Chin. Geogra. Sci. 2021 Vol. 31 No. 2 pp. 234−247
https://doi.org/10.1007/s11769-021-1187-7

Springer Science Press
www.springerlink.com/content/1002-0063

Influences of Seasonal Freezing and Thawing on Soil Water-stable Aggregates in Orchard in High Cold Region, Northeast China

LIANG Yunjiang[1], DENG Xu[1], SONG Tao[1], CHEN Guoshuang[2], WANG Yuemei[1], ZHANG Qing[1], LU Xinrui[2]

(1. *College of Agriculture*, *Yanbian University*, *Yanji* 133002, *China*; 2. *Northeast Institute of Geography and Agroecology*, *Chinese Academy of Sciences*, *Changchun* 130012, *China*)

Abstract: Soil aggregate stability, as an important indicator of soil functions, may be affected by seasonal freezing and thawing (SFT) and land use in high cold and wet regions. Therefore, comprehensive understanding the effects of SFT on aggregate stability in orchards during winter and spring is crucial to develop appropriate management strategies that can effectively alleviate the degradation of soil quality to ensure sustainable development of orchard ecosystems. To determine the mechanism of degradation in orchard soil quality, the effects of SFT on the stability of water-stable aggregates were examined in apple-pear orchards (*Pyrus ussuriensis* var. *ovoidea*) of four different ages (11, 25, 40, and 63 yr) on 0 to 5% slopes before freezing and after thawing from October 2015 to June 2016 in Longjing City, Yanbian Prefecture, Northeast China, involving a comparison of planted versus adjacent uncultivated lands (control). Soil samples were collected to investigate water-stable aggregate stability in three incremental soil layers (0–20, 20–40 and 40–60 cm). In the same samples, iron oxide, organic matter, and clay contents of the soil were also determined. Results showed that the destructive influences of SFT on water-stable aggregates were more pronounced with the increased orchards ages, and SFT exerted severe effects on water-stable aggregates of older orchards (40 and 63 yr) than juvenile orchards. Undergoing SFT, the soil instability index and the percentage of aggregate destruction increased by mean 0.15 mm and 1.86%, the degree of aggregation decreased by mean 1.32%, and the erosion resistance weakened, which consequently led to aggregate stability decreased. In addition, soil free, amorphous, and crystalline iron oxide as well as soil organic matter and clay contents are all important factors affecting the stability of water-stable aggregates, and their changes in their contents were consistent with those in the stability of water-stable aggregates. The results of this study suggest that long-term planting fruit trees can exacerbate the damaging effects of SFT on aggregate stability and further soil erosion increases and nutrient losses in an orchard, which hider sustainable use of soil and the productivity orchards.

Keywords: water-stable aggregates; orchard age; apple-pear orchard; soil seasonal freezing and thawing; soil degradation; high cold region

Citation: LIANG Yunjiang, DENG Xu, SONG Tao, CHEN Guoshuang, WANG Yuemei, ZHANG Qing, LU Xinrui, 2021. Influences of Seasonal Freezing and Thawing on Soil Water-stable Aggregates in Orchard in High Cold Region, Northeast China. *Chinese Geographical Science*, 31(2): 234−247. https://doi.org/10.1007/s11769-021-1187-7

1 Introduction

Soil aggregates are complex structural units of soil structure whose stability and size distribution within the soil matrix substantially affect physical, chemical, and biological environments within and among agroecosystems (Jakšík et al., 2015; Lehmann and Kleber, 2015), such as affecting soil water transport and retention (Zeng et al., 2018), nutrient cycling (Steinweg et al., 2008), microbial assemblages (Rillig et al., 2017), and

---

Received date: 2020-05-20; accepted date: 2020-08-31
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 31460117, 41877024)
Corresponding author: LU Xinrui. E-mail: luxinrui@iga.ac.cn

protection against soil loss by erosion (Moreno-de las Heras, 2009), among others. Thus, aggregate stability is a critical indicator of soil quality. To propose an appropriate land use or restoration method for degraded soils, how aggregates affect these processes or lead to changes in some basic soil properties needs to be explained and quantified. Seasonal freezing and thawing (SFT) are a constantly repeating process of material exchange and energy transfer that occurs in the surface soil and also extends downward into deeper soil layers (Musa et al., 2016). Therefore, SFT can strongly affect the arrangement and bonding of soil particles (Cheng et al., 2014; Gruber, 2020). Ongoing global warming is thinning the snowpack, increasing initial soil moisture content, and increasing the frequency and intensity of freezing and thawing during winter and spring, especially in temperate regions (Gray, 2007; Xiao et al., 2020), which likely influence soil structure and aggregation. Therefore, it is essential to evaluate the effects of freeze-cycles on water stable aggregates under scenarios of global warming.

Freezing and thawing, commonly occurs in regions that have seasonally frozen soils, is a potent disintegrating force for soil aggregates which contributes substantially to the breakdown of macroaggregates and increasing percentages of microaggregates (e.g., Edwards, 2013; Chai et al., 2014). Therefore, how soil aggregate stability is influenced by SFT has received increased attention (e.g., Li et al., 2020; Xiao et al., 2020). In most studies, SFT decreases the fraction of large aggregates and increases the fractions of small aggregates, thereby decreases aggregate stability, leading to fragmentation and loosening of aggregates, (e.g., Oztas and Fayetorbay, 2003; Henry, 2007; Song et al., 2017). By contrast, in other studies, SFT strengthens particle bonding, which generally increases aggregate stability from disruption to reconstruction (Edwards, 2013; Zhang et al., 2016). These contradictory results might be attributed to freeze-thaw conditions (e.g., the freezing temperatures and the number of soil freeze-thaw events) (Oztas and Fayetorbay, 2003; Kværnø and Øygarden, 2006; Li et al., 2020), the soil type (e.g., Dagesse, 2013), the method used to describe aggregate stability (Wang et al., 2014a; Zeng et al., 2018), or the initial soil water content (Li et al., 2020), as well as aggregate size, clay, soil organic matter, and iron oxide contents, among others. Aggregate formation and stability are not only affected by particle compositions and changes in the soil environment but are also affected by aggregate-binding agents such as soil organic carbon, iron oxides, clay, and carbonates (Shi et al., 2015). Clay, soil oxides, and soil organic carbon are positively related to aggregate stability, and all act as aggregating factors in soils (e.g., Xu et al., 2012; Dagesse, 2013). Iron oxides have large total surface area, and react with clay particles, resulting in the determinative binding effect in microaggregates (e.g., Sumner, 1992; Zhang and Horn, 2001).

Seasonally frozen soils are primarily located in northern latitudes above 30° and are widely distributed worldwide (Li et al., 2012). The Longjing City of Yanbian Prefecture in Northeast China, is typical of such regions suffering long and cold winters. Freeze events occur in mid-November and thawing occurs at the end of May in the following year. Thus, there are seasonal cycles of freezing and thawing, which can strongly influence soil aggregate formation and stability. Apple-pear (*Pyrus ussuriensis* var. *ovoidea*) orchards in the study area has been identified as one of the best ‘eugenic’ apple-pear production bases in China (Jin, 2013) because of the unique cold and wet climate as well as eco-environmental conditions. The orchards are an important source of cash income for local farmers, which is important in the development of modern agriculture in Yanbian (Shang and Quan, 2016). However, the orchards, special land use in high cold regions, are established on a sloping (~5%) terrain and are facing the problems of soil quality degradation and nutrient losses because of inappropriate high application amounts of inorganic fertilizers, tillage, steep slopes, orchard age, and concentrated rainfall between July and September. It is worth noting that with an increase of orchard age, the quality of orchard soils degraded, thus obviously aged, fruit yield and quality declined in aging trees. These problems restrict the sustainable development of apple-pear production and the apple-pear industry.

Aggregate size and stability can affect the transfer of essential nutrients, liquids, and gases in soil, which is crucial for crop production and agroecosystem health (Tisdall and Oades, 1982; Lal, 1991; Askari et al., 2015; Rabot et al., 2018). Orchards have high requirements for macro- and micronutrients and their uptake efficiency is influenced by soil structure (Von Bennewitz et al., 2015). Increasing numbers of studies have found that the freeze-thaw cycles caused by global climate change are affecting the dynamics of aggregate stability and possibly affect plant growth during the next growing season (Song et al., 2017; Xiao et al., 2020). Although these effects should not be ignored, little information is available on how SFT affects the stability of water-stable aggregates in orchards of different ages in high cold regions. In addition, little is known about the mechanism responsible for the aggregate breakdown with SFT that leads to changes in aggregate stability. Therefore, in the long-term cultivation of apple-pear, the effects of SFT on soil aggregates need to be investigated in order to promote sustainable development of the regional orchard industry.

Therefore, to investigate the effects of SFT on aggregate stability in orchards in high cold regions, Northeast China, the following questions were addressed in this study: 1) Does SFT influence the stability of water-stable aggregate in apple-pear orchard, and if so, do they do so differently in orchards of different productive ages compared to an adjacent uncultivated land of the same soil types? and 2) Does SFT affect the aggregate-associated factors in apple-pear orchards? The results of this study are expected to provide reference data to promote the sustainable development of the fruit industry and to improve soil quality and health of orchards in high cold regions.

2 Materials and Methods

2.1 Study area

Yanbian Prefecture in Northeast China is the major apple-pear (*Pyrus ussuriensis var ovoidea*) producing area in China. The apple-pear orchards in the study were part of the Hualong Fruit Tree Farm, Longjing City, Yanbian, China (42°21′N to 43°24′N, 128°54′E to 129°48′E). The farm has a long history of apple-pear planting. These orchards were situated on the Hosoda Plain at an altitude of 280 m and with slopes that ranged from 0 to 5%. All studied soils were classified as a dark brown soil type (cold leaching soil). The orchards had clean cultivation with fallow between rows, were equipped with no irrigation facilities, and had good management conditions. The apple-pear trees were fertilized annually with urea, diammonium phosphate, and potassium sulfate in the ratio $N : P_2O_5 : K_2O = 1 : 0.50 : 0.04$. The region is characterized by humid and semi-humid continental monsoon climate in the mid-temperate zone with an annual mean temperature of 5.0℃, which varied from −20.9℃ in October 2015 to 23.9℃ in April 2016. The mean annual precipitation is approximately 574 mm, with most falling as snow during winter and as rain between June and August, accounting for 70%–80% of the total. The area is subjected to a distinct seasonal freeze-thaw cycle with freezing beginning at the end of October and thawing occurring in June of the following year. As the ambient temperature fell below 0℃ in late October 2015, soil temperatures decreased accordingly, and the surface soil entered a freeze-thaw cycle because of the changes in day and night ambient temperatures. Then, the soil began to freeze from the topsoil down to the deep layers and entered a frozen state in mid-November, with the ambient temperature continued to decline to the extreme lowest temperatures (−20.0℃). Until the temperature rose above 0℃ in mid-March in 2016, the soil temperature also rose above 0℃, and the upper layers of frozen soil began to thaw, and the soil again entered a freezing and thawing cycle.

2.2 Soil sampling

Soil samples were collected from the test apple-pear orchards before the first soil freeze on October 15–17, 2015, and after thawing in the spring from April 29–May 2, 2016, once soils had thawed. Apple-pear trees growing well in orchards with ages of 11, 25, 40, and 63 yr were randomly selected. Twenty-five sample sites avoiding fertilizing sites were set up according to the five-point sampling method for each planting year and then mixed as one soil sample. At the same time, five sample sites in the adjacent uncultivated land were selected as a control. There were 25 sample sites in total. At each sampling point, after the removal of the litter layer, three undisturbed soil samples were collected from the soil layers at depths of 0–20, 20–40, and 40–60 cm and samples collected and mixed into a composite sample, and 150 soil samples were collected in total. The soil was pre-treated and air-dried for determination of the aggregates and other necessary soil parameters.

2.3 Soil analysis

Water-stable aggregates were determined according to wet-sieving mechanically stable aggregates using a dry-sieving method according to the modified procedure described by Yi. (2009). Briefly, the air-dried soil samples from each aggregate size group were mixed into a subsample of approximately 50 g in a certain proportion that came from the the ratios of the different aggregate fractions classified by dry-sieving. Next, they were placed on the top of a stack of sieves (20 cm diameter) with decreasing meshes (5.00, 3.00, 2.00, 1.00, 0.50 and 0.25 mm) in a bucket immersed in water for wet-sieved in laboratory. The stack was shaken by hand horizontally for 2 min at a speed of 30 times per min. Consequently, all soil samples were sieved into five size fractions of aggregates: < 0.25, 0.25–0.50, 1.00–0.50, 2.00–1.00, 3.00–2.00, 5.00–3.00, and > 5.00 mm. The soil fractions remaining in each sieve were collected and dried at 60℃ for 48 h to a constant weight and the percentage content of aggregates in each particle size fraction was weighed and calculated. The soil structural stability was assessed by computing the mean weight diameter (MWD) of soil aggregates, the percentage of aggregate destruction (PAD), and the degree of aggregation (DOA). The instability index calculated as the difference of the MWD of the dry sieving minus the MWD of the wet sieving, was taken as a characterization of the stability of the aggregates (Barthès and Roose, 2002).

MWD was calculated by (Zhang and Horn, 2001):

$$MWD = \sum W_i \times X_i \tag{1}$$

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

PAD was determined as following (Zhang and Horn, 2001):

$$PAD = \frac{W_\mathrm{a} - W_\mathrm{b}}{W_\mathrm{a}} \times 100\% \tag{2}$$

where W_a is the mass fraction of aggregates > 0.25 mm from wet sieving and W_b is the mass fraction of aggregates > 0.25 mm from dry sieving.

DOA can be used to evaluate particle aggregation in the soil, and is defined

$$DOA = \frac{M_\mathrm{a}}{M_\mathrm{b}} \times 100\% \tag{3}$$

where M_a is the total amount of water-stable aggregates at all sizes > 0.25 mm minus the mass of sand grains < 0.25 mm, and M_b is the total amount of mechanical composition < 0.25 mm (obtained from mechanical composition analysis).

The mechanical composition was determined by the hydrometer method; The free iron oxide content was determined by the dithionite sodium-citrate sodium-bicarbonate method; the amorphous iron oxide content was determined by Tamm method; the organic matter content was determined by the using an oil bath-$K_2Cr_2O_7$ titration method; and the pH was measured by the potentiometric method in laboratory (Lu, 2000). The general soil properties of apple-pear orchards are shown in Table 1.

2.4 Data processing

The paired sample tests were used to detect the significant effects of SFC on soil variables before and after freezing-thawing. The results are presented as the means ±standard error in the figures in this paper. All statistical analyses were performed using SPSS 20.0 for Windows (SPSS Inc., Chicago, IL, USA).

3 Results

3.1 Effects of seasonal freezing and thawing on water-stable aggregates in apple-pear orchards

3.1.1 Instability index

Paired-samples t-tests were performed on the instability index before freezing and after thawing in the three soil layers in the orchards and uncultivated lands (Table 2). In the 0–20 cm layer, the instability index had significant differences ($P < 0.05$) undergoing SFT. however, there were no significant differences in the other soil layers.

The instability indices in different soil layers in orchard of different ages before freezing and after thawing are shown in Fig. 1. Undergoing SFT, the instability index increased significantly in the 0–20 cm topsoil layer, except for a small decline in the soils of the 63-year-old orchard and uncultivated area. Notably, the largest variations in the instability index were in the uncultivated land, and the index was significantly higher than those of the orchard soils ($P < 0.05$). Most importantly, there were significant differences before soil freezing and after thawing in the 11- and 25-year-old orchards and the uncultivated land ($P < 0.05$). In 20–40 cm layer, the soil instability index of the 25-year-old orchard decreased, but the index increased to different degrees in the orchards of other ages. In 40–60 cm layer, the index generally increased after SFT, except in the 25-year-old orchard. However, the increases at this depth were not as large as those in the 20–40 cm depth. None of the changes were significant ($P > 0.05$).

Table 1 General soil properties in the apple-pear orchard of Longjing City, Northeast China

Land uses	Planting years / yr	Soil layers / cm	Particle size distribution			pH	Organic matter / (g/kg)	Total N / (g/kg)	Total P / (g/kg)	Total K / (g/kg)
			2–0.02 mm / %	0.02–0.002 mm / %	<0.002 mm / %					
Apple-pear orchards	11	0–20	37.15	24.51	5.69	5.69	24.51	1.90	17.89	0.18
		20–40	37.86	21.17	6.13	6.13	21.17	0.99	19.09	0.13
		40–60	38.90	21.68	6.38	6.38	21.68	1.10	19.71	0.11
	25	0–20	40.35	25.21	5.01	5.01	25.21	1.45	24.59	0.33
		20–40	37.83	22.43	5.17	5.17	22.43	1.22	25.91	0.15
		40–60	35.95	22.74	5.73	5.73	22.74	1.19	25.52	0.10
	40	0–20	37.93	24.57	5.12	5.12	24.57	2.18	17.88	0.35
		20–40	36.51	20.72	5.15	5.15	20.72	2.01	18.92	0.22
		40–60	35.99	20.58	5.05	5.05	20.58	1.92	18.13	0.16
	63	0–20	41.90	20.55	5.50	5.50	20.55	2.18	20.02	0.23
		20–40	42.67	19.86	5.01	5.01	19.86	1.47	20.08	0.19
		40–60	39.89	18.98	5.48	5.48	18.98	1.20	19.26	0.16
Uncultivated land	—	0–20	46.98	23.50	5.85	5.85	23.50	1.95	20.61	0.17
		20–40	44.82	22.23	5.64	5.64	22.23	1.53	21.47	0.13
		40–60	45.41	20.91	6.11	6.11	20.91	1.38	20.27	0.11

Table 2 Paired samples test result (P value) for the instability index undergoing freezing and thawing in the apple-pear orchard in Longjing City, Northeast China

Soil layers /cm	The instability index	Organic matter	PAD	DOA	Free iron oxide	Amorphous iron oxide	Crystalline iron oxide	Clay content
0–20	0.042^{*}	0.000^{**}	0.116^{ns}	0.409	0.114^{ns}	0.116^{ns}	0.310^{ns}	0.002^{*}
20–40	0.513^{ns}	0.000^{**}	0.512^{ns}	0.540	0.533^{ns}	0.512^{ns}	0.358^{ns}	0.213^{ns}
40–60	0.065^{ns}	0.000^{**}	0.024^{*}	0.356	0.027*	0.024*	0.061^{ns}	0.893^{ns}

Note: PAD, the percentage of aggregate destruction; DOA, the degree of aggregation; *, a significant difference at $P < 0.05$; **, a very significant difference at $P < 0.01$; ns, no significant difference

The instability index in the uncultivated land was higher than that in the orchard soils in all soil layers, indicating that the stability of orchard soils was better than that of uncultivated land. In the 20–40 cm and 40–60 cm layers, the index in the 25-year-old orchard decreased slightly after freezing and thawing, whereas it increased by varying degrees in the other aging orchards, with the largest increase in the 63-year-old orchard. As expected, SFT had a greater effect on older orchards than that on younger orchards, indicating that the structure of water-stable aggregates declined more in elder orchards. The lower soil layers were more affected by freezing and thawing than the top soil layer. In addition, in the two seasons, the same trend was observed in all orchards. The variable amplitude decreased with increasing soil depth.

3.1.2 Percentage of aggregate destruction

The PAD in orchards against planting years before freezing and after thawing is shown in Fig. 2. According to paired-samples t-tests (Table 2), there were no significant differences in the PAD before freezing and after thawing in the three soil layers between the orchards and uncultivated lands ($P > 0.05$).

Undergoing SFT, the PAD values in 0–20 cm layer decreased in the 11- and 25-year-old orchards, but increased in the 40- and 63-year-old orchards and the uncultivated land. The PAD values were most variable in the 11-year-old orchard, and there was a significant difference in the PAD in the 63-year-old orchard ($P < 0.05$, Fig. 2). In 20–40 cm layer, the PAD values decreased in the 11- and 25-year-old orchards, but increased significantly in the other orchard ages. The PAD was the largest

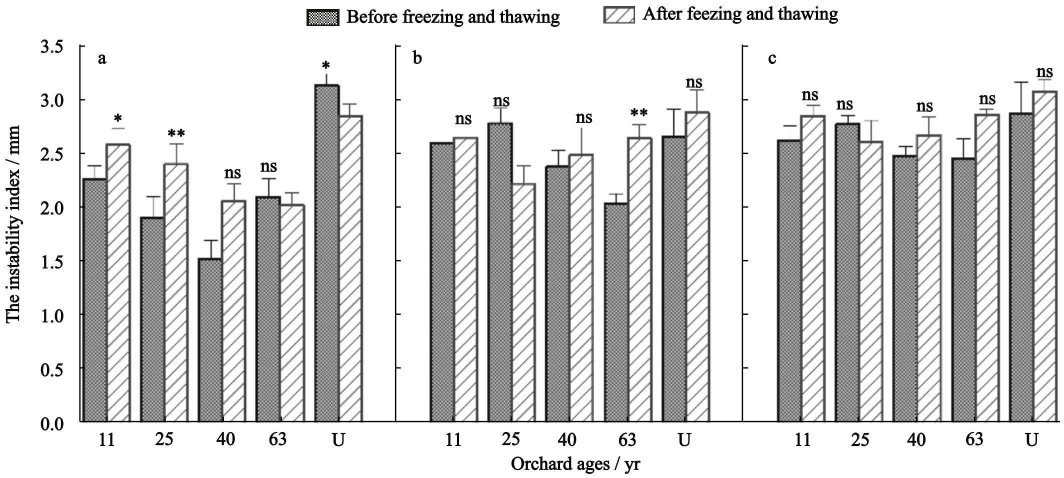

Fig. 1 The instability index against the orchard ages for the before soil freezing and after thawing situations in the (a) 0–20, (b) 20–40, and (c) 40–60 cm depth in apple-pear orchard in Longjing City, Northeast China; *, a significant difference at $P < 0.05$; **, a very significant difference at $P < 0.01$; ns, no significant difference; U, uncultivated land

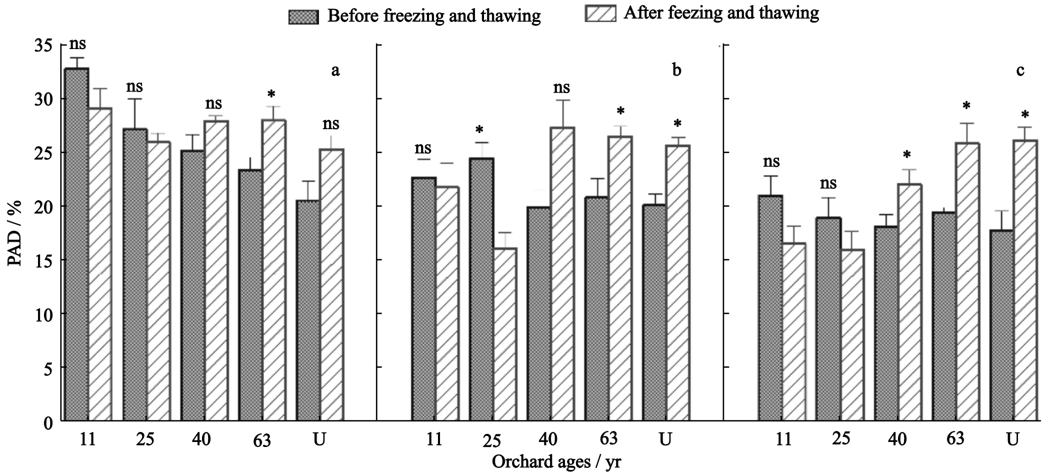

Fig. 2 The percentage of aggregate destruction (PAD) against the planting years in responses to seasonal freezing and thawing in the (a) 0–20, (b) 20–40, and (c) 40–60 cm depth in apple-pear orchard in Longjing City, Northeast China; * indicates a significant difference between treatments ($P < 0.05$), ** indicates a very significant difference ($P < 0.01$), ns indicates no significant difference; U, uncultivated land

and increased by 7.37% in the 40-year-old orchard, followed by the 63-year-old orchard, in which the PAD increased by 5.64%. The PAD was significantly different in the uncultivated land, 25- and 63-year-old orchards ($P < 0.05$) before freezing and after thawing. In 40–60 cm layer, the trend in the PAD before freezing and after thawing was consistent with that in the other two soil layers.

The maximum PAD value in the three soil layers was 32.88%. The PAD values in the 11- and 25-year-old orchards decreased undergoing SFT, but they increased in the other orchard ages, which showed that SFT had a greater destructive effect on water-stable aggregates in the older orchards than that in the younger orchards. After freezing and thawing, the PAD values in uncultivated land increased by 4.72%, 5.53%, and 8.39% in 0–20 cm, 20–40 cm and 40–60 cm soil depth, respectively, which had a larger increase than those in the orchard soils. Thus, the decline in the stability of water-stable aggregates was more substantial in the uncultivated land than in the orchard soils. Furthermore, the amplitude of PAD changes gradually increased with depth.

3.1.3 Degree of aggregation

The DOA was plotted against the orchard ages in different soil layers undergoing SFT (Fig. 3). According to

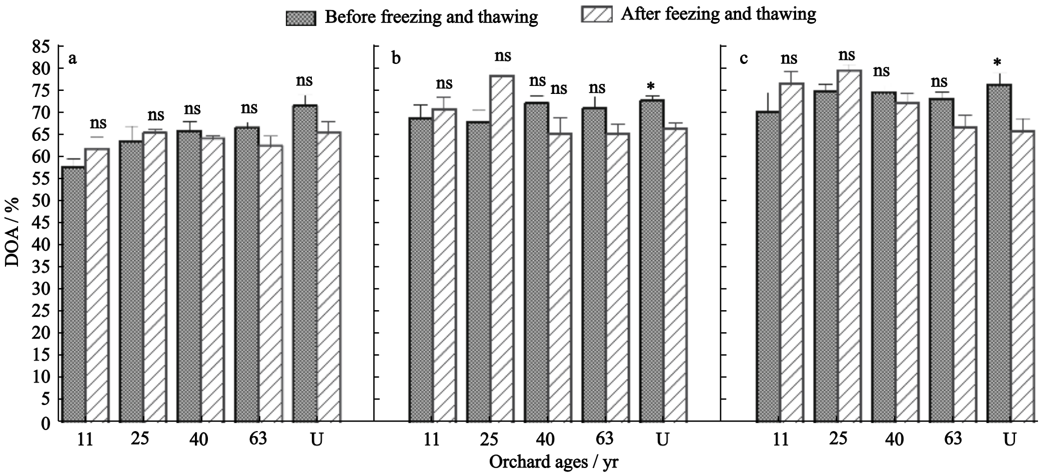

Fig. 3 Degree of aggregation (DOA) against the orchard ages for the before soil freezing and after thawing situations in the (a) 0–20, (b) 20–40, and (c) 40–60 cm depth in apple-pear orchard in Longjing City, Northeast China; * indicates a significant difference between treatments ($P < 0.05$), ** indicates a very significant difference ($P < 0.01$), ns indicates no significant difference; U, uncultivated land

paired-samples tests, there were no significant differences in the DOA before freezing and after thawing in the three soil layers in the orchards and uncultivated land ($P > 0.05$, Table 2).

As shown in Fig. 3, after SFT, in 0–20 cm topsoil layer, the DOA declined to different degrees, except for some slight increases in the 11- and 25-year-old orchards. The greatest DOA occurred in uncultivated land, but none of the differences with orchards ages were significant; In 20 –40 cm layer, small changes occurred in DOA between the two seasons, but no differences in the orchard soils were significant ($P < 0.05$). However, the change in DOA in the uncultivated land was significant ($P < 0.05$). The DOA in all soils exceeded 58%, with the highest values in the 25-year-old orchard in the spring of 2016 where DOA reached as high as 78.63%. The DOA in the three soil depths of 11-year-old and 25-year-old orchards increased, with a maximum increase of 10.6% in the latter. In the uncultivated soil and orchards of other ages, the DOA declined by 5.75% to 6.78%. In 40–60 cm layer in the uncultivated land, the DOA decreased significantly undergoing SFT ($P < 0.05$), and the decrease was the largest, reaching 10.42%. In addition, at this depth, no significant changes in DOA before freezing and after thawing were detected in orchard soils ($P > 0.05$).

Overall, the DOA in the three soil layers ranged from 58.06% to 79.80%. A similar trend in the DOA was observed in the different soil layers with the increase in orchard age, which all showed that the DOA increased after SFT in the 11- and 25-year-old orchards but decreased in the older orchards. In the uncultivated land, the DOA declined more sharply in comparison with that observed in the orchard soils. In addition, the change in DOA gradually increased with increasing soil depth.

3.2 Changes in aggregate-associated factors under seasonal freezing and thawing

3.2.1 Free iron oxide

Fig. 4 provides a comparison of the free iron oxide content in the different layers of orchard soils before freezing with that after thawing. According to paired-samples tests on the free iron oxide content in the three soil layers in the orchards and uncultivated land (Table 2), in 40–60 cm layer, the free iron oxide content was significantly different ($P < 0.05$) before freezing and thawing, whereas there were no significant differences in the other soil layers.

As shown in Fig. 4, in 0–20 cm topsoil layer, the free iron oxide content decreased by different degrees in the orchards of different ages, with an exception in the 25-year-old orchard in which the free iron oxide content increased undergoing SFT, which indicated that the older the orchard were, the larger free iron oxide decrease. For example, in the 63-year-old orchard the free iron oxide content decreased significantly ($P < 0.05$), decreasing by 3.29 g/kg. In 20–40 cm and 40–60 cm depths, the free iron oxide content followed a similar pattern in the different aged orchards undergoing SFT. Specifically, SFT significantly changed the free iron oxide content ($P = 0.001$). The largest decrease in the free iron oxide content was found in 40–60 cm layer of the

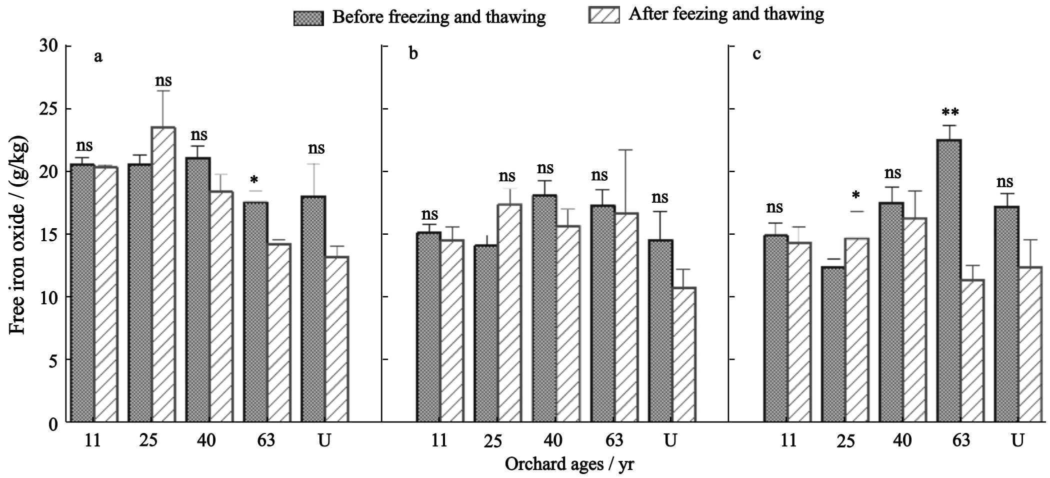

Fig. 4 Free iron oxide against the orchard ages for the before soil freezing and after thawing situations in the (a) 0–20, (b) 20–40, and (c) 40–60 cm depth in apple-pear orchard in Longjing City, Northeast China; * indicates a significant difference between treatments ($P <$ 0.05), ** indicates a very significant difference ($P < 0.01$), ns indicates no significant difference; U, uncultivated land

63-year-old orchard, with a decrease of 11.13 g/kg. In addition, the free iron oxide content in soil at this depth in the 25-year-old orchard was also significantly different ($P < 0.05$) undergoing SFT. In the uncultivated land, the free iron oxide content also decreased in each soil layer after freezing and thawing.

Overall, SFT had a greater effect on the free iron oxide content in the older orchards than in the younger orchards, which had sharper declines. A decrease in the free iron oxide content was not conducive to the formation of water-stable aggregates. Furthermore, the declines in free iron oxide content increased with increasing soil depth. These results suggested that SFT substantially influenced the free iron oxide content in the deep soil layers of the older orchards. These changes were consistent with those in the instability index, which indicated that the changes in soil free iron oxide might explain the changes in water-stable aggregates.

3.2.2 *Amorphous iron oxide*

The amorphous iron oxide content was plotted against orchard ages in the different soil layers undergoing SFT (Fig. 5). According to the paired-samples tests on the amorphous iron oxide content in the three soil layers in the orchards and uncultivated land (Table 2), there were no significant differences in the three soil layers before freezing and after thawing ($P > 0.05$).

As indicated in Fig. 5, in 0–20 cm layer, SFT increased the amorphous iron oxide content in the 11-and

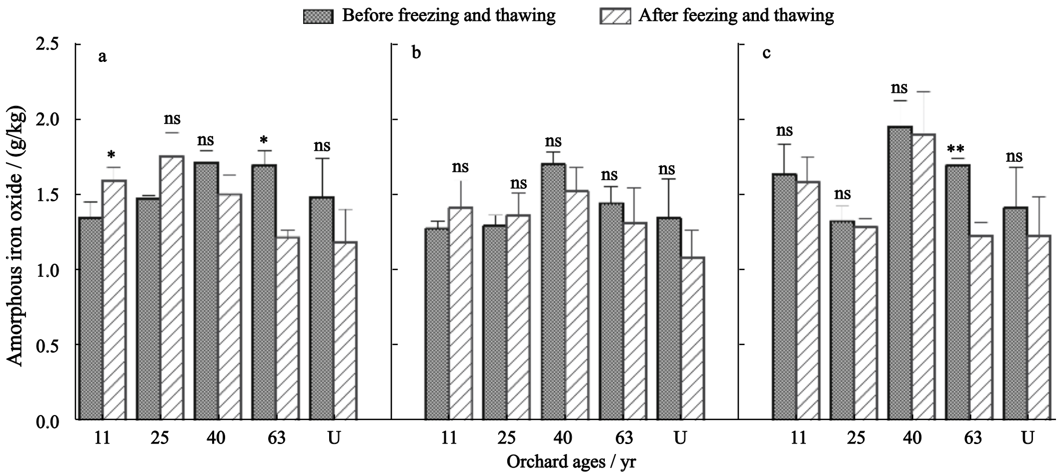

Fig. 5 Amorphous iron oxide against the orchard ages for the before soil freezing and after thawing situations in the (a) 0–20, (b) 20–40, and (c) 40–60 cm depth in apple-pear orchard in Longjing City, Northeast China; * indicates a significant difference between treatments ($P < 0.05$), ** indicates a very significant difference ($P < 0.01$), ns indicates no significant difference; U, uncultivated land

25-year-old orchard soils, whereas it decreased the amorphous iron oxide content in the other aged orchards and the uncultivated land. The greatest decrease (0.48 g/kg) was in the 63-year-old orchard. Significant differences were found in the 11- and 63-year-old orchards ($P < 0.05$). The change in amorphous iron oxide in 20–40 cm layer was similar to that in the 0 to 20 cm layer. The highest amorphous iron oxide content occurred in the 40-year-old orchard, although no significant differences were found between before freezing and after thawing ($P > 0.05$). In 40–60 cm layer, SFT decreased the amorphous iron oxide content in the orchards of different ages. With increasing orchard age, the decrease was greater, and the effects of SFT on amorphous iron oxide content were highly significant in the 63-year-old orchard ($P = 0.001$). The amorphous iron oxide content in the 40-year-old orchard was significantly higher than that in the orchard ages ($P < 0.05$). The amorphous iron oxide content in soil from the uncultivated control group in each soil layer also decreased after SFT. Additionally, the amorphous iron oxide content also declined undergoing SFT.

Overall, SFT led to slight increases in the amorphous iron oxide content in the 11-and 25-year-old orchards but to decreases in orchards of the other ages. However, the content decreased in 40–60 cm depth in all orchards.

3.2.3 Crystalline iron oxide

The crystalline iron oxide content was plotted against orchard ages in different soil layers undergoing SFT (Fig. 6). According to the paired-samples tests on crystalline iron oxide content in the three soil layers of the orchard and uncultivated land (Table 2), in 40–60 cm layer, there were significant differences in crystalline iron oxide content before freezing and after thawing ($P < 0.05$), but there were no significant differences in the other soil layers ($P > 0.05$).

In the 0–20 cm topsoil layer, the crystalline iron oxide content decreased in the different orchards, except for an increase in the 25-year-old orchard undergoing SFT, which shows that the older was the orchard, the larger the crystalline iron oxide decrease (Fig. 6). Specifically, SFT have a significant influence on the crystalline iron oxide content in the 63-year-old orchard, with a decrease of 2.82 g/kg ($P < 0.05$). In 20–40 cm layer, the crystalline iron oxide content followed a similar trend to that in the 0 to 20 cm layer, with significant effects of SFT on it in the 25-year-old orchard ($P < 0.05$). In 40–60 cm layer, SFT significantly decreased the content in the 63-year-old orchard, which had the lowest value of 10.66 g/kg ($P = 0.002$). Additionally, SFT significantly decreased the crystalline iron oxide content in the 35-year-old orchard ($P < 0.05$).

3.2.4 Organic matter content

Across all soil depths in the orchards and uncultivated lands, SFT had a highly significant effect on organic matter content ($P < 0.01$, Table 2).

SFT significantly decreased the organic matter content, with the trend being 25 yr > 11 yr > 40 yr > 63 yr (Fig. 7). The differences were highly significant in the 11- and 25-year-old orchards ($P < 0.01$), with a substan-

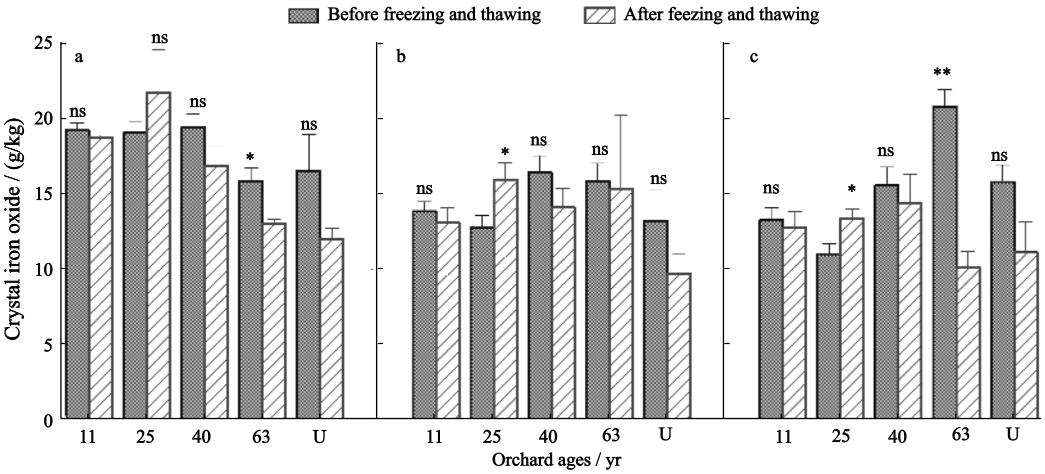

Fig. 6 Crystal iron oxide against the orchard ages for the before soil freezing and after thawing situations in the (a) 0–20, (b) 20–40, and (c) 40–60 cm depth in apple-pear orchard in Longjing City, Northeast China; * indicates a significant difference between treatments ($P < 0.05$), ** indicates a very significant difference ($P < 0.01$), ns indicates no significant difference; U, uncultivated land

tial decline in the 25-year-old orchard. There was also a decrease of 2.30 g/kg in the uncultivated land after thawing. In the 20–40 cm layer, the same trend was observed in the 25-year-old orchard, which had the most obvious decline (5.53 g/kg). In addition, some significant differences were detected between before freezing and after thawing in the 11-, 25-, and 40-year-old orchards, as well as in the uncultivated soil ($P < 0.05$). In the 40–60 cm layer, the organic matter content decreased with increasing orchard ages, with decreases of 4.16 g/kg, 5.45 g/kg, 2.56 g/kg, and 1.35 g/kg, respectively. In the uncultivated land, the organic matter content decreased by 2.96 g/kg. At this depth, SFT significantly affected the organic matter content ($P < 0.05$) across orchards and in the uncultivated soil, except in the 63-year-old orchard.

3.2.5 Clay content

According to paired-samples tests on clay content in the three soil layers in the orchards and uncultivated land (Table 2), in the 0–20 cm layer, clay content was significantly different ($P < 0.01$) undergoing SFT, but there were no significant differences in the other soil layers ($P > 0.05$).

As shown in Fig. 8, the clay contents were significantly lower after thawing than those before freezing in the 0–20 cm layer in orchards, which had declines of 1.73%, 3.34%, 3.92%, and 1.05%, respectively, with increasing orchards age. The largest decrease occurred in the 40-year-old orchard, but no differences were significant ($P > 0.05$). In the 2–40 cm and 40–60 cm layers, the clay content decreased across all orchards undergoing SFT, except for an increase in the 25-year-old orchard under SFT. There was a significant increase in the clay content in the 20–60 cm layer in the 25-year-old orchard ($P < 0.05$). The 63-year-old orchard had the smallest change in clay content, and the uncultivated land had some declines in clay content across all soil layers undergoing SFT. These results suggest that the agglomeration by clay particles generally decreased, and therefore, the cementing effect of clay was weakened after SFT.

4 Discussion

In this study, the effects of SFT on the stability of water-stable aggregates as well as the factors that influence aggregate stability were investigated in the soils of apple-pear orchards of different ages in Northeast China. Subjected to SFT, the instability index of water-stable aggregates in the orchards increased to different extents (Fig. 1), indicating that the structural stability of the soil decreased and the quality of the water-stable aggregates deteriorated. These results were in accordance with those of Dagesse (2013), who reported that although freezing improved aggregate stability, the addition of a thaw component following freezing, was responsible for degradation of aggregate stability. More recently, Li et al. (2020) found that freeze-thaw cycles significantly reduced aggregate stability by disrupting large aggregates, thereby increasing the fraction of small aggregates in a

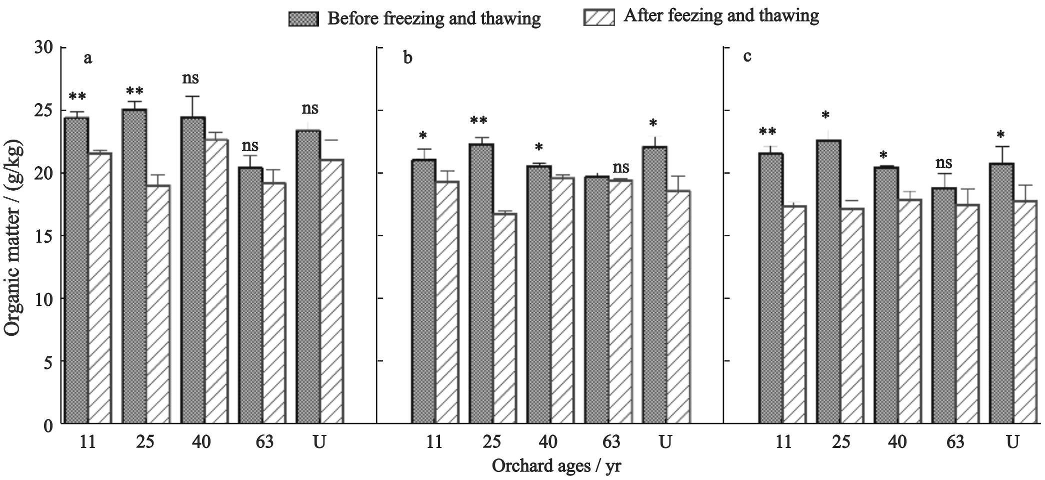

Fig. 7 The soil organic matter against the orchard ages for the before soil freezing and after thawing situations in the (a) 0–20, (b) 20–40, and (c) 40–60 cm depth in apple-pear orchard in Longjing City, Northeast China; * indicates a significant difference between treatments ($P < 0.05$), ** indicates a very significant difference ($P < 0.01$), ns indicates no significant difference; U, uncultivated land

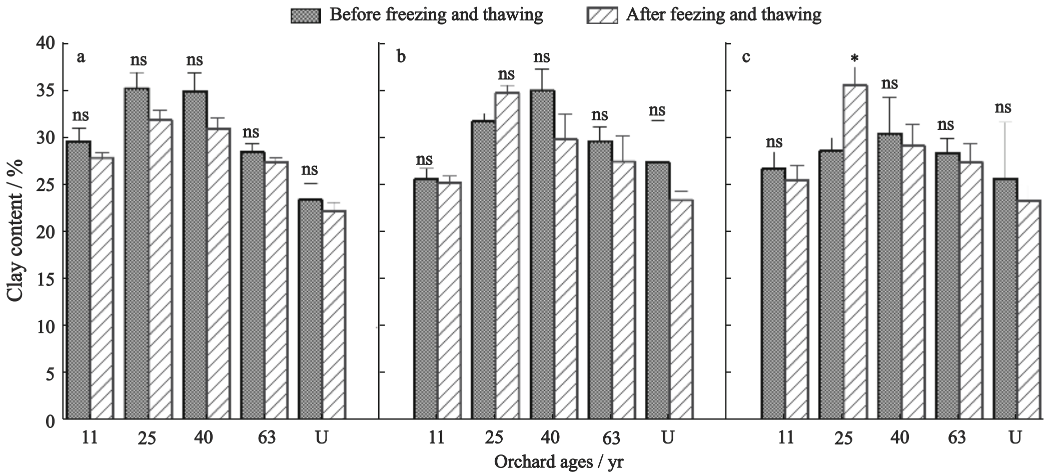

Fig. 8 Clay content against the planting years in responses to seasonal freezing and thawing situations in the (a) 0–20, (b) 20–40, and (c) 40–60 cm depth in apple-pear orchard in Longjing City, Northeast China; * indicates a significant difference between treatments ($P < 0.05$), ** indicates a very significant difference ($P < 0.01$), ns indicates no significant difference; U, uncultivated land

Chinese pine forest soil. However, these results apparently contradict the conclusions of Edwards (2013) and Zhang et al. (2016) who concluded that SFT increased aggregate stability by strengthening particle bonding. These disparities indicated that freeze-thaw process might not be the primary control on aggregate stability, and instead, the stability is controlled by the combined effects of a variety of soil and environmental factors, such as vegetation type and initial soil water content. The method used to determine stability may also contribute to the disparities. Furthermore, the DOA increased in the 11- and 25-year-old orchards but decreased in the older orchards (Fig. 3). The PAD decreased in the 11- and 25-year-old orchards but increased in the older orchards (Fig. 2). The changes in DOA and PAD also showed that SFT had a destructive effect on water-stable aggregates, which gradually deteriorated. Simultaneously, the DOA showed an increase in the 11- and 25-year-old orchards, whereas it decreased in the older orchards (40- and 63-year-old). Collectively, the findings revealed that SFT caused aggregate fragmentation, which get deteriorated with increased age of the orchard, and may be interpreted as the differences by four aspects. Firstly, long-term excessive application of inorganic fertilizer had influenced the stability of soil aggregates (Chivenge et al., 2011). Secondly, soil calcium degradation with increasing orchard age, which resulted in a decrease in the cementing agent of water-stable aggregates (Paradelo et al., 2015). Third, both intermittent snowmelt and the saturated or super-saturated thawed layer increasing the soil water content, and the subsequent greater ice expansion into inter- and intra-aggregate pores helped to the crush aggregates (Kahimba et al., 2008), thus which reduced the stability that identified freeze-thaw cycling as a proximate cause of stimulating overwinter aggregate breakdown. Fourth, some factors contributing to the formation of water-stable aggregates, such as organic matter, clay, and crystalline and free iron oxides decreased by different degrees because of human interference (Zhang et al., 2010; Banwart, 2011). More specifically, the young orchards were greatly influenced by frequent management practices because of the short cultivating period (e.g., tillage, over-fertilization, trampling, retention of pruning residues, and so on), and thus the effects of SFT on water-stable aggregates were not obvious (Hu et al., 2011; Xiao et al., 2016). For example, clean cultivation in apple orchards can destroy soil aggregate stability, which adversely affects soil structure (Zhu et al., 2018). By contrast, in the older orchards, there was less management and tillage, and their larger root systems resulted in leaching loss of active ions, and the translocation and accumulation of iron oxides and clay particles to deep soil layers that led to soil aggregate breakdown (Goebel et al., 2011; Sun et al., 2013). Moreover, the changes in the ranges of indices in uncultivated land were significantly higher than those found in the apple-pear orchards ($P < 0.05$), which indicated that SFT had a greater destructive effect on the stability of water-stable aggregates in uncultivated soil than in orchard soil. Therefore, the results also showed that planting fruit trees increased the stability of water-stable aggregates, which is in agreement with the conclusion of Yang et al. (2020) who showed that the change in the stability of aggregates was mainly caused by the conversion of the uncultivated land to apple orchards in a semiarid loess region. The findings of this study had also been experimentally confirmed by Wang et al. (2014a), indicating that soil aggregation may be variably influenced by diverse plant species under different land uses. Yang et al. (2020) reported that the MWD under apple orchards was significantly ($P < 0.05$) lower than that under ecological plantations in the 0 to 40 cm layer, even lower than that in arable land on China' s Loess Plateau. This behavior might be attributed to soil properties, plant residual inputs, tillage, fruit varieties, orchard age, and so on.

Soil organic matter can significantly affect the resistance of soil aggregates in response to SFT, and the strong resistance to freezing and thawing occurs with the organic matter contents >3% and the clay content >17%, as reported by Lehrsch et al. (1991). In this study, the organic matter content in the apple-pear orchard soil decreased significantly in spring 2016 after thawing, which could explain the decrease in the stability of water-stable aggregates undergoing SFT. However, soil organic matter is not the primary controlling factor of aggregate stabilization during freeze-thaw conditions in a Chinese pine forest soil (Li et al., 2020). The free iron oxide, amorphous iron oxide, and crystalline iron oxide contents in the soils either increased or decreased slightly in the 11-and 25-year-old orchards but decreased in orchards of the other ages after SFT, especially significant in the older orchards ($P < 0.05$). A possible explanation was that freezing and thawing changed the forms of iron oxide, inducing the decrease of the overall iron oxide content, which seemed to prove the results of Wang et al. (2014a; b). They reported that freezing and thawing altered the morphology of iron oxides and decreased the activity in black soil. This is because free iron oxide is an important mineral cement that can strongly bridge, connect, and bond mineral particles, and amorphous iron oxide as 'active iron' has a large surface area that can adsorb different types and quantities of electrical charge (Six et al., 2004; Koopmans et al., 2020). Thus, the decrease in the stability of aggregates caused by soil freezing and thawing could be attributed to the decrease in iron oxides. On the basis of the results of this study, some management practices (e.g., tillage, cover crops, groundcover, organic matter manipulation) should be implemented to protect soil structure from the disruptive effects of freezing and thawing during early spring in orchards, especially in the older orchards. Overall, SFT has a significant effect on orchard soil aggregate, and then significantly affects the accumulation and decomposition of soil organic carbon (Banwart, 2011; Gruber, 2020), thus will have an important effect on sustainable use of soil and the productivity of fruit trees in orchards. In the future, research should be expanded to explore the underlying mechanisms causing the changes in the stability of water-stable aggregates during the freezing and thawing process in order to give recommendations on management practices that alleviate the degradation of the orchards and promote sustainable development of orchard.

5 Conclusions

In this study, the influences of seasonal freezing and thawing on the stability of water-stable aggregates and aggregate-associated factors such as soil organic matter, free, amorphous, and crystalline iron oxide, and clay contents were evaluated in apple-pear orchards in Yanbian Prefecture, Northeast China. Fruit-planting could improve the stability of soil water-stable aggregates, but seasonal freezing and thawing caused the fragmentation of soil aggregates, which deteriorated with the increase of orchard age. After freezing and thawing, the stability of water-stable aggregates decreased, as indicated by the increase in instability index and the percentage of aggregate destruction, the decrease in the degree of aggregation and the erosion resistance. Free, amorphous, and crystalline iron oxides, organic matter, and clay content were important factors that affected the stability of water-stable aggregates. The changes in each of these factors were consistent with those in the stability of water-stable aggregates undergoing seasonal freezing and thawing. Thus, seasonal freezing and thawing can stimulate the destruction of aggregate stability in long-term fruit-planting of high cold regions,which do harm to the sustainable productivity of orchards. The implication of our findings is that as orchards continue to degrade under global warming scenarios, which can attribute significantly to soil freeze-thaw cycles in high cold regions, and long-time planting exacerbate the degradation. In addition, the outcomes presented may strengthen the significance of relieving the destruction of soil freeze-thaw cycles on the orchards to help the conservation or even the improvement of the soil natural capital and can be supportive for the implementation of appropriate managements for fruit-planting industry to ensure the establishment of sustainable fruit tree ecosystems in high cold regions.

References

Askari M S, Cui J F, O'Rourke S M et al., 2015. Evaluation of soil structural quality using VIS-NIR spectra. *Soil and Tillage Research*, 146: 108–117. doi: 10.1016/j.still.2014.03.006

Banwart S, 2011. Save our soils. *Nature*, 474(7350): 151–152. doi: 10.1038/474151a

Lu, R K. Analysis method of soil and agricultural chemistry, 2000. China Agricultural Science and Technology, Beijing, PP 12–288. (in Chinese)

Barthès B, Roose E, 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. *Catena*, 47(2): 133–149. doi: 10.1016/S0341-8162(01)00180-1

Chai Y J, Zeng X B, E S Z et al., 2014. Effects of freeze–thaw on aggregate stability and the organic carbon and nitrogen enrichment ratios in aggregate fractions. *Soil Use and Management*, 30(4): 507–516. doi: 10.1111/sum.12153

Cheng Q, Sun Y, Jones S B et al., 2014. In situ measured and simulated seasonal freeze–thaw cycle: a 2-year comparative study between layered and homogeneous field soil profiles. *Journal of Hydrology*, 519: 1466–1473. doi: 10.1016/j.jhydrol.2014.09.023

Chivenge P, Vanlauwe B, Gentile R et al., 2011. Organic resource quality influences short-term aggregate dynamics and soil organic carbon and nitrogen accumulation. *Soil Biology and Biochemistry*, 43(3): 657–666. doi: 10.1016/j.soilbio.2010.12.002

Dagesse D F, 2013. Freezing cycle effects on water stability of soil aggregates. *Canadian Journal of Soil Science*, 93(4): 473–483. doi: 10.4141/cjss2012-046

Edwards L M, 2013. The effects of soil freeze-thaw on soil aggregate breakdown and concomitant sediment flow in Prince Edward Island: a review. *Canadian Journal of Soil Science*, 93(4): 459–472. doi: 10.4141/cjss2012-059

Goebel M, Hobbie S E, Bulaj B et al., 2011. Decomposition of the finest root branching orders: linking belowground dynamics to fine - root function and structure. *Ecological Monographs*, 81(1): 89–102. doi: 10.1890/09-2390.1

Gray V, 2007. Climate change 2007: the physical science basis summary for policymakers. *Energy & Environment*, 18(3–4): 433–440. doi: 10.1260/095830507781076194

Gruber S, 2020. Ground subsidence and heave over permafrost: hourly time series reveal interannual, seasonal and shorter-term movement caused by freezing, thawing and water movement. *The Cryosphere*, 14(4): 1437–1447. doi: 10.5194/tc-14-1437-2020

Henry H A L, 2007. Soil freeze-thaw cycle experiments: trends, methodological weaknesses and suggested improvements. *Soil Biology and Biochemistry*, 39(5): 977–986. doi: 10.1016/j.soilbio.2006.11.017

Hu W, Shao M A, Han F P et al., 2011. Spatio-temporal variability behavior of land surface soil water content in shrub- and grass-land. *Geoderma*, 162(3–4): 260–272. doi: 10.1016/j.geoderma.2011.02.008

Jakšík O, Kodešová R, Kubiš A et al., 2015. Soil aggregate stability within morphologically diverse areas. *Catena*, 127: 287–299. doi: 10.1016/j.catena.2015.01.010

Jin X Y, 2013. Let fragrance of apple-pear inYanbian floating everywhere. *New Long March*, (2): 62–63.

Kahimba F C, Ranjan R S, Froese J et al., 2008. Cover crop effects on infiltration, soil temperature, and soil moisture distribution in the Canadian prairies. *Applied Engineering in Agriculture*, 24(3): 321–333. doi: 10.13031/2013.24502

Koopmans G F, Hiemstra T, Vaseur C et al., 2020. Use of iron oxide nanoparticles for immobilizing phosphorus *in-situ*: increase in soil reactive surface area and effect on soluble phosphorus. *Science of the Total Environment*, 711: 135220. doi: 10.1016/j.scitotenv.2019.135220

Kværnø S H, Øygarden L, 2006. The influence of freeze-thaw cycles and soil moisture on aggregate stability of three soils in Norway. *Catena*, 67(3): 175–182. doi: 10.1016/j.catena.2006.03.011

Lal R, 1991. Soil structure and sustainability. *Journal of Sustainable Agriculture*, 1(4): 67–92. doi: 10.1300/J064v01n04_06

Lehmann J, Kleber M, 2015. The contentious nature of soil organic matter. *Nature*, 528(7580): 60–68. doi: 10.1038/nature16069

Lehrsch G A, Sojka R E, Carter D L et al., 1991. Freezing effects on aggregate stability affected by texture, mineralogy, and organic matter. *Soil Science Society of America Journal*, 55(5): 1401–1406. doi: 10.2136/sssaj1991.03615995005500050033x

Li R P, Shi H B, Flerchinger G N et al., 2012. Simulation of freezing and thawing soils in Inner Mongolia Hetao Irrigation District, China. *Geoderma*, 173 –174: 28–33. doi: 10.1016/j.geoderma.2012.01.009

Li Z B, Geng Z, Li P et al., 2020. Soil organic matter and glomalin-related soil protein contents do not explain soil aggregate stability after freeze-thaw cycles at contrasting soil moisture contents. *Archives of Agronomy and Soil Science*, 66(11): 1497–1508. doi: 10.1080/03650340.2019.1676891

Moreno-de las Heras M, 2009. Development of soil physical structure and biological functionality in mining spoils affected by soil erosion in a Mediterranean-continental environment. *Geoderma*, 149(3–4): 249–256. doi: 10.1016/j.geoderma.2008.12.003

Musa A M, Liu Y, Wang A Z et al., 2016. Characteristics of soil freeze-thaw cycles and their effects on water enrichment in the rhizosphere. *Geoderma*, 264: 132–139. doi: 10.1016/j.geoderma.2015.10.008

Oztas T, Fayetorbay F, 2003. Effect of freezing and thawing processes on soil aggregate stability. *Catena*, 52(1): 1–8. doi: 10.1016/S0341-8162(02)00177-7

Paradelo R, Virto I, Chenu C, 2015. Net effect of liming on soil organic carbon stocks: a review. *Agriculture, Ecosystems & Environment*, 202: 98–107. doi: 10.1016/j.agee.2015.01.005

Rabot E, Wiesmeier M, Schlüter S et al., 2018. Soil structure as an indicator of soil functions: a review. *Geoderma*, 314: 122–137. doi: 10.1016/j.geoderma.2017.11.009

Rillig M C, Muller L A H, Lehmann A, 2017. Soil aggregates as massively concurrent evolutionary incubators. *The ISME Journal*, 11(9): 1943–1948. doi: 10.1038/ismej.2017.56

Shang C Y, Quan Z N, 2016. Problems existing in apple pears industry development of Yanbian prefecture. *Agricultural Engineering*, 6(6): 157–159. (in Chinese)

Shi Z L, Li X Y, Zhang L et al., 2015. Impacts of farmland conversion to apple (*Malus domestica*) orchard on soil organic carbon stocks and enzyme activities in a semiarid loess region. *Journal of Plant Nutrition and Soil Science*, 178(3): 440–451. doi: 10.1002/jpln.201400211

Six J, Bossuyt H, Degryze S et al., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, 79(1): 7–31. doi: 10.1016/j.still.2004.03.008

Song Y, Zou Y C, Wang G P et al., 2017. Altered soil carbon and nitrogen cycles due to the freeze-thaw effect: a meta-analysis. *Soil Biology and Biochemistry*, 109: 35–49. doi: 10.1016/j.soilbio.2017.01.020

Steinweg J M, Fisk M C, McAlexander B et al., 2008. Experimental snowpack reduction alters organic matter and net N mineralization potential of soil macroaggregates in a northern hardwood forest. *Biology and Fertility of Soils*, 45(1): 1–10. doi: 10.1007/s00374-008-0305-3

Sumner M E, 1992. The electrical double layer and clay dispersion. In: Sumner M E, Stewart B A (eds). *Advances in Soil Science. Soil Crusting–Chemical and Physical Processes*. Boca Raton: Lewis Publishers, 1–31.

Sun T, Mao Z J, Han Y Y, 2013. Slow decomposition of very fine roots and some factors controlling the process: a 4-year experiment in four temperate tree species. *Plant and Soil*, 372(1–2): 445–458. doi: 10.1007/s11104-013-1755-4

Tisdall J M, Oades J M, 1982. Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, 33(2): 141–163. doi: 10.1111/j.1365-2389.1982.tb01755.x

Von Bennewitz E, Cooper T, Losak T et al., 2015. Effects of decreasing levels of n amendments on organic 'granny smith' apple trees. *Journal of Soil Science and Plant Nutrition*, 15(4): 979–990. doi: 10.4067/S0718-95162015005000068

Wang L, Li J, Li J et al., 2014a. Effects of tillage rotation and fertilization on soil aggregates and organic carbon content in corn field in Weibei Highland. *Chinese Journal of Applied Ecology*, 25(3): 759–768. (in Chinese)

Wang Z, Zhang Y L, Zou H T et al., 2014b. The effect of the freezing/thawing cycles on iron oxide forms in the soil. *Chinese Journal of Soil Science*, 45(1): 1–5. (in Chinese)

Xiao C P, Yang L M, Zhang L X et al., 2016. Effects of cultivation ages and modes on microbial diversity in the rhizosphere soil of Panax ginseng. *Journal of Ginseng Research*, 40(1): 28–37. doi: 10.1016/j.jgr.2015.04.004

Xiao L, Yao K H, Li P et al., 2020. 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. *Journal of Soils and Sediments*, 20(3): 1222–1230. doi: 10.1007/s11368-019-02526-w

Xu Q X, Wang T W, Cai C F et al., 2012. Effects of soil conservation on soil properties of citrus orchards in the Three-Gorges Area, China. *Land Degradation & Development*, 23(1): 34–42. doi: 10.1002/ldr.1045

Yang M, Wang S F, Zhao X N et al., 2020. Soil properties of apple orchards on China's Loess Plateau. *Science of the Total Environment*, 723: 138041. doi: 10.1016/j.scitotenv.2020.138041

Yi Y L, 2009. *Soil Physics Research Method*. Beijing: Peking University Press, 59. (in Chinese)

Zeng Q C, Darboux F, Man C et al., 2018. Soil aggregate stability under different rain conditions for three vegetation types on the Loess Plateau (China). *Catena*, 167: 276–283. doi: 10.1016/j.catena.2018.05.009

Zhang B, Horn R, 2001. Mechanisms of aggregate stabilization in Ultisols from subtropical China. *Geoderma*, 99(1–2): 123–145. doi: 10.1016/s0016-7061(00)00069-0

Zhang Z, Ma W, Feng W J et al., 2016. Reconstruction of soil particle composition during freeze-thaw cycling: a review. *Pedosphere*, 26(2): 167–179. doi: 10.1016/S1002-0160(15)60033-9

Zhang Z Q, Yu D S, Shi X Z et al., 2010. Effect of sampling classification patterns on SOC variability in the red soil region, China. *Soil and Tillage Research*, 110(1): 2–7. doi: 10.1016/j.still.2010.05.007

Zhu G Y, Deng L, Shangguan Z P, 2018. Effects of soil aggregate stability on soil N following land use changes under erodible environment. *Agriculture, Ecosystems & Environment*, 262: 18–28. doi: 10.1016/j.agee.2018.04.012