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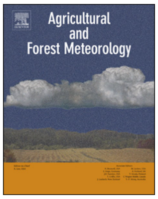

Planned snow compaction approach (*yuki-fumi*) contributes toward balancing wheat yield and the frost-kill of unharvested potato tubers

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ABSTRACT

Snow compaction implements the thermal conditions compatible with both killing volunteer potatoes and good wheat growth. To reveal how soil freezing regulates volunteer potatoes without preventing the growth of winter wheat, we conducted experiments in a wheat field in Hokkaido, Japan (42°53′N, 143°05′E), from winter 2013 to summer 2017. Owing to the enhanced thermal conductivity of snowpack during cold periods, different timings and frequencies of snow compaction allowed us to target different soil temperatures and frost depths. In most years and blocks, snow compaction achieved soil frost depth > 0.3 m and killed all potato tubers, but in 2016–17, soil frost depth was < 0.3 m in DC, and 7% of potatoes sprouted. These findings indicate that snow compaction before a heavy snowpack can effectively kill tubers. Wheat grain yield did not differ among treatments except in 2013–14. Deep soil freezing did not always reduce the wheat yield, but delayed snowmelt and thus delayed growth enhanced the likelihood of plants experiencing higher air temperature at the early spike development stage. Although changes in yield components such as culm length and spikelet density were associated with varietal responses to temperature, warm conditions in 2014 reduced the dry matter and shortened the grain-filling period, resulting in a greater decrease in yield. Furthermore, rapid hard freezing and direct physical impact may have caused much greater injury to wheat under a shallow snowpack in 2013–14. Thus, our findings indicate that proper snow compaction can balance wheat production and kill unharvested potatoes in crop rotation, and except for hot summer, gentle procedure of grain-filling could compensate the grain weight even in less spring growth.

1. Introduction

Recent climate change has increased interest in the environmental effects of crop management in boreal regions (Peltonen-Sainio et al., 2009). Climate warming leads to the invasion of weeds, pests, and diseases in various crops (Baker et al., 2000). Volunteer potato (*Solanum tuberosum* L.) regrowth is a serious weed problem caused by climate change, and recent gentle soil freezing has led to numerous unharvested potatoes surviving the winter and emerging as weeds in the spring (Boydston et al., 2006; Hirota et al., 2006; Nieuwenhuizen et al., 2010). When not controlled, volunteer potatoes host diseases and insects, including the serious global pest the potato cyst nematode (Nicol et al., 2011; Suffert and Ward, 2014).

Daily mean soil temperature needs to be approximately −3 °C or below to achieve complete frost-kill of potato tubers (Chen and Li, 1980; Boydston et al., 2006; Yazaki et al., 2013), and the annual maximum frost depth (D_{max}) needs to exceed 0.3 m to prevent sprouting (Hirota et al., 2011; Yazaki et al., 2013; Iwata et al., 2015). Soil freezing has decreased since the late 1980s because the increasingly common early onset of deep snowpack can thermally insulate the soil from cold air (Hirota et al., 2006). The practice of snow removal using a tractor equipped with a snowplow, termed *yuki-wari* (Hirota et al., 2011), can regulate the sprouting of volunteer potatoes, allowing farmers without using agrochemicals or manual labor during the crop growth season (Hirota et al., 2011). Over the largest area of production of winter wheat (*Triticum aestivum* L.) and potato in the Tokachi region of Hokkaido, Japan (Mori et al., 2015). As part of the regional crop rotation, potatoes are harvested immediately before winter wheat sowing in the same field (Matsuzaki, 2014). However, *yuki-wari* cannot be performed in winter wheat fields because the removal of snow would physically damage the soil surface as well as shoots and roots.

Thus, to ensure the survival of winter wheat while killing

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unharvested potato tubers, farmers must control the soil freezing. The practice of snow compaction, termed *yuki-fumi*, may help to control soil temperature and frost by utilizing snow's thermal insulation effect (Shimoda et al., 2015a), and some farmers in the Tokachi and Okhotsk regions are testing the effectiveness of this practice. Snow cover thickness and density determine the duration of high thermal conductivity of the snowpack during cold periods. The soil temperature and frost depth can be regulated by controlling the timing and number of compactions (Shimoda et al., 2015a).

Freezing and frost heaving can cause extreme injury to the roots and stems of winter wheat. Studies on cold acclimatization and freezing survival are usually based on a regulated freezing test (Fowler et al., 1999; Skinner and Garland-Campbell, 2008). We do not yet understand how artificially regulated snow cover affects wheat growth underground, and further research of the potential adverse effects of snow compaction on winter wheat growth is needed. Improved cold tolerance, such as freezing resistance and snow mold resistance (Yoshida et al., 1998; Nishio et al., 2016), has been developed in commercial cultivars of winter wheat grown in Hokkaido. The leading cultivars of soft wheat (Kitahonami) and hard wheat (Yumechikara) have some differences in winter hardiness and ear formation (Araki, 2016; Terasawa et al., 2016), and these different responses to environmental conditions may influence appropriate snowpack control. Furthermore, environmental changes associated with recent climate warming may affect both the sprouting of volunteer potatoes and wheat growth.

The aims of this study were (1) to clarify the thermal and freeze conditions after planned snow compaction; (2) to understand the growth and yield of wheat plants subjected to soil frost and compacted snow; and (3) to determine the conditions compatible with both killing volunteer potatoes and good wheat growth. We investigated the temporal changes of snow and wheat growth at two targets of maximum soil frost depth (0.3 and 0.5 m) compared with a control field (no snow compaction). More than half of the global area of potato and wheat production is located between 44 °N and 58 °N (Hijmans, 2001; Sacks et al., 2010), and crop rotation from potato to wheat is common in some of these regions (Peralta and Stockle, 2002; Gabriels et al., 2003). Our findings may help to overcome the problems associated with crop rotation of potato and winter wheat in cold regions.

2. Material and methods

2.1. Site description and meteorological data

Field experiments were carried out at the Memuro Experiment Station (42°53′N, 143°05′E), which is part of the Hokkaido Agricultural Research Center (NARO/HARC), in eastern Hokkaido. Daily meteorological data, including air temperature and snow cover thickness, were measured at the meteorological station at the experiment station. Continuous snow cover was defined as snow cover thickness at 09:00 JST. The mean annual temperature was 6.1 °C (from September 2008 to August 2017), and the monthly mean temperature was −9.8 °C in January and 20.1 °C in August at the station. The soil type is volcanic ash soil (classified as an Andosol by the World Reference Base for Soil Resources; International Union of Soil Sciences (IUSS) IUSS Working Group WRB, 2006), and the field had a mean soil pH of 5.6 (Shimoda et al., 2015a).

2.2. Planned snow compaction

The experimental design was a randomized complete block with three replicates. Eighteen plots (4.0 m × 3.0 m) were established for the three treatments (control: CO, $n = 3$; designed compaction: DC, $n = 3$; and frequent compaction, FC, $n = 3$) and two wheat cultivars (Kitahonami, currently the leading soft wheat cultivar (Yanagisawa et al., 2007), and Yumechikara, the leading hard wheat cultivar (Tabiki et al., 2011; Ito et al., 2015) in Japan). Relying on depths recorded previously at the station (Shimoda et al., 2015a), we designed a snow compaction schedule to generate a soil frost depth of 0.3 m in DC and of 0.5 m in FC to frost-kill the potato tubers. Snow was compacted with the tire (size 600/65R38) of a tractor (EDR-PKCPS6, Massey Ferguson, France).

2.3. Environmental observation and data analyses

Snow cover thickness, snow density, snow water equivalent, and soil frost depth were measured from the onset of snow cover until snowmelt. Snow cover thickness was measured with a ruler once every 5 to 10 days. We drove a linear soil sampler with a 30-mm internal diameter (04.04.00.30.C and 0.1.10.11.C; Eijkelkamp Co., Giesbeek, the Netherlands) into the frozen ground with a hammer, sampled frozen and lower unfrozen soil, and determined soil frost depth from the hardness of the soil profile in each plot (Iwata et al., 2012). We collected natural snow in an aluminum snow survey tube with a 50-mm internal diameter (Climate Engineering Co., Niigata, Japan) and compacted snow with a soil sampler with a 30-mm internal diameter, and measured gravimetric water equivalents were from snow samples weighed on an electronic scale (HL-300WP, A&D Co., Tokyo, Japan) within an acrylic plate case in the field. Snow density was calculated as the snow water equivalent divided by the snowpack volume.

To monitor the soil temperatures during winter, we installed thermometers with data loggers (Thermochron-SL, KH Laboratories Inc., Osaka, Japan) at 2-h intervals in each block at a depth of 0.08 m from November 2013 and soil sensors (SDI-12 digital TDT sensors; Acclima Inc., Bushland, TX, USA) in each block at depths of 0.08 m, 0.15, 0.23, and 0.40 m from December 2014 onward. Temperatures were measured at 30-min intervals and stored as 2-h means in data loggers (CR1000, Campbell Scientific, Logan, UT, USA) from December 2014. We define the snowmelt date at the end of winter as the first snow-free day after the last snow cover sequence with a duration of at least 1 month (Vitasse et al., 2017).

2.4. Crop management and field sampling

To assess the rate of potato tuber sprouting during wheat growth, we buried five tubers at depths of 0.05 and 0.15 m in 2014 and 2015 and at 0.15 m in 2016, with three replicates in each plot. Most unharvested tubers in farmer's fields are positioned from the surface to 0.15 m depth (Yazaki et al., 2013). The tubers (cv. Irish Cobbler) were harvested in September and stored in a dark, cool (~10 °C) room; tubers weighing from 10 to 30 g each were buried in late October. In 2016–17, test tubers were obtained from a field submerged by Typhoon No. 10 on 31 August to 1 September 2016 (Nguyen-Le and Yamada, 2017), so their likelihood of sprouting was lower in 2016–17, even in the control block.

The two wheat cultivars were sown in mid September at 255 seeds m^{-2} using a seed drill. Nitrogen was applied (as ammonium sulfate) at 60 kg N ha^{-1} three times: incorporated into the soil at seeding, broadcast by hand at the regrowing stage in mid April, and broadcast by hand at the flag leaf stage in late May. Fungicide was applied to control snow mold disease in early November and leaf rust and *Fusarium* head blight in early June to early July.

To determine yield, we harvested wheat from a 1.0-m × 1.8-m area in the center of each plot at maturity from four rows within 1 m, with three replicates. The stem density was recorded once before snow cover and every 7 to 10 days after snowmelt until heading. By daily observation of three replicates in each block, heading date was defined as the first day when 50% of all panicles had emerged (Maruyama et al., 2010). Panicle number was counted on 50 stems selected from the row at the center of the plot. Culm length and the number of spikelets were measured in the field and converted to the value per square meter. Grain yield was measured after threshing and cleaning, grain weight was recorded as the weight of whole filled grains adjusted to 15% grain