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Effects of freeze-thaw cycles and initial soil moisture content on soil aggregate stability in natural grassland and Chinese pine forest on the Loess Plateau of China

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Abstract

Purpose Ongoing global warming is decreasing the thickness of snow covers and increasing initial soil moisture content (SMC), which increase the number of freeze-thaw cycles (FTCs) at mid-high latitudes and high elevations, especially at temperate regions. FTCs substantially affect the stability of soil aggregates, which may increase soil erosion. A comprehensive understanding of aggregate stability under different types of vegetation restoration in response to FTCs, however, has not yet been attained.

Materials and methods We evaluated the effects of number of FTCs (0, 1, 3, and 9) and initial SMC (40, 60, and 80% field capacity) on aggregate distribution and stability in cropland, natural grassland, and Chinese pine forestland, the three typical types of vegetation on the Loess Plateau in China. The experiment was conducted under simulated conditions in the laboratory using disturbed soil samples.

Results and discussion Most aggregate-size fractions and mean weight diameters (MWDs) were significantly ($P < 0.05$) affected by FTCs, initial SMC, and vegetation types. FTCs significantly decreased MWD by 3.6–18.1% through disrupting larger macroaggregates, which increased with SMC. Increased SMC increased MWD by 2.0–53.0% through binding soil particles, the effect of which was much larger than the disruptive effects under the freeze-thaw conditions, especially at high SMC. MWD was in the order of cropland < Chinese pine forestland < natural grassland under each freeze-thaw condition.

Conclusions The results indicated that natural vegetation succession was better than Chinese pine forest plantation for resisting seasonal FTCs and that aggregate stability may increase due to increased initial SMC under scenarios of future global warming.

Keywords Aggregate stability · Freeze-thaw cycles · Initial soil moisture content · Loess Plateau · Vegetation type

1 Introduction

The stability of soil aggregates is an important soil physical property and significantly affects soil aeration, temperature, mechanical resistance, and the retention of water and nutrients (Abiven et al. 2009; Zeng et al. 2018). Maintaining high aggregate stability is very important for reducing soil erosion, increasing the ability to conserve soil, and improving soil fertility (Canton et al. 2009; Guidi et al. 2017). The restoration of vegetation is an efficient way to reform soil structure and increase the stabilization of soil aggregates in degraded ecosystems (An et al. 2013; Tang et al. 2016a; Gu et al. 2019). Soil in ecosystems at mid-high latitudes and high elevations suffers seasonal freezing and thawing (Grogan et al. 2004; Yu et al. 2011; Song et al. 2017b), which can substantially influence the stability of aggregates. Ongoing global warming will also thin the snowpack and increase soil moisture content (SMC) and the frequency of freezing and thawing during winter and spring, especially at temperate regions (IPCC 2007; Park et al. 2010; Makoto et al. 2014). Determining the effect of freezing and thawing on aggregate stability would clearly

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contribute to a complete assessment of the ecological effects of vegetation restoration and provide guidance for the restoration of degraded ecosystems.

Freeze-thaw cycling is a process of energy input and output in soil (Li et al. 2002; Zhang et al. 2016; Wang et al. 2019) and can strongly affect the arrangement and bonding of soil particles and thus soil structure. Numerous studies have evaluated the effects of freeze-thaw cycles (FTCs) on the stability of soil aggregates (Wang et al. 2012; Dagesse 2013; Skvortsova et al. 2018). Most studies have reported that FTCs decrease the fractions of large aggregates and increase the fractions of small aggregates, thus decreasing aggregate stability (Oztas and Fayetorbay 2003; Dagesse 2011; Song et al. 2017a). Some studies, though, have found that FTCs strengthen particle bonding, which generally increases aggregate stability from disruption to reconstruction (Edwards 2013; Zhang et al. 2016). These contradictory results were mainly associated with freeze-thaw conditions (e.g., freezing temperatures, the number of FTCs, and the moisture content at freezing) (Oztas and Fayetorbay 2003; Kværnø and Øygarden 2006; Li and Fan 2014), soil type (Ozgul et al. 2011; Edwards 2013), and the method used to determine aggregate stability (Wang et al. 2012; Zeng et al. 2018). Some studies have also found that adding fertilizer, diatomite, municipal solid waste compost, sewage sludge, and/or fly ash to soil could offset the negative effect of FTCs on aggregate stability (Sahin et al. 2008; Angin et al. 2013, 2016; Chai et al. 2014). Skvortsova et al. (2018) reported that differences in soil mechanical strength, water stability, particle size distribution, and organic matter content affected the stability of aggregates in freeze-thaw treatments.

Promoting vegetation restoration by reducing artificial disturbances could effectively increase aggregate stability and prevent erosion in fragile ecosystems (Zhou et al. 2012; Tang et al. 2016a). Different types of vegetation have differentially improved the physical, chemical, and biological properties of soil (Zhao et al. 2017a; Li et al. 2018; Xiao et al. 2019a), so may contribute to the response to FTCs. Little information, however, is available on the effect of vegetation restoration types on the stability of aggregates subjected to FTCs, especially under scenarios of global warming (Yi et al. 2015; Watanabe et al. 2019), which has hindered a comprehensive evaluation of different vegetation types on the control of soil erosion.

The Loess Plateau of China is in the mid-latitude zone and has distinct seasonal cycles of freezing and thawing during winter and spring, which strongly influence soil structure and aggregate stability (Li et al. 2013; Xiao et al. 2019b). The plateau has suffered serious soil erosion, so the “Grain for Green” project was implemented to control the erosion and improve soil quality (Chang et al. 2011; Wang et al. 2016). Sloped cropland was abandoned for natural succession grassland or was planted with artificial forests, the two main types for restoring the vegetation (Zhu et al. 2017). Much attention had been paid to evaluating the influence of these two vegetation restoration types on aggregate stability, especially during the growing season (An et al. 2013; Zhao et al. 2017b; Zhu et al. 2017; Zeng et al. 2018). An increasing number of studies, however, have found that the effects of winter processes, especially freeze-thaw cycling caused by global climate change, on the dynamics of aggregate stability should not be ignored and may affect plant growth during the next growing season (Urakawa et al. 2014; Tang et al. 2016b; Song et al. 2017a; Xiao et al. 2019b). We simulated freeze-thaw cycling using soil collected from a natural succession grassland and a forest of Chinese pine on the Loess Plateau to evaluate the effects on aggregate distribution and stability. Our purpose was to examine the influence of the number of FTCs and initial SMC on aggregate stability and to evaluate natural succession grassland and artificial Chinese pine forest for maintaining a higher aggregate stability during winter under scenarios of global climate change.

2 Materials and methods

2.1 Site description

Soil samples used in this study were obtained from research sites in the Wangmaogou watershed (37°34′13″-37°36′03″N, 110°20′26″-110°22′46″E) of Suide County in Shaanxi Province. The watershed has a continental monsoon climate with a mean annual precipitation of 513 mm and a mean annual temperature of 10.2 °C. The altitude of the watershed ranges from 940 to 1200 m a.s.l. The soil type is mainly loessial (Calcaric Cambisols, FAO), which is extremely susceptible to erosion. The Chinese government launched the “Grain for Green” program in 1999 to plant Chinese pine trees and to allow the natural recovery of grassland. We collected soil from a representative cropland, Chinese pine forestland, and natural succession grassland for simulating FTCs in the laboratory.

The Chinese pine forest was a pure stand with an understory mainly of *Salsola collina*, *Artemisia sacrorum*, and *Carex lanceolata*. *Bothriochloa ischaemum* has been the main grass species in natural succession grassland restoration. Before vegetation restoration, the land was used as cropland. The history of the sampling sites was determined through inquiries from village elders and by relevant rental contracts. These sites have similar aspect, gradient, elevation, and had been subjected to similar farming practices. After the cropland abandoned for natural recovery or planted with Chinese pine, those lands were remained natural condition with litter human interference and no management practices such as watering and fertilization. The main soil characteristics of the three types of land use are shown in Table 1. The watershed has

Table 1 Main soil characteristics of the three vegetation types

Main species	Vegetation types	Clay (%)	Silt (%)	Sand (%)	BD	Cover (%)	SOC (g/kg)
Setaria italica	Crop land	14.0 ± 1.7	23.0 ± 1.0	63.0 ± 1.0	1.15 ± 0.06	62	9.60 ± 0.52
Pinus tabuliformis	Forest land	12.7 ± 1.6	23.7 ± 1.5	63.7 ± 1.5	1.16 ± 0.04	36	10.93 ± 0.76
Bothriochloa ischaemum	Grass land	13.0 ± 1.7	24.0 ± 1.0	63.0 ± 1.0	1.20 ± 0.07	86	11.69 ± 0.61

BD bulk density, *SOC* soil organic carbon

distinct seasonal freezing and thawing. We chose − 15 and + 10 °C as the freezing and thawing temperatures, respectively, for the simulated experiments based on the ranges of the average lowest and extreme lowest temperatures (− 13.2 and − 21.0 °C, respectively) and the average highest and extreme highest temperatures (+ 0.7 and 15.4 °C, respectively) during the freeze-thaw seasons for 2000–2015.

2.2 Soil sampling and experimental design

Soil samples were collected before freezing in late autumn 2017. After the removal of the litter layer, undisturbed samples (0–20 cm) from area without vegetation were collected from each of three plots for each vegetation type and stored in aluminum containers (10 × 10 × 20 cm, depth × width × length). The containers were then sealed in plastic bags and transported to the laboratory. The field-moist samples of each vegetation type were air-dried at room temperature to approximately 8% gravimetric water content. The samples were carefully broken by hand into clods < 1 cm in diameter and then passed through a sieve with 8-mm openings. The samples of the same vegetation type were pooled, mixed, and then separated into three subsamples. The field capacity (FC) of soil samples was determined by cutting ring method and then calculated the amount of distilled water that was added to obtain 40, 60, and 80% FC. These water contents were assumed to represent different moisture conditions before soil freezes. We added water from a container to soil samples along the glass breaker wall through a plastic head dropper to reach the target water content (Li and Fan 2014; Ye et al. 2017), and stored in plastic bags for at least 24 h to obtain uniform water content in the soil. The soil was then packed into aluminum containers (10 × 10 × 20 cm, depth × width × length) at the same bulk density as in the field (about 1.2 g cm^{-3}). Twelve containers were prepared for each SMC, three of which were stored at 10 °C as unfrozen controls. The other nine containers were frozen at − 15 °C for 24 h and thawed at 10 °C for 24 h. This FTC was repeated one, three, and nine times. A preliminary test indicated that the soil in the containers could freeze or thaw completely within 24 h. A total of 3 × 4 = 12 treatments (SMC × FTC) for each vegetation type was tested. Each treatment had three replicates. Usually, the laboratory studies cannot always reflect what actually occurs in the field, such as it might missing the influence of mechanical stabilization of aggregates through the roots and fungi hyphae (Demenois et al. 2018; Xiao et al. 2019b; Li et al. 2019), but it can exactly reveal the effects of FTCs and initial SMC on soil aggregate stability.

2.3 Aggregate fractionation

Each soil sample was air-dried after freezing and thawing for aggregate fractionation. The aggregates were separated by placing 500 g of air-dried clods (< 5 mm) on the topmost of a set of sieves (2- and 0.25-mm openings). The sieves were then manually shaken (amplitude 4 cm) at a rate of 1 oscillation s^{-1} for 2 min to separate the clods into three aggregate fractions: > 2.00 mm (large macro-aggregates), 0.25–2.00 mm (small macro-aggregates), and < 0.25 mm (micro-aggregates). The soil for each aggregate size class was dried at 60 °C for 48 h to a constant weight and weighed for determining the mass distribution and mean weight diameter (MWD) of the aggregates. MWD was calculated by:

$$\mathrm{MWD} = \sum_{i=1}^{n} (W_i \times X_i)$$

where W_i is the mean diameter of aggregate fraction i, and X_i is the proportion of aggregate fraction i in the total sample weight.

2.4 Statistical analyses

Three-way ANOVAs were used to analyze the effects of SMC, number of FTCs, and vegetation type (ecosystem type) on aggregate-size distribution and MWD. The data were first checked for normality and the homogeneity of the variances and were log-transformed to correct deviations from these assumptions when needed. Duncan's multiple range tests were performed to determine the differences in aggregate size and MWD among the freeze-thaw treatments and run separately for the different SMCs and vegetation types. One-way ANOVA was performed to determine the differences in aggregate distribution and MWD in the three vegetation types. A general linear model (GLM) was used to examine the effects of number of FTCs and initial SMC on MWD.

3 Results

3.1 Effects of FTCs on aggregate stability

FTCs had a significant influence on the proportion of aggregates > 2000 and < 250 μm and on MWD ($P < 0.001$) (Table 2). The proportion of aggregates > 2000 μm in the *Setaria italica* soil for 60 and 80% FC and in the *Pinus tabuliformis* soil for the three SMCs decreased significantly as the number of FTCs increased (Fig. 1). The proportion of aggregates > 2000 μm in the *B. ischaemum* soil for the three SMCs first significantly decreased and then slightly increased as the number of FTCs increased. The proportion of aggregates < 250 μm had an opposite trend for the soil under three vegetation types. MWD of the *S. italica* soil and *P. tabuliformis* soil decreased by 3.6–18.1% as the number of freeze-thaw cycles increased (Fig. 1). MWD of the *B. ischaemum* soil for 40 and 80% FC first decreased by 2.6–15.5% and then slightly increased as the number of FTCs increased. The GLM test showed that MWD of the *S. italica* soil and *P. tabuliformis* soil for the three SMCs decreased significantly as the number of FTCs increased ($P < 0.05$) (Fig. 2, Table 3).

3.2 Effects of initial SMC on aggregate stability

SMC had a significant influence on aggregate distribution and MWD ($P < 0.001$) (Table 2). The proportion of aggregates > 2000 and 250–2000 μm increased significantly ($P < 0.05$), but the proportion of aggregates < 250 μm decreased significantly ($P < 0.05$), as the SMC increased (Fig. 1). MWD thus significantly increased by 2.0–53.0% with SMC. The number of FTCS and the SMC had significant interactive effects on MWD ($P < 0.001$) (Table 2). FTCs had a decreasing effect on MWD with increasing SMC for the soil under three vegetation types. The GLM test indicated that MWD had increased significantly with SMC under different FTC treatments ($P < 0.05$) (Fig. 3, Table 4).

3.3 Effects of different vegetation type to FTCs

Vegetation type had a significant influence on aggregate distribution and on MWD ($P < 0.001$) (Table 2). The *S. italica* soil at 40 and 60% FC had a significantly lower proportion of aggregate 250–2000 μm and a significantly higher proportion of aggregates < 250 μm ($P < 0.05$) (Fig. 1). The *P. tabuliformis* soil at 60 and 80% FC had a significantly lower proportion of aggregates > 2000 μm and a significantly higher proportion of aggregates < 250 μm than the *B. ischaemum* soil ($P < 0.01$ or < 0.001) (Fig. 1). MWD of *B. ischaemum* soil was 5.9–8.7% higher than the *P. tabuliformis* soil at 60 and 80% FC under each freeze-thaw condition ($P < 0.05$). Vegetation type and SMC had significant interactive effects on MWD ($P < 0.001$) (Table 2). MWD was significantly higher for the *B. ischaemum* than the *P. tabuliformis* soil as the SMC increased. Vegetation type, SMC, and number of FTCs had significant interactive effects on MWD ($P < 0.05$). The decrease in MWD at the higher SMCs (60 and 80% FC) was larger in *S. italica* than *P. tabuliformis* and *B. ischaemum* soil as the number of FTCs increased. The decrease in MWD at the lower SMCs (40 and 60% FC) was larger for the *P. tabuliformis* than the *B. ischaemum* soil as the number of FTCs increased. The decrease in MWD at the highest SMC (80% FC) was smaller for the *P. tabuliformis* than the *B. ischaemum* soil as the number of FTCs increased, but MWD was higher for the *B. ischaemum* than the *P. tabuliformis* soil after nine FTCs.

4 Discussion

4.1 Effects of FTCs on aggregate stability

The stability of soil aggregates is usually used to characterize soil erodibility (Díaz-Zorita et al. 2002; Le Bissonnais 2016). Vegetation restoration is expected to increase aggregate stability and therefore decrease erosion (Zhou et al. 2012; Wang et al. 2018). Our results suggested that FTCs significantly decreased aggregate stability in the *P. tabuliformis* and

Table 2 Results (*F* values) of the ANOVAs of the effects of vegetation type (VT), soil moisture content (SMC), and number of freeze-thaw cycle (FTC) on aggregate-size distribution and mean weight diameter (MWD)

	Large macro-aggregates	Small macro-aggregates	Micro-aggregates	MWD
VT	60.74***	203.22***	191.71***	134.48***
SMC	1870.04***	412.56***	2092.21***	2340.88***
FTC	98.00***	0.63	46.24***	76.36***
VT × SMC	24.68***	40.57***	14.82***	13.57***
VT × FTC	7.43***	2.91*	2.91*	4.69***
SMC × FTC	22.21***	3.84**	8.71***	14.99***
VT × SMC × FTC	4.55***	2.47**	1.53	2.53**

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

Fig. 1 Effects of soil moisture content and number of freeze-thaw cycles on aggregate distribution and mean weight diameter (MWD) for the three vegetation types. Lowercase letters indicate significant differences between FTCs within an aggregate class size and vegetation pattern. Greek letters indicate significant differences between different vegetation types under same soil moisture conditions. Uppercase letters indicate significant differences between soil moisture contents. FC, field capacity; FTC, freeze-thaw cycles

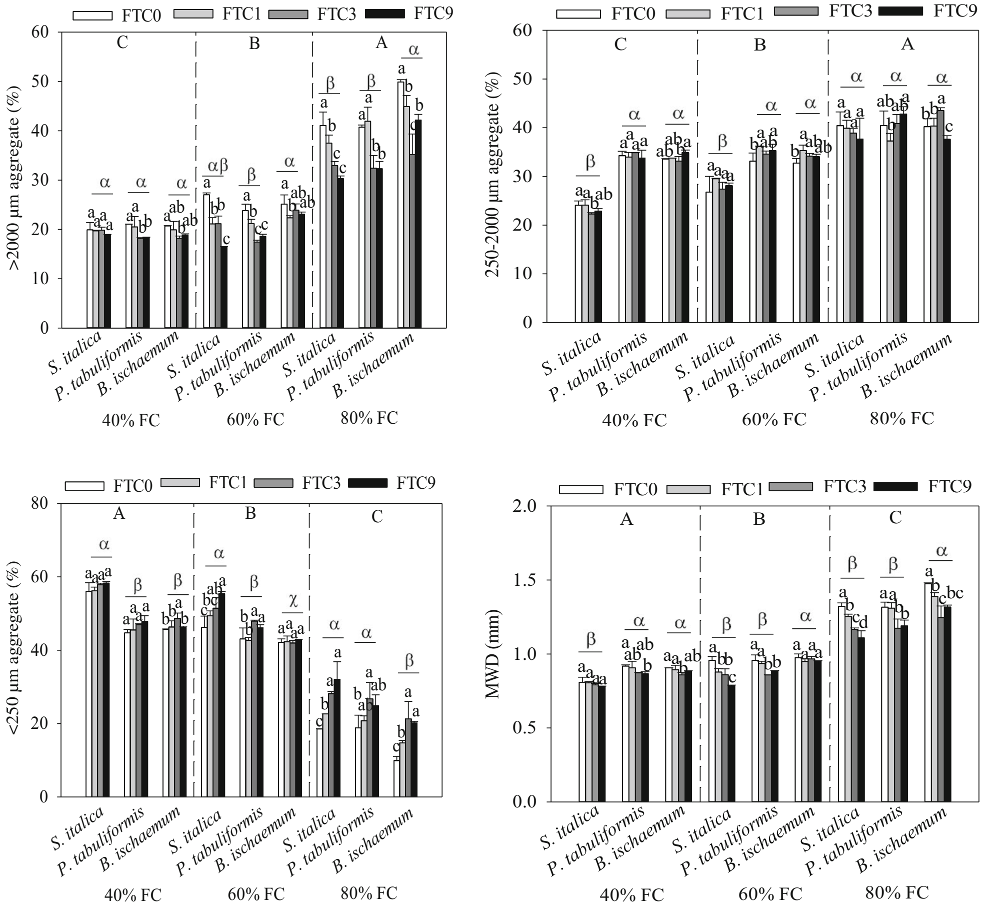

Fig. 2 Effect of number of freeze-thaw cycles on mean weight diameter (MWD) for the *S. italica* (**a**), *P. tabuliformis* (**b**), and *B. ischaemum* (**c**) soil. FC, field capacity; FTC, freeze-thaw cycles

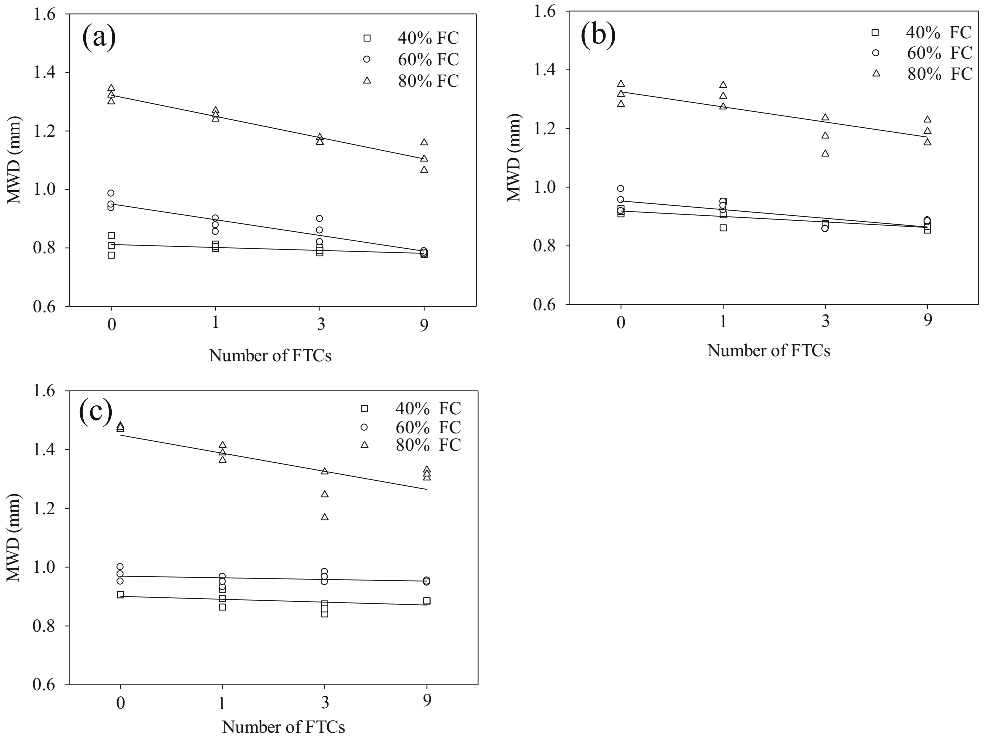

Table 3 Linear regression equations and coefficients of determination (R) between the number of freeze-thaw cycles and mean weight diameter (MWD) for the three vegetation types

Soil moisture content	*S. italica*			*P. tabuliformis*			*B. ischaemum*		
	Linear regression equation	R	P	Linear regression equation	R	P	Linear regression equation	R	P
40% FC	$y = 0.822 - 0.010x$	0.603	*	$y = 0.938 - 0.019x$	0.718	**	$y = 0.910 - 0.010x$	0.486	0.109
60% FC	$y = 1.004 - 0.054x$	0.921	***	$y = 0.983 - 0.030x$	0.773	**	$y = 0.975 - 0.006x$	0.353	0.260
80% FC	$y = 1.395 - 0.073x$	0.961	***	$y = 1.377 - 0.051x$	0.767	**	$y = 1.511 - 0.062x$	0.754	**

FC field capacity

$^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$

B. ischaemum soil on the Loess Plateau, especially after three cycles. These results were consistent with those by Oztas and Fayetorbay (2003), Kværnø and Øygarden (2006), and Song et al. (2017b), who reported that freezing and thawing disrupted the large aggregates, increasing the fraction of small aggregates and decreasing aggregate stability. Our results suggested that FTCs in winter and spring would reduce the resistance to soil erosion in areas under vegetation restoration. More attention should thus be paid to how aggregate stability is altered by freezing and thawing after vegetation restoration in areas with seasonal FTCs.

4.2 Effects of initial SMC on aggregate stability

Initial SMC is the key factor affecting aggregate stability (Li and Fan 2014). The increase in SMC in our study significantly increased aggregate stability before FTCs, likely due mainly to the promotion of soil particle bonding and reunion as SMC increased (Wang et al. 2012; Li and Fan 2014). Aggregate stability is also associated with the method used to aggregate separation (Zeng et al. 2018). Wang et al. (2012) also reported that the SMC of aggregate samples had opposing influences on dry- vs. wet-sieved aggregates and that MWD of dry aggregates increased significantly with SMC.

FTCs are associated with energy transmission in soil (Li et al. 2002; Zhang et al. 2016). The disruptive strength of the FTCs consequently increased significantly with initial SMC. The decreased effects of FTCs on aggregate stability was more pronounced as SMC increased at freezing (Oztas and Fayetorbay 2003; Dagesse 2011). The volume of water inevitably expands during freezing when the water becomes ice, thus increasing the disruption of aggregates, which was likely

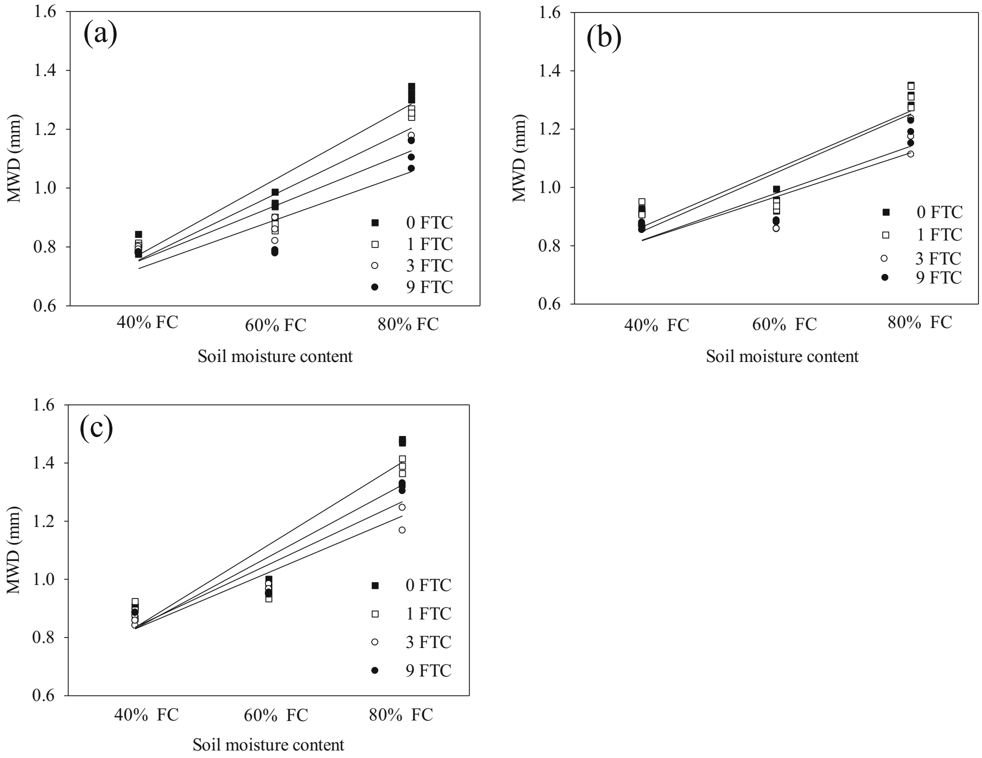

Fig. 3 Effect of initial soil moisture content on mean weight diameter (MWD) for the *S. italica* (**a**), *P. tabuliformis* (**b**), and *B. ischaemum* (**c**) soil. FC, field capacity; FTC, freeze-thaw cycles

Table 4 Linear regression equations and coefficients of determination (*R*) between the initial soil moisture content and mean weight diameter (MWD) for the three vegetation types

Number of FTC	*S. italica*			*P. tabuliformis*			*B. ischaemum*		
	Linear regression equation	*R*	*P*	Linear regression equation	*R*	*P*	Linear regression equation	*R*	*P*
0 FTC	$y = 0.516 + 0.257x$	0.966	***	$y = 0.665 + 0.199x$	0.898	***	$y = 0.550 + 0.285x$	0.916	***
1 FTC	$y = 0.530 + 0.225x$	0.929	***	$y = 0.647 + 0.202x$	0.887	**	$y = 0.583 + 0.248x$	0.909	***
3 FTC	$y = 0.564 + 0.188x$	0.932	***	$y = 0.666 + 0.151x$	0.829	**	$y = 0.634 + 0.194x$	0.944	***
9 FTC	$y = 0.561 + 0.165x$	0.862	**	$y = 0.657 + 0.162x$	0.881	*	$y = 0.620 + 0.216x$	0.928	***

FTC freeze-thaw cycles

$^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$

responsible for the more obvious decrease in aggregate stability under the higher SMCs (Li and Fan 2014). On the other hand, the internal gas of the aggregate seems to be an ideal gas, which increases the combining effect because of shrinkage caused by cooling after freezing (Li and Fan 2014). So, the effect of increased initial SMC on aggregate stability was generally a combined effect of particle bonding and disruption during freezing and thawing. In our study, the combining effect was larger than the disruptive effects of the FTCs, so aggregate stability was higher at 80% FC than at 40% FC, even after FTCs. These results suggested that increased SMC in winter would offset the negative effect on soil aggregate stability and may increase aggregate stability under scenarios of future global warming.

4.3 Effects of different vegetation type to FTCs

Chinese pine forest and natural recovery from abandoned cropland are two typical types of vegetation on the Loess Plateau (Zhu et al. 2017; Xiao et al. 2019b). Vegetation restoration has increased a variety of aggregate binding agents (e.g., soil organic carbon (SOC), microbial biomass carbon (MBC), glomalin-related soil protein (GRSP), and carbohydrates) that can improve aggregate stability (Bedini et al. 2009; Spohn and Giani 2010). Different types of vegetation restoration, such as forest and grassland, have differentially increased SOC, GRSP, and MBC contents (Hu et al. 2010; Deng et al. 2014; Xiao et al. 2016), which would contribute to different responses to FTCs. Changes of SOC, GRSP, and MBC contents during freezing and thawing have been associated with soil microbial activity. FTCs usually lyse microbial cells and thus decrease soil microbial activity (Sorensen et al. 2018; Han et al. 2018a, b). Fungi grow more rapidly than bacteria at low temperatures, so microbial communities are usually dominated by fungi during freezing and thawing (Lipson et al. 2002; Pietikäinen et al. 2005). SOC content is a key factor for the rapid recovery of microbial communities from the stress of freezing and thawing (Han et al. 2018a). The higher SOC content in *B. ischaemum* soil may contribute to the better adjustment of microbial communities, especially fungi communities, to freeze-thaw conditions, and more GRSP would likely contribute to soil aggregation, which may have caused the slight increase in aggregate stability after nine FTCs in *B. ischaemum* soil in our study. Xiao et al. (2019b) found that winter freezing and thawing in a field experiment decreased aggregate stability more in a pine forest than in a nature-succession grassland. The results of our study generally indicated that abandoning cropland for grassland succession was more beneficial than Chinese pine forest plantation for resisting the effects of FTCs on the Loess Plateau. More researches should be conducted to evaluate the changes of various aggregate binding agents to better explain the mechanisms of soil aggregation under seasonal freeze-thaw conditions.

It should be noted that the results based on sieved and mixed soils may not better reflect the soil aggregate variation under FTCs compared to those based on undisturbed soils. Considering the high heterogeneity feature of soil, we used disturbed soil samples to provide a uniform start point to evaluate the aggregate stability variation caused by FTCs. But due to the homogenization of soils, it changed the soil structure that might be significantly different to the field conditions. Future researches should be conducted in the field to further evaluate the variations of soil aggregate variations during winter-spring season in seasonal freeze-thaw areas.

5 Conclusions

Global climatic warming is affecting the freezing and thawing of soil, which will substantially alter soil structure under different types of vegetation restoration in areas with seasonal freezing and thawing. We found that increased initial SMC significantly increased aggregate stability by binding soil particles and that FTCs disrupted soil aggregates, which increased with SMC. The effects of particle bonding were larger than the disruptive effects, so aggregate stability increased with increasing SMC. The structure of the natural grassland soil was less sensitive to FTCs than the structure of the Chinese pine forest soil. The results from this study indicated that natural succession grassland may be more suitable than Chinese pine forest for vegetation restoration in areas with seasonal freezing and thawing and that higher initial SMCs might increase aggregate stability under conditions of global warming in the future.

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