Decreasing soil-frost depth and its influence on the snowmelt infiltration in Tokachi, Hokkaido, Japan

Yukiyoshi Iwata[A], Tomoyoshi Hirota[B], Masaki Hayashi[C], Shinji Suzuki[D] and Shuichi Hasegawa[E]

[A]National Agricultural Research Center for Hokkaido Region, NARO, Memuro, Hokkaido, Japan, Email iwatayuk@affrc.go.jp
[B]National Agricultural Research Center for Hokkaido Region, NARO, Sapporo, Hokkaido, Japan, Email hirota@affrc.go.jp
[C]Department of Geoscience, University of Calgary, Calgary, Alberta, Canada, Email hayashi@ucalgary.ca
[D]Dep. of Bioproduction and Environment Engineering, Tokyo Univ. of Agriculture, Tokyo, Japan, Email s4suzuki@nodai.ac.jp
[E]Research Faculty of Agriculture, Hokkaido University, Sapporo, Hokkaido, Japan, Email hasegawa@env.agr.hokudai.ac.jp

Abstract
A dramatic reduction in soil frost depth occurred in the Tokachi region in northern Japan over the last 20 years. Since soil frost strongly affects snowmelt infiltration and runoff, the reduction in frost depth may have altered the water and nutrient cycles in this region. Soil temperature, water content, matric potential, and snowcover were monitored to quantify snowmelt infiltration flux at an agricultural field for five winters that had various soil frost conditions. When snowmelt began, the soil frost was 0.1 to 0.2 m thick in three winters and was absent in two other winters, providing a unique opportunity to compare snowmelt infiltration under frozen and unfrozen conditions. Most of the snowmelt water infiltrated into the soil under both frozen and unfrozen conditions indicating that the frozen soil layer of less than 0.2 m did not impede infiltration. Previous frost conditions in agricultural fields was simulated by the snow removal manipulation, which induced deep penetration of the freezing front. The snowmelt infiltration was restricted by a thick (about 0.4 m) frozen layer in this field. These results imply that a regional-scale change in the soil water dynamics has probably occurred with the reduction of frost depth in Tokachi.

Key Words
Soil freezing, snowcover, soil water flux, soil temperature, arable field, climate change.

Introduction

The depth of soil frost and the length of the frozen period are decreasing in cold regions around the world as a result of climate warming (e.g., Cutforth *et al.* 2004; Fruenfeld *et al.* 2004). The reduction of frost depth and the frozen period has important implications for hydrology in winter and early spring because the condition of the frozen soil layer strongly affects the amount and timing of snowmelt infiltration.
Potato producers in the Tokachi region of eastern Hokkaido (Figure 1) have recently noticed a significant reduction in frost depth. They rely on the soil frost to kill the potatoes left in the soil after harvest, which would become weeds when other crops are grown in the following year. Therefore, effects of climatic variability on soil frost have major implications on agricultural practices. However, there is little scientific knowledge about the effects of climate change on frost depth in this region. Moreover, very limited knowledge about the relationships between the frost depth and snowmelt infiltration makes it difficult to reveal the hydrological shift in this region. To overcome these problems, we analysed the frost depth data for the past 20 years, which was measured at the experimental field in the National Agricultural Research Center for Hokkaido Region (NARCH) located in the central part of Tokachi (Figure 1). The trend of frost depth was also estimated from the air temperature and thickness of snowcover to examine whether the same trend would be observed in other part of Tokachi. We also established a soil and snow monitoring site in the experimental field in NARCH, equipped with tensiometer, soil temperature and water content sensors, and meteorological instruments in the fall of 2001 to quantify the amount of snowmelt infiltration in recent years. The snow-removal treatment was operated in the winter of 2005-2006 to simulate the snowmelt infiltration in the past at Tokachi. The objective of this study is to reveal the change in soil-frost depth during the recent 20 years and gain insight into the influence of frost-depth reduction on the agricultural environment of Tokachi.

Methods

Analysis of the long-term data of frost depth and freezing index

The field data of the soil-frost depth in recent years (from 1986-2005) was collected in the experimental field at NARCH (42^{o}53'N, 143^{o}05'E) using a frost tube filled with 0.03 % methylene blue solution (e.g., Iwata *et al* 2008). Between 1979 and 2000, mean annual precipitation was 969 mm and mean monthly air temperature was -8.7 °C for January and 18.1 °C for July at the Memuro meteorological station, located 2.5 km west of NARCH(Japan Meteorological Agency, 2008) (Figure 1).

1 – 6 August 2010, Brisbane, Australia. Published on DVD.

Under the snow-free surface condition, annual maximum frost depth was strongly correlated with freezing index, which is a cumulative temperature index given by the summation of daily average air temperature for days with an average temperature below 0^{o}C (e.g., Lunadini 1981). Fukuda (1982) and Tsuchiya (1985) reported that frost depth was strongly correlated with freezing index until the snow depth reached 0.2 m (F_{20}), and proposed the following equation

$$D_{max} = \alpha\sqrt{F_{20}} \quad (1)$$

where D_{max} is the annual maximum frost depth and α is an empirical coefficient that integrates the effects of land topographical factors and soil thermal properties. Since α does not change by year for a given location, trends in D_{max} correlate with $\sqrt{F_{20}}$. Therefore, we used $\sqrt{F_{20}}$ to estimate the trend of D_{max} from the air temperature and thickness of snowcover at each meteorological station (Figure 1). The air temperature data from 1965 to 2005 were used for the calculation.

Mann-Kendall rank statistic was used to judge whether the trend of the frost depth or $\sqrt{F_{20}}$ is significant or not (see Hirota *et al*. (2006) for detailed calculation methods).

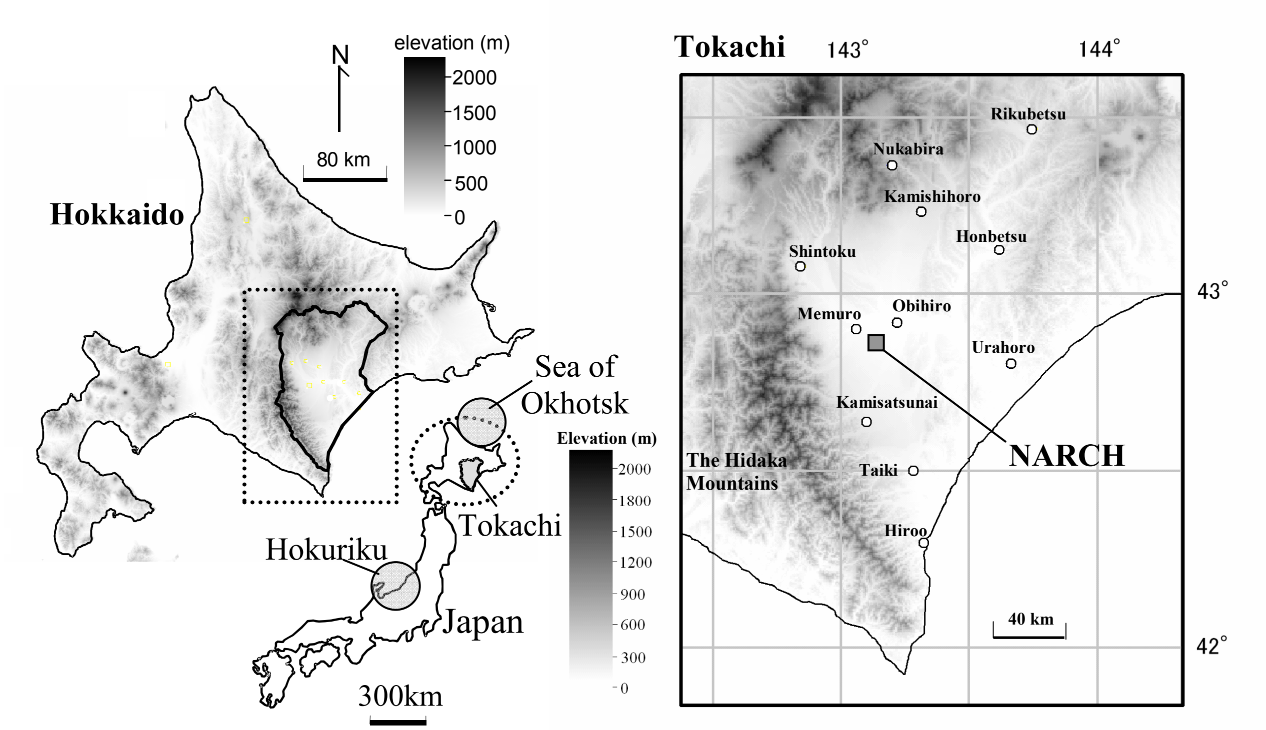

Figure 1. Location of the study site and the meteorological station used by Japan Meteorological Agency. Open circles and a solid square in the right panel mean the location of the meteorological stations and the study site in NARCH, respectively.

Site instrumentation for the measurement of soil water movement during the winter period

Soil water content was monitored using water content reflectometers (WCR) (CS615, Campbell) or time domain reflectometry (TDR) system (TDR100, Campbell) at a depth interval of 0.1 m from 0.05 to 1.05 m. The soil samples were collected from individual soil horizons to calibrate the probes in the laboratory. The water content measured by TDR in frozen soil is generally considered to represent liquid water content, as the dielectric permittivity of ice is similar to that of solid soil particles. Soil matric-potential below the frozen layer was measured continuously through the winter using tensiometers specifically designed for monitoring the potential of unfrozen soil below the frozen soil layer (Iwata and Hirota 2005a, b). Soil temperature was monitored using copper-constantan thermocouples installed from the surface down to 1.0-m depth. Soil was considered frozen when the temperature was below 0°C. A heat-flux plate (REBS, HFT1.1) was installed at a depth of 0.02 m to monitor ground heat flux. Precipitation was measured using an overflow-type tipping-bucket rain gauge with a heated water reservoir and a windshield. These data were collected automatically using data logger. Snowcover thickness and snow water equivalent (SWE) were measured manually twice a week. SWE was measured using a 50-mm internal diameter aluminum snow-survey tube. The study was conducted from November 2001 to April 2006. In the winter of 2005-2006, a similar new study plot was prepared next to the original plot, and simulated the snow and soil frost conditions in the past at Tokachi by the snow removal operation.

Estimation of snowmelt infiltration

Snowmelt infiltration was estimated from the water balance method (Iwata *et al.* 2008). To evaluate the snowmelt infiltration in recent years, we divided the snowmelt period into two, the early and late snowmelt periods. The early snowmelt period starts at the beginning of the snowmelt period and ends when the continuous increase of the water at the soil layer to the depth of 1 m (ΔS) finishes. Since ΔS was much greater than the amount of percolation to below 1 m during this period, we evaluated the snowmelt infiltration (ΣI_{nf}) from:

$$\Sigma I_{nf} = \Delta S \quad (2)$$

Late snowmelt period was the period just after the early snowmelt period. In contrast to the early snowmelt period, the percolation to below 1-m depth was much greater than ΔS in the late snowmelt period. Therefore, the soil water flux in the subsoil, which was calculated from Darcy's law for unsaturated soil using the tensiometer data, was used to evaluate the snowmelt infiltration (see Iwata *et al.* (2008) for the detailed calculation methods).

These methods will not be applicable for a thicker (>0.2 m) frozen layer (e.g., Tokachi in the past) because of the large amounts of ice melting, which can not be monitored using our soil moisture censors (TDR or WCR), increasing the uncertainty of the infiltration estimation using the water balance equation. Therefore, the following liquid-base water balance equation was used to evaluate the cumulative snowmelt infiltration (ΣI_{nf}) at the field which simulated past field conditions by using the snow removal treatment.

$$\Sigma I_{nf} = \Delta S - \Sigma I_m - \Sigma q \quad (3)$$

where ΣI_m is the amount of ice melt in the frozen layer and Σq is the cumulative soil water flux (positive upward) at 1-m depth. The ΣI_m was calculated from soil temperature and heat flux plate data using the heat balance method (see Iwata *et al.* (in review) for detailed calculation methods).

The amount of snowmelt infiltration was compared with the amount of snowmelt, which was calculated from the measurement of SWE on the ground and precipitation (Iwata *et al.* 2008).

Results

Frost depth in recent 20 years

Figure 2 shows the maximum frost depth monitored from 1986 to 2005 at the experimental field of NARCH (Figure 1). The average annual maximum frost depths were 0.38 and 0.13 m during 1986-1996 and 1997-2005, respectively, suggesting a reduction of the frost depth. The decreasing trend was statistically significant at a confidence level of $P < 0.05$. The decreasing trends of $\sqrt{F_{20}}$ were also statistically significant in most of the meteorological stations in Tokachi (Figure 1), suggesting that a regional-scale reduction in the frost depth had occurred in the last 20 years in this region. These are induced by the increased occurrence of heavy snowfall in early winter, decreasing the effective time window for soil-frost penetration (Hirota *et al.* 2006). The major decrease in $\sqrt{F_{20}}$ started from mid to late 1980's. The timing coincided with the sharp decreases of snowfall in the Hokuriku region of Japan (Figure 1) and the amount of drift ice in the southern part of the Sea of Okhotsk (Figure 1), which are regarded as indicators of the strength of the East Asian winter monsoon activities (Hirota *et al.* 2006).

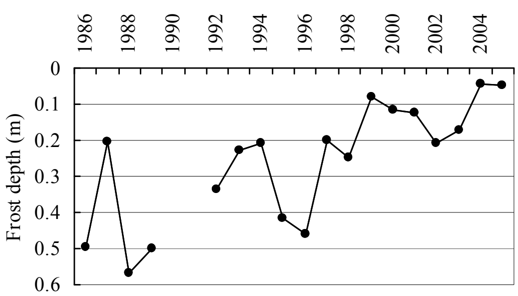

Figure 2. The annual maximum frost depth monitored at NARCH (Hirota *et al.* 2006).

Present snowmelt infiltration

The ΣI_{nf}, during the early snowmelt period was almost the same as the cumulative snowmelt (ΣM) regardless of the presence or absence of the frozen layer (Table 1). The ΣI_{nf} and ΣM were also similar in the late snowmelt period dor both frozen and unfrozen winters although the snowmelt rate (i.e., rate of water input) in this period was greater than that in the early snowmelt period (Iwata *et al.* 2008). These results indicate that most of the snowmelt-water will infiltrate into the soil even when a thin frozen layer exists during the snowmelt period.

Table 1. Frost depth before the snowmelt period, Amount of snowmelt water (ΣM), and cumulative snowmelt infiltration (ΣI_{nf}) during the early snowmelt period.

Year	Frost depth (m)	ΣM (mm)	ΣI_{nf} (mm)	$\Sigma I_{nf}/\Sigma M$
2002	0.17	119	109	0.92
2003	0.09	87	93	1.07
2004	0	39	40	0.98
2005	0	40	37	0.93
2006	0.10	41	35	0.85

Snowmelt infiltration 10 to 20 years ago

To simulate snowmelt infiltration, snowcover was removed after each snowfall event, several times between December 19, 2005 and January 13, 2006. The snow was put back on this field to prevent further penetration of the freezing front in January. As a result, the maximum frost penetration depth, which occurred in late February, was 0.43 m. The maximum thickness of the snowcover was 0.43 m, which was comparable to the maximum thickness of snow cover in the past Tokachi. The snowmelt period was started on March 10 and snowcover disappeared on March 22. The values of ΣI_{nf} and ΣM during the snowmelt period were 26 and 126 mm, respectively, suggesting the limitation of the snowmelt infiltration by the thick snow cover. The difference between ΣI_{nf} and ΣM, which is considered to be the sum of runoff and the change in surface storage, was 100 mm on March 22. This implies the substantial amount of surface runoff or prolonged surface ponding after the snowmelt period.

Conclusion

These results suggest that major shifts in the winter soil water dynamics and snowmelt runoff generation have probably occurred at NARCH as frost depths decreased from > 0.4 m to 0.05-0.2 m over the last 20 years. Since the meteorological factors causing the shift observed at the Memuro study site will also affect the entire Tokachi region, the hydrological shift (i.e. soil water and snowmelt runoff) may be occurring at a regional scale, affecting the soil water and nutrient cycles in winter and early spring and the snowmelt runoff regime.

References

Cutforth H, O'Brien EG, Tuchelt J, Rickwood R (2004) Long-term changes in the frost-free season on the Canadian prairies. *Canadian Journal of Plant Scence* **84**, 1085-1091.

Fruenfeld OW, Zhang T, Barry RG (2004) Interdecadal changes in seasonal freeze and thaw depths in Russia. *Journal of Geophysical Research* **109**, D05101, doi:10.1029/2003JD004245.

Fukuda M (1982) The estimation method of frost penetration depth under snow packs condition. In 'Research reports of grant-in-aid for special project of Hokkaid university in study on snow distribution and characteristics and its effect on frozen soil depth, vegetation and insect ecology in Hokkaido'. pp. 55-74. (in Japanese)

Hirota T, Iwata Y, M. Hayashi, S. Suzuki, T. Hamasaki, R. Sameshima, and I. Takayabu (2006) Decreasing soil-frost depth and its relation to climate change in Tokachi, Hokkaido, Japan. *J. Meteor. Soc. Jpn.* **84**, 821-833.

Iwata Y, Hirota T (2005a) Development of tensiometer for monitoring soil-water dynamics in a freezing and snow covered environment. *Journal of Agricultural Meteorology* **60**, 1065-1068.

Iwata Y, Hirota T (2005b) Monitoring over-winter soil water dynamics in a freezing and snow covered environment using thermally insulated tensiometer. *Hydrological Processes* **19**, 3013-3019.

Iwata Y, Hayashi M, Hirota T (2008) Comparison of snowmelt infiltration under different soil-freezing conditions influenced by snow cover. *Vadose Zone Journal* **7**, 79-86.

Iwata Y, Hayashi M, Suzuki S, Hirota T, Hasegawa S (in review) Effects of snowcover on soil freezing, water movement and snowmelt infiltration. *Water Resources Research.*

Japan Meteorological Agency (2009) Source of the archived meteorological data (Japan Meteorological Agency: Tokyo) http://www.data.jma.go.jp/obd/stats/etrn/index.php.

Lunadini V (1981) 'Heat transfer in cold climate'. (Van Nostrand Reinhold: New York)

Tsuchiya F (1985) Effect of soil frost and frost penetration on volcanic ash soil in agricultural field in Tokachi, eastern Hokkaido, Japan. Ph.D. thesis, Hokkaido University. (in Japanese).