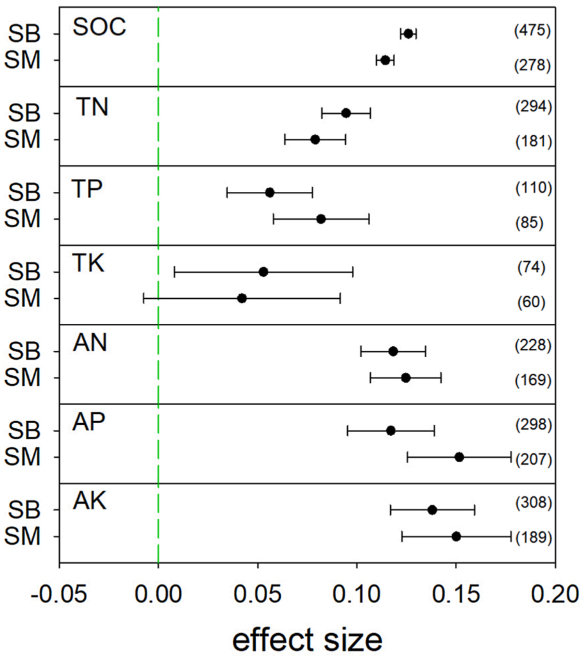

Fig. 2. Effect of straw mulching (SM) and straw burying (SB) on soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), soil total potassium (STK), soil available nitrogen (SAN), soil available phosphorus (SAP), and soil available potassium (SAK). Error bars and numbers in parentheses represent 95 % confidence intervals and sample size, respectively, for SM and SB. Dashed line indicates effect size = 0.

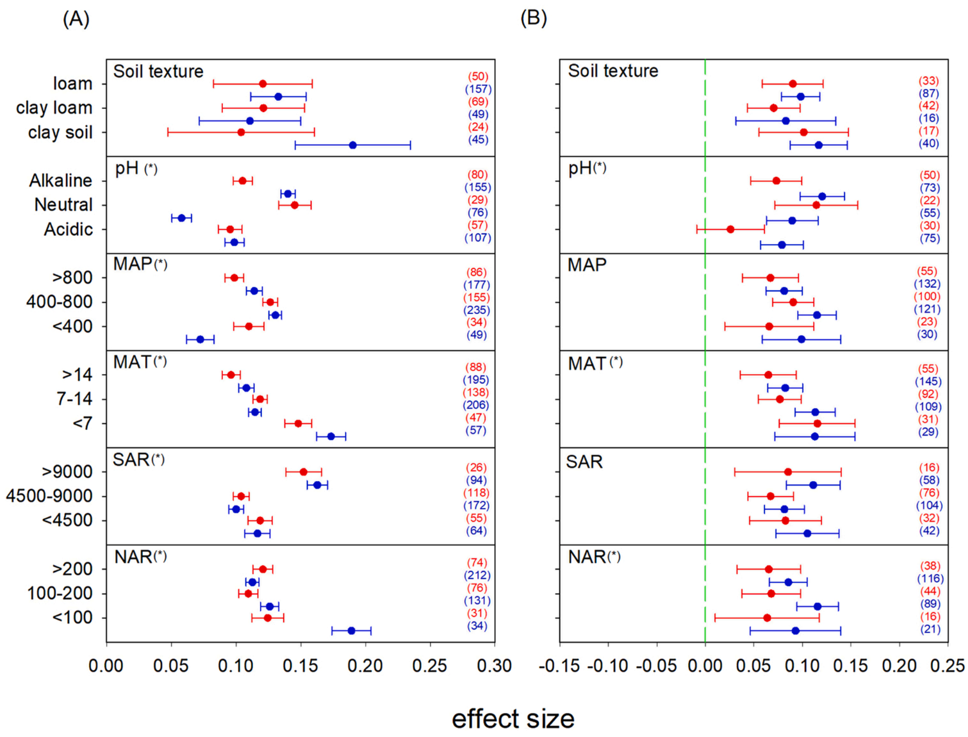

Fig. 3. Effect of straw mulching (SM) and straw burying (SB) on (A) soil organic carbon (SOC) and (B) soil total nitrogen (STN) with different edaphic, environmental, and agronomic management factors. pH represents initial soil pH. MAP is mean annual precipitation, MAT is mean annual temperature, SRA is straw returning amount, and NAR is N application rate. Red and blue error bars and numbers in parentheses represent 95 % confidence intervals and sample sizes for SM and SB, respectively. * indicates significant differences between subcategories at $P < 0.05$. Dashed line indicates effect size = 0.

Table S1). The largest positive effect size of straw returning on SOC occurred under straw burying with SRA >9000 kg ha^{-1} and NAR < 100 kg ha^{-1}.

Straw burying increased STN (mean effect size: 0.095, 95 % CI: 0.082–0.107) more than straw mulching (mean effect size: 0.079, 95 % CI: 0.064–0.094) (Fig. 2). The results of the subgroup analysis showed significant heterogeneities between STN and subgroups of MAT, NAR, pH (Fig. 3B). When MAT was <7 °C, straw returning improved STN more than when MAT was >7 °C. Straw burying increased STN more than straw mulching in acidic and alkaline soils.

3.2. *Effect of straw returning on SAN, SAP, and SAK*

Straw mulching and straw burying substantially increased SAN (mean effect size: 0.125 and 0.118, respectively) and SAP (mean effect size: 0.152 and 0.117, respectively) (Fig. 2), with the mean effect size significantly affected by agronomic management, environmental, and edaphic factors (Fig. 4A). Straw burying significantly increased SAN more than straw mulching at MAT >14 °C and MAP > 800 mm (Fig. 4A). Straw mulching significantly increased SAN more than straw burying at MAT 7–14 °C, MAP 400–800 mm, NAR 100–200 kg ha^{-1}, SRA 4500–9000 kg ha^{-1}, alkaline soil, and clay loam soil texture (Fig. 4A). Straw mulching significantly increased SAN more than straw burying under MAP 400–800 mm, MAT 7–14 °C, and SRA > 9000 kg ha^{-1}. The

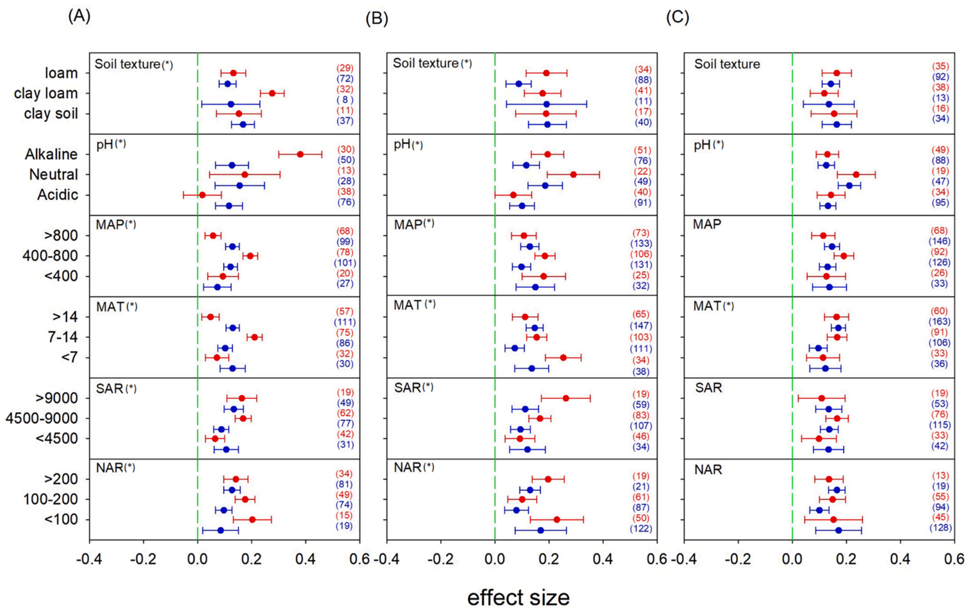

Fig. 4. Effect of straw mulching (SM) and straw burying (SB) on (A) soil available nitrogen (SAN), (B) soil available phosphorus (SAP), and (C) soil available potassium (SAK) with different edaphic, environmental and agronomic management factors. pH represents initial soil pH. MAP is mean annual precipitation, MAT is mean annual temperature, SRA is straw returning amount, and NAR is N application rate. Red and blue error bars and numbers in parentheses represent 95 % confidence intervals and sample sizes for SM and SB, respectively. * indicates significant differences between subcategories at $P < 0.05$. Dashed line indicates effect size = 0.

effect size of SAP under straw mulching decreased with increasing MAT ($P < 0.05$) and increased with increasing SRA ($P < 0.05$, Table S1).

Straw mulching increased SAK more than straw burying (mean effect size: 0.150 and 0.138, respectively) (Fig. 2), with significant heterogeneities between subgroups of MAT and pH (Fig. 4B). Straw mulching significantly increased SAN more than straw burying with MAT 7–14 °C. When pH was neutral, straw returning improved SAK more than when pH was alkaline and acidic. The effect size of SAK under straw mulching decreased with increasing NAR ($P < 0.05$), and the effect size of SAK under straw burying increased with increasing MAT ($P < 0.05$, Table S1).

3.3. *The relationship between effect sizes of straw returning on yield and soil nutrients*

Approximately 90 % of the comparison studies (135/152 for straw mulching and 280/302 used for straw burying) revealed a positive effect of straw returning on yield, relative to straw removal (Fig. 5A, B). The mean effect sizes did not differ significantly between straw mulching and straw burying (Fig. 5C). The lnRs of yield had a significant positive relationship with the lnRs of SAK ($R^2 = 0.044$, $P < 0.05$), SAP ($R^2 = 0.051$, $P < 0.05$), and SOC ($R^2 = 0.13$, $P < 0.05$) for straw burying but no significant relationship for straw mulching (Fig. 6). The mean effect size of crop yield was significantly affected by MAP (Fig. S2). Straw mulching had a significantly greater effect on yield (mean effect size: 0.178, 95 % CI: 0.139–0.217) than straw burying (mean effect size: 0.109, 95 % CI: 0.083–0.136) at MAP < 400 mm; the gap between straw burying and straw mulching gradually decreased with increasing MAP (Fig. S2).

3.4. *Effect of straw returning on soil nutrients with experimental duration*

Straw returning significantly increased yield and soil nutrient contents (except STK and SAP) (Fig. 7), and experimental duration had a significant positive relationship with the lnRs of yield, SOC, STN, and SAK (Table 1). The lnRs of STP increased with experimental duration under straw mulching and decreased under straw burying (Table 1). The experimental duration had no significant relationship with the lnRs of STK, SAN, or SAP (Table 1), and subgroups had no significant heterogeneities for STK or SAN (Fig. 7E, F). STN and SOC improved more under straw burying than straw mulching for the three experimental durations (Fig. 7B, C). For experimental durations <3 years, STP, STK, and SAK improved more under straw burying than straw mulching. For experimental durations of 4–10 years, SAN improved more under straw burying than straw mulching, and STP, SAP, and SAK improved more under straw mulching than straw burying. For experimental durations >10 years, SAN and SAP improved more under straw burying than straw mulching, and SAK and STP improved more under straw mulching than straw burying (Fig. 7D–H).

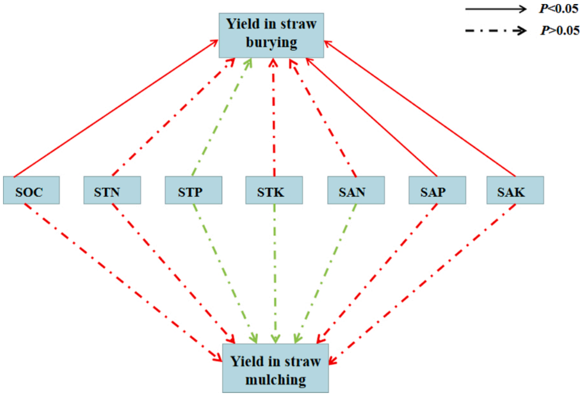

Fig. 6. Relationship between the effect size of yield and soil nutrients on straw mulching and straw burying. SOC, soil organic carbon; STN, soil total nitrogen; STP, soil total phosphorus; STK, soil total potassium; SAN, soil available nitrogen; SAP, soil available phosphorus; SAK, soil available potassium. Red arrow represents positive correlation; green arrow represents negative correlation.

4. Discussion

4.1. *Response of SOC, STN, and available nutrients to different straw returning methods*

Our study confirmed that straw returning improves soil nutrient contents and availability, as reported elsewhere (Guan et al., 2019; Li et al., 2020; Su et al., 2020; Yang et al., 2020). Straw burying is more beneficial for increasing SOC, STN, and STK than straw mulching (Fig. 2) because it increases the contact area of straw with soil microorganisms and enzymes (Stemmer et al., 1999; Wingeyer et al., 2012), forming more humus in soil than straw mulching. With straw mulching, the straw is left on the surface of the soil in a semi-dry state—the changing temperature and humidity of the soil surface results in more carbon and nitrogen losses in the gaseous form during straw decomposition than straw burying. Thus, straw burying is more conducive to straw

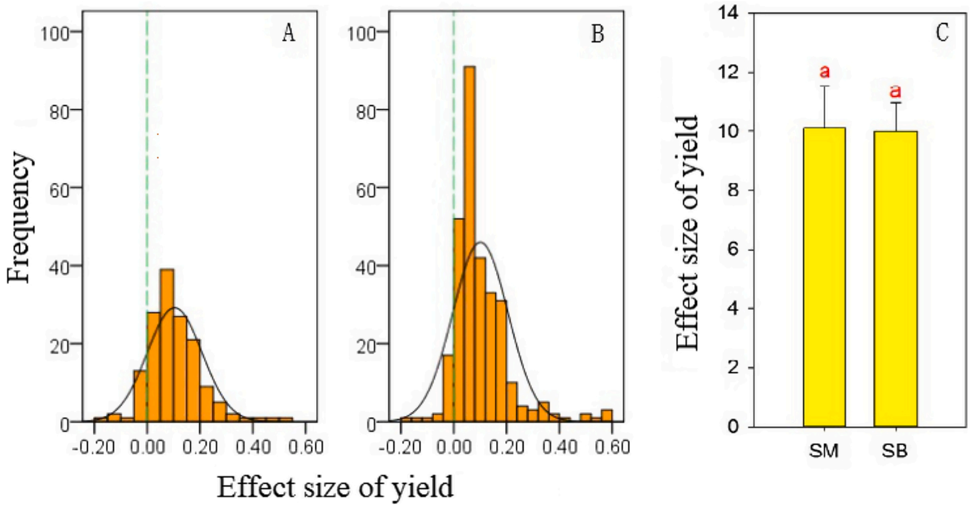

Fig. 5. Density distribution of the effect size for yield with (A) straw mulching (SM) and (B) straw burying (SB). Dashed line indicates effect size = 0; (C) effect size for yield with SM and SB. Letters indicate no significant difference between treatments.

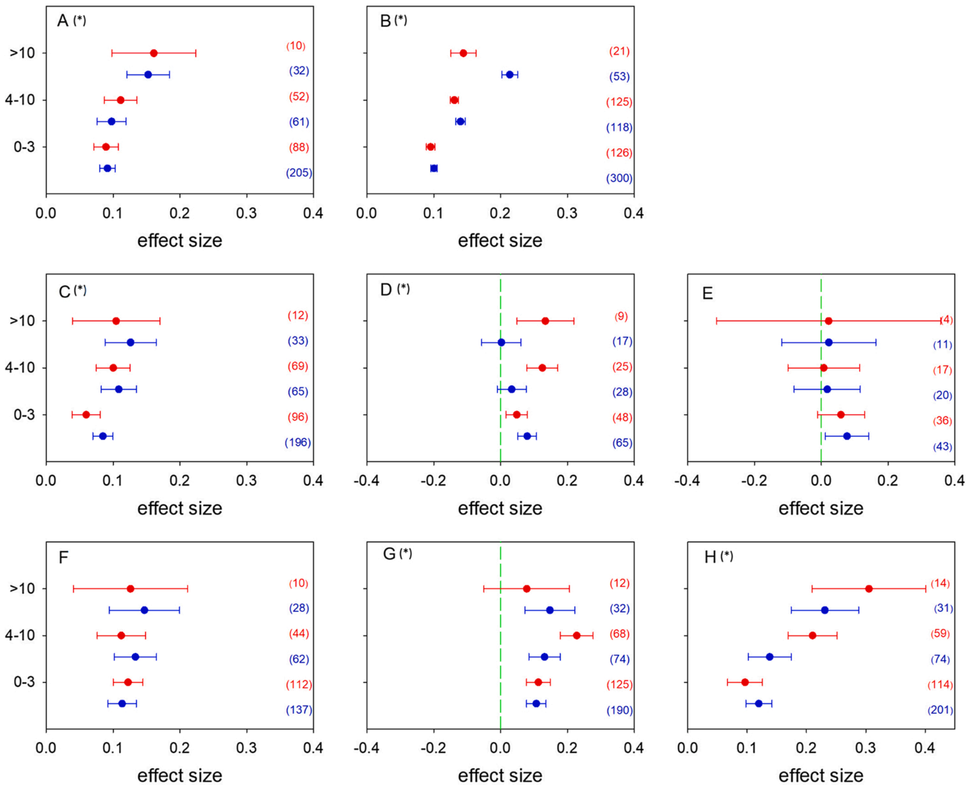

Fig. 7. Effect of straw mulching (SM) and straw burying (SB) on (A) yield, (B) soil organic carbon (SOC), (C) soil total nitrogen (STN), (D) soil total phosphorus (STP), (E) soil total potassium (STK), (F) soil available nitrogen (SAN), (G) soil available phosphorus (SAP), and (H) soil available potassium (SAK) with experimental duration. Red and blue error bars and numbers in parentheses represent 95 % confidence intervals and sample size for SM and SB, respectively. * indicates significant differences between subcategories at $P < 0.05$. Dashed line indicates effect size = 0.

Table 1
Relationship between experimental duration and the effect size of straw mulching and straw burying on yield and soil nutrients.

	Straw mulching				Straw burying			
	n	Coefficient	R^2	P	n	Coefficient	R^2	P
Yield	150	0.006	0.027	0.024	298	0.003	0.016	0.017
Soil organic carbon	272	0.012	0.127	<0.001	471	0.005	0.015	0.005
Soil total nitrogen	178	0.007	0.024	0.022	296	0.003	0.012	0.036
Soil total phosphorus	82	0.187	0.021	<0.001	111	−0.004	0.078	0.002
Soil total potassium	56	0.000	−0.018	0.974	74	−0.003	0.006	0.232
Soil available nitrogen	166	0.004	−0.003	0.480	227	0.003	0.004	0.165
Soil available phosphorus	205	0.000	−0.005	0.973	296	−0.002	−0.001	0.446
Soil available potassium	187	0.018	0.096	<0.001	306	0.007	0.030	0.001

decomposition, releasing more C, N, and K into the soil than straw mulching (Chen et al., 2006; Kuang et al., 2012).

However, the soil available nutrients content under straw mulching was more than straw burying (Fig. 2) because: (1) available nutrient loss caused by ground runoff loss is less than straw burying (Tan et al., 2015); (2) the nutrient release from straw under straw mulching are distributed in the soil surface, but straw burying not limited to surface soil; (3) straw mulching suppresses water evaporation from soil and enhances soil surface water content (Dong et al., 2018; Yu et al., 2018), which improve the mineralization ratio of soil organic matter.

4.2. Effect of straw returning on soil nutrients under MAP, MAT, soil texture, and pH

In the field, MAT and MAP directly affect soil temperature and humidity (Jarvis et al., 1996; Shen and Chen, 2009). Generally, soil temperatures from 28 to 35 °C and relative soil moisture contents from 60 to 70 % are most conducive to straw decomposition (Nan et al., 2010). Our study found that MAT had significant effects on all soil nutrients, while MAP only had significant effects on SOC, SAN, and SAP after straw returning. In arid areas of China with MAP 400–800 mm, straw mulching had greater SAN, SAP, SAK than straw burying, which may be because straw mulching can regulate surface soil temperatures and suppress water evaporation from soil (Dong et al., 2018; Gong et al., 2003; Yu et al., 2018), improving the mineralization ratio of soil organic matter and availability of soil nutrients. In addition, straw mulching reduces surface water runoff loss, reducing soil nutrient losses (Yi et al., 2007). So, straw burying may have better effects on nutrient enhancement in arid areas if the ridges and furrows are covered with plastic film to collect rain and improve soil moisture. In areas of China with MAP > 800 mm, straw burying significantly increased SAN, SAP, SAK more than straw mulching, which could be ascribed to the higher decomposition rate after straw burying than straw mulching, or that the fields are moisture-rich in these areas, leaching nutrients more easily than drier areas. Straw burying could reduce soil available nutrient leaching by promoting soil nutrient uptake and nutrient immobilization induced by soil organic matter (Wang et al., 2014; Yang et al., 2018).

Initial soil pH can affect soil microbial and soil enzyme activity, and thus straw decomposition (Akhtar et al., 2019b) and soil nutrient conversion (Dancer et al., 1973; Katyal et al., 1988). In our study, soil pH significantly affected all soil nutrients—straw burying in acidic soils increased SAN and SAP, while straw mulching in neutral and alkaline soils increased soil available nutrient contents (Fig. 4)—and may be related to the geographical distribution of pH in China. Acidic soils are mostly distributed in East China and South China, while alkaline soils are generally distributed in Northwest China (Dai et al., 2009).

Soil texture usually determines soil aeration (Yu et al., 2018), with clay content playing a critical role in soil water holding capacity (Liu et al., 2014). Studies have shown that clay content is a critical soil property influencing the soil's capacity to store C (Jagadamma and Lal, 2010; Six et al., 2004). We found that straw returning is more conducive to increasing SOC accumulation in clay soil (Fig. 3). Clay soils often have poor air permeability, inhibited aerobic microorganisms, relatively slow decomposition of organic material, and high organic matter accumulation (Jagadamma and Lal, 2010; Yu et al., 2018). Straw burying is more conducive to straw decomposition and increasing soil available nutrients in clay soil (Fig. 4). Loam soil has better drainage capacity than clay soil (Yu et al., 2018), such that straw mulching is more conducive to soil water storage, straw decomposition, and increasing soil available nutrients (Fig. 4).

4.3. Effect of different straw returning methods on soil nutrients under NAR and SRA

Straw returning can improve the physical and chemical properties and nutrient storage capacity of soil (Akhtar et al., 2019b), but inorganic N fertilizer is needed when returning straw to the field. Inorganic N fertilizer will accelerate the decomposition of straw with a high C/N ratio (Conde et al., 2005; Shaukat et al., 2011). Our research showed that straw burying increased STN more than straw mulching at various N fertilizer gradients and straw return amount gradients. A high NAR did not significantly increase STN and SAN, relative to a low NAR (Figs. 3 and 4). Therefore, N fertilizers should not be used excessively as they will waste fertilizer and pollute the environment. At SRA > 9000 kg ha^{-1} and NAR < 100 kg ha^{-1}, straw returning improved soil nutrients the most.

4.4. The relationship between effect sizes of straw returning on yield and with soil nutrients

Our research showed that both straw mulching and straw burying significantly increase crop yields but for differing reasons. Under straw burying, the lnR of yield had a positive relationship with the effect size of SOC, SAP and SAK (Fig. 6), revealing that increasing soil nutrient contents is important for increasing crop yield after straw burying. However, for straw mulching, the lnR of yield had no significant relationship with the changing soil nutrients. Straw mulching is mainly used in the arid and semi-arid northwest and central China (Fig. 1), and improvements in crop yields are mainly due to the improved soil moisture conditions after straw mulching (Fig. S3).

5. Conclusion

Straw returning significantly increases soil nutrient contents—with more significant positive effects on SAN, SAP, and SAK than STN, STP, and STK. Straw burying is more beneficial for increasing SOC, STN, and STK, while straw mulching is more beneficial for increasing available nutrients. STN and SOC increased with experimental duration, more so under straw burying than straw mulching. Appropriate straw returning methods should be adopted under different climates, soil textures, and farming measures. Straw mulching is recommended when moisture is the main limiting factor, while straw burying is more conducive to improving soil nutrients than straw mulching. In conclusion, our results provide a scientific basis for the rational selection of straw returning methods to improve soil fertility and yield.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

Financial support was provided by the National Natural Science Foundation of China (No. 32071980 and No. 31701384).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2021.105171.

References

Ahmed, W., Qaswar, M., Huang, J., Dong, W., Sun, G., Liu, K., et al., 2020. Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. J. Soil Sediments. 20, 850–861.

Akhtar, K., Wang, W., Ren, G., Khan, A., Wang, H., 2019a. Integrated use of straw mulch with nitrogen fertilizer improves soil functionality and soybean production. Environ. Int. 132, 105092.

Akhtar, K., Wang, W., Khan, A., Ren, G., Zaheer, S., Sial, T.A., et al., 2019b. Straw mulching with fertilizer nitrogen: an approach for improving crop yield, soil nutrients and enzyme activities. Soil Use Manage. 35 (3), 526–535.

Bai, Y., Wang, L., Lu, Y., Yang, L., Zhou, L., Ni, L., et al., 2015. Effects of long-term full straw return on yield and potassium response in wheat-maize rotation. J. Intege. Agr. 14 (12), 2467–2476.

Bradford, J.M., Peterson, G.A., 2000. Conservation tillage. In: Sumner, M.E. (Ed.), Handbook of Soil Science. CRC, Boca Raton, pp. 247–269.

Chen, S., Zhu, Z., Wu, J., Liu, D., Wang, C., 2006. Decomposition characteristics of straw return to soil and its effect on soil fertility in purple hilly region. J. Soil Water Conserv. 20 (6), 141–144 (in Chinese with English abstract).

Chen, B., Liu, E., Tian, Q., Yan, C., Zhang, Y., 2014. Soil nitrogen dynamics and crop residues. A review. Agron. Sustain. Dev. 34 (2), 429–442.

Conde, E., Cardenas, M., Ponce-Mendoza, A., Luna-Guido, M.L., Cruz-Mondragón, C., Dendooven, L., 2005. The impacts of inorganic nitrogen application on mineralization of 14c-labelled maize and glucose, and on priming effect in saline alkaline soil. Soil Biol. Biochem. 37 (4), 681–691.

Coppens, F., Garnier, P., Findeling, A., Merckx, R., Recous, S., 2007. Decomposition of mulched versus incorporated crop residues: modelling with PASTIS clarifies interactions between residue quality and location. Soil Biol. Biochem. 39, 2339–2350.

Curtis, P.S., Wang, X., 1998. A meta-analysis of elevated CO 2 effects on woody plant mass, form, and physiology. Oecologia 113 (3), 299–313.

Dai, W., Huang, Y., Wu, L., Yu, J., 2009. Relationships between soil organic matter content (SOM) and ph in topsoil of zonal soils in China. Acta Pedol. Sin. 46 (5), 851–860 (in Chinese with English abstract).

Dancer, W.S., Peterson, L.A., Chesters, G., 1973. Ammonification and nitrification of n as influenced by soil ph and previous n treatments1. Soil. Soc. Am. Proc. 37 (1), 67–69.

Dong, Q., Yang, Y., Yu, K., Feng, H., 2018. Effects of straw mulching and plastic film mulching on improving soil organic carbon and nitrogen fractions, crop yield and water use efficiency in the Loess Plateau, China. Agr. Water Manage 201, 133–143.

Döring, T.F., Brandt, M., Heß, J., Finckh, M.R., Saucke, H., 2005. Effects of straw mulch on soil nitrate dynamics, weeds, yield and soil erosion in organically grown potatoes. Field Crop. Res. 94 (2-3), 238–249.

Feng, Y., Liu, Q., Tan, C., Yang, G., Qin, X., Xiang, Y., 2014. Water and nutrient conservation effects of different tillage treatments in sloping fields. Arid Land Res. Manag. 28 (1), 14–24.

Gong, J., Huang, G., Chen, L., 2003. Comprehensive ecological effect of straw mulch on spring wheat field in dryland area. Agric. Res. Arid Areas 21 (3), 69–73 (in Chinese with English abstract).

Guan, S., Liu, S., Liu, R., Zhang, J., Ren, J., Cai, H., et al., 2019. Soil organic carbon associated with aggregate-size and density fractions in a Mollisol amended with charred and uncharred maize straw. J. Integr. Agr. 18 (7), 1496–1507.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80 (4), 1150–1156.

Jagadamma, S., Lal, R., 2010. Distribution of organic carbon in physical fractions of soils as affected by agricultural management. Biol. Fert. Soils. 46, 543–554.

Jarvis, S.C., Stockdale, E.A., Shepherd, M.A., Powlson, D.S., 1996. Nitrogen mineralization in temperate agricultural soils: processes and measurement. Adv. Agron. 57, 187–235.

Katyal, J.C., Carter, M.F., Vlek, P.L.G., 1988. Nitrification activity in submerged soils and its relation to denitrification loss. Biol. Fert. Soils. 7 (1), 16–22.

Kuang, E., Chi, F., Su, Q., Zhang, J., Jin, L., 2012. Decomposition characteristics of maize straws under different returning methods. J. Maize Sci. 20 (02), 99–101. +106. (in Chinese with English abstract).

Li, H., Dai, M., Dai, S., Dong, X., 2018. Current status and environment impact of direct straw return in China's cropland- a review. Ecotox. Environ. Safe 159 (September), 293–300.

Li, Y., Song, D., Dang, P., Wei, L., Qin, X., Kadambot, H.M.S., 2020. Combined ditch buried straw return technology in a ridge-furrow plastic film mulch system: implications for crop yield and soil organic matter dynamics. Soil Till. Res. 199.

Li, Y., Hu, Y., Song, D., Liang, S., Qin, X., Siddique, K.H.M., 2021. The effects of straw incorporation with plastic film mulch on soil properties and bacterial community structure on the Loess Plateau. Eur. J. Soil Sci. 72, 979–994.

Liu, Z., Yi, X., Sun, L., Xu, M., Fu, J., 2007. Current situation analysis of biomass waste utilization. J. Environ. Sci. Manag. 32, 104–106 (in Chinese with English abstract).

Liu, C., Lu, M., Cui, J., Li, B., Fang, C., 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob. Change Biol. Bioenergy 20, 1366–1381.

Ma, E., Zhang, G., Ma, J., Xu, H., Cai, Z., Yagi, K., 2010. Effects of rice straw returning methods on N_2O emission during wheat-growing season. Nutr. Cycl. Agroecosys. 88 (3), 463–469.

Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. Science 296, 1694–1697.

Nan, X., Tian, X., Zhang, L., You, D., Cao, Y., 2010. Decomposition characteristics of maize and wheat straw and their effects on soil carbon and nitrogen contents. Plant Nutr. Fert. Sci. 16 (03), 626–633 (in Chinese with English abstract).

Niu, X., Ju, X., 2017. Organic fertilizer resources and utilization in China. J. Plant Nutr. Fert. Sci (in Chinese with English abstract).

Shaukat, A. Abro, Tian, X., Wang, X., Kuyide, J.E., 2011. Decomposition characteristics of maize (*Zea mays* L.) straw with different carbon to nitrogen (c/n) ratios under various moisture regimes. Afr. J. Biotechnol. 10 (50), 10149–10156.

Shen, Y., Chen, H., 2009. The progress of study on soil improvement research with straw stalk. Chin. Agric. ence Bullet. 25 (19), 291–294 (in Chinese with English abstract).

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob. Change Biol. Bioenergy 10, 155–160.

Stemmer, M., von Lützow, M., Kandeler, E., Pichlmayer, F., Gerzabek, M.H., 1999. The effect of maize straw placement on mineralization of C and N in soil particle size fractions. Eur. J. Soil Sci. 50, 73–86.

Su, Y., Yu, M., Xi, H., Lv, J., Ma, Z., Kou, C., et al., 2020. Soil microbial community shifts with long-term of different straw return in wheat–corn rotation system. Sci. Rep-UK 10, 6360.

Tan, C., Xue, C., Shuai, Y., Wang, W., Feng, Y., Bo, Q., 2015. Effects of long-term conservation tillage on soil nutrients in sloping fields in regions characterized by water and wind erosion. Sci. REP-UK. 5, 17592.

Tian, X., Engel, B.A., Qian, H., Hua, E., Sun, S., Wang, Y., 2021. Will reaching the maximum achievable yield potential meet future global food demand? J. Clean. Prod. 294.

Wang, L., Shangguan, Z., 2015. Water-use efficiency of dryland wheat in response to mulching and tillage practices on the Loess Plateau. Sci. Rep-UK 5, 12225.

Wang, J., Wang, D., Zhang, G., Wang, Y., Wang, C., Teng, Y., et al., 2014. Nitrogen and phosphorus leaching losses from intensively managed paddy fields with straw retention. Agr. Water Manage. 141, 66–73.

Wingeyer, A.B., Walters, D.T., Drijber, R.A., Olk, D.C., Francis, C.A., 2012. Fall conservation deep tillage stabilizes maize residues into soil organic matter. Soil Sci. Soc. Am. J. 76 (6), 2154–2163.

Xia, L., Lam, S.K., Wolf, B., Kiese, R., Chen, D., Butterbach-Bahl, K., 2018. Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. Glob. Change Biol. Bioenergy 24, 5919–5932.

Yang, S., Wang, Y., Liu, R., Xing, L., Yang, Z., 2018. Improved crop yield and reduced nitrate nitrogen leaching with straw return in a rice-wheat rotation of Ningxia irrigation district. Sci. Rep. 8, 9458.

Yang, F., He, B., Zhang, L., Zhang, G., Gao, Y., 2020. 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. J. Soil Sci. Plant Nut. 20 (1), 125–138.

Yi, Z., Zhou, W., Tu, N., Tu, X., Wu, Y., Yang, W., 2007. Effects of no-tillage and straw mulching on soil nutrient content and drought resistance of maize on dry land. Res. Agric. Modern 490–493 (in Chinese with English abstract).

Yu, Y., Turner, N.C., Gong, Y., Li, F., Fang, C., Ge, L., 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.

Zalles, V., Hansen, M.C., Potapov, P.V., Stehman, S.V., Tyukavina, A., Pickens, A., Song, X.-P., Adusei, B., Okpa, C., Aguilar, R., 2019. Near doubling of Brazil's intensive row crop area since 2000. Proc. Natl. Acad. Sci. U. S. A. 116 (2), 428e435.

Zhang, D., Hui, D., Luo, Y., Zhou, G., 2008. Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors. J. Plant Ecol. 1 (2), 85–93.