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Source: Mountain Research and Development, 28(3) : 272-278

Published By: International Mountain Society

URL: https://doi.org/10.1659/mrd.0890

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Mountain Research and Development Vol 28 No 3/4 Aug–Nov 2008: 272–278 doi:10.1659/mrd.0890

Taeho Kim

Thufur and Turf Exfoliation in a Subalpine Grassland on Mt Halla, Jeju Island, Korea

Thufur*, 42–200 cm long and 9–27 cm high, are distributed in a summit crater of Mt Halla where freeze–thaw days occur over 70 times annually. The cryogenic mounds are frozen as a hard solid mass during winter and their lower part remains frozen until late April even though they begin to thaw in mid-March. Since the water content of* thufur *increases and exceeds a liquid limit during March and April,* thufur *soils may be subject to cryoturbation. An exfoliating terrace in a northwestern grassland of Mt Halla retreated at a rate of 22.2 mm/year from 2002 to 2004. Frost action is the process contributing most to turf exfoliation, with the maximum retreat rate observed from late March to early May.* Thufur *and turf exfoliation indicate that the subalpine grassland of Mt Halla is likely to be situated in a periglacial environment. However, global warming has affected these periglacial features through vegetation changes. The withering of alpine shrubs is partly responsible for the formation of crater-like* thufur *and subsequent rupture of* thufur*, while the rapid spread of* Sasa quelpaertensis *checks the retreat of turf terraces.*

Keywords: Thufur*; turf exfoliation; periglacial environment; global warming; subalpine grassland; Mt Halla; South Korea.*

Peer-reviewed: *May 2007* **Accepted:** *July 2008*

Introduction

The Korean Peninsula was not glaciated during the Last Glacial Age except for its northern alpine region (Lautensach 1945; Demek 1973). Glacial sea level change, which caused the disappearance of the Yellow Sea between Korea and China, implies that intensive frost action was widespread across the peninsula. As a consequence, relict periglacial landforms such as cryogenic structures and block streams are widely distributed even in the southern coastal region (Kwon 1979; Matsukura et al 1998; Oguchi and Tanaka 1998). Although periglacial landforms can be found in the alpine zone of Korea's central mountains (Kee 1999; Park 2000), the southern peninsula is unlikely to have any active periglacial environments.

By contrast, *thufur* have been found on Mt Halla on Jeju Island even though the mountain is located in the southernmost part of Korea (Kim 1970; Kim 2001). *Thufur* are miniature mounds formed by the local displacement of surface soil material due to seasonal frost penetration (Schunke and Zoltai 1988; Grab 2005). Turf exfoliation is also found in the subalpine zone of Mt Halla (Kim 2006), suggesting that it has unique thermal environments. In addition, Mt Halla contains numerous alpine plants in its subalpine zone. It has been known as the southern limit in the Northern Hemisphere of *Diapensia lapponica* subsp. *obovata* (Kong 1998). However, global warming has shrunk the distributional range of these alpine plants (Kong 1999). Geomorphic processes in cold climate regions can be affected by vegetation changes due to global warming (Hastenrath 1977; Mizuno 1991, 2003), which is probably more obvious in places with marginal periglacial environments. This paper examines the characteristics of *thufur* and turf exfoliation as periglacial features in a subalpine grassland of Mt Halla in Jeju Island, and the impacts that global warming has on them.

Study area

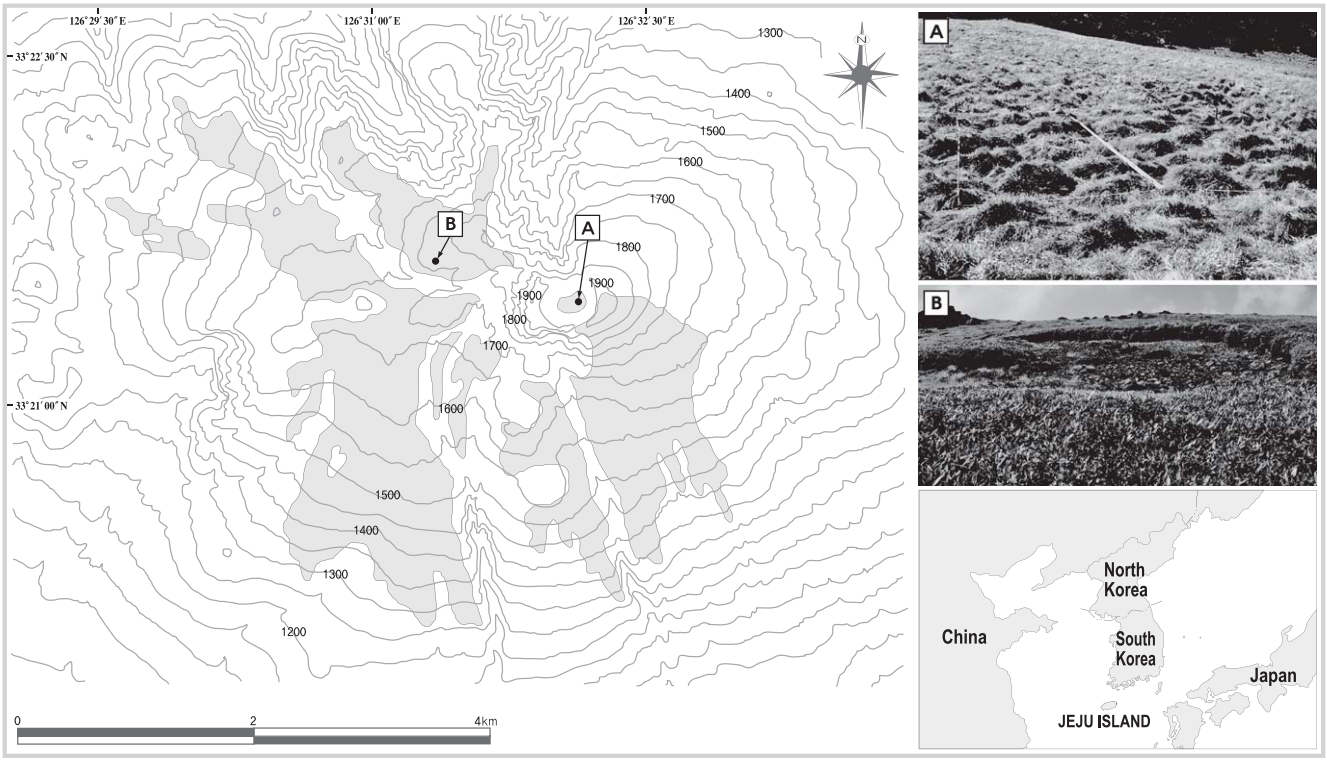
Mt Halla, the highest mountain in South Korea, is a central summit on Jeju Island, which lies 120 km away from the Korean Peninsula (33°21′N, 126°32′E). The mountain is an extinct shield volcano and its summit rises to 1950 m asl. Mt Halla was formed by intermittent volcanic eruptions between 1.2 million and 25,000 years ago (Lee 1982). Rocks of the volcanic edifice consist of basalt and trachyte (Lee 1982). Grassland is widely distributed on western and southern gentle slopes in the subalpine zone, which ranges between 1400 and 1860 m in altitude (Figure 1). Grasses such as *Festuca ovina* and *Agrostis clavata*, and shrubs such as *Empetrum nigrum* var. *japonicum*, *Rhododendron mucronulatum*, and *Rhododendron yedoense* var. *poukhanense*, occupy the gentle grassland slopes, except the north-facing and riparian slopes, on which *Abies koreana* dominates (Kim 1985; Kim et al 1999). Mean annual air temperature at Orimok weather station, at 970 m asl, is 9.7°C, and that of the subalpine zone is estimated to be 4.5 to 7.3°C, based on Mt Halla's temperature lapse rate of 0.58°C/100 m (Kong 1999). Annual precipitation at Orimok is 3356 mm, which is the maximum rainfall amount in Korea.

Methodology

Field observations were undertaken in a subalpine grassland on Mt Halla, and detailed investigations were conducted in two sites. *Thufur* were examined on the summit crater floor at 1840 m asl (Figure 1A). Seventy mounds were measured for their diameter and height.

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FIGURE 1 Distribution of subalpine grassland (gray surface) on Mt Halla and two sites for studying *thufur* in a summit crater (A: 1840 m asl) and turf exfoliation on a gentle northwestern slope (B: 1710 m asl). (Map and photos by Taeho Kim)



Thawed *thufur* were excavated to describe soil profiles and to collect soil samples from three horizons. The samples were analyzed for their physical properties such as bulk density, void ratio, water content, particle-size distribution, and liquid limit. Frozen *thufur* were also sectioned to identify cryogenic structures. Air and ground temperatures were recorded at 40 cm above and 2 cm below the respective mound apex using a HOBO H8 data logger (H08-008-04) with two temperature sensors (TMC6). Temperatures were measured at 1-hour recording intervals from 15 November 2002 to 15 May 2003.

Semi-circular and circular patches of bare ground were observed on gentle slopes and near-level ridge surfaces in the northwestern grassland between 1600 and 1800 m asl. These soil erosion scars were about 1–50 m wide, 1–50 m long, and less than 1 m deep. A horseshoe-shaped patch (Rost 1999) on a gentle slope (7.6°) at 1710 m asl was selected to examine a denudation process in the grassland (Figure 1B). A near-vertical terrace riser surrounds the patch, 26 × 12 m in diameter, except for the southwestern part, which is covered with *Sasa quelpaertensis*. In order to monitor the lateral retreat of the terrace, 40 erosion pins were horizontally inserted into 15 sections along the terrace riser. The protruding length of the pins was measured every two months from 29 September 2002 to 1 October 2004.

Results

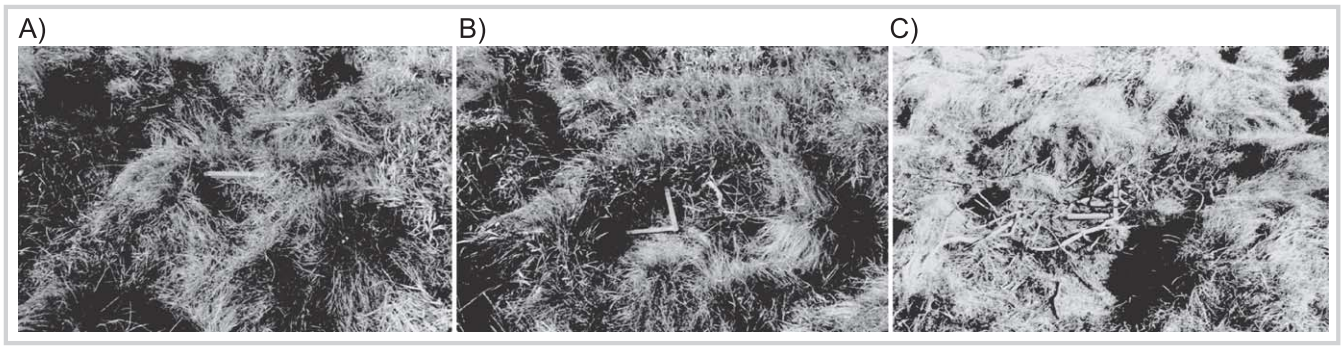
Morphological characteristics of *thufur*

Seventeen *thufur* occurred in a 5 × 5 m plot, indicating a density of 0.68 mound/m^2. Four or five mounds were distributed at an interval of 20–40 cm along a 5-m transect. The vegetation growing on the *thufur* was predominantly *Festuca ovina*. The *thufur* were dome-shaped except for two crater-like mounds. Small soil erosion scars were also found on the crater floor, which had been formed by the disintegration of *thufur* (Figure 2). The *thufur* on Mt Halla had an average height of 16.9 cm, ranging from 9–27 cm, and an average diameter of 98.3 cm. They were oval in outline; their long and short diameters were 42–200 cm and 41–172 cm, respectively.

The sections of thawed *thufur* showed two soil horizons of different colors underlying a root mat of grass 1–5 cm thick; the upper was dark brown (10YR 2/3–3/3) while the lower was brown (10YR 4/4–4/6). The soil horizons were likely to be cryoturbated; the brown soil layer, 1–4 cm thick and 46 cm wide, was captured in the dark brown horizon on a transverse section, while the horizon boundary was irregular and the brown soil layer stretched into the dark brown horizon on a longitudinal section (Figure 3). The disturbed soil had produced an obscure boundary that was composed of soils of a mixed color (10YR 3/4).

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FIGURE 2 Crater-like *thufur* showing disintegration stages (A–C) of cryogenic mounds. (Photos by Taeho Kim)



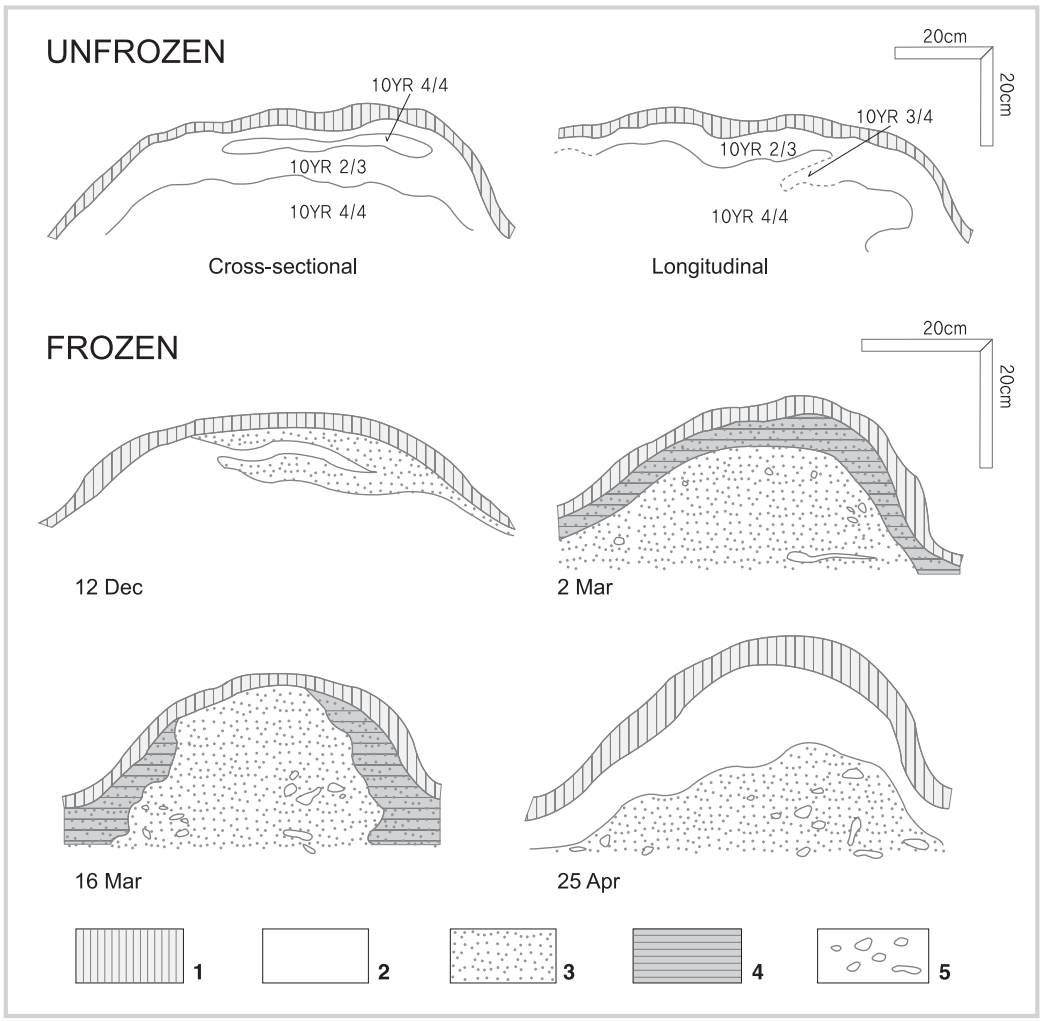


FIGURE 3 Cryoturbated *thufur* soil horizons (unfrozen) and cryogenic *thufur* structures (frozen) on Mt Halla. The right side of frozen mounds is a northern aspect. 1: root mat; 2: thawed soil; 3: frozen soil; 4: layer with high ice content; 5: segregated ice crystal. (Sketch by Taeho Kim)

Soil freezing began at the *thufur* apex and freezing rate depended on mound aspect; the southern aspect remained unfrozen while the northern aspect was almost frozen on 12 December when the mound was frozen 10 cm deep in the crest (Figure 3). During winter months, *thufur* were frozen as a hard solid mass and an ice layer occurred in the root mat and upper soil horizon. The ice layer showed an assemblage of ice crystals in an upper part and a mixture of ice and soil particles in a lower part. The ice layer began to thaw in mid-March; it disappeared in the crest on 16 March even though it remained 5 cm thick in the lower sides, suggesting that the apex thawed most quickly due to its warmer thermal conditions (Figure 3). The ice layer

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TABLE 1 Soil properties of *thufur* on Mt Halla.

Horizon	Soil color	Bulk density (g/cm^3)	Void ratio	Water content (%)	Particle-size distribution (%)		
					Silt/clay	Sand	Gravel
Upper	10YR 2/3–3/3	0.801	1.986	59.1	61.8	29.2	9.0
Middle	10YR 3/3–3/4	0.860	1.883	38.7	49.5	30.6	19.9
Lower	10YR 4/4–4/6	0.967	1.558	27.5	46.5	28.1	25.4

completely disappeared on 2 April but segregated ice still occurred in the dark brown soil horizon. Freezing state of soil also became less hard and thawing occurred 1–2 cm below the root mat in the crest. The upper part of *thufur* had almost thawed by late April; thawing occurred 12–16 cm below the root mat in the crest and 5–9 cm below in the lower sides on 25 April (Figure 3). The brownish horizon, however, remained frozen to a freezing front 43 cm below the mound apex.

Soil and thermal characteristics of *thufur*

Particle-size distribution of soils indicated that total silt and clay content varied between 46.5 and 61.8% (Table 1). By contrast, sand and gravel contents ranged from 28.1 to 30.6% and from 9.0 to 25.4%, respectively. Bulk density ranged from 0.801 to 0.967 g/cm^3 and void ratio from 1.558 to 1.986, suggesting that the soils become more compact with increasing depth. They also become drier with increasing depth because water content was 59.1% for dark brown soil and 27.5% for brown soil. Water content increased to 73.9–118.0% for dark brown soil and 49.9–82.8% for brown soil during early spring months. For instance, thawed dark brown soil showed a high water content of 62.3–111.7% in late April. The liquid limit of soils amounted to a water content of 72.7%.

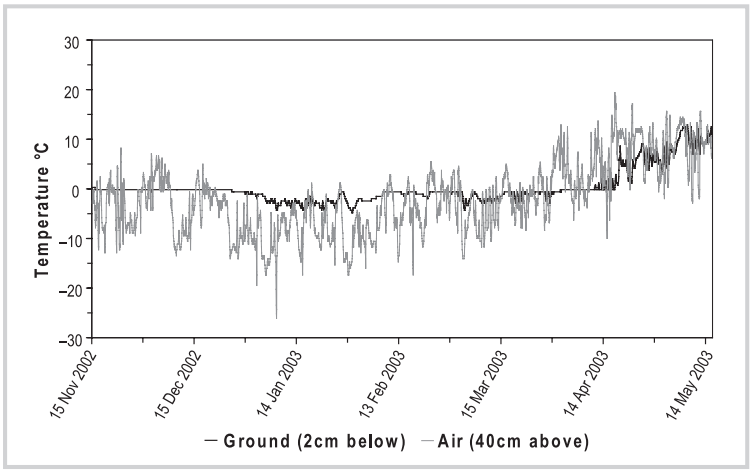
Mean daily air temperature was below 0°C on 125 days and, in particular, remained below 0°C continuously from 8 December to 9 February, for 64 days (Figure 4). The lowest temperature was –16.1°C on 29 January. There were no days with a mean daily air temperature below 0°C after 9 April. Freeze–thaw days occurred 70 times, including 16 days in March and 13 days in April, while freeze days occurred 79 times, including 28 days in January and 16 days in February. Ground temperature indicated that the mound was frozen at the latest in late December and freezing state remained until late March (Figure 4). The lowest mean daily ground temperature was –4.3°C on 30 January. The first freeze–thaw day in terms of ground temperature is likely to be in mid-March. No ground temperature below 0°C was observed after 18 April.

Lateral retreat of an exfoliating terrace

The exfoliating terrace riser, 30–80 cm high, was well exposed even though it had an overhanging edge, 10–28 cm long, that hung down and partly covered the riser beneath. The vegetation found on the retreating terrace was largely composed of *Empetrum nigrum* var. *japonicum*, *Sasa quelpaertensis*, and grasses such as *Festuca ovina* and *Agrostis clavata*.

The mean extent of riser retreat for the 2002–2004 period was 44.3 mm, equivalent to 22.2 mm/year. The extent of retreat, however, was different in each section; the maximum was 131 mm and the minimum 4 mm. The minimum extent of retreat was observed on the section partially covered with *Sasa quelpaertensis*. Riser retreat varied with the seasons (Table 2). The maximum extent of retreat occurred between December and April; 17.3 mm was monitored in 2003 and 16.6 mm in 2004. However, the riser was actively eroded in April because the terrace riser was usually covered with snow from mid-December to early April. Between October and early December, the extent of retreat was –3.0 and –3.4 mm. It resulted from soil particles that fell down from the upper riser and accumulated around erosion pins, indicating that the riser was also eroded during a freezing period. By contrast, retreat rates were relatively low during the summer and autumn months.

FIGURE 4 Air and ground temperatures in a summit crater of Mt Halla from 15 November 2002 to 14 May 2003.



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TABLE 2 Seasonal mean extent of riser retreat from 40 exfoliation sites between September 2002 and September 2004.

Riser retreat (mm)	2002		2003					2004		
	29 Sep–5 Dec	5 Dec–26 Apr	26 Apr–16 Jun	16 Jun–25 Jul	25 Jul–1 Oct	1 Oct–30 Nov	30 Nov–5 May	5 May–18 Jun	18 Jun–2 Aug	2 Aug–1 Oct
Mean	–3.0	17.3	3.2	3.4	2.3	–3.4	16.6	1.6	3.6	2.7
Maximum	35	91	22	22	23	9.5	72	20	20	44

Discussion

Periglacial features in the subalpine zone of Mt Halla

A mean annual air temperature of 6°C is regarded as the climatic limit for the formation and preservation of *thufur*, which are observed in seasonally and perennially frozen regions, suggesting that these cryogenic mounds are the most widespread periglacial landform (Lundqvist 1969; Koaze et al 1974; Grab 1994). Since frost-patterned ground was suggested as an index marking the boundary of periglacial regions (Troll 1948), the occurrence of *thufur* in the summit crater indicates that the subalpine zone of Mt Halla has a periglacial environment.

The formation of *thufur* has usually been explained by differential frost heave associated with small-scale variations in soil material and moisture, vegetation cover, and pre-existing topography. These variations produce pockets of frozen ground and permit localized frost heave, thereby initiating mound formation (Grab 2005). *Thufur* develop quickly when all factors are favorable and then remain relatively stable for a long period of time (Tarnocai and Zoltai 1978), even though involutions occur within the mounds (Scotter and Zoltai 1982). Although the *thufur* on Mt Halla have convoluted soil horizons, they are unlikely to experience intense frost heave because all excavated frozen *thufur* showed the massive cryogenic structure (Tsytovich 1975) characterized by well-bonded frozen soil with uniformly distributed invisible excess ice or frozen soil with individual ice crystals less than 25 mm thick (Andersland and Ladanyi 1994). Water content increased and exceeded the liquid limit during the early spring months so that the soil may become liquefied and displaced in response to pressure changes during the frequent freeze-back periods (Scotter and Zoltai 1982; Van Vliet-Lanoë 1991). Miyata (1988) also found that the involution in seasonally frozen regions resulted from high water content caused by melting of segregation ice. Thus, the disturbed soil profiles were attributable to ice segregation generating particle displacement during the freezing period and to high water content, beyond the liquid limit, during the thawing period.

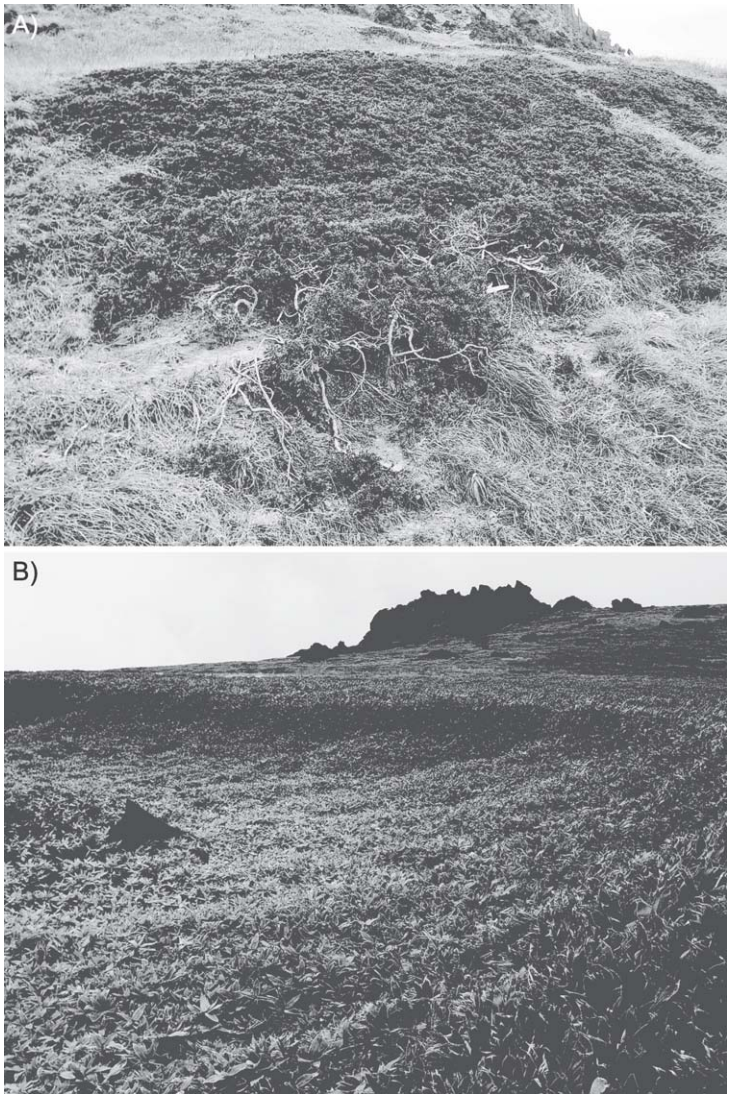
The lateral retreat of turf terraces is influenced by several processes such as aeolian deflation, frost action, rainsplash, rainwash, and animal activity (Pérez 1992; Grab 2002). Frost action is predominant in the subalpine zone of Mt Halla in that the maximum rate was observed during the thawing period when needle ice developed most frequently. Freeze–thaw days at the bare patch are estimated to occur 105 times annually. Frequent temperature fluctuation around 0°C is a favorable condition for the growth and ablation of needle ice, causing soil creeping on terrace risers. Thus, turf exfoliation in high-alpine regions is primarily caused by needle ice activity (Hastenrath and Wilkinson 1973; Troll 1973; Hastenrath 1977; Pérez 1992; Grab 2002). During the thawing and freezing periods, the terrace riser was covered with loose soil produced by needle ice. Soil saturated with melted ice, beyond its liquid limit, flowed down the riser. The loose soils can be easily removed by running water and wind. In addition, needle ice activity plays a primary role in *thufur* rupture (Scotter and Zoltai 1982; Grab 1994; Van Vliet-Lanoë et al 1998). Ruptured *thufur* were also found in the summit crater (Figure 2), which is a favorable place for needle ice development because *thufur* soil has a high silt and clay content and a high water content during the thawing period.

Effects of global warming on periglacial features

Mean annual air temperatures on Jeju Island have increased by 0.72°C on a north-facing slope and by 1.56°C on a south-facing slope over the last 40 years (Lim et al 2006). This temperature increase has caused a decline in alpine plants in the subalpine zone of Mt Halla (Kong 1999; Kim et al 2005; Lim et al 2006). A dendrochronological study also indicates that global warming is responsible for the decline of *Abies koreana*, the representative tree species of the subalpine zone of Mt Halla (Koo et al 2001). Vegetation decline due to global warming is more conspicuous for the alpine plants in the summit area with narrow thermal amplitudes. For instance, alpine shrubs such as *Diapensia lapponica* subsp. *obovata*, *Juniperus chinensis* var. *sargentii*, *Empetrum nigrum* var. *japonicum*, and *Vaccinium uliginosum* are severely affected by even a slight increase in temperature because they grow in a narrow range of daily maximum temperatures during the warmest month (Kong 1999).

Withered shrubs, eg *Juniperus chinensis* var. *sargentii* and *Empetrum nigrum* var. *japonicum*, were often

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FIGURES 5A AND 5B Vegetation changes affecting periglacial features of the subalpine grassland on Mt Halla. A) A withering shrub of *Juniperus chinensis* var. *sargentii* produces exposed soil surfaces; B) *Sasa quelpaertensis* covers a terrace riser and spreads onto bare ground. (Photos by Taeho Kim)

observed on crater-like and disintegrated *thufur* (Figure 2). In addition, the withering branches of shrubs exposed small soil surfaces around the northwestern grassland at 1800 m asl, making them more frost-susceptible (Figure 5). It might suggest that the withering of alpine shrubs on *thufur* initiates soil surface exposure on their apexes, after which frost action advances the formation of crater-like and ruptured mounds.

Global climate change has also caused the rapid spread of *Sasa quelpaertensis* all over Mt Halla (Kim 2002; Kim and Koh 2003). As *S. quelpaertensis* has expanded into the subalpine zone, the habitats of alpine plants have been reduced because grasses and dwarf shrubs are easily covered by *S. quelpaertensis*. Its rapid spread also affects the sequence of turf exfoliation: as a terrace riser is eroded, an overhanging edge on the riser protrudes and hangs down due to its own weight and its snow-cover. The overhanging edge eventually detaches and collapses from the vegetation cover and then is rapidly destroyed. It produces a vertical riser without an overhanging edge (Pérez 1992). The retreat of terrace risers on Mt Halla highlights a similar sequence in a terrace dominated by grasses and *Empetrum nigrum* var. *japonicum*. By contrast, a new vertical riser with exposed soil surface hardly appears in a terrace dominated by *S. quelpaertensis*. Since these plants are connected to each other by rhizomes, *S. quelpaertensis* is rarely detached from the vegetation cover on the terrace. It subsequently spreads onto bare ground and covers the riser, thereby stopping terrace retreat (Figure 5).

In addition to cryoturbated *thufur* and exfoliating terraces, the fact that *thufur* are broken on their apexes indicates that the subalpine grassland of Mt Halla is still dominated by periglacial processes because needle ice plays a primary role in the removal of vegetation and soil from the ruptured surfaces and the subsequent disintegration of *thufur*. The exposure of soil surfaces can be initiated by the withering of alpine shrubs on *thufur*, which is partly related to temperature increase. On the other hand, it is due to global warming that *Sasa quelpaertensis* spreads into the subalpine grassland and stabilizes the shallow soil erosion scars by covering their exfoliating terraces, suggesting the contrary effect of controlling vegetation destruction caused by frost-induced terrace retreat.

Conclusions

The subalpine grassland of Mt Halla on Jeju Island is likely to be under a climatic regime where periglacial processes are dominant. This can be inferred from the existence of miniature cryogenic mounds that are frozen during winter and show convoluted soil horizons. In addition, frost action is the process contributing most to turf exfoliation in the grassland. Disintegrated *thufur* formed by needle ice activity also indicate the presence of periglacial environments on Mt Halla. Recently, global warming has caused vegetation changes that have an indirect effect on the periglacial features of Mt Halla. The withering of alpine shrubs on *thufur* initiates soil surface exposure, facilitating the subsequent disintegration of mounds by needle ice activity. On the other hand, the spread of *Sasa quelpaertensis* prevents turf destruction caused largely by needle ice activity. Although the temperature increase due to global warming has not influenced the periglacial features directly, it will modify the geomorphic landscapes in the subalpine grassland of Mt Halla through vegetation changes which affect periglacial processes.

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ACKNOWLEDGMENTS

This work was supported by a research grant from the Chuongbong Academic Research Fund of Cheju National University in 2004. Many thanks to Professor W. Kong, Professor S. Kwon, and two anonymous referees who helped improve the final manuscript.

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