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Original Research Paper

Studies on Chemical Pretreatment of Straw for Enhancing Soil Structure Formation and Stability

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ABSTRACT

The direct straw incorporation to soils can lead to problems of slow decomposition, diseases and pests, and nitrogen immobilization by microorganisms competing with crop uptake. We examined how straw pretreatments (either comminution, addition of liquid urea or blending with ferric hydroxide) aimed at decreasing these risks affected aggregation, bulk density, porosity and water evaporation of amended soils. Results showed that comminuted and urea treated straw significantly improved soil aggregation and increased soil porosity. Whereas a direct incorporation of straw had no impact on aggregate stability or porosity. Pretreatment of the straw doubled the MWD measured with wet sieving method and increased porosity by up to 12%; the application of ferric hydroxide effectively improved soil porosity distribution and further controlled the soil water evaporation; the combined application of ferric hydroxide and straw had a better effect on soil water conservation. The above results provided a theoretical basis for the selection of an optimal straw-returning method.

INTRODUCTION

Organic matter and soil amendments can significantly improve soil structure and improve soil water retention (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 microorganisms competing with crop uptake (Wang et al. 2012). The impacts of straw to soil structure depends on the application method. Uniform application improves soil structure stability more than straw mulching, which can lead to worse soil conditions than control with no straw application (Spaccini et al. 2001). Finely-cut straw can improve soil structure more quickly than long-cut straw because of the easy decomposition of finely-cutting straw (Tarafdar et al. 2001, Kasteel et al. 2007, Cabiles et al. 2008). The C/N ratio refers to the ratio of carbon to nitrogen. 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, Price & Norsworthy 2013, Wells et al. 2013, Ram et al. 2013), straw 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 improve soil structure and increase infiltration capacity (Buondonno & Coppola 2001, Rhoton et al. 2003, Bronick & Lal 2005, Wilson et al. 2013). So far, however, there have been few reports on effect of the combined application of straw and inorganic amendment on soil structure.

This study examined how the pretreatment of straw would affect soil physical properties. Straw was either left long or chopped finely before incorporation. Finely-cut straw was amended with either liquid urea, ferric hydroxide or both. We hypothesise that direct incorporation of straw will have minimal impact on soil physical properties, but pretreatments will result in large improvements. The research was conducted on a soil from northwest China that has poor initial soil carbon content. By improving the effectiveness of straw incorporation, the findings will help identify management practices that could enhance carbon storage and stability of these fragile soils.

MATERIALS AND METHODS

Experimental materials: The soil came from the 0-20 cm layer in a field at Northwest A&F University at Yangling (N34°16'56.24", E108°04'27.95"). It was air-dried and passed though a 2 mm sieve. The soil is classified as Dystric Anthrosol (FAO and USDA) and has a texture of silt loam. The particle size fractions are sand (0.02-2 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 at the same field as 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 or chopped into 2 cm long. A sub-sample of the finely-cut straw was sprayed with a solution of urea and calcium hydroxide to give a final C/N ratio lower than 95. The wet straw was mixed and placed into plastic bags which were sealed and kept at 40°C for 48h.

Experimental Design: There were seven treatments, each in triplicate: (1) control (C), (2) long-cut straw (LC), (3) finely-cut straw (FC), (4) finely-cut and urea treated straw (FCU), (5) finely-cut straw treated with ferric hydroxide (FCFH), (6) finely-cut straw treated with urea and ferric hydroxide (FCUFH) and (7) ferric hydroxide amendment only (FH). For each treatment, straw was applied at 0.5% of the total soil weight and the ferric hydroxide accounted for 0.1% of the total soil weight. For the treatments of FCFH and FCUFH (three replications), the ferric hydroxide was firstly mixed with straw before the mixture being added into soil. For each treatment (three replications), after the soil was mixed with the corresponding material (straw and ferric hydroxide), the mixture was added into 10 cm diameter PVC column that was either 12 cm or 35 cm high. The bottom of the column was sealed with gauze. Packing was done in 5 cm layers to achieve a bulk density of 1.25g cm^{-3}.

Indexes and determination methods: All soil columns were saturated from the bottom. After 24 h, they were put into a temperature controlled climate cabinet (35°C, relative humidity 70%). Columns were left open at the top and incubated for 60 days. Each day the columns were weighed and if the water content had dropped to less than 0.40 m^3m^{-3}, the column was resaturated for 24 hours.

At 60 d, we sampled smaller columns using a 50 mm (d)×1 inch (h) cutting ring. These samples were firstly used for the determination of soil water characteristic curves by a centrifuge method. After that they were oven dried (105°C, 24 h) to calculate the soil bulk density. The remaining soil in the columns was used to measure the aggregate distribution (>10, 10-7, 7-5, 5-3, 3-2, 2-1, 1-0.5, 0.5-0.25 and <0.25 mm) using a dry-sieve method and water-stable aggregate distribution (>5, 5-2, 2-1, 1-0.5, 0.5-0.25 and <0.25 mm) by a wet-sieve method.

At 60d, the soil in the larger columns was resaturated from the bottom. Then a tensiometer was buried at the soil center at 12 cm depth. After 24 h, these columns were returned to the climate cabinet (35°C, relatively humidity of 70%). The bottoms of the columns were sealed and top left open to allow evaporation for 13d. The column weights and water potentials were recorded at 12h intervals.

Data processing: Mean values were calculated in Excel and the multiple comparison was made by the new multiple range method of Duncan in SPSS15.0.

Based on the aggregate contents of various particle size fractions, the MWD (mean weight diameter), GMD (geometric mean diameter) and D (soil aggregate fractal dimension, it refers to) were calculated. D was calculated by Yang Peiling method (Yang et al. 1993):

$$D=3-lg(w_i/w_0)/lg(d_i/d_{max}) \quad ...(1)$$

Where D is the soil aggregate fractal dimension; w_i is the cumulative weight of various particle size fractions with diameters less than d_i (g); w_0 is total weight (g); d_i means the average particle diameter of the two adjacent fractions di and d_i+1(mm); d_{max} means the mean particle diameter of the largest fractions (mm).

Total soil porosity = (1-soil bulk density/soil specific weight)*100%, the value of soil specific weight was assumed to be 2.65 g/cm^3. Capillary porosity is the difference between field capacity and wilting point (from soil water characteristic curves fitted); non-capillary porosity is the difference between of total soil porosity and capillary porosity.

Based on the soil water characteristic curves at the most negative water potentials, the porosity fractal dimension was calculated using the soil water characteristic curves model elicited by Huang & Zhan (2002) based on a Menger spongisum structure:

$$H/H_s=[W/W_a]^{Dp-3} \quad ...(2)$$

Where Dp is the porosity fractal dimension; H is the soil water content (m^3m^{-3}); H_s is the saturated soil water content (%); W is the negative water potential (kPa) and W_a is the air pressure (kPa).

RESULTS

Soil aggregation: Pretreatments (with an exception of treatments LC and FC) effectively increased soil macroaggregates contents (Tables 1 and 2). Treatments FCU and FCUFH increased the content of macroaggregate of >10 mm significantly by 32.02% and 32.89% respectively. Treatments FCFH and FH increased the content of macroaggregate of >10 mm obviously. Treatment FC increased the macroaggregate of >10 mm less effectively, while there was a decrease for Treatment LC. In terms of the content of aggregate of >5 mm, Treatments FCU, FCUFH, FCFH, FH and FC all had obvious increases in various extent over Treatment C. Treatments LC increased the content of water-stable aggregate of >5 mm less effectively. Treatment LC increased the content of water-stable macroaggregate over control the least; while it increased the fractions of 2-1 mm (dry-sieve method) and 1-0.5 mm (wet-sieve method) obviously by 13.45% and 11.03% respectively.

Soil structure stability: Treatments FCU and FCUFH both increased the content of water-stable aggregate of >0.25 mm over control effectively (Table 4). Treatments FCFH and FH increased the contents of water-stable soil aggregate of >0.25 mm obviously by 4.23% and 2.68% respectively (Table 4). Treatment FC also increased the content of water-stable soil aggregate of >0.25 mm obviously but in a less extent than Treatments FCFH and FH (Table 4). Treatment LC reduced both the contents of aggregate of > 0.25 mm and water-stable aggregate of >0.25 mm over control (Tables 3 and 4).

The variation rule of indexes of MWD and GMD basically followed the same pattern as the content of water-stable aggregate of >0.25 mm. Treatments FCU and FCUFH both significantly increased the indexes of MWD and GMD over control (dry-sieve method and wet-sieve method) (Tables 3 and 4).

The fractal dimension of soil aggregate by dry-sieve method (Dd) was correlated with the content of water-stable aggregate of > 0.25 mm highly significantly ($P<0.01$) and significantly with MWD and GMD ($P<0.05$), the correlation coefficients being -0.85, -0.83 and -0.75 respectively. The fractal dimension of soil aggregate by wet-sieve method (Dw) was all correlated with the content of water-stable aggregate, MWD and GMD highly significantly ($P<0.01$); the correlation coefficients being -0.97, -0.86 and -0.91. Based on the above correlation, the fractal dimension of soil aggregate can be used to evaluate the soil structure stability (it decreased as the soil structure stability was improved). Based on the results of the fractal dimension of soil aggregate under dry-sieve and wet-sieve conditions, Treatments FCU and FCUFH both effectively enhanced soil aggregate stability.

Soil bulk density and soil porosity: Treatment FCUFH decreased soil bulk density over control the most significantly by 11.09% (increased soil porosity) followed by Treatments FCU, FCFH, FC and LC. Treatment FH also improved soil structure by decreasing soil bulk density significantly (Table 5).

The fractal dimension of soil aggregate (Dw) was correlated with soil bulk density significantly ($P<0.05$) and highly significantly with soil porosity ($P<0.01$). Treatment FCUFH had the least value of Dw among treatments (Table 4).

Soil water evaporation rate: The cumulative evaporation was correlated with time basically by a power relationship ($E_c = at^b$); the correlation between evaporation rate and time was obtained as $E_t = a\#bt^{b-1}$ by a derivation of E_c over t. Based on the property of power function, the difference in the coefficients of a#b can reflect the difference in evaporation rates E_t. Based on the data of a#b (Table 6), the evaporation rates were in the following sequence: LC>FC>C>FCU> FCFH>FH>FCUFH. Treatments LC, FC and FCU resulted in relatively higher evaporation rates. Compared with Treatments FC and FCFH, Treatments FCU and FCUFH reduced soil water evaporation rate respectively (Table 6); compared with Treatments FC and FCU, Treatments FCFH and FCUFH decreased soil water evaporation obviously respectively (Table 6).

Soil porosity fractal dimension and soil water evaporation: There basically existed a linear relation between fractal dimension of soil porosity (Dp)and a#b, $y = -0.1085x + 0.3468$, $R^2 = 0.827$. Dp was correlated with a#b negatively highly significantly ($P<0.01$), with a coefficient of -0.91, i.e. in the low-suction section, the evaporation rate basically decreased as the fractal dimension of soil porosity increased. The fractal dimension of soil porosity was in the following sequence: LC<FC<FCU<C<FCFH<FCUFH<FH.

Treatments FCFH, FCUFH and FH increased the fractal dimension of soil porosity in the low-suction section obviously over control (significantly for Treatment FH); while Treatment FCU decreased it slightly (slightly lower than control) (Fig. 2), however, Treatments LC and FC decreased the fractal dimension of soil porosity obviously.

DISCUSSION AND CONCLUSION

The straw comminution degree and C/N ratio affected soil structure greatly. The comminution of straw and the ammoniation of straw could both enhance the improving effect of regular straw on soil structure. The long-cut straw influenced the soil aggregate negatively, decreasing the soil structure stability.

There was a large difference in the mechanisms of soil structure improvement between straw and inorganic amendment. Straw mainly affected soil aggregation positively, while not so good as soil porosity distribution, which may be due to the significant increase in soil macroporosity after the application of straw (which may be due to the blocking-up of soil by the straw, resulting in a poor connection of soil porosity), while ferric hydroxide

Table 1: Particle size distribution of soil aggregate.

Trea-tment	Particle size fraction (mm/%)							
	>10	10-7	7-5	5-3	2-1	1-0.5	0.5-0.25	<0.25
C	45.6b	5.1ab	0.2a	7.9a	11.9ab	8.4a	3.3a	2.2ab
LC	44.9ab	7.8ab	2.6a	7.4abc	13.5ab	7.4a	2.7a	2.5a
FC	50.4b	10.5a	2.6a	7.6ab	13.2ab	7.6a	2.6a	1.7bc
FCU	60.2a	9.0b	2.5a	5.6bcd	10.0ab	6.0a	2.1a	1.3c
FCFH	57.2ab	6.7ab	1.1a	6.5abcd	11.3ab	8.7a	2.5a	1.9bc
FCUFH	60.6a	9.5b	2.8a	5.5cd	9.6b	6.5a	2.5a	1.4c
FH	55.6ab	6.2b	0.8a	5.3d	15.4a	8.7a	3.0a	1.8bc

*The same letters in the same column indicate no significant difference ($P<0.05$). The same meaning in other Tables also. Dry-sieve method.

Table 2: Particle size distribution of soil aggregate.

Treatment	Particle size fraction of soil aggregate (mm/%)					
	>5	5-2	2-1	1-0.5	0.5-0.25	<0.25
C	0.2b	6.2a	17.2a	27.2ab	17.1ab	29.1ab
LC	5.8b	5.1a	13.0ab	30.2bc	18.3a	30.6a
FC	14.3a	7.4a	11.4b	18.7d	10.9c	27.3ab
FCU	21.7a	7.9a	13.6ab	19.6d	12.5c	24.7b
FCFH	20.0a	7.7a	12.6ab	20.5d	13.1c	26.1ab
FCUFH	23.3a	7.5a	14.3ab	23.0cd	12.4c	24.5b
FH	18.1ab	6.4a	16.0ab	34.2a	14.1bc	27.2ab

*Wet-sieve method.

Table 3: Evaluation indexes for soil aggregate.

Treatment	Dry-sieve method			
	>0.25mm/%	MWD/mm	GMD/mm	Dd
C	97.8bc	8.007cd	4.921c	2.222ab
LC	97.5c	7.692d	4.878c	2.260a
FC	98.3ab	9.574abc	6.098abc	2.210c
FCU	98.7a	10.540a	7.031a	2.164c
FCFH	98.1ab	8.410bcd	5.338bc	2.192bc
FCUFH	98.9a	9.964ab	6.601ab	2.180bc
FH	98.5ab	8.473bcd	5.023c	2.185bc

Table 4: Evaluation indexes for soil aggregate.

Treatment	Wet-sieve method			
	>0.25mm/%	MWD/mm	GMD/mm	Dw
C	70.9ab	0.812b	0.493b	2.720ab
LC	69.4b	0.980b	0.507b	2.730a
FC	72.7ab	1.885a	0.830a	2.673bcd
FCU	75.3a	1.812a	0.832a	2.644cd
FCFH	73.9ab	1.714a	0.775a	2.653cd
FCUFH	75.5a	1.660a	0.781a	2.640d
FH	72.8ab	0.915b	0.538b	2.696abc

Table 5: Soil physical properties and its correlation with Dw.

Treat-ment	Bulk density($g.cm^{-3}$)	Total porosity(%)	Capillary porosity(%)	Non-capillary porosity(%)
C	1.461a	44.874d	18.995c	25.879c
LC	1.412ab	46.570cd	19.438bc	27.880abc
FC	1.401ab	47.148cd	19.268bc	27.132bc
FCU	1.316cd	50.996a	21.516a	29.681ab
FCFH	1.381bc	47.899bc	20.734ab	26.516bc
FCUFH	1.299d	50.331ab	21.580a	25.050bc
FH	1.323cd	50.073ab	20.113abc	20.672a
Correlation with Dw	0.72*	-0.72*	-0.85**	-0.5

The same letters in the same column indicate no significant difference ($P<0.05$); *significant correlation ($P<0.05$), **highly significant correlation ($P<0.01$).

Table 6: Regression analysis of cumulative evaporation (Ec/kg) and time (t).

Treatment	Fitting parameters		R^2	a#b
	a	b		
C	0.0577	0.7501	0.9970	0.0433
LC	0.0567	0.7935	0.9958	0.0458
FC	0.0579	0.8249	0.99740	0.0450
FCU	0.0574	0.8114	0.9982	0.0432
FCFH	0.0567	0.7743	0.9986	0.0426
FCUFH	0.0574	0.7429	0.9995	0.0420
FH	0.0548	0.7641	0.9983	0.0419

mainly influenced soil porosity distribution positively, having more soil capillary porosity than straw.

The combination of comminuted-urea-treated straw and ferric hydroxide improved soil aggregation the most effectively (followed by comminuted-urea-treated straw), which can be attributed to the respective effectiveness of pretreated straw and inorganic amendment. The effect of the combination of comminuted straw and ferric hydroxide was better than ferric hydroxide and less than comminuted-urea-treated straw, which may be due to the highly effectiveness of ammoniation, which stimulated the activity of microorganisms (Dong et al. 2013, Hu et al. 2013, Lin et al. 2013). Long-cut straw increased the content of macroaggregate the least, which may be due to the slow decomposition of long straw.

The pretreatment of comminution and ammoniation enhanced the soil structure stability, consistent with the experimental results of Tejada et al. (2009), pointing out the application of organic matter of low C/N ratio could better improve soil structure, which may be attributed to the increase in dissolved organic matter (Wang et al. 2012) and there was a better effect after the mixing with ferric hydroxide (due to the respective effectiveness of pretreated straw and inorganic amendment). However, the long-cutting of straw had a negative effect on soil structure in a short term, which may be due to the scattering of long straw.

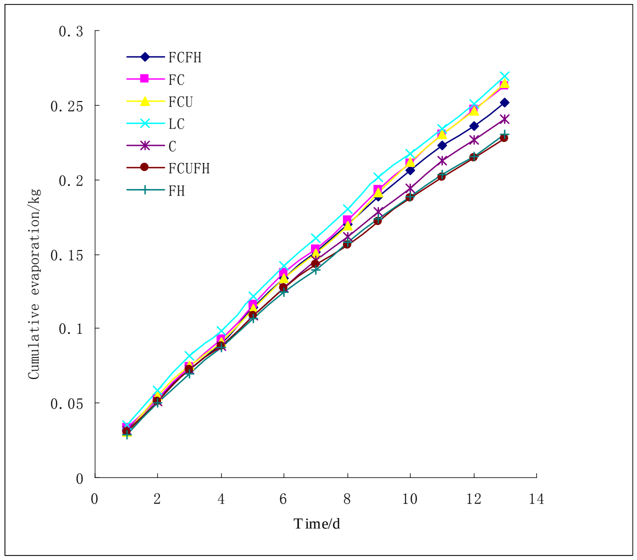

Fig. 1: Cumulative evaporation capacity for each treatment.

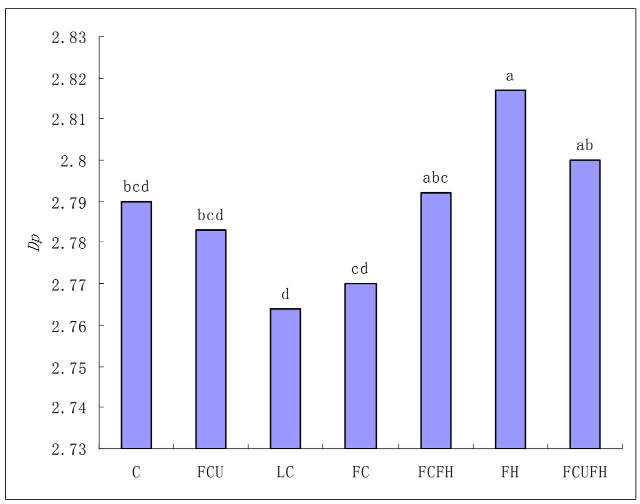

Fig. 2: Soil porosity fractal dimension in low-suction section for each treatment.

The comminuted-ammoniated straw reduced soil bulk density effectively, which was attributed to the straw pretreatment of comminution and ammoniation. The combination of the comminuted-urea-treated straw and ferric hydroxide had a better effect, which indicated that the combined application of ammoniated straw and inorganic amendment (ferric hydroxide) improved soil structure the most effectively, which may be due to the combined effect of comminuted-urea-treated straw and ferric hydroxide.

Long-cut straw and comminuted straw increased soil water evaporation rate although it improved soil structure to some extent and the comminuted-ammoniated straw only decreased soil water evaporation slightly; while the application of inorganic amendment decreased soil water evaporation rate effectively, which may be due to a uniform soil porosity distribution and a better porosity connectivity. When it was blended with comminuted-ammoniated straw, the water-stable soil structure was enhanced and soil water evaporation was further inhibited. The long-term effects of the combined application of straw and inorganic amendment on soil structure remain to be studied further.

In conclusion, the comminuted-ammoniated straw had a better improving effect in terms of soil aggregate improvement, while it was less effective on soil porosity distribution than inorganic amendment. When the comminuted-ammoniated straw was applied blended with inorganic amendment, its disadvantage of higher soil water evaporation rate was greatly overcame, which was more beneficial for increasing the utilization efficiency of rain water. The concrete application methods and application proportions remain to be studied further.

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