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REVIEW

Promotion to Farmers of Snow Compaction (Yuki-Fumi) on Winter Wheat to Control Volunteer Potatoes without Depending on Chemical Materials

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Abstract
Adaptation to climate change in response to changes in snow cover has led to the development of snow control technology on agricultural fields in Hokkaido. In the control of the soil frost depth and freezing to death of potato tuber leftovers in harvesting during the subsequent cultivation, winter wheat has been an effective countermeasure in crop rotation systems in Hokkaido. We investigated a method used to control soil frost depth by snow compaction (yuki-fumi) to balance between killing potatoes and growing winter wheat. In an experimental test in NARO, we found that snow compaction has a negative effect on wheat growth at a very early stage of the snow cover. Snow compaction does not reduce soil temperatures as much as snow removal, but in potato-to-wheat rotation, it reduced volunteer potatoes by 1/10 because of the shallow position of unharvested potatoes. Snow compaction on wheat can control volunteer potatoes without depending on pesticides and does not adversely affect wheat growth. These environment-friendly agricultural systems have gradually become widespread in eastern Hokkaido.

Discipline: Agricultural Environment
Additional key words: climate change adaptation, environment-friendly, physical weed control, soil frost

Introduction

Located in the north of Japan, Hokkaido is Japan's leading cold-season field crop production region, with wheat accounting for 2/3 of domestic production and approximately 80% of the total production of potatoes (Shimoda et al. 2018a, 2022). Eastern Hokkaido, in particular, is one of the rare regions in Japan where the farmland area is still increasing (Shimoda et al. 2018b), agricultural profitability is high, and farmers are highly motivated to farm. In the field crop rotation system of Hokkaido, the most commonly grown crop after potato is winter wheat. In wheat fields just before harvest, there are many potatoes sprouting from tuber leftovers after the previous year's harvest (Fig. 1). Climate change adaptation is the background for the development of snow control technology. In the 1990s, the increased snow cover in early winter in the Tokachi region of eastern Hokkaido, Japan, caused tubers to survive and sprout the following year instead of dying due to soil frost (Hirota et al. 2006, 2011). Sprouting potatoes, or so-called volunteer potatoes, continue to increase during wheat cropping and become a source of renewal volunteer potatoes in the following year. High summer temperatures have reduced potato yields (Shimoda et al. 2018a, 2023a; Sugawara et al. 2021), and volunteer potatoes have

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become a reservoir of disease and nematode infestation, reducing product quality and causing growers to lose their motivation to produce potatoes. The main method to control volunteer potatoes has been glyphosate-based herbicides, which are costly, ineffective, and not sustainable and have not been widely adopted in the region.

The primary volunteer potato control developed in Hokkaido is snow plowing (yukiwari; Yazaki et al. 2013). The ground surface is exposed to the atmosphere after removing the snow, which has an insulating effect. Soil temperature then drops, and volunteer potatoes die at −3°C (Boydston et al. 2006, Chen & Li 1980). Soil frost depth (SFD) is used as an indicator, with snow removal reaching a temperature of −3°C at a depth of 0.15 m as the threshold for the control of volunteer potatoes (Hirota et al. 2011). Soil frost control has been established as a major volunteer potato control technique and has been implemented in >5,000 ha in Hokkaido (Hirota & Kobayashi 2019), and an information system that allows farmers to view the simulation of the SFD response to snow plowing has been established. Soil frost control is also increasingly used to improve soil physical and physicochemical properties (Iwata et al. 2015, Yoshimura 2018). However, snow plowing is not possible in wheat-growing fields because removing snow damages wheat stems and leaves.

The second strategy developed in Hokkaido to control volunteer potato is "yuki-fumi" (Fig. 2), a simple compacted snow removal method that uses a tractor with tire rollers to run on and compact snow (Shimoda et al. 2015). Yuki-fumi removes air within the snowpack, which serves as insulation, without disturbing the soil surface (Shimoda & Hirota 2018). There are few regions in the world like Hokkaido where winter wheat is grown under heavy snow. Winter wheat is a serious risk for snow mold (Yoshida & Kawakami 2013) and frost damage (Bergjord Olsen et al. 2018) during overwintering. In particular, snow compaction exposes wheat plants to a colder environment than normal overwintering, and agricultural stakeholders are concerned regarding frost damage due to low temperatures. Many farmers consider snow compaction difficult over winter wheat fields, but advanced growers' efforts have encouraged local agronomists and researchers (Shimoda et al. 2021) and "yuki-fumi" has been implemented over >1,000 ha in eastern Hokkaido as a control technique for volunteer potatoes. In relation to the soil frost control using snow compaction, this report describes the following: 1) the effects of snow compaction on winter wheat growth through testing at the NARO Hokkaido Agricultural Research Center, Memuro Experimental Station (NARO/HARC/M), 2) volunteer potato control in farmer field tests in Hokkaido, and 3) operational considerations found in the study until now.

Testing the impact of snow compaction on wheat growth at NARO/HARC/M

Snow compaction on wheat has been conducted continuously every year since 2013 (Shimoda et al. 2015, 2023b; Shimoda & Hirota 2018) in the Hokkaido Agricultural Research Center, Memuro Research Station (NARO/HARC/M). NARO/HARC/M is located in the Tokachi region, a major field crop farming area in Hokkaido, Japan, with an average temperature of 6.0°C, a cold climate with daily average temperatures below −20°C in midwinter, annual precipitation of

Fig. 1. Volunteer potatoes appearing near the harvest of winter wheat
Pictured at a farmer's field in Obihiro, Japan, in July 2015

Fig. 2. Tire rollers attached to a tractor to compact snow
Pictured in NARO/HARC/M in Memuro, Japan, in December 2020

approximately 1,000 mm, and volcanic ash soil representative of the region (Shimoda 2022).

Farmers' concerns are delayed growth and reduced yields due to frost damage after snow compaction on winter wheat in the region. The heading and flowering time of "Kitahonami" is delayed by 0.3 days at a target SFD of 0.30 m and 1.4 days at a target SFD of 0.50 m (Table 1). The use of snow-melting materials could accelerate spring growth and improve later growth (Shimoda & Hamasaki 2021).

Over the years, the experience of low soil temperatures below −10°C after snow compaction did not directly correspond to reduction in wheat growth. Because the latest Hokkaido varieties are highly resistant to freezing (Ito et al. 2021), the current major varieties have low potential for frost damage due to snow compaction. However, there was little snow cover in December 2019, and yields were greatly reduced because of frequent snow compaction (Fig. 3). If wheat is exposed outside, the direct friction of tires and direct encounter with cold air may affect the growth of wheat (Fig. 4). The first snow compaction time was earlier in 2018/2019 (Table 2). In NARO/HARC/M, after the first snow compaction on 10 December 2018 under low snow cover, yields in 2019 were reduced to 279 g m^{-2} for the Kitahonami variety compared to 651 g m^{-2} for the control. Conversely, no significant difference in yield occurred in 2020 after the first yuki-fumi on 9 January 2020 when snow covered the area (Fig. 3). If more wheat leaves are exposed to low temperatures, wheat growth may be significantly delayed and may not recover (Shimoda et al. 2023b). A previous study suggested that high temperatures in July shortened the grain-filling period and delayed growth led to a shortened fullness period, possibly resulting in significantly lower yields (Shimoda & Sugikawa 2020, Shimoda et al. 2023b) and physical disturbance (Shimoda & Hirota 2018). Considering the local climate, we can consider that snow compaction above a certain snow depth would remove the volunteer potatoes and would avoid negative effects on wheat growth.

Table 1. Heading date and average delayed days of winter wheat owing to snow compaction with soil frost depth (SFD) targets of 0.30 and 0.50 m for 7 years (2014-2020 harvest)

	Year							Different days
	2014	2015	2016	2017	2018	2019	2020	
Control	4-Jun	3-Jun	8-Jun	7-Jun	4-Jun	31-May	4-Jun	-
Target SFD = 0.30m	4-Jun	3-Jun	8-Jun	7-Jun	5-Jun	31-May	5-Jun	0.3
Target SFD = 0.50m	6-Jun	4-Jun	10-Jun	8-Jun	5-Jun	2-Jun	4-Jun	1.4

Variety is "Kitahonami," and experimental site is NARO/HARC/M.

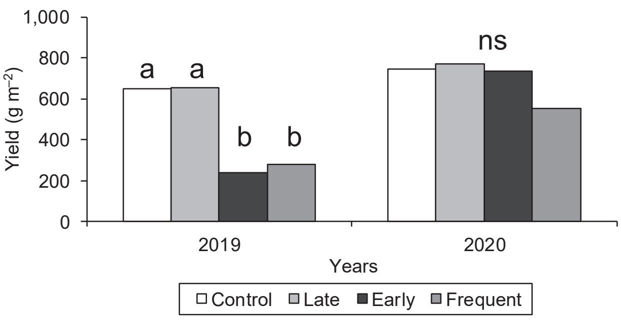

Fig. 3. Wheat yield of snow-compacted plots (late, early, and frequent compaction) compared to the control plot in NARO/HARC/M

Values labeled with different letters differ significantly (*P* < 0.05, Tukey's honest significance test). Fungicides were applied before overwintering (for details of the experiments, see Shimoda et al. (2023b)).

Testing the effect of snow compaction on volunteer potatoes at farmers' fields

Farmers, production groups, and extension organizations suspected that snow compaction would have a negative impact on wheat growth. In farmers' tests, we decided to apply snow compaction after the snow cover reached approximately 0.15 m to avoid adverse effects to wheat growth based on the results of the NARO test (Shimoda & Hirota 2018). We conducted a trial in farmers' plots in the Tokachi, Okhotsk, and Ishikari regions of Hokkaido (Shimoda et al. 2021). The reduction in soil temperature after snow compaction was slower than that after snow plowing. In snow plowing in previous studies, reaching a temperature of −3°C at a depth of 0.15 m (Hirota et al. 2011, Yazaki et al. 2013),

Fig. 4. Wheat plant visible above snow after snow compaction (left: photo taken on December 10, 2018) and covered with snow (right: photo taken on January 9, 2020) in NARO/HARC/M

Table 2. Snow compaction date in 2018/19 and 2019/20

Treatment	Year	
	2018/19	2019/20
Early	10-, 14-Dec	5-Dec
Late	7-Feb	2-, 4-Feb
Frequent	10-, 14-Dec, 16-Jan, 7-Feb	9-, 21-Jan, 2-, 4-, 19-Feb

Snow compaction times were early, late, and frequent practice (for details of the experiments, see Shimoda et al. (2023b)). Experimental site is at NARO/HARC/M.

which is considered the threshold for the control of volunteer potatoes. Some sites did not achieve a soil temperature of −3°C only in the surface layer below a depth of 0.05 m (Fig. 5). Snow compaction reduced the averaged volunteer potato occurrence to <1/10 of that of untreated snow (Fig. 6). Snow compaction can control volunteer potatoes without the use of pesticides. The source tubers of volunteer potatoes are located at a shallow depth of 0.04 m, on average, in potato-to-wheat rotation (Shimoda et al. 2021). Winter wheat cultivated after potatoes indicated that the unharvested potatoes were located at shallow depths. Then, snow compaction is effective in the removal of volunteer potatoes at even shallow depths. The maximum rate of yield reduction owing to yuki-fumi was 15% at Nakasatsunai in 2015/16 (Fig. 7), but the mean change of seven sites was only 1.0% in the Tokachi region.

Farmers in eastern Hokkaido conduct snow compaction by attaching a compaction roller to their tractors. Most compaction rollers for soil have a diameter of ≤500 mm. However, regionally commercially available tire rollers for both soil and snow compaction, which use overused truck tires and have a diameter of ≥600 mm, can compact snow up to 0.3 m, and many farmers use them.

Timing of snow compaction

The most critical point to note regarding snow compaction for wheat growth is the timing of the initial snow compaction. The implementation of the images of using snow as protection for wheat stems and leaves can avoid disturbances. Snow compaction was conducted twice in December during the early snow period, resulting in a 15% decrease in yields at a site although the decrease in soil temperature was not remarkable. Some disease may have occurred under early snow compaction. An initial snow compaction will not damage wheat plants in case of a snow depth of >0.15 m (Shimoda & Hirota 2018). In case the snow cover is >0.10 m, a trial run should be conducted to check snow compact traces. In years with a long snowfall period, leaves may turn yellow/brown immediately after the snow melts. This is because the uppermost leaves often die. However, the leaves and stems below yellow/brown leaves are alive, and this is not an outbreak of a disease. Therefore, growth rate recovers quickly (Fig. 8) and does not lead to a significant reduction in yield. If snow covers the fields with high soil moisture, a tractor will likely be stuck in the slush and will not be able to drive, or the tires will dig into the soil. Then, wheat plants will be damaged by the passing tracks of the tires. Snow compaction operations should be conducted on slightly frozen soil. In the morning, when the snow is slow to melt, tractor tires have less opportunity to be buried in the soil, leading to more uniform compaction after the operation.

Future considerations

Coping with heavy snowfall is a challenging problem with snow compaction. In heavy snowpack, tire rollers do not rotate sufficiently, reducing work efficiency and making it difficult to obtain sufficient compaction.

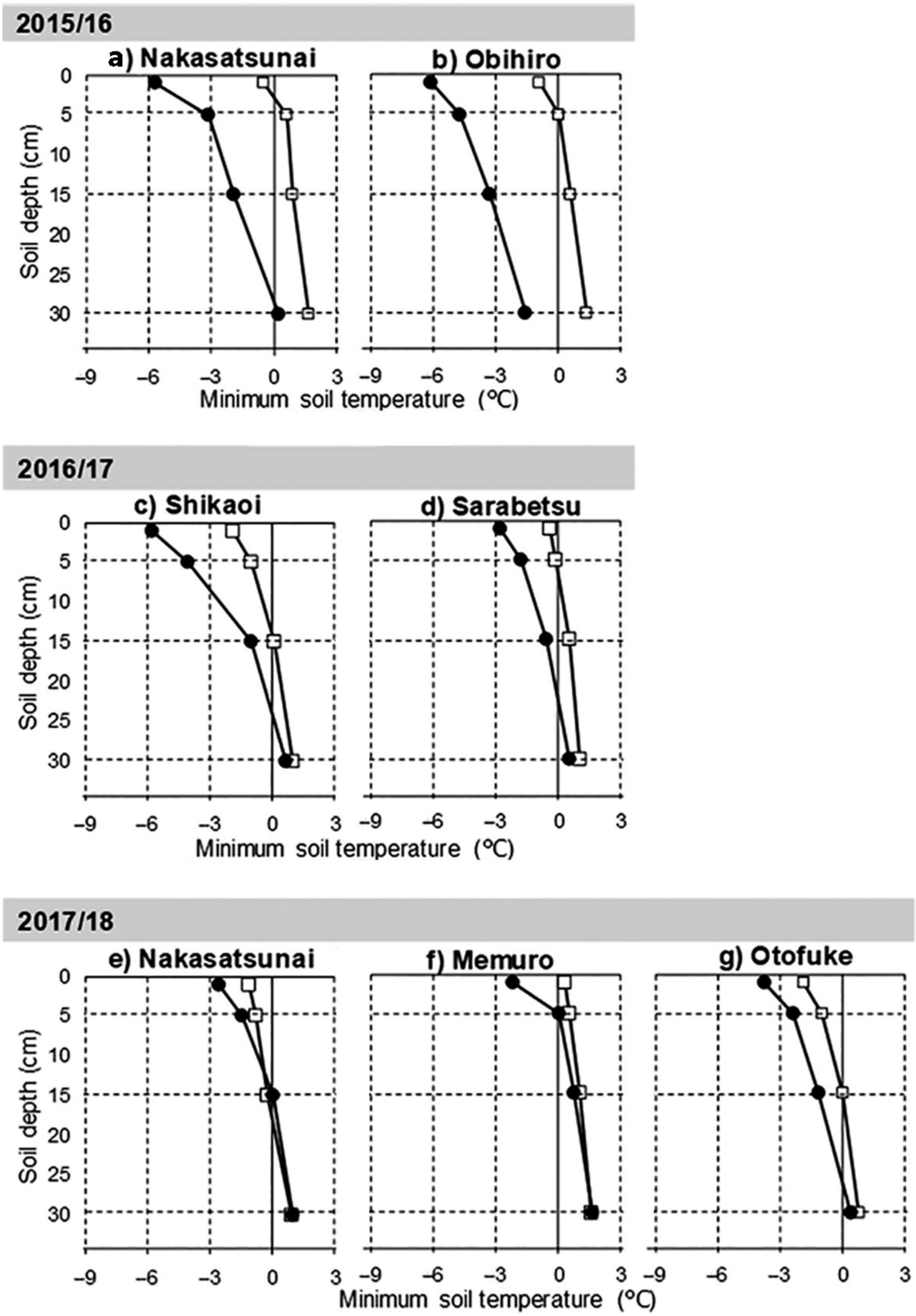

Fig. 5. Vertical distribution of annual minimum soil temperatures in control (white square plots) and adjacent snow-compacted (black circle plots) plots of seven fields with volunteer potato occurrence in Tokachi District

The site locations are the following: a) Nakasatsunai, 42°41′N, 143°09′E; b) Obihiro, 42°45′N, 143°13′E; c) Shikaoi, 43°05′N, 142°59′E; d) Sarabetsu, 42°41′N, 143°11′E; e) Nakasatsunai, 42°42′N, 143°09′E; f) Memuro, 42°50′N, 143°01′E; and g) Otofuke, 43°02′N, 143°10′E (for details of the experiments, see Shimoda et al. (2021)).

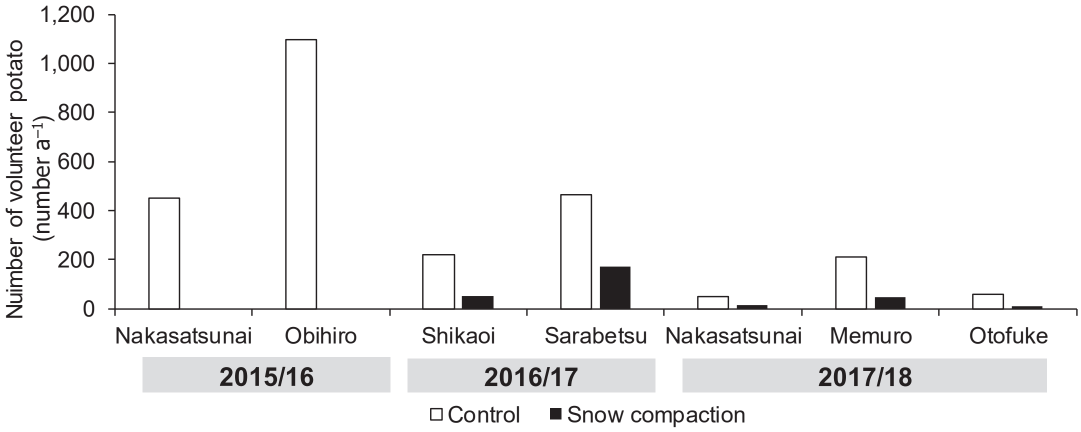

Fig. 6. Number of volunteer potatoes in control (white bars) and adjacent snow-compacted (black bars) plots of seven fields with volunteer potato occurrence in Tokachi District
The site locations are the same as those in Figure 5.

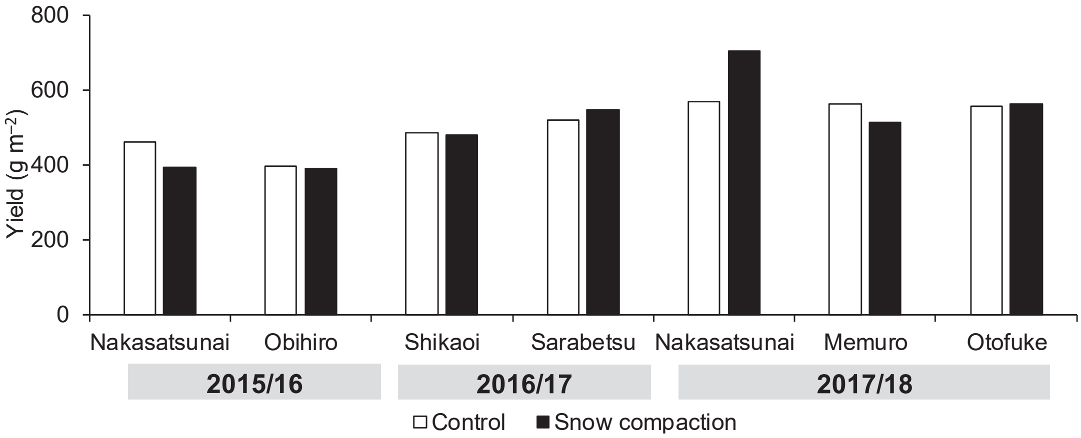

Fig. 7. Wheat yield in control (white bars) and adjacent snow-compacted (black bars) plots of seven fields with volunteer potato occurrence in Tokachi District
The site locations are the same as those in Figures 5, 6.

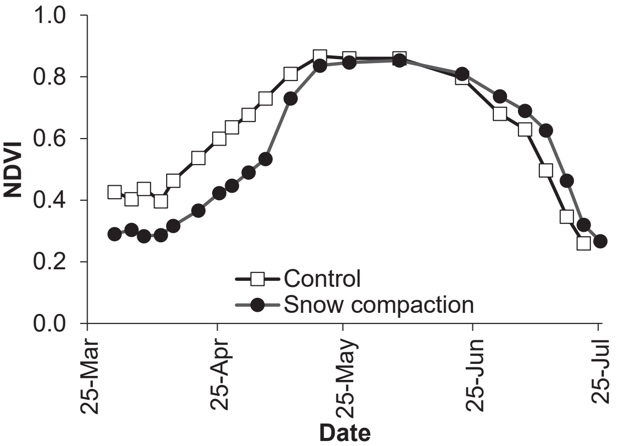

Fig. 8. Temporal change in normalized difference vegetation index (NDVI) for wheat in control (white square) and snow-compacted (black circle) plots after snowmelt in 2016 in NARO/HARC/M
NDVI was monitored using a portable handheld device Greenseeker (GreenSeeker, Trimble Navigation, Ltd.).

Operators have devised methods such as using tractors with larger tires to make running tracks or using crawlers with caterpillar to compact snow. In the future, work improvements may be implemented in more areas. Climate change may also increase the number of regions to implement. In northern Japan, rainfall in December is expected to increase and snowfall is expected to decrease in the future (Inatsu et al. 2016, Kawase et al. 2021), which could lead to widespread implementation in regions previously unimplemented. Refinement of winter weather information (Fukushima et al. 2019, Murakami et al. 2020, Yazaki et al. 2017) will also contribute to the advancement of snow compacting operations in the future. Previous studies have shown that soil frost can be useful for the efficient use of water resources and nitrogen in natural ecosystems (Fukuzawa et al. 2021, Makoto et al. 2014) and agricultural fields (Iwata et al. 2018, Onodera et al. 2022, Yanai et al. 2011). Recently, Shimoda et al. (2023b) indicated that snow compaction of winter wheat was found to have a positive impact on the regulation of snow mold. Temperature control under snow is effective in controlling resource transfer and plant diseases. Snow compaction is a useful means of environmental control, and there will be great potential worldwide for controlling the environment using physical changes other than snow.

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