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Original Research Paper

Effect of Straw Pretreatment on the Soil Water-Holding Capacity and Evaporation in Low-Suction Section

Yumei Li, Hao Feng* and Zhen Wang**
College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, Shaanxi, China
*Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, Shaanxi, China
**China Institute of Water Resources and Hydropower Research, Haidian District, Beijing, China
Corresponding Author: Hao Feng

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ABSTRACT

The direct return of straw to soils can lead to problems of slow decomposition, disease and pest occurrence, and nitrogen immobilization by microorganisms competing with crop uptake. In this study, we have examined straw pretreatments (comminution, addition of liquid ammonia and blending with ferric hydroxide) that can be applied before returning it to the soil. We have conducted a laboratory experiment to investigate the effects of these treatments on soil water content, water-holding capacity and soil water characteristic curves. Finely-cut straw (powdery) increased soil saturated water content and improved soil water-holding capacity and water-supplying capacity, while long-cut straw (2 cm long) had smaller effects on these properties and comminuted-ammoniated straw led to a significant increase in these properties. Finely-cut straw and long-cut straw both led to rapid soil dehydration, while for the ammonia-amended straw and straw blended with ferric hydroxide the dehydration rate was lower. The above results provide a basis for the selection of the novel and efficient methods for returning straw to soils.

INTRODUCTION

Organic matter and soil amendments can significantly improve soil structure and improve soil water (Dong et al. 2012, Pascual et al. 1999). Currently, when straw is returned directly to soil there can be problems associated with slow decomposition, disease and pest occurrence, and nitrogen immobilization by microorganism competing with crop uptake (Wang et al. 2012). Uniformity in application could better improve soil structure stability than straw mulching, which even had a worse situation than control (no straw application) (Spaccini et al. 2001); finely-cut straw could improve soil structure more quickly than long-cut straw (Tarafdar et al. 2001, Kasteel et al. 2007, Cabiles et al. 2008). Low C/N ratio straws, such as alfalfa, better improve soil structure stability compared with crop straw with a medium C/N ratio (Adesodun et al. 2001, Tejada et al. 2009). Many researchers studied direct mulching (Tian et al. 1993, Cho et al. 2003, Scopel et al. 2004, Corti et al. 2012, Wells et al. 2013, Ram et al. 2013), or incorporation (Ding et al. 2013, Lam et al. 2013, Lin et al. 2013, Massoni et al. 2013) or straw composting (Wang et al. 2012, Hosseini & Aziz 2013), without proposing the straw pretreatments that could help solve the problems and maximizing the effectiveness of returning straw.

Inorganic amendments, such as Fe^{3+}, Al^{3+} and Ca^{2+} can play an important role in the improvement of soil structure stability by promoting the formation of soil macroaggregates and significantly improving soil structure and increasing infiltration capacity (Buondonno & Coppola 2001, Rhoton et al. 2003, Bronick & Lal 2005, Wilson et al. 2007). So far, however, there have been only a few reports on effect of the combined application of straw and inorganic amendment on soil structure.

In this study, we treated straw by communition (chopping) and mixing it with urea solution to increase the contact area between straw and soil and lower the C/N ratio of straw, respectively, and we added metal hydroxides to the straw to determine their effect on soil physical properties.

MATERIALS AND METHODS

Experimental materials: The soil (Lou soil) was brought from the 0-20 cm layer in the a field at Northwest A & F University at Yangling. It was air-dried and sieved (2 mm). The properties of the experimental soil are as follows: The soil type is Lou soil; the soil texture is silt loam; the particle-sized fractions are sand (2-0.02 mm) 25.820%, silt (0.02-0.002 mm) 61.126% and clay(< 0.002 mm) 13.054% respectively; the organic C content is 13.150 g/kg.

Wheat straw with a C/N ratio of 95 was air-dried after harvest in the same field of soil sampling. The inorganic amendment was ferric hydroxide ($Fe(OH)_3$).

Samples of the straw were either finely-cut to less than 1 mm particle size by machine or chopped into 2 cm long by knife. A sub-sample of the straw was sprayed with a solution of of urea and calcium hydroxide solution to give a final C/N ratio lower than 95. The wet straw was mixed and placed into plastic bags which were sealed and at 40°C for 48h.

Experimental design: There were seven treatments, each in triplicate: control (CK), long-cut straw (C), finely-cut straw (F), finely-cut and urea treated straw (NF), finely-cut straw treated with ferric hydroxide (FT), finely-cut straw treated with urea and ferric hydroxide (NFT) and ferric hydroxide amendment only (T). For each treatment, the straw applied accounted for 0.5% of the total soil weight and the ferric hydroxide accounted for 0.1% of the total soil weight. As for the treatments of FT and NFT, the ferric hydroxide was first mixed with straw before the mixture being added into soil. For each treatment, after the soil was mixed with the corresponding material, the mixture was added into the PVC columns (with an inner diameter of 10 cm and height of 35 cm, the bottom should be sealed with gauze) layer by layer (5cm, totally 30 cm) to control the bulk density as 1.25 g cm^{-3}.

Indexes and determination methods: A vacuum gauge was buried in the centre of each column (the centre of the clay pipe should be 12cm from the top soil) and the tensiometer was read while weight recording. According to the correlation between soil moisture contents and soil water suctions, the soil water characteristic curves (the dehydration curve from wet to dry) in the low-suction section for each treatment could be obtained. The soil in the columns was saturated with water by penetration from the bottom. These saturated soil columns were then placed in a temperature controlled cabinet at 35°C for incubation and a relative humidity of 70% for 30 d. The water content was maintained at 80% of the field capacity. After 30 d, the height of soil in each column was measured and used to calculate soil volume and bulk density. The soils were then re-saturated by water penetration at the bottom, allowed to drain for 24 h and placed back in the controlled cabinets at 35°C and 70% relative humidity. Water evaporation was determined by weighing the columns at 12 h intervals for 30 days.

Data processing: Means of three replicates were calculated and the data were analysed by *t*-test and F-test. The softwares of Excel and SPSS15.0 were adopted to conduct data analysis.

In our study, the empirical equation $\theta = AS^{-B}$ (θ means volumetric water content, %; S means soil water suction, kPa; A and B are parameters), proposed by Gardner (Yao & Cheng 1986) was used to fit the soil water characteristic curve for each treatment, and the fitting curves and parameters are shown in Fig. 1 and Table 3. The parameter A in the equation determines the height of the curve, i.e. the water-holding capacity and the larger the value of A is, the higher the water-holding capacity is; parameter B determines the trend of the curve, i.e. the decreasing rate of soil water content with the decrease in soil water potential.

RESULTS

Soil bulk density and saturated moisture content: The soil bulk densities in the all treatments decreased and the saturated water contents increased compared to the control (Table 1). Compared with long-cut straw, finely-cut straw had a lower bulk density and a higher soil saturated water content, and finely-cut and urea treated straw had the lowest bulk density and the highest saturated water content (Table 1).

Ferric hydroxide improved the soil structure, while finely-cut straw treated with ferric hydroxide and finely-cut straw treated with urea and ferric hydroxide had a lesser effect in soil structure improvement than ferric hydroxide. Finely-cut straw treated with ferric hydroxide and finely-cut straw treated with urea and ferric hydroxide also had a lesser effect on soil structure compared with finely-cut straw, and finely-cut and urea treated straw respectively (Table 2).

Soil water-holding capacity: Treatments NF and T increased the water-holding capacities the most significantly over control, with increase of 8.9% and 9.7% respectively at 10 kPa and 7.4% and 8.6% respectively at 50 kPa (Fig. 1). The other treatments also increased the water-holding capacity over control and treatment F increased the water-holding capacity more than treatment C (Fig. 1). The saturated water content for the combined application of straw and inorganic amendment was not significantly different from the other treatments.

The values of R^2 in Table 2 indicate that the Gardner model fitted the soil water characteristic curve for each treatment. Each treatment had a water-holding capacity in the following sequence of T > NF > FT > F > NFT > C > CK (Fig. 1 and Table 2). Compared with other treatments, treatments T and NF improved soil water-holding capacity the most significantly. There was no larger difference in soil water-holding capacity among F, FT and NFT; the improving effect of long-cut straw on soil water-holding capacity was obviously lower than finely-cut straw and urea treated straw (Fig. 1).

Soil water-supplying capacity in the low-suction section: Soil water-supplying capacity refers to the capability of soil to supply water to meet the physiological need of plants

Table 1: Soil bulk density and saturated water content for each treatment.

Treatments	Soil bulk density ($g\ cm^{-3}$)	Saturated water content(%)
Control	1.361±0.0021a	48.8±0.1528d
Long-cut straw	1.348±0.0021ab	49.9±0.1528cd
Finely-cut straw	1.336±0.0021bc	51.2±0.1528c
Finely-cut and urea treated straw	1.298±0.0025e	55.3±0.1528a
Finely-cut straw treated with $Fe(OH)_3$	1.331±0.0021c	50.1±0.0764cd
Finely-cut straw treated with urea and $Fe(OH)_3$	1.317±0.0026d	53.3±0.1528b
$Fe(OH)_3$	1.309±0.0015de	54.4±0.1528ab

Note: The soil moisture contents in the column (%) refer to the volumetric water content; The same letters affixed to the data in the same column indicate an insignificant difference at $p < 0.05$ (T-test).

Table 2: Fitting parameters of soil water characteristics curves.

Treatments	*A*	*B*	R^2
Control	0.2868	0.1164	0.9594
Long-cut straw	0.2963	0.1143	0.9643
Finely-cut straw	0.3005	0.1200	0.9765
Finely-cut and urea treated straw	0.3031	0.1349	0.9222
Finely-cut straw treated with $Fe(OH)_3$	0.3018	0.1227	0.9746
Finely-cut straw treated with urea and $Fe(OH)_3$	0.2993	0.1281	0.9791
$Fe(OH)_3$	0.3074	0.1291	0.9301

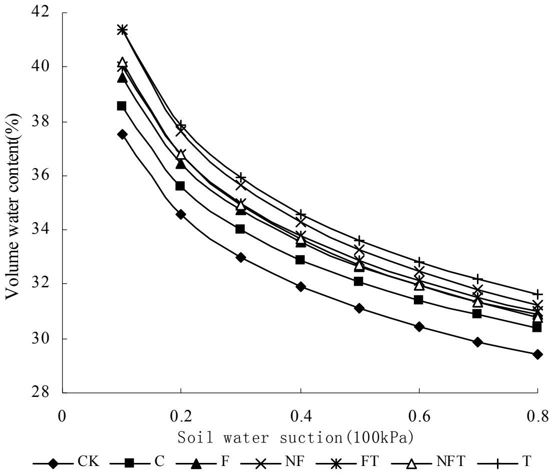

Fig. 1: Soil water characteristic curves fitted with Gardner model for each treatment.

under certain conditions, which is usually evaluated by specific water capacity and is an important index to evaluate the ability of soil to endure drought. Specific water capacity C_θ is the derivative of soil moisture content θ to matric potential ψ, which is obtained from the regression equation $\theta = AS^{-B}$ by derivation. $C_\theta = d_\theta/d\psi = -d_\theta/dS = ABS^{-(B+1)}$. In this equation, S means soil water suction and $S = -\psi$. In general, with the specific water capacity being 10^{-2}, the soil moisture is or equivalent to Breakage of Capillary Moisture (BCM), the water-supplying capacity of soil is difficult to meet the need of crop growth; the larger the suction obtained with the specific water capacity of 1.0×10^{-2} is, the better the drought tolerance is. With the specific water capacities in each treatment under various soil water suctions (Table 3), due to the differences in specific water capacity in the low-suction section, the water-supplying capacities are different among various treatments. Treatments CK and C had a specific water capacity of 10^{-2} at 40 kPa, while all the other treatments had a specific water capacity of 10^{-2} at 50 kPa, which indicated an effective improvement of the water-supplying capacity and further the drought tolerance of soil both through finely-cut straw application and inorganic amendment application. Treatment NF had the largest specific water capacity at various suctions (Table 3), which shows that the urea treated straw can improve the soil water-supplying capacity in the low-suction section the most significantly.

Dehydration rate in the early stage of drought: In the evaporation test in our study, the ambient temperature and humidity were constant and higher than those outdoor, which led to a stronger evaporation intensity than natural conditions. For the convenience of expression, the experimental data of every 12h were processed by being named as 1d. A number of researches show that the soil water within the availability range is not available on an equal basis and the water consumed with the soil water suction increasing from 10 kPa to 80 kPa has a strong mobility, which is the most available to plants. Richards and Taylor pointed out that with the soil water suction increasing from 10 kPa to 30 kPa, 15% of the soil available water was consumed; with a continuing increase to 80 kPa, the percentage became 50% (Hankes 1984). The experimental soil in our study was just silt loam soil and we can make an assumption that 50% of the available water was consumed with the soil water suction increasing from 10 kPa to 80 kPa for each treatment. The soil water characteristic curve under the low-suction section can be used to reflect the soil water and energy change in the stage of from moist state to early drought in the evaporation process for each treatment. Fig. 2 shows the change in soil water suction with time in each treatment.

With the time consumed in each treatment with the soil water suction increasing from 10 kPa to 80 kPa (available water consumption of 50%) (Table 4), treatments NFT and T used the longest time of 22 d, longer than control by 6 d; treatment FT also decreased the dehydration rate significantly. It can then be concluded that the inorganic amendment (ferric hydroxide) can effectively slow the loss of soil available water and further enhance the drought tolerating capability of soil; treatments C and F both consumed 50%

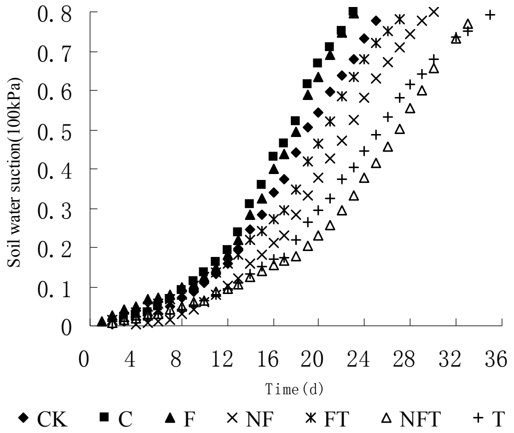

Fig. 2: Variation of soil water suction with time for each treatment.

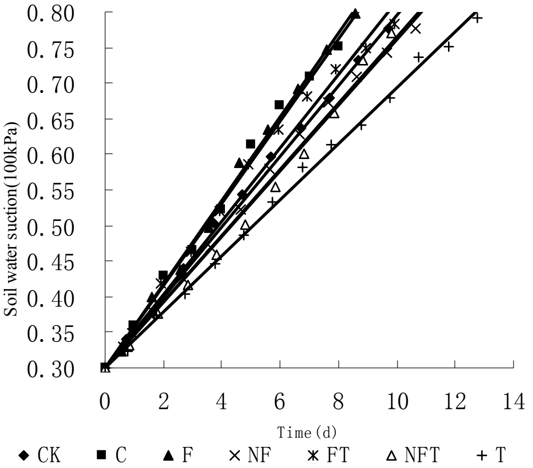

Fig. 3: Daily variation of soil water suction from 30 kPa to 80 kPa for each treatment.

*CK = control; C = long-cut straw; F = finely-cut straw; NF = finely-cut and urea treated straw; FT = finely-cut straw treated with $Fe(OH)_3$; NFT = finely-cut straw treated with urea and $Fe(OH)_3$; T = $Fe(OH)_3$

of soil available water using 14d. According to the analysis of the soil saturated water contents in treatments, treatments C and F both had a higher soil saturated water content than treatment CK. Therefore, the straw application tended to accelerate the soil dehydration in the low-suction section, which is not beneficial to the utilization of soil available water by crops in the low-suction section. Treatment NF underwent 18 d with soil water suction increasing from 10 kPa to 80 kPa, which indicated that the ammoniation (urea addition) of straw can to some extent avoid the problem with regular (with a medium C/N ratio) straw of the over-fast increase in the soil water suction in the low-section. With the time consumption in each treatment with the soil water suction increasing from 10 kPa to the suction with the soil water content of BCM (Table 4), under the experimental condition in our study, after 8d treatment CK had a insufficient capacity of water supply and the drought appeared; treatment NFT had a soil water content of BCM after 14d. Obviously, the inorganic amendment can decrease the loss of available water content in the top soil significantly; finely-cut straw also inhibited the loss of available water positively and the finely-cut and urea treated straw had a better impact; the long-cut straw accelerated the evaporation of the available water in top soil and the drought appeared earlier than control.

Within 0-30kPa, the soil water suction increased slowly with time and within 30-80kPa, there was almost a line relationship (Fig. 2). The linear fitting of the daily change in suction of 30-80kPa was conducted for each treatment and the fitting results were presented in Fig. 3 and Table 5. Each treatment had a better linear fitting of daily change in suction of 30-80kPa (Fig. 3 and Table 5). The trend of the fitting parameter *k* was consistent with the former analysis. Treatment T had a gradient obviously lesser than control, decreasing the evaporation within the suction range of available water the most significantly. The finely-cut and urea treated straw can also decrease the dehydration rate within 30-80 kPa obviously.

DISCUSSION AND CONCLUSIONS

It can be concluded from Table 1 that the finely-cut straw can effectively decrease soil bulk density and increase soil saturated water content compared with the long-cut straw, which was consistent with the previous studies. Compared with long-cut straw, the finely-cut straw could better improve soil structure, decrease soil bulk density and enhance the water-holding and water-supplying capacities of soil. However, there was no obvious difference in the dehydration rates in the low-suction section (10-80 kPa) (both higher than control), which may be due to the fact that the straw itself could also work as a path for the soil water flow in the evaporation process, which accelerated the increase in soil water suction. The finely-cut and urea treated straw can significantly decrease bulk density, increase saturated water content and water-supplying capacity compared with other treatments; it better enhanced soil water-holding capacity than finely-cut straw and the dehydration rate in the low-suction section was lower than straw untreated with urea and control, which obviously enhanced the capability of soil to endure drought. The better improving effect of finely-cut and urea straw may be due to the acceleration of straw decomposition by the treatments of comminution (finely-cut) and ammoniation (urea addition), which further stimulated the activity of microorganisms (Dong et al. 2013, Hu et al. 2013, Lin et al. 2013), whose secretion can improve the aggregate formation, which further enhanced soil structure stability (Oyedele et al. 1999, Wang et al. 2012).

Table 3: Specific water capacities for various treatments and soil water suctions.

	Various soil water suctions (100 kPa)							
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
CK	4.36×10^{-1}	2.01×10^{-1}	1.28×10^{-1}	9.29×10^{-2}	7.24×10^{-2}	5.90×10^{-2}	4.97×10^{-2}	4.28×10^{-2}
C	4.41×10^{-1}	2.04×10^{-1}	1.30×10^{-1}	9.40×10^{-2}	7.33×10^{-2}	5.98×10^{-2}	5.04×10^{-2}	4.34×10^{-2}
F	4.75×10^{-1}	2.19×10^{-1}	1.39×10^{-1}	1.01×10^{-1}	7.84×10^{-2}	6.39×10^{-2}	5.38×10^{-2}	4.63×10^{-2}
NF	5.58×10^{-1}	2.54×10^{-1}	1.60×10^{-1}	1.16×10^{-1}	8.98×10^{-2}	7.30×10^{-2}	6.13×10^{-2}	5.27×10^{-2}
FT	4.91×10^{-1}	2.26×10^{-1}	1.43×10^{-1}	1.04×10^{-1}	8.06×10^{-2}	6.57×10^{-2}	5.53×10^{-2}	4.76×10^{-2}
NFT	5.15×10^{-1}	2.36×10^{-1}	1.49×10^{-1}	1.08×10^{-1}	8.38×10^{-2}	6.82×10^{-2}	5.73×10^{-2}	4.93×10^{-2}
T	5.34×10^{-1}	2.44×10^{-1}	1.55×10^{-1}	1.12×10^{-1}	8.68×10^{-2}	7.07×10^{-2}	5.94×10^{-2}	5.11×10^{-2}

*CK=Control; C=Long-cut straw; F=Finely-cut straw; NF=Finely-cut and urea treated straw; FT=Finely-cut straw treated with $Fe(OH)_3$; NFT=Finely-cut straw treated with urea and $Fe(OH)_3$; T=$Fe(OH)_3$. The unit of the specific water capacity is $(100\ kPa)^{-1}$. The differences between Control and other treatments are all at an extremely significant level $p<0.01$ *(F-test).*

Table 4: Time for the change in soil water suction for each treatment.

Treatments	10kPa to 80kPa Time$^{(1)}$(d)	10kPa to the suction (a water content of BCM) Time$^{(2)}$(d)
Control	16	8
Long-cut straw	14	7
Finely-cut straw	14	10
Finely-cut and urea treated straw	18	11
Finely-cut straw treated with $Fe(OH)_3$	19	12
Finely-cut straw treated with urea and $Fe(OH)_3$	22	14
$Fe(OH)_3$	22	13

*(1)The time needed for the soil water suction change from 10 kPa to 80 kPa; (2) the time needed for the soil water suction change from 10 kPa to the value when the soil water content equals to the BCM (capillary connection fracture water content). The differences between Control and other treatments are all at an extremely significant level p <0.01 (F-test).

Table 5: Linear fitting of daily variation in soil suction from 30 to 80 kPa for each treatment.

Treatments	k	R^2
Control	0.0496	0.9961
Long-cut straw	0.0578	0.9929
Finely-cut straw	0.0588	0.9963
Finely-cut and urea treated straw	0.0461	0.9916
Finely-cut straw treated with $Fe(OH)_3$	0.0514	0.9820
Finely-cut straw treated with urea and $Fe(OH)_3$	0.0466	0.9911
$Fe(OH)_3$	0.0393	0.9973

Besides, the urea treated straw itself may have more hydrophilic component, which rendered treatment NF a higher saturated water content over control and other treatments. The inorganic amendment (ferric hydroxide) could significantly improve soil structure, enhance soil water-holding and water-supplying capacities and the dehydration rate in the early stage of drought was obviously decreased compared with other treatments, while its combination with straw did not improve soil water characteristics better than the single application. The saturated water content for the combined application of straw and inorganic treatment was not significantly different from the other treatments, which indicated no positive interaction between the straw and inorganic amendment applied together.

The long-cut straw buried in the top soil using a straw-returning machine, one common practice, cannot increase soil saturated water content and improve soil water-holding and water-supplying capacities greatly, whereas it can cause the over-fast dehydration of top soil in the early drought, which is not beneficial to the water conservation for drought resistance. However, the finely-cut and urea treated straw can effectively improve soil structure, increase soil saturated water content, water-holding and water-supplying capacities and decrease the dehydration rate in the low-suction section, which is beneficial to the conservation of soil available water that enhances the drought-resistance capability of soil and has a significance for the increase in rainwater use efficiency in the arid-semiarid region. The inorganic amendment (ferric hydroxide) decreased the dehydration rate in the low-suction section very significantly. The combined application of inorganic amendment (ferric hydroxide) and straw can inhibit their respective improving effect and the possible causes remain to be found out. It can be concluded that inorganic amendment can better improve soil water-holding capacity than straw, while with urea treated straw mixed with inorganic amendment, the improving effect was less, which can be related to the chemical reaction between inorganic amendment (ferric hydroxide) and the denatured straw by ammoniation. While the effects of the combination of straw and inorganic amendment on soil properties remain to be further studied, and we propose the methods for the combination and application of straw and inorganic amendment to give full play to their soil improving effects.

In our study, we assumed the moisture content at the soil depth of 12 cm approximately equal to the average water content, which may cause a certain error for the experimental results. Therefore, consideration should be given for the determination of soil moisture content and soil matric potential at the same soil depth in the future study.

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