Effects of snow compaction ‘yuki-fumi’ on soil frost depth and volunteer potato control in potato–wheat rotation system in Hokkaido

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ABSTRACT

Emergence of unharvested potatoes that survived during winter becomes source for nematodes and diseases, causing serious weed problems in rotational crop fields. Herein, we describe frost killing of unharvested potatoes in potato–wheat rotation fields using snow compaction ‘yuki-fumi’ under multiple climate conditions. The effect of snow compaction in controlling volunteer potato over winter wheat was verified in 17 farm fields in Hokkaido, Japan from 2015–16 to 2017–18. A reduction in the temperature of soil under ‘yuki-fumi’ was slower than that under snow removal ‘yuki-wari’, which was used in previous studies. However, snow compaction achieved a substantial reduction in volunteer potato sprouting in most of the experimental sites. The spraying of volunteer potatoes was reduced in snow-compaction blocks with soil temperatures below −3°C. For winter wheat sowing in potato–wheat rotation, the soil is tilled to a shallower depth than that for other crops, and thus, unharvested potato tubers are not pushed down during field preparation for wheat sowing. Consequently, even if the soil temperature drops slightly, snow compaction can regulate the sprouting of volunteer potatoes. Snow compaction did not exert any apparent influence on wheat growth and grain yield. At some sites with a deeper snowpack, development of soil frost and reduction in soil temperature did not progress with continued snow compaction owing to fallen snow. We validated the usefulness of snow compaction as a countermeasure to control volunteer potatoes in snowy regions.

KEYWORDS

crop rotation; volunteer potato; winter wheat; soil frost; cold region; weed control

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Introduction

In potato (Solanum tuberosum L.) crop management, the growth of volunteer potatoes is a serious global weed problem, as they are a source of insect pests, potato cyst nematodes, and diseases (Lutman, 1977). Unharvested potatoes can survive the winter and emerge as volunteers in the next cropping season. Global warming has shortened the soil freezing period, and this has exacerbated the problem of volunteer potatoes in northern potato-producing regions, such as the Nordic countries (Cooke et al., 2011) and northern Japan (Hirota et al., 2011). As these potatoes often survive for long periods, it is often difficult to achieve their optimal control with herbicides. Consequently, farmers spend several hours per hectare to manually remove volunteer potatoes from their fields (Nieuwenhuizen et al., 2007). Potatoes have become labour-intensive cultivars in crop rotations. Furthermore, high temperatures in summers during recent years have reduced potato yield (Shimoda et al., 2018), and consequently, farmers tend to exclude potatoes from their crop rotation systems.

Potato–wheat rotation is common where potato is grown (Meyer-Aurich et al., 2009; Myers et al., 2008; Peralta & Stockle, 2002). Potatoes are harvested just before winter wheat sowing in a typical crop rotation system in Hokkaido. Snow removal, known as ‘yuki-fumi’, is practiced after potato harvest. It temporarily removes snow cover and allows frost to penetrate the soil and kill unharvested potato tubers. However, snow removal cannot be performed in potato–wheat rotation because it would also remove the wheat shoots.

A previous study suggested the use of a snow-compaction practice, called ‘yuki-fumi’ (Shimoda et al., 2015) to enhance the thermal conductivity of snowpack during cold periods. The differences in the timing and frequency of snow compaction can reduce the thermal insulation effect of snowpack, leading to lower soil temperatures. Currently, snow compaction ‘yuki-fumi’ is not used as a common management practice in potato–winter wheat rotation in Hokkaido. However, progressive farmers in the area are interested in utilizing it to manage volunteer potato sprouting. Low winter temperatures and thin snowpacks are beneficial for the development of frost over soil depth profile. In previous studies, snow compaction was performed in the central part of the Tokachi region (Shimoda & Hirota, 2018; Shimoda et al., 2015). Even the southern part (STO) of the Tokachi region often experiences a large amount of snowfall during early winter due to the strengthening of low pressure along the southern coast (Hirota et al., 2006). The northern part (NTO) experiences higher temperatures due to the warmer west wind during winter (Fukushima et al., 2019; Yazaki et al., 2017). Furthermore, farmers in other regions hope to establish a method to control soil frost depth under various meteorological conditions.

In this study, we aimed to demonstrate the applicability of snow compaction to kill unharvested volunteer potato tubers without exerting adverse effects on the succeeding crop in a typical crop rotation system in Hokkaido. Volunteer potato sprouting and wheat yield in snow-compacted fields were compared with those in control fields by voluntary farmer participation. The paired-plot approach allowed us to quickly assess agro-ecosystems in fields affected by regional climate. Seventeen paired plots were tested to determine the effectiveness of snow compaction in controlling volunteer potato sprouting in potato–wheat rotation fields in the Tokachi, Okhotsk (OKH), and Ishikari (ISH) regions in Hokkaido, northern Japan. Soil freeze–thaw events could cause water logging or nitrate release after snowmelt (Andrews, 1996; DeLuca et al., 1992). To examine the effects of these events on the subsequent crops after soil freezing, wheat grain yield and protein content were also investigated.

Material and methods

Site description

We evaluated 17 paired plots of control and snow-compacted blocks in Hokkaido, northern Japan (Figure 1). The soil types (FAO/UNESCO) at the sites evaluated in the study were as follows: Andisol at 14 sites, Eutric Fluvisol at three sites, and Dystric Cambisol at one site. The temperature in the study sites were recorded at 2-h intervals. Daily air temperature was measured 1.6 m above the ground surface at 1-h intervals using a portable data logger (Onototori, TR-71S; T&D Co., Matsumoto, Japan). Snow depth was measured using a ruler every 10–20 d. The periodic mean and the lowest temperatures from December 15 to February 15 ranged from −5.6°C to −10.6°C and from −12.6°C to −20.8°C, respectively, in these sites (Table 1). The snow depth recorded on December 15 and February 15 corresponded to the annual maximum values.

Snow compaction

Snow compaction was conducted by four farmers each in NTO, STO, and OKH, and by one farmer in ISH. These farmers were verifying the effectiveness of this practice. Snow was compacted using a tire pressure roller from a tractor in 11 sites (Table 1). Seventeen sites were
established for comparison between snow compaction (SC) and control (CO) conditions at each site. To determine the effects of snow compaction at each site, the adjacent flat fields were selected as blocks for comparison to avoid the influence of soil erosion and heterogeneity in soil properties among the blocks. The minimum size of snow-compacted areas within a block was 4.0 m × 6.0 m at site no. 13. Snow-compaction blocks greater than 10 m in width and length were established at the other sites. Tire pressure rollers for snow-compaction purposes are commercially available, and they have a standard width of approximately 5 m. Snow was compacted using a flat circular wooden bar of approximately 3 m in width at two sites (nos. 2 and 5), whereas the snow was compacted using a tractor tire directly at one site (no. 3) and an all-terrain vehicle at another (no. 9). At two sites, the snow was manually compacted using a snowshoe (nos. 12 and 13). We designed the snow-compaction schedule to generate a soil frost depth of approximately 0.3 m to frost-kill potato tubers, as described by Shimoda and Hirota (2018). Direct loading on wheat plant parts is the most likely cause of damage associated with the loss of stems after snow compaction. Farmers performed the first snow compaction when the snow depth was more than 0.10 m to avoid direct physical damage to the wheat plants. A tractor with a tire roller or an all-terrain vehicle cannot run under heavy snow conditions; in such cases, snow compaction ceased. The farmers, agricultural extension centre, and researchers cooperated to develop a sustainable method of snow management with snow compaction (Hirota & Kobayashi, 2019).

**Snow and soil investigation**

Snow and soil frost depth were measured from December, during the onset of snow cover, to May, when the snow began to melt. In NTO and STO, samples of frozen and lower unfrozen soil were collected using a soil auger of internal diameter 30 mm (04.04.00.30.C and 0.1.10.11.C; Eijkelkamp Co., Giesbeek, The Netherlands) inserted into the ground with a hammer; soil frost depth was determined using the hardness depth (Shimoda & Hirota, 2018). In OKH and ISH, soil frost depth was measured using frost tubes filled with 0.03% methylene blue solution (Iwata et al., 2012; Onodera et al., 2019). Iwata et al. (2012) reported that soil frost depth between the soil auger and frost tube differed by ±0.028 m. To monitor soil temperature during the winter, thermometers with data loggers (Thermochron-SL; KH Laboratories Inc., Osaka, Japan) were installed at soil depths of 0.01, 0.05, 0.15, and 0.30 m in each block, with two or three replicates.

Snow density, snow depth, and snow water equivalent were measured after snow compaction. Natural snow was collected in an aluminium snow survey tube (Climate Engineering Co., Niigata, Japan) or PVC pipe of internal diameter 50 mm and compacted snow was collected using a soil auger of internal diameter 30 mm. The gravimetric water equivalents were
Table 1. Site description, wheat cultivar and snow compaction method of the observed fields. NTO, STO, OKH and ISH indicates north and parts of Tokachi region, Okhotsk region and Ishikari region.

| No | Year | Region | City   | Site               | Latitude (N) | Longitude (E) | Soil type  | Mean (°C) | Lowest (°C) | Maximum snow depth (m) | Wheat cultivar | Methods of snow compaction | Compaction times |
|----|------|--------|--------|--------------------|--------------|---------------|------------|-----------|-------------|------------------------|----------------|----------------------------|-----------------|
| 1  | 15/16| NTO    | Shikaoi| 43°5'             | 143°0'       | Andisol       | −5.6       | −12.9     | 0.22        | Kitahonami             | Tire pressure roller | 2                          |
| 2  | 15/16| STO    | Nakasatsunai | 42°41'         | 143°9'       | Andisol       | −8.8       | −15.8     | 0.61        | Kitahonami             | Wooden bar or board | 2                          |
| 3  | 15/16| STO    | Obihiro | 42°45'           | 143°13'      | Andisol       | −8.0       | −14.8     | 0.54        | Kitahonami             | Tractor tires    | 2                          |
| 4  | 16/17| NTO    | Shikaoi | 43°5'             | 142°59'      | Andisol       | −6.7       | −16.1     | 0.34        | Kitahonami             | Tire pressure roller | 2                          |
| 5  | 16/17| STO    | Sarabetsu | 42°41'           | 143°11'      | Eutric Fluvisol | −10.6     | −20.8     | 0.86        | Kitahonami             | Wooden bar or board | 2                          |
| 6  | 16/17| NTO    | Otofuke | 42°59'            | 143°13'      | Andisol       | −8.2       | −19.1     | 0.40        | Kitahonami             | Tire pressure roller | 2                          |
| 7  | 16/17| OKH    | Kunneppu| 43°46'            | 143°47'      | Andisol       | −8.1       | −14.9     | 0.49        | Kitahonami             | Tire pressure roller | 2                          |
| 8  | 16/17| OKH    | Kunneppu| 43°45'            | 143°47'      | Andisol       | −8.0       | −15.6     | 0.51        | Kitahonami             | Tire pressure roller | 2                          |
| 9  | 16/17| OKH    | Biohoro | 43°48'            | 144°11'      | Andisol       | −8.4       | −18.3     | 0.69        | Kitahonami             | All terrain vehicle | 1                          |
| 10 | 16/17| ISH    | Chitose | 42°55'            | 141°49'      | Andisol       | −7.0       | −16.3     | 0.51        | Kitahonami             | Tire pressure roller | 5                          |
| 11 | 17/18| STO    | Sarabetsu| 42°39'           | 143°12'      | Andisol       | −8.1       | −14.7     | 0.80        | Kitahonami             | Tire pressure roller | 2                          |
| 12 | 17/18| STO    | Otofuke | 43°2'             | 143°10'      | Andisol       | −7.7       | −17.2     | 0.47        | Kitahonami             | Tire pressure roller | 2                          |
| 13 | 17/18| NTO    | Memuro  | 42°50'            | 143°1'       | Andisol       | −6.6       | −12.6     | 0.69        | Kitahonami             | Snowshoe          | 4                          |
| 14 | 17/18| NTO    | Otofuke | 43°2'             | 143°10'      | Andisol       | −7.7       | −17.2     | 0.47        | Yumechikara             | Tire pressure roller | 4                          |
| 15 | 17/18| OKH    | Kunneppu| 43°45'            | 143°45'      | Andisol       | −8.4       | −14.9     | 0.62        | Kitahonami             | Tire pressure roller | 4                          |
| 16 | 17/18| OKH    | Biohoro | 43°46'            | 143°44'      | Dystric Cambisol | −7.6       | −14.8     | 0.59        | Yumechikara             | Tire pressure roller | 4                          |
| 17 | 17/18| ISH    | Chitose | 42°55'            | 141°49'      | Andisol       | −8.0       | −16.5     | 0.45        | Kitahonami             | Tire pressure roller | 4                          |
measured with snow samples weighed on an electronic scale.

To analyse the nitrate content profiles, soil samples from the three replicates in each block were collected from 0.60 m depth at 0.20-m intervals in 16 sites. Soil sampling was conducted before the soil froze in November and after thawing in April. Extraction of nitrate-N (NO$_3$-N) from the soil samples was conducted using 10% KCl solution. Soil samples (20 g) were added into polyethylene bottles and vigorously shaken with 100 mL of 10% KCl solution for 1-h. Thereafter, the suspension was percolated, and the resulting solution was used to measure NO$_3$-N using auto-analysers (FlAstar 5000 System, FOSS, Hillerød, Denmark and QuAAtro39; SEAL Analytical Ltd., Southampton, UK). Soil NO$_3$-N was estimated in the same three sites in OKH reported by Onodera et al. (2019).

**Crop management**

Wheat cultivars of the leading soft winter wheat ‘Kitahonami’ was planted at 13 sites and the leading hard wheat cultivar ‘Yumechikara’ was planted at 4 sites. These commercial cultivars of winter wheat planted in Hokkaido are resistant to freezing and snow mold (Matsumoto & Hsiang, 2016). They were sown in late September at 16 sites and early October at 1 site (no. 1) using a seed drill. Nitrogen was incorporated into the soil at seeding, and then applied twice or thrice in the form of ammonium sulphate as a supplement using a broadcaster at the following stages: the re-growing stage after snowmelt in early April, panicle formation stage in late April or early May, and flag leaf formation stage in late May. Most farmers applied total nitrogen at approximately 160 kg N ha$^{-1}$ for Kitahonami and 200 kg N ha$^{-1}$ for Yumechikara, according to fertilisation guidelines (Fueki et al., 2015). One farmer incorporated a slow-release fertiliser at seeding to avoid additional nitrogen application. A fungicide was applied to protect against snow molds in late October or early November.

**Crop investigation**

To determine wheat yield, we harvested three replicates of wheat from a 1.5-m × 1.0-m or 1.5-m × 2.0-m area in the centre of each block at maturity. The panicles in the plants in the centre row of the block or after harvest were counted. The number of wheat stems was recorded once within 10 days after snowmelt. The spikelet number was measured in the field and was used to estimate the value per square meter. Wheat yield and grain weight were estimated as the weight of whole-filled grains adjusted to 15% water content of the grain. The emerged volunteer potato tubers in the CO and SC blocks were counted at each site before wheat harvest. We estimated the grain protein content from grain nitrogen content using an NC analyser (Sumigraph N22; Sumika Chemical Analysis Services Ltd., Tokyo, Japan) as N × 5.7.

The sprouted volunteer potatoes were counted during the wheat grain-filling period or after harvest in areas of more than 20 m$^2$ within the blocks. The sprouted volunteer potato tubers were pulled out by hand or using a shovel scoop. The depth of sprouted tubers was estimated as the length from the tuber and green parts of the main stem. The results are presented as mean ±SEM.

**Results**

**Environmental conditions**

Snow compaction reduced snow depth in the SC blocks compared with that in the CO blocks, with a maximum difference of 0.05–0.35 m at each site (Figure 2(a)). The average snow density was 0.42 ± 0.02 Mg m$^{-3}$ in SC during the maximum difference in snow depth between SC and CO (Figure 2(b)). Snow compaction with snowshoes at site nos. 12 and 13 was 0.39 and 0.40 Mg m$^{-3}$ snow density, respectively. It rained after snow coverage in December 2017, which might have enhanced snow density; thus, at some sites, snow compaction reached >0.30 Mg m$^{-3}$ snow density in both SC and CO. Snow compaction caused soil freezing, with the annual maximum depth ranging from 0.02 to 0.27 m in CO and 0.13 to 0.40 m in SC (Figure 2(c)). We recorded <0.5°C as the difference in the minimum soil temperature at a depth of 0.05 m between SC and CO in site nos. 9 and 11, indicating inadequate soil freezing (Table 2). A wooden bar was used to compact snow at site nos. 2 and 5, and it increased snow densities from 0.37 and 0.31 to 0.57 and 0.45 Mg m$^{-3}$, respectively (Table 2). The maximum soil frost depth was 0.40 m at site nos. 1 and 3 in 2016, and the average maximum soil frost depth in CO and SC was 0.11 ± 0.02 m and 0.26 ± 0.02 m at all sites (Table 2).

The minimum soil temperature during the snow cover period ranged from 0.3°C to −4.6°C and −0.2°C to −7.4°C in CO and SC, respectively, at a depth of 0.01 m (Figure 3(a)). At two of the 17 sites, that is, nos. 8 and 2, the minimum soil temperature was below −3°C in SC at a depth of 0.15 m (Figure 3(c)), whereas site nos. 9 and 11 showed a difference of 0.3°C in soil temperature between SC and CO at all depths. This was most likely due to inadequately compacted snow. The mean difference between the SC and CO periodic minimum soil temperature during the snow cover period was 2.7°C, 2.5°C, 1.5°C, and 0.8°C at depths of 0.01, 0.05, 0.15, and 0.30 m, respectively, except at site nos. 9
The difference depth during freezing (Figure 2). The dotted lines are 0°C lines. The dashed line is the 1:1 line. The triangles represent the two sites where the difference in soil temperatures was within 0.5°C between CO and SC at depths of 0.01, 0.05, 0.15, and 0.30 m due to insufficient snow compaction.

### Table 2. Comparison of minimum soil temperature of 0.05 m depth and snow density at maximum difference in snow depth and maximum soil frost depth at control (CO) and snow compaction (SC) plots.

| No | Minimum soil temp (°C) | Snow density (m³ m⁻³) | Maximum soil frost depth (m) |
|----|------------------------|------------------------|-----------------------------|
|    | CO | SC | CO | SC | CO | SC |
| 1  | −2.2 | −4.2 | 0.33 | 0.48 | 0.27 | 0.40 |
| 2  | 0.6  | −3.2 | 0.37 | 0.57 | 0.03 | 0.29 |
| 3  | 0.1  | −4.7 | 0.21 | 0.48 | 0.11 | 0.40 |
| 4  | −1.0 | −4.1 | 0.19 | 0.49 | 0.13 | 0.26 |
| 5  | −0.1 | −1.8 | 0.31 | 0.45 | 0.09 | 0.27 |
| 6  | −1.5 | −4.5 | 0.15 | 0.22 | 0.14 | 0.20 |
| 7  | 0.6  | −1.0 | 0.21 | 0.45 | 0.05 | 0.22 |
| 8  | 0.2  | −1.3 | 0.21 | 0.40 | 0.05 | 0.20 |
| 9  | 0.3  | −0.1 | 0.28 | 0.34 | 0.04 | 0.13 |
| 10 | 0.1  | −3.0 | -    | -    | 0.05 | 0.30 |
| 11 | −0.8 | −0.7 | 0.29 | 0.36 | 0.18 | 0.22 |
| 12 | −0.2 | −2.3 | 0.20 | 0.39 | 0.14 | 0.25 |
| 13 | 0.0  | −1.4 | 0.22 | 0.41 | 0.02 | 0.19 |
| 14 | −1.0 | −2.3 | 0.13 | 0.36 | 0.09 | 0.25 |
| 15 | −1.1 | −2.4 | -    | -    | 0.16 | 0.32 |
| 16 | −0.9 | −3.8 | 0.23 | 0.37 | 0.17 | 0.35 |
| 17 | −1.2 | −3.5 | 0.34 | 0.53 | 0.13 | 0.25 |
| Mean | −0.5 | −2.6 | 0.25 | 0.42 | 0.11 | 0.26 |

and 11 (Figure 3). The minimum soil temperature during the snow cover period depended on frost depth (Figure 4).

The soil nitrate concentration (NO₃-N) in response to snow compaction was separately evaluated at three soil depths (0–0.60 m, Figure 5). Soil NO₃-N showed no clear trend with snow compaction, but at soil depths of 0.20–0.40 m, soil NO₃-N was higher in SC compared to the CO at soil depths of 0.20–0.40 and 0.40–0.60 m at site nos. 11 and 8, respectively.

### Volunteer potatoes

In the SC blocks, the number of emerged potato tubers during wheat cropping was considerably less than that in the CO blocks (Supplemental Fig. S1). In the CO blocks, volunteer potato tubers showed a mean sprouting density of 2.1 ± 0.7 tubers m⁻², whereas snow compaction reduced this value to 0.2 ± 0.2 tubers m⁻². At a soil temperature of less than −3°C, the density of volunteer potato tubers was less than 0.1 tuber m⁻² at a soil depth of 0.05 m (Figure 6(a)). Volunteer potato tubers did not sprout in the experimental blocks in 3 CO sites and 7 SC sites. The sprouted tubers were observed at soil depths of less than 0.05 m at seven sites in the CO blocks, whereas sprouted tubers were located at depths of more than 0.05 m in the SC blocks (Figure 6(b)). Therefore, volunteer-sprouted tubers were found at deeper soil depths in the SC blocks than in the CO blocks.

### Wheat growth

Stem density after spring snowmelt ranged between 413 and 1933 stems m⁻² in the CO blocks, which varied substantially depending on the site (Supplemental Fig. S2). However, the number of stems between the CO and SC blocks was similar. Wheat yield also differed substantially depending on the location, but the difference between the SC and CO blocks was not significant (Figure 7(a)). Panicle number was controlled to approximately 600 m⁻² (Figure 7(b)), which is recommended for regional stable wheat yield in Hokkaido (Kasajima & Araki, 2020). Grain weight showed no clear trend with the treatments (Figure 7(c)). Some sites in the SC block presented higher grain protein concentrations than those in the CO block; however, there were no apparent differences among the treatments in this experiment (Figure 7(d)). Blocks at site nos. 1 and 3 had the highest soil frost depth (0.40 m) but deep freezing in these sites did not have an adverse effect on wheat growth and yield. The maximum rate of yield reduction was 15% at site no. 3, but the mean change in
the yield rate showed a 4% increase with snow-compaction treatment. Deeper soil frost did not decrease wheat yield despite snow compaction.

Discussion

Relationship between frost depth and soil temperature under snow compaction

The ‘yuki-fumi’ snow-compaction approach promoted gentler snowpack thermal insulation than snow removal. The dependence of soil temperature on frost depth during snow compaction was not as strong as that during snow removal using the ‘yuki-wari’ method. Studies have shown that a frost depth of 0.3 m corresponds to a minimum temperature of −3°C at 0.15 m depth under snow removal conditions (Hirota et al., 2011; Yazaki et al., 2013). Snow removal ‘yuki-wari’ causes a direct loss of heat from the soil surface. Snow compaction ‘yuki-fumi’ caused a gentler decline in temperature because the soil frost depth increased due to the presence of snow. Even under snow compaction, the snow coverage reduces the cold thermal conductivity of the soil compared with that under snow removal and creates a gentler gradient between soil temperature and frost depth.

Our results suggested that snow compaction can reduce the emergence of volunteer potato tubers despite higher soil temperatures compared with that reported previously; for example, the critical soil temperature for killing volunteer tubers at 0.15 m was determined to be −3°C in on-farm snow-removal testing, except for potato–wheat rotation in Hokkaido (Yazaki et al., 2013). When sowing and transplanting in autumn or before spring, most farmers often till with a bottom plough to a depth of 0.30 m (Niwa et al., 2008). However, the short interval (less than 2 weeks) between potato harvesting and winter wheat sowing does not necessitate farmers to perform deep tillage multiple times. Consequently, farmers always till by harrowing to a depth of approximately 0.15 m to shorten the interval between tilling. Therefore, unharvested potato tubers would be located at shallower depths during winter wheat
planting than other crop planting. Thus, based on the results of the present on-farm testing of snow compaction, a soil temperature threshold of $-3\degree C$ at 0.05 m would be effective to kill most volunteer potato tubers. We found that snow compaction in potato–wheat rotation enables the control of potato tubers even at a shallow soil depth of 0.05 m compared with snow removal.

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**Figure 4.** Relationship between the maximum soil frost depth and minimum soil temperature during the snow compaction period at depths of (a) 0.01, (b) 0.05, (c) 0.15, and (d) 0.30 m. Black and white circles represent the control (CO) and snow compaction (SC) blocks. The triangles represent the two sites where the difference in soil temperatures was within 0.5$\degree C$ between CO and SC at depths of 0.01, 0.05, 0.15, and 0.30 m due to insufficient snow compaction.

**Figure 5.** Comparison of soil nitrate (NO$_3$-N) between the control (CO) and snow compaction (SC) blocks at soil depths of (a) 0–0.20, (b) 0.20–0.40, and (c) 0.40–0.60 m ($n = 16$). The dashed line is the 1:1 line. The triangles indicate the two sites where the difference in soil temperatures was within 0.5$\degree C$ between CO and SC at depths of 0.01, 0.05, 0.15 and 0.30 m due to insufficient snow compaction.
high snow density of 0.57 and 0.45 m$^3$ m$^{-3}$, respectively; whereas, the minimum soil temperature in site no. 5 was −1.8°C owing to the subsequent snowfall (over 0.6 m) that occurred after snow compaction in these sites. A large amount of snow often falls in early winter in STO (Hirot a et al., 2006). The duration of high thermal conductivity in the snowpack during cold periods determines the soil frost depth and soil temperature, and this additional snowfall resumes thermal insulation despite the previous snow compaction. Here, in sites with a deeper snowpack, soil frost development toward deeper soil layers and declines in soil temperature were slower even at the compaction treatment blocks. Annual snowfall would be important in considering the regional adaptivity of snow compaction. We verified snow compaction in ISH, which is relatively warm but has little snowfall; in addition, it is the main production area in eastern Hokkaido. The region from the central to the western part of Hokkaido, which experiences heavier snowfall, is the major table potato-producing region; it accounts for approximately 20% of potato production in Hokkaido (MAFF, 2020). Thus, there is a need to develop countermeasures against volunteer potatoes in the snowy region.

**Effects on wheat growth and yield**

Snow compaction did not affect the yield components of wheat in our study, indicating that deep soil freezing does not always reduce crop yield. A previous study reported that hard snow compaction under shallow snow depths contributed to rapid freezing of plants and a decrease in tillers during spring, and it directly determined the number of spikelets and grain yield (Shimoda & Hirota, 2018). Here, most farmers performed snow compaction when the snow depth exceeded 0.10 m. A certain amount of snow during snow compaction may be adequate to prevent a rapid decrease in plant temperature or directly damage wheat plants. A previous study showed that flooding damage resulted in a high soil moisture content that was fatal to winter wheat due to ice encasement (Andrews, 1996). A low hydraulic conductivity of the soil can enhance water logging after snowmelt in frosted soil fields, whereas a regional improvement in drain systems in eastern Hokkaido farms might mitigate the possible adverse effects of water retention after snow compaction (Niwa et al., 2008). Environmental conditions during the grain-filling period strongly affected wheat yield in Hokkaido (Shimoda & Sugikawa, 2020). To verify the application of snow compaction in other regions, the effects of regional weather, including the wheat-growing season and winter, should be considered. Our findings suggest that wheat grain yield is not always reduced by soil freezing from snow compaction.
Conclusions

Deepen soil frost by snow removal ‘yuki-wari’ has been used for the management of volunteer potatoes in Hokkaido. However, the ‘yuki-wari’ practice is not applied in potato–wheat rotation systems, which are common in cool temperature crop rotations, due to the damage to the wheat shoots. In the present study, snow compaction ‘yuki-fumi’ resulted in a large reduction in volunteer potato sprouting in most of the experimental sites. Investigation of farmers’ fields in which winter wheat was cultivated after potatoes indicated that the unharvested potatoes were located at shallow depths. Although the reduction in soil temperature occurred more slowly in fields with a deeper snowpack, spraying was greatly reduced at soil temperatures below −3°C and soil depth of 0.05 m. ‘yuki-fumi’ had no negative effects on wheat growth. Wheat yield showed a slight (4%) increase on average, and there was no considerable improvement in winter wheat growth. Snow compaction requires minimal labour and helps overcome the volunteer potato problem in cold regions without considerably reducing winter wheat yield. Continued cooperation between farmers, agricultural extension
centres and researchers will lead to the establishment of a new agricultural system with snow management.

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