Influence of Global Warming on Aggregate Stability and Hydraulic Conductivity Under Highland Soil Order in Turkey

Müdahir Özgül,[1] Ekrem Lütfi Aksakal,[1] Adem Günes,[1] İlker Angın,[2] Metin Turan,[1] and Taşkın Öztaş[1]

Abstract: Ongoing global warming may cause an increase in air and soil temperatures. These increases can then lead to increase in the frequency of soil freezing and thawing cycle during the winter in cool-temperate and other high-latitude regions. The purpose of this study was to explore the effects of repeated soil freezing and thawing treated cycles (FTTC) on wet aggregate stability (WAS) and hydraulic conductivity (HC) in incubation laboratory and field experiment on Pellustert, Argiustoll, Haplustept, and Fluvaquent soils, the major soil groups in the eastern part of Turkey. To provide long-term climatic effect of soil FTTC on WAS and HC, a laboratory study was conducted simulating with three steps based on 60-year temperature cycles occurring in the region. The results demonstrated that the initial WAS increased with increases in FTTC from 3 to 6, by 18% to 113% but decreased after that point in all the soil freeze-thaw treatments by 2% to 25%, depending on soil type. The effect was more pronounced with increased moisture contents at freezing. The percent decrease in HC of soils ranged from 19% to 44%. The highest WAS values of soil samples under laboratory condition were determined in the Argiustoll soil, followed by Pellustert > Haplustept > Fluvaquent but was Fluvaquent > Haplustept > Pellustert > Argiustoll for HC of the soils. The field study results showed that global climate changes occurring in recent decades in the region deeply affected the WAS and HC values and that the highland soils are most sensitive to the global climatic change. Increasing air temperature has resulted in the rise of soil temperature, increasing the frequency of soil freeze-thaw cycles during the winter in cool-temperature and other high-latitude regions. If ongoing global warming continues this trend, WAS and HC changes in highland soils may lead to decrease and alterations in regional agricultural production such that regular organic manure or green manure amendments will be needed to sustain soil management and crop production for these major soil groups.

Key words: Aggregate stability, hydraulic conductivity, freeze-thaw cycle, soil orders, soil temperature.

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Aggregate stability, a measure of a soil aggregate's resistance to breakdown, influences many soil physical and hydraulic characteristics, such as surface sealing rate, infiltration rate, and hydraulic conductivity (HC). Freezing affects aggregate stability, although not in the same manner for all soils, because soils have differing texture, mineralogy, and organic matter. A multitude of factors of soil wet aggregate stability (WAS) and HC would respond differently to freezing. Ongoing global warming (IPCC, 2007) will increase the frequency of freezing and thawing treated cycles (FTTC) in cool-temperate and other high-latitude regions previously subject to prolonged winter soil frost periods. The maximum extent of seasonally frozen ground is 55 million km^2 or 55% of the total land area of the northern hemisphere (Zhang et al., 2003). Although in some areas temperature increase will lead to an overall disappearance of soil freezing, in many regions a reduced snow cover in the winter, and the consequentially decreased insulation of the soils against freezing, may increase the FTTC (Groffman et al., 2001). Observations and future projections show that reduced amounts of snow increase the number of freeze-thaw events, especially at temperate sites, even though annual soil freezing days generally decline with increasing mean winter air temperature (Henry, 2007).

The WAS is a dynamic property of soils. Both management factors and climatic processes cause stability to vary temporally. Climatic processes include precipitation (wetting), evaporation (drying), freezing, and thawing. In temperate regions, freezing and thawing cause stability to vary greatly (Bullock et al., 1988; Lehrsch et al., 1991; Mostaghimi et al., 1988; Staricka and Benoit, 1995). In many areas subject to freezing, wind and water erosion occur in the spring before vegetation covers clean-tilled fields. If surface soil aggregates enter the winter in relatively stable condition, they may be weakened somewhat by winter freezing (Lehrsch and Jolley, 1992), but they will be more capable of resisting breakdown and movement from these erosive forces in the spring. The WAS may increase under some conditions. For example, soil drying during periods of low rainfall or near and below enlarging ice lenses (Czurda et al., 1995) can precipitate cementing or bonding agents such as $CaCO_3$, silica, gypsum, or iron oxides at contact points between primary particles or smaller aggregates. This precipitation often enables aggregates to withstand subsequent disruption by water (Lehrsch et al., 1991; Perfect et al., 1990). Drying both gathers and arranges clay domains at contacts between sand and silt particles, thus increasing aggregate stability (Lehrsch, 1995; Rowell and Dillon, 1972). Aggregate stability can also be decreased by freeze-drying aggregates on or near the soil surface (Staricka and Benoit, 1995) and, in general, by freeze-thaw cycles.

Most of the studies assessing the effects of freezing and thawing on aggregate stability have shown that an increase in the number of freeze-thaw cycles tends to decrease soil structure, aggregate stability, and hydraulic conductivity (Bullock et al., 1988; Edwards, 1991; Staricka and Benoit, 1995; Bajracharya et al., 1998). For example, Mostaghimi et al. (1988), Edwards (1991), and Oztas and Fayetorbay (2003) reported weak aggregate stability of soils after freeze-thaw cycles. Freezing and thawing processes occur especially at the soil surface. Any disturbance of dispersive soils at the surface is likely to result in a rapid decline of their structure and a subsequent reduction in their permeability (Oster et al., 1999). However, there is also evidence that frost action may actually increase the stability (Perfect et al., 1990). The initial moisture conditions of the soil

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at freezing have been pointed out as a key factor in the freeze-thaw process. In general, aggregate stability has been shown to be inversely proportional to soil water content at the time of freezing (Perfect et al., 1990; Staricka and Benoit, 1995). Different soils also respond differently to freezing and thawing due to, for example, differences in texture, structure, organic matter content, chemical properties, and root development (Lehrsch et al., 1991; Oztas and Fayetorbay, 2003).

Large areas of land at middle and high latitudes are regularly exposed to subzero temperatures, and the soils freeze. Seasonally frozen soil plays a significant role in the management of soil and water resources in northern latitudes. Freezing of soil is known to affect soil conditions through various physical, physicochemical, and biological mechanisms. Erzurum-Turkey (39°55′N, 41°61′E) suffers long, cold winters; on average, the soil freezes for 159 days, based on 60 years of meteorological data. But the last 5 years of meteorological data show that both air and soil temperatures have increased about 10°C in Erzurum/Turkey and average 40°C in Turkey, because of its geographical position, which results in different climatic zones in almost every period of the year (Anonymous, 2010). Because this climatic diversity depends on global warming, every region should be considered as unique for agricultural production. Because of its geographical position, climatic changes of Northeastern Anatolia show great variation. Variation in precipitation, freeze-thaw, and temperature affects some physical, chemical, and microbiological properties of soils and thus affects productivity. This effect, which varies with different soil types (big group), is especially important for water movement, erosion, and nutrient uptake in growing period. Four big soil groups were used in field study in Erzurum plain (Turkey). In Turkey, where most soils freeze annually, the effects of freezing on laboratory condition have also created interest (Oztas and Fayetorbay, 2003), but hardly any studies have dealt with global climatic changes effects on soil WAS and HC in laboratory or field condition.

The present study was carried out to investigate the effects of time of freezing, number of freeze-thaw cycles, and freezing temperatures on the WAS and HC of four of Turkish major soil groups formed from different parent materials. The effects of multiple freeze-thaw cycles were compared to improve our understanding of the management of the various soil groups in these regularly freezing-thawing soils and to establish the relationship between laboratory and field study data regarding the effects of climate change.

MATERIALS AND METHODS

Description of the Site and Materials

The field study area was situated at an altitude between 1,880 and 2,030 m above sea level in the eastern part of Turkey. The parent materials mostly consisted of volcanic, marl, and lacustrine residual and transported material. The mean annual temperature, precipitation, evapotranspiration, and relative humidity for the region are 6.3°C, 398 mm, 1,060 mm, and 64%, respectively. The average summer temperatures rarely exceed 35°C, whereas in the winter, temperatures of −35°C are not uncommon; the mean (60 years' average) air and soil temperatures at 5- and 10-cm depth are listed in Fig. 1. On average, snow remains on the ground for 94 days, and the region has 124 rainy days per year (Anonymous, 2010). The soil humidity and temperature regimens are defined as Ustic and Mesic (Saroğlu and Yılmaz, 1986). According to soil taxonomy (Soil Survey Staff, 2006), the soils are Argiustoll, Fluvaquent, Haplustept, and Pellustert.

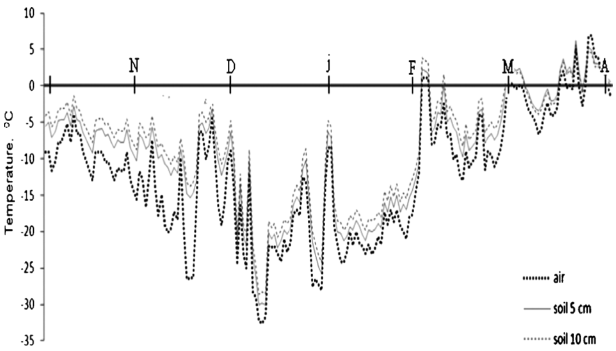

FIG. 1. Air temperatures and soil temperature at 5- and 10-cm depth in the studied area from November to April (60 years' average).

Soil Analysis

Soil samples were taken over 0- to 10-cm depths to determine some chemical and physical properties. Soil samples were air dried, crushed, and passed through a 2-mm sieve prior to chemical analysis. Cation exchange capacity was determined using sodium acetate (buffered at pH 8.2) and ammonium acetate (buffered at pH 7.0) according to Sumner and Miller (1996). The Kjeldahl method (Bremner, 1996) was used to determine organic N, whereas plant-available P was determined by using the sodium bicarbonate method of Olsen et al. (1954). Electrical conductivity was measured in saturation extracts according to Rhoades (1996). Soil pH was determined in 1:2 extracts, and calcium carbonate concentrations were determined according to McLean (1982). Soil organic matter was determined using the Smith-Weldon method according to Nelson and Sommers (1982). Ammonium acetate buffered at pH 7 (Thomas, 1982) was used to determine exchangeable cations. The percentage of WAS was then determined by a wet sieving procedure (Kemper and Rosenau, 1986), and HC was determined according to Klute and Dirksen (1986) methods. After extraction, the P, K, Ca, Mg, and Na contents were determined using an inductively couple plasma spectrophotometer (Optima 2100 DV, ICP/OES; PerkinElmer, Shelton, CT). Clay mineralogy of these soils was determined using X-ray diffractometer (Max-2200/PC; Rigaku D, Tokyo, Japan). Specific surface area of soils was determined ethylene glycol monoethyl ether methods according to Calter et al. (1993). The analysis results of soils are given in Table 1.

Freeze and Thaw Experiment

This study was conducted in the laboratory and field during 2008–2009.

Laboratory Experiment

The major soil orders, Pellustert, Argiustoll, Haplustept, and Fluvaquent, in the freezing- and thawing-treated cycles (FTTC) study in the laboratory were subject to long-term temperature cycles to simulate the temperature under the field condition. For this purpose, the soil samples were put into small pots, saturated (to the field capacity), and placed in an Environmental Test Chamber (GFL 6485). The soil samples were then subjected to a freeze and thaw process from +20 to −30°C to simulate field condition. For this study, subsamples (500 g, fresh weight passed through a 4-mm sieve) of each soil were incubated in repacked plastic cores in the dark. Sufficient deionized water was added to each sample to produce a soil at either 15% or 26% gravimetric moisture content. These two

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TABLE 1. Some Chemical and Physical Properties of the Experimental Soils

	Pellustert	Argiustoll	Haplustept	Fluvaquent
pH (1:2.5 s/w)	7.22	7.01	7.8	7.3
$CaCO_3$, %	0.37	0.44	1.15	0.98
Organic matter, %	1.21	1.33	2.43	1.84
Total nitrogen, %	0.0060	0.0052	0.0122	0.0092
Cation exchange capacity, $cmol_c$ kg^{-1}	25.73	35.64	20.75	22.39
K, $cmol_c$ kg^{-1}	2.36	2.12	3.15	2.82
Ca $cmol_c$ kg^{-1}	15.24	14.22	14.1	12.14
Mg $cmol_c$ kg^{-1}	2.63	2.88	2.5	3.25
Na $cmol_c$ kg^{-1}	0.52	0.7	1.22	0.61
P, mg kg^{-1}	8.25	10.67	21.25	24.27
Clay, %	57.82	53.11	28.81	13.86
Silt, %	23.83	23.59	50.39	32.99
Sand, %	18.35	23.30	20.80	53.15
Aggregate stability, %	40.20	48.48	30.25	25.05
EC, μmhos cm^{-1}	285	260	470	425
Specific surface area, m^2 g^{-1}	372	417	103	283
Bulk density, g mL^{-3}	1.09	1.15	1.22	1.34
Qualitative clay mineralogy	M > I > K > H > V	H > I > K > M > V	I > M > K > V > H	H > I > K > M > V

C: chlorite, H: halloysite, EC: electrical conductivity; Ka: kaolinite, I: illite, M: montmorillonite, V: vermiculite.

moisture contents were representative of values measured at these field sites during the late autumn to early spring period. The highest value (27%, wt/wt) ensured that all of the samples were fully saturated despite differences in the individual water-holding capacities. The long-term (60 years) air temperature average has been reported to be −10°C, −15°C, and −20°C for December, January, and February, respectively; the actual average air temperature range was 0°C to 10°C (+2.5°C, +5°C, + 7.5°C, and +10°C), and the average sunny hours and thawing hours per day were 18 and 6 h for March, April, and May, respectively. Therefore, the laboratory study was conducted in three steps (Step 1, Step 2, and Step 3), as summarized in Fig. 2.

Freezing temperature °C	Thawing temperature °C	Freeze-thaw cycles
Step 1		
-10 (30 day); -15 (30 day); -20 (30 day); -10 (15 day)	2.5	3, 6, 9
	5.0	3, 6, 9
Total samples	450	
Step 2		
-10 (30 day); -15 (30 day); -20 (30 day); -10 (15 day); -5 (15 day)	2.5	3, 6, 9
	5.0	3, 6, 9
	7.5	3, 6, 9
Total samples	675	
Step 3		
-10 (30 day); -15 (30 day); -20 (30 day); -10 (15 day); -5 (15 day); 0 (15 day)	2.5	3, 6, 9
	5.0	3, 6, 9
	7.5	3, 6, 9
	10.0	3, 6, 9
Total samples	900	

FIG. 2. Laboratory experimental design.

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Field Experiment

Field experiment study was conducted in 2008 to 2009 in the Pellustert, Argiustoll, Haplustept, and Fluvaquent major soil groups. Individual plots were 1.5×4 m^2. The available moisture content of soil was 105.3 mm m^{-1}. All plots were irrigated as rainy irrigation with water, which had no restriction of use (C_2S_1), an electrical conductivity of 0.27 dS m^{-1}, sodium adsorption ratio of 0.42, and pH of 7.6. Soil moisture contents in all plots were increased to the field capacity at the beginning of periods.

Soil sampling was taken from 0 to 10 cm every 15 days, and soil moisture and temperature were measured.

Statistical Analysis

All data were subjected to analysis of variance, and significant means were compared by Duncan's multiple range test method, performed using SPSS 13.0 (SPSS Inc., 2004).

RESULTS

Effects of Time of Freezing, the Number of Freeze-Thaw Cycles, and Freezing Temperatures on the WAS in the Major Soil Groups

Although the disintegration forces applied in the laboratory may attempt to simulate freeze-thaw long-term effects (about 60 years) found in the field, they do not fully duplicate field conditions. During 2008 and 2009, the field experiment reflects only 2 years' average effects of the freeze-thaw observations on soil and HC data due to the climate change occurring over the last decades. To evaluate the effects of global climate change on soil properties, as currently exist, we need the long-term observations. So, laboratory experiments using a long-term temperature cycle to simulate the field temperature conditions provide long-term behavior of soils in the field long-term observations (Matkin and Smart, 1987). Consequently, the relationship between WAS and HC in the laboratory and dynamics in the field is largely empirical. For diagnostic purposes, however, the determination of WAS and HC in the laboratory under different treatments may provide information on the soil behavior in relation to several disintegrating forces. The aim of WAS and HC tests is to give a reliable description and ranking of physical behavior of soils under several stresses or at least to allow a discrimination between soils in accordance with field observations. The Pellustert, Argiustoll, Haplustept, and Fluvaquent major soil groups were used to study the impact of FTTC in a laboratory study using long-term temperature cycles to simulate the field temperature conditions. The laboratory study was conducted in three steps (Fig. 2).

The laboratory experiment showed that Fluvaquent had the lowest WAS of all the soils studied, and these values, obtained from soil samples subjected to freezing at −10°C for 30 days, −15°C for 30 days, and −20°C for 30 days; refrozen at −10°C for 15 days; and then thawed at +2.5°C and +5.0°C for 18 h under laboratory conditions (Step 1), were 30%, 43%, and 23% at 2.5°C and 47%, 54%, and 24% at 5°C for 3, 6, and 9 times FTTC, respectively. It was 26% for the untreated (UT) sample. Increases in the ratio of the WAS value compared with the UT sample were about 15% and 65% at 2.5°C thaws after 3 and 6 FTTC, and decreases in the ratio were 11% at 2.5°C thaws after 9 FTTC and 81% and 108% at 5°C thaws after 3 and 6 times, and a decrease in the ratio was 8% at 5°C thaws after 9 times FTTC, respectively. In contrast, Argiustoll had the highest WAS of all the soils studied. The values were 59%, 71%, and 46% at 2.5°C and 40%, 42%, and 33% at 5°C for 3, 6, and 9 FTTC, respectively, compared with 49% for UT sample. Increases in the ratio of the WAS value compared with UT sample were 20% and 45% at 2.5°C thaws after 3 and 6 FTTC, and decreases in the ratio were 7% at 2.5°C thaws after 9 FTTC and 18%, 14%, and 32% at 5°C thaws after 3, 6, and 9 FTTC, respectively (Fig. 3A).

A similar WAS trend was observed with Steps 2 and 3 for the different soil groups, but the amount of the WAS varied between the soil groups (Fig. 3B, C). In Step 2, for Fluvaquent, the WAS values obtained from soil samples subjected to freezing at −10°C for 30 days, −15°C for 30 days, and −20°C for 30 days and refrozen at −5°C for 15 days, and then thawed at +2.5°C, +5.0°C, and 7.5°C in an 18-h thaw temperature process were 34%, 48%, and 19% at 2.5°C; 36%, 55%, and 22% at 5°C; and 38%, 57%, and 21% at 7.5°C for 3, 6, and 9 FTTC, respectively, but it was 26% for the UT sample. Increases in the ratio of the WAS value compared with the UT sample were 31% and 87% at 2.5°C thaws after 3 and 6 FTTC, decreases in the ratio were 26% at 2.5°C thaws after 9 FTTC and 42% and 113% at 5°C thaws after 3 and 6 FTTC, respectively, and decreases in the ratio were 10% at 5°C thaws after 9 FTTC and 50% and 124% at 7.5°C thaws after 3 and 6 FTTC, respectively, and a decrease in the ratio was 16% at 7.5°C thaws after 9 FTTC, respectively. In contrast, WAS values of the Argiustoll were 65%, 78%, and 37% at 2.5°C, 71%, 81%, and 37% at 5°C and 74%, 85%, and 39% for 3, 6, and 9 FTTC, respectively, but it was 49% for the UT sample. Increases in the ratio of the WAS value compared with the UT sample were 33% and 59% at 2.5°C thaws after 3 and 6 FTTC, and decreases in the ratio were 25% at 2.5°C thaws after 9 FTTC and 45% and 65% at 5°C thaws after 3 and 6 FTTC, respectively. The decreases in the ratio were 23% at 5°C and 51% and 73% at 7.5°C thaws after 3 and 6 FTTC, respectively. The decrease in the ratio was 20% at 7.5°C thaws after 9 FTTC (Fig. 3B). Similar trends were observed from Step 3; soil samples treated with −10°C, −15°C, and −20°C treatment were refrozen at −10°C for 15 days, at −5°C for 15 days, and at 0°C for 15 days then thawed at +2.5°C, +5.0°C, +7.5°C, and 10.0°C in 18 h; these cycles were repeated three, six, and nine cycles (Fig. 3C). In the field, the results showed that the WAS value was similar to Step 1 (5°C thaws) laboratory results (Fig. 4). Fluvaquent with the lowest WAS of all the soils studied under field conditions increased approximately 70% and 85% after 3 and 6 FTTC and a decreased ratio of 10% after 9 FTTC, compared with the UT sample. In contrast, Argiustoll had the highest WAS of all the soils studied, which was 19% and 39% after 3 and 6 FTTC. The ratio decreased 8% after 9 FTTC, respectively (Fig. 4).

Effects of Time of Freezing, the Number of Freeze-Thaw Cycles, and Freezing Temperatures on the HC in the Four Major Soil Groups

The laboratory experiment showed that Fluvaquent had the highest HC of all the soils studied. The values, obtained from soil samples subjected to freezing at −10°C for 30 days, −15°C for 30 days, and −20°C for 30 days, refrozen at −10°C for 15 days, and then thawed at +2.5°C and +5.0°C for 18 h under laboratory conditions (Step 1), were 18.6, 16.0, and 17.7 cm h^{-1} at 2.5°C and 15.2, 14.6, and 12.5 cm h^{-1} at 5°C for 3, 6, and 9 FTTC, respectively, compared with 21.5 cm h^{-1} for the UT sample. Decreases in the ratio of the HC value compared with the UT sample were 13%, 25%, and 18% at 2.5°C thaws after 3, 6, and 9 FTTC and 29%, 32%, and 42% at 5°C thaws after 3, 6, and 9 FTTC, respectively. In contrast, Argiustoll had the lowest

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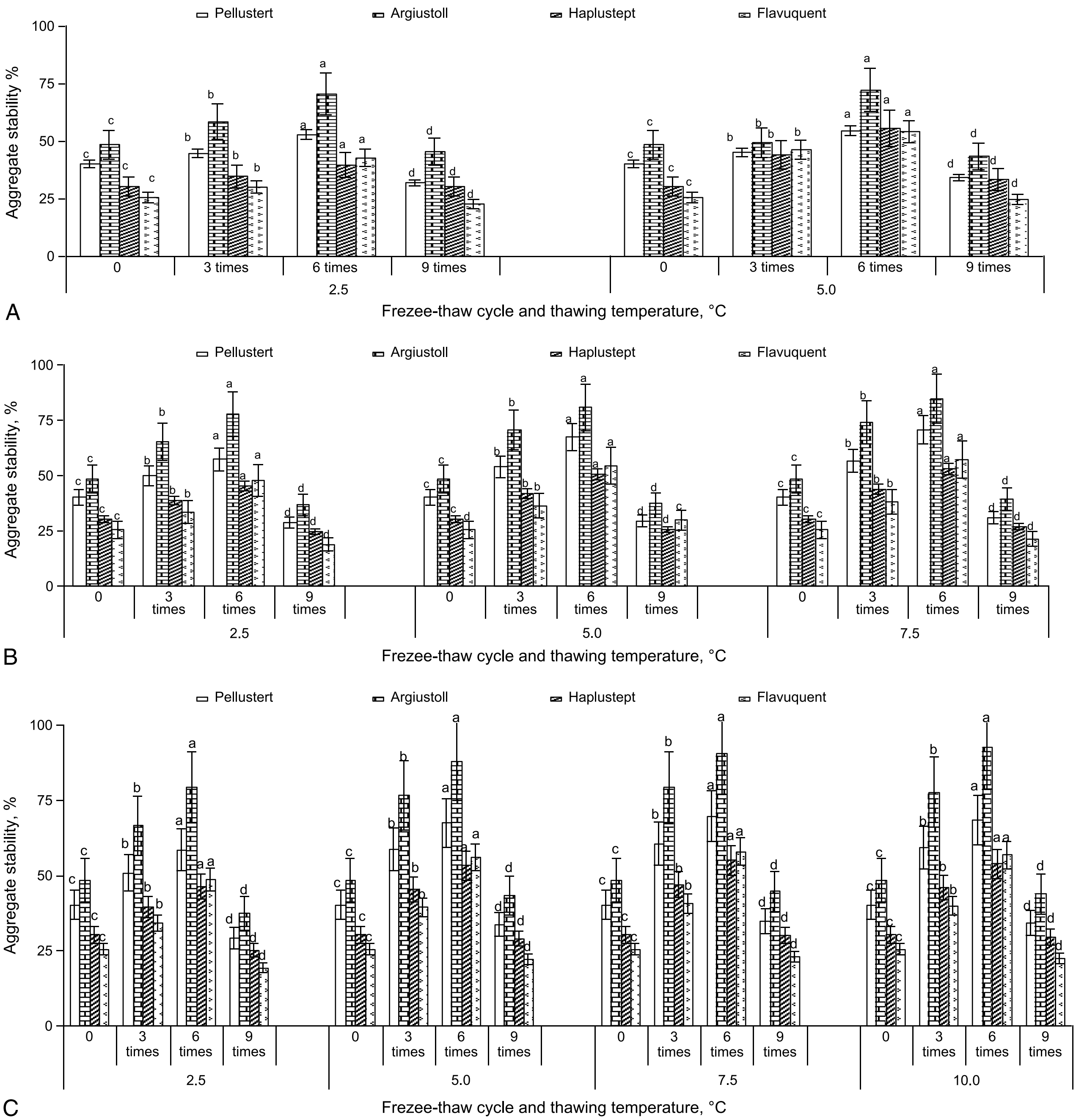

FIG. 3. Aggregate stability for freeze-thaw–treated and untreated samples (FTTC) at selected temperature in laboratory condition (A, Step 1), (B, Step 2), and (C, Step 3).

HC of all of the studied soils: 5.1, 4.2, and 3.8 cm h^{-1} at 2.5°C and 4.9, 4.7, and 4.0 cm h^{-1} at 5°C for 3, 6, and 9 FTTC, respectively, compared with 6.3 cm h^{-1} for the UT sample. Decreases in the ratio of the HC value compared with the UT sample were 19%, 32%, and 39% at 2.5°C thaws after 3, 6, and 9 FTTC and 22%, 25%, and 36% at 5°C thaws after 3, 6, and 9 FTTC, respectively (Fig. 5A).

A similar HC trend was observed from the application to different soil groups, but the HC varied between soil groups with Steps 2 and 3 (Fig. 5B, C). In Step 2, for Fluvaquent, the HC values obtained from soil samples subjected to freezing at −10°C for 30 days, −15°C for 30 days, and −20°C for 30 days, refrozen at −5°C for 15 days, and then thawed at +2.5°C, + 5.0°C, and 7.5°C an 18-h thaw temperature process were 16.9, 14.2, and 13.41 cm h^{-1} at 2.5°C; 14.1, 13.5, and 12.7 cm h^{-1} at 5°C; and 16.9, 15.3, and 12.1 cm h^{-1} at 7.5°C for 3, 6, and 9 FTTC, respectively, compared with 21.5 cm h^{-1} for the UT sample. Decreases in the ratio of the HC value compared with the UT sample were 21%, 34%, and 38% at 2.5°C thaws after 3, 6, and 9 FTTC 34%, 37%, and 41% at 5°C thaws after 3, 6, and 9 FTTC, and 22%, 29%, and 44% at 7.5°C thaws after 3, 6, and 9 FTTC, respectively. In contrast, HC values of the Argiustoll

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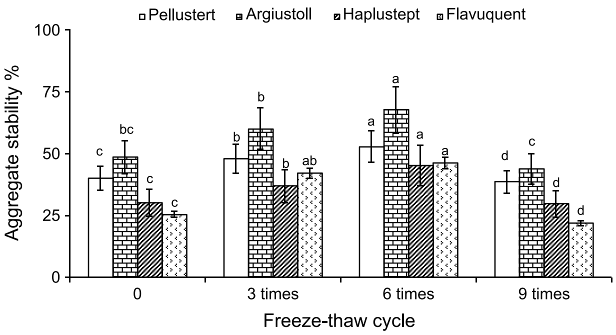

FIG. 4. Soil aggregate stability for freeze-thaw processes in the field condition (2008–2009).

were 4.8, 4.3, and 4.1 cm h^{-1} at 2.5°C; 4.5, 4.3, and 4.0 cm h^{-1} at 5°C; and 5.7, 4.9, and 3.9 cm h^{-1} for 3, 6, and 9 FTTC, respectively, but it was 6.3 cm h^{-1} for the UT sample. Decreases in the ratio of the HC value compared with the UT sample were 23%, 32%, and 34% at 2.5°C thaws after 3, 6, and 9 FTTC; 27%, 30%, and 36% with the 5°C thaws after 3, 6, and 9 FTTC; and 8%, 20%, and 38% at 7.5°C thaws after 3, 6, and 9 FTTC, respectively (Fig. 5B). Similar trends were observed for Step 3 soil samples with −10°C, −15°C, and −20°C treatment subjected to refreezing at −10°C for 15 days, at −5°C for 15 days, and 0°C for 15 days then thawed at +2.5°C, +5.0°C, +7.5°C, and 10.0°C over 18 h. The cycles were repeated three, six, and nine cycles (Fig. 5C). In the field, the results showed that the HC value was similar to Step 1 (5°C thaws) laboratory results (Fig. 5). Decreases in the ratio of the HC value for Fluvaquent, which had the higher HC of all the soils studied under filed condition, were about 25%, 30%, and 37% after 3, 6, and 9 FTTC, respectively, compared with the UT sample. In contrast, in Argiustoll, with the lowest HC of all the soil studied soils, decreases in the ratio of the HC value were 19%, 25%, and 27% after 3, 6, and 9 FTTC, respectively (Fig. 5).

DISCUSSION

The initial WAS of the untretated freeze-thaw cycles (UT) was the highest in Argiustoll and Pellustert soil, followed by Haplustept and Fluvaquent, but HC was the lowest in Pellustert and Argiustoll soil, followed by Haplustept and Fluvaquent, because of the high clay content (both >50%). The initial WAS of the Haplustept and Fluvaquent was the lowest (30% and 26%), indicating that these soils are very susceptible to erosion even before freeze-thaw process. The WAS of the soils was significantly affected by the time of freezing, the number of freeze-thaw cycles, and freeze-thaw temperatures. The WAS generally increased with increases in FTTC from 3 to 6, but

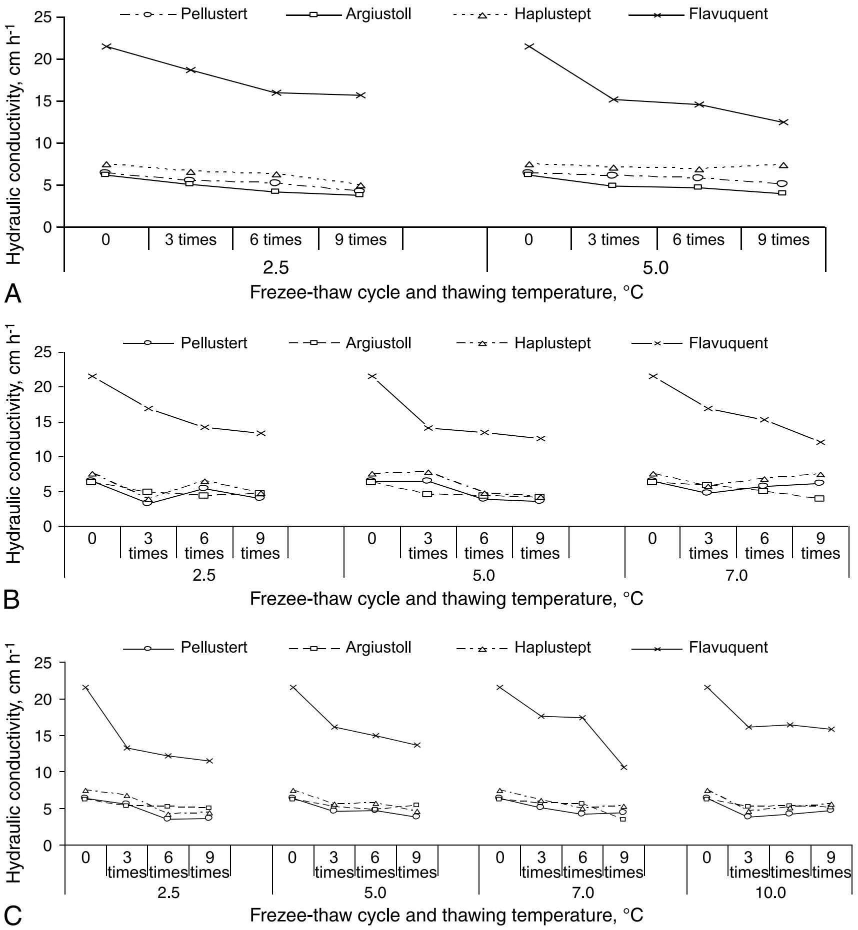

FIG. 5. Hydraulic conductivity for freeze-thaw–treated and untreated soils (FTTC) at selected temperature in laboratory condition (A, Step 1), (B, Step 2), and (C, Step 3).

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decreased after that point in all of the soils. The temperature of freezing had a significant effect on the WAS. At a lower temperature (−10°C), it was less than that at a higher freezing temperature (−5°C and 0°C).

The highest WAS values of all the soils studied under laboratory conditions were observed with soils frozen at −10°C for 30 days, −15°C for 30 days, and −20°C for 30 days; subjected to refreezing at −10°C for 15 days, −5°C for 15 days, and 0°C for 15 days; and then thawed at +10°C in 18 h and 6 FTTC at Argiustoll soil followed by Pellustert > Haplustept > Fluvaquent. In the field, the study results showed that the WAS values exhibited a similar trend to Step 1 in the laboratory results (Fig. 4). The effect of the number of FTTC on WAS was not consistent. Generally, it increased as the number of FTTC was increased from 3 to 6, but thereafter the WAS values decreased. The field based on the climate change occurring over the last decade showed that freeze-thaw temperature is getting higher and that the WAS of soil was lower under the field conditions than occurred in the laboratory experiment. Accordingly, the WAS of soil during the global climate change period is reduced after 3 or 6 FTTC, but is increased after 9 FTTC at present or in the future. If the global climate changes continue on this trend, the WAS of soils will decrease. Especially, the Fluvaquent major soil group will be deeply affected by this trend followed by Haplustept and Pellustert in the future.

Soil aggregate stability is the ability of the aggregates to remain intact when subjected to stress. The maintenance of a "good" soil structure is critical for agricultural sustainability and depends on the stability of the aggregates. Thus, soil aggregate stability influences a wide range of physical and biogeochemical processes in the agricultural environment, such as root density and elongation, macropore formation and macroporosity, water storage capacity, infiltration, HC and surface runoff rates, soil erosion, nonpoint source pollution from surface applied agricultural chemicals, biological activity, and crop production. Consequently, soil aggregate stability can be used as an index of soil quality. This property is closely related to primary soil characteristics. Other external factors such as climate, age, biological factors, and agricultural management greatly influence it as well. To obtain sustainable crop production and increase soil quality, some precautions should be taken, such as soil tillage management, use of organic manure, and alternate crop management in this agricultural land.

Several other results reported by Bullock et al. (1988), Edwards (1991), Staricka and Benoit (1995), Bajracharya et al. (1998), and Lehrsch et al. (1991) have also shown similar results. They found that aggregate stability usually increased only with the first few freeze-thaw cycles. This increase in the WAS with the first one or two FTTC was considered by Lehrsch et al. (1991) to be a normal or common response. Lehrsch et al. (1993) described a process that could cause these increases. In brief, ice formation in interaggregate pores or ice lens enlargement could bring nearby soil particles into contact. Slightly soluble, inorganic bonding agents would then move by mass flow or, to minimize their potential energy, diffuse to those contact points. Once there, the bonding agents would precipitate, thereby increasing the aggregate's stability, as the soil dried as a result of freeze-induced soil water redistribution (Czurda et al., 1995; Perfect et al., 1990). Because this precipitation was probably irreversible, these bonding agents did not reenter the soil solution during subsequent thaw periods. Freezing and ice formation have been reported to improve aggregation and increase aggregate stability (Perfect et al., 1990; Czurda et al., 1995).

The HC of soils was also significantly affected by the time of freezing, the number of freeze-thaw cycles, and freezing temperatures. The HC generally decreased with increased FTTC, from 3 to 9, and thaw temperature. The highest HC values of the studied soil under laboratory conditions resulted from freezing at −10°C for 30 days, −15°C for 30 days, and −20°C for 30 days, and refreezing at −10°C for 15 days, −5°C for 15 days, and 0°C for 15 days then thawed at +10°C for 18 h, and for 6 FTTC for Fluvaquent soil followed by the Haplustept > Pellustert > Argiustoll.

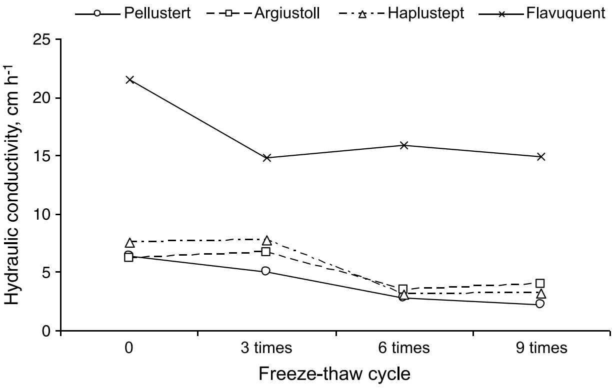

FIG. 6. Hydraulic conductivity of soils following freeze-thaw processes in the field conditions (2008–2009).

The field study results showed similar trend for Step 1 frozen laboratory results (Fig. 6). The field result showed that, depending on climate change over the last decade, freeze-thaw temperature is increasing and that the soil HC was lower under the field condition than predicted by the laboratory experiment. Accordingly, the HC of soil change will increase after 3, 6, and 9 FTTC because of climate change at present or in the future. Hydrologic regimens of the soil can vary greatly over short horizontal spatial scales, with depth, and over time. It is well documented that the HC of ice-rich permafrost soils can be several orders of magnitude lower than their unfrozen counterparts (Burt and Williams, 1976; Kane, 1980; Kane and Stein, 1983). Furthermore, ice-rich conditions at the freeze-thaw interface significantly reduce the permeability of the soil, effectively limiting the soil water capacity of the soil (Woo, 1990).

Our results show that freeze-thaw generally increased the WAS with 3 to 6 FTTC, but decreased after that point in all of the soils. The greatest WAS values for all of the studied soils under laboratory and field conditions were observed with the Argiustoll soil, followed by Pellustert > Haplustept > Fluvaquent soil. In contrast, the HC generally decreased with increasing FTTC from 3 to 9. The highest HC values for soils under laboratory and field conditions were observed with the Fluvaquent soil, followed by Haplustept > Pellustert > Argiustoll soil. The percent increase or decrease in the WAS and HC depended on the soil type, the number of freeze-thaw cycles, and the freezing temperature. Based on our results, we emphasize that highland soils are most sensitive to the global climatic change. Increasing air temperature has resulted in a rise in soil temperature and an increasing frequency of soil freeze-thaw cycles during the winter in cool-temperature and other high-latitude regions. If ongoing global warming continues this trend, WAS and HC soil of highland may decrease, requiring alterations in regional agricultural management. A cover of crop residues should be maintained on the soil surface to insulate it from this climatic variation. In addition, soil organic matter content should be increased by the incorporation of farmyard manure or green manure to improve soil aggregation and HC.

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