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Soil water movement during periods of soil freezing and snowmelt in an agricultural field on volcanic ash soil

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Summary

Climate change over recent decades is thought to be responsible for the observed decrease in the depth of soil frost in Hokkaido, Japan. Specifically, in an experimental field of the National Agricultural Research Center for Hokkaido Region (NARCH) in the Tokachi district (42° 53' N, 143° 04'E) of Hokkaido, the annual maximum frost depth of the seasonal soil frost has decreased from > 0.4 m to 0.05–0.2 m over the last 20 years. A frozen soil layer generally increases the amount of runoff from snowmelt by decreasing soil permeability and impeding infiltration. This increase in the amount of runoff results in increased soil erosion, reduced soil moisture recharge and deep percolation, and an increase in the magnitude of the spring freshet. However, the recent decrease in soil frost depth is expected to increase snowmelt infiltration, which will in turn affect many of the aforementioned processes. Moreover, the development of soil frost causes a marked reduction in the soil matric potential at the freezing front, inducing a large potential gradient between the freezing front and the deeper soil layers. Development of this gradient results in the movement of water from the deeper soil to the freezing front, significantly influencing frost heaving and nutrient transport. Since the magnitude of this upward soil water movement may have decreased in response to the formation of a shallower frost depth, the upward flux of soil water during the cold winter is expected to decrease with the observed decrease in frost depth. Numerous field observations have been conducted in cold regions with deep frost depths (> 0.5 m), and infiltration tests using ring infiltration meters or numerical simulations based on field observation data have revealed that total soil water content (ice + liquid water) in the frozen layer is a dominant factor affecting the infiltration of snowmelt. However, relatively few studies have examined soil water movement (including snowmelt infiltration) in areas with relatively shallow frozen layers, such as in the agricultural fields of the Tokachi region.

To reveal recent soil water movements during the winter in Tokachi, we developed and installed a novel and comprehensive water and heat transfer monitoring system in the NARCH experimental field. The measurement components of this system were: (1) electromagnetic devices for producing a profile of the soil water content using either water content reflectometers or time domain reflectometry, (2) a specially designed tensiometer to characterize the matric potential head at the unfrozen layer below the frozen layer, (3) a copper–constantan thermocouple to determine soil and snow temperature profiles, (4) a frost tube for soil frost depth, (5) a heat flux plate for heat flux at the soil surface, (6) a small weighing lysimeter for evaporation, (7) an ultrasonic snow-depth gauge for the thickness of snow cover, (8) a snow survey tube for snow water equivalent, (9) a rain gauge with heated water reservoir for precipitation, (10) a resistive platinum sensor with forced ventilated shield for air temperature, (11) a ventilated hygrometer for air humidity, (12) a four-component radiometer for short and long wave radiation, and (13) an anemometer for wind speed.

From November 2001 to April 2007, there were

three winters with maximum frost depths of approximately 0.2 m (frozen winter). In contrast, soil generally remained unfrozen during the other three winters (unfrozen winter). During frozen winters, a substantial quantity of water (ca. 40 mm) was drawn from deeper layers into the 0-0.2 m topsoil layer when this froze, resulting in a drying of the subsoil (below a depth of 0.2 m); this drying is not unlike that which arises due to low rainfall combined with high evaporation from the soil surface. Under such conditions, the progression and regression of the freezing front, both of which are regulated by the thickness of snow cover and air temperature, affected the magnitude of soil water flux below the frozen layer. During unfrozen winters, soil water content was constant to a depth of 1.0 m due to a continuous supply of water from the bottom of the snow cover to the frozen layer. While the magnitude of the water flux was small, it was sustained for almost three months, which resulted in 13-62 mm of water infiltrating to a depth of 0.2 m before the spring snowmelt. During the period of snowmelt at the end of each winter, most of the snowmelt was observed to infiltrate into the ground. In frozen winters, the frozen layer had a thickness of 0.06-0.17 m at the soil surface during the snowmelt period, which implies that the thin frozen soil layer did not impede snowmelt infiltration. During the period of snowmelt, the extensive infiltration of snowmelt water (122-294 mm) resulted in the soil water content above 1.0 m reaching its highest levels over the duration of the study. The accumulated soil water fluxes at 0.2 and 1.0 m during the snowmelt period were 159-300 mm and 126-255 mm, which represented 32-63% and 28-51% of the total annual soil water fluxes at these depths, respectively. Taken together, these findings indicate that snowmelt infiltration is an important source of groundwater recharge in this region.

In the experimental field, the heat-insulating effect of snow cover played an important role in regulating the penetration of the freezing front. To evaluate the effect of snow cover on the land-atmosphere energy exchange, field data from the winter of December 2002 to March 2003 were analyzed. During this time, the soil froze to a depth of 0.2 m in early December while the snow cover was relatively thin (0.3 m). The soil started thawing from the bottom of the frozen layer after the snow cover reached a thickness of 0.7 m on January 4. This thawing was induced by a dramatic reduction in the heat flux from the soil surface to the snow, while the upward flux from the deep soil zone (> 1 m) provided a steady supply of heat. The magnitude of the heat flux in the deep soil zone is normally considerably less than the flux in the near-surface soil which is exposed to marked variations in air temperature. However, when the soil surface was insulated by snow, the magnitude of the near-surface heat flux decreased and became comparable to that in the deeper soil zone, indicating that the effect of the latter on thawing increased as the thickness of the insulation (i.e., snow cover) increased.

Statistical analysis of soil frost depths and meteorological parameters collected at the study site over the previous 20 years suggested that the decrease in frost depth was caused by snow cover developing relatively earlier in recent years. Consequently, it may be possible to simulate the dynamics in soil frost depth of previous years at the Tokachi site by physically removing snow from the ground in early and mid winter. Based on this idea, a paired-plot experiment was conducted at a study site located approximately 100 m from the abovementioned field. Two study plots were prepared and measurement systems similar to the one described above were installed at both plots. To simulate the frost depth conditions of previous years, the snow covering one of the plots (treatment plot) was removed in early and mid winter, while the snow on the other plot (control plot) was left undisturbed for the duration of the winter. The study was conducted from November 2005 to April 2008.

During the winter of 2005-2006, the soil of the treatment plot froze to a maximum depth of 0.43 m, which was comparable to the average maximum soil frost depth observed in previous years at the research station (from 1986 to 1996); conversely, the soil in the control plot only froze to a depth of 0.11 m. During the period of freezing, the magnitude of the upward soil water flux towards the freezing front (the upward soil water flux at a depth of 0.4 m) in the treatment plot was more than twice that in the control plot. During the snowmelt period, the infiltration of snowmelt water was unimpeded by the thin frozen layer in the control plot, whereas the relatively thick frozen layer in the treatment plot impeded the infiltration of water and generated 63 mm of runoff. These results clearly show that the changes in the timing and thickness of snow cover deposition can cause a dramatic reduction in frost depth and marked changes in soil water dynamics.

To more accurately elucidate the main factors affecting snowmelt infiltration to the deep soil layers, the relationships between the amount of snowmelt infiltration and soil frost condition (frost depth, soil temperature, and soil water content) were examined. From November 2005 to April 2008, field data for the aforementioned parameters were collected for three winters when soil frost depths ranged between 0.1 and 0.5 m at the paired-plot site. At a depth of 0.5 m, the amount of downward soil water flux during the snowmelt period was calculated based on the soil water content of the soil layer between 0.5 and 0.95 m and the soil water flux at a depth of 0.95 m. The infiltration ratio was then calculated by dividing the amount of downward flux into the amount of snowmelt water that had infiltrated to depths below 0.5 m. Although the infiltration ratio was strongly correlated with frost depth, there were no clear relationships between the infiltration ratio and other parameters (i.e., soil temperatures or soil water contents during the snowmelt period). Thus, frost depth was considered to be a very important factor for estimating the magnitude of snowmelt infiltration when the frost depth was relatively shallow (between 0 and 0.5 m).

These results clearly show the dramatic changes in soil water movement that have arisen over the last 20 years due to a decrease in frost depth, which itself can probably be attributed to global warming. Based on these findings, the relationship between soil frost depth and the extent of snowmelt infiltration are likely to play an increasingly important role in water resource management in the Tokachi region, as these factors provide important information regarding the changes in spring runoff and the infiltration regime. In addition, since nitric acid readily dissolves in water, our results also provide insights into the movement of dissolved mass components during the winter and early spring, which may be useful for determining fertilizer requirements for crop production, or for estimating the groundwater quality under an agricultural field.