SNOW REDISTRIBUTION AND SOIL WATER STORAGE AS IMPACT BY SURFACE RESIDUE CONDITIONS

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of HANXUE QIU find it satisfactory and recommend that it be accepted.

Chair

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SNOW REDISTRIBUTION AND SOIL WATER STORAGE AS IMPACTED

BY SURFACE RESIDUE CONDITIONS

Abstract

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Water availability is a major limiting factor affecting agricultural productivity especially for the dryland farming regions of the Great Plains and the Pacific Northwest (PNW). Studies show that no-tillage (NT) practices result in more soil water storage by retaining more snow in stubble, enhancing infiltration and reducing evaporation in areas where winter is the primary recharge season, whereas conventional tillage (CT) practices result in considerable redistribution of precipitation with elevated surface runoff. We hypothesize that the residue effects on precipitation redistribution also affects the spatial variation of soil water. Studies show that spatial variation of available soil water has important environmental and economic effects and implications by affecting crop yield and quality and effective fertilization recommendation. Our objectives were to evaluate residue effects on snow redistribution and the spatial variation of soil water in the Palouse area of the PNW. Two side-by-side farms near Pullman, WA, one under NT, the other under CT, were surveyed for snow depth, snow water equivalent (SWE), and resultant soil water storage during the winter season of 2007–2008. Results indicated that snow pack on average was distributed more evenly and had less spatial variation under NT. Compared to CT, NT retained 10–20 cm more snow by its standing residue at the ridge top for the events surveyed. Snow water equivalents followed the same pattern of larger spatial variation in CT. The resultant soil water in the spring was the lowest at the ridge top areas, and highest at valleys in both treatments. However, under CT, soil water at the ridge top area was 6% less than, and in valleys 17% more than, the average over the whole treatment. Such variation was much smaller in NT where soil water at the ridge top was only 4% less than, and in valleys 6% more than, the average. Although many factors may have contributed to the spatial variation of soil water, residues under NT retarded the generation of runoff, retained more snow at the ridge top and steep-sloped areas, and likely reduced the soil water spatial variation.

Keywords: Snow drifting, snow-holding capacity, snow water equivalent (SWE), soil water storage, standing stubble, no-tillage, conventional tillage

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Introduction

Water availability is one of the major limiting factors affecting agricultural productivity (Sinai et al., 1981; Wright et al., 1990; Campbell, 1992; Afyuni et al., 1993). This is particularly true for the dryland farming regions of the Great Plain and the Pacific Northwest (PNW) where annual precipitation is generally between 25–60 cm. Zentner et al. (1993) reported that average spring wheat yield increased by 80 kg ha^{-1} for a 1.3 cm increase in soil water storage from winter recharge in Saskatchewan, Canada, and the yield response to soil water increase doubled during years with dry growing season. In Northern Great Plains of the United States the yields of spring and winter wheat increased by 50–290 kg ha^{-1} per 2.5-cm increment soil water stored over the winter recharge season (Johnson, 1964). To evaluate the relationship between available soil water and grain yield, Schllinger et al. (2006) conducted a study in eastern Washington between 1993 and 2005, and discovered that 6.4 cm of baseline soil water was required for vegetative growth of wheat and each 2.5 cm of above-baseline soil water produced 363.2 kg/ha grain.

Quantifying the relationship of wheat yield and soil water has been an on-going effort since the synthetic N fertilizer became widely available in 1940's (Pan et al., 2008) with the intention to recommend N fertilizer application rate for highest grain yield. Although such N fertility recommendation models are satisfactory on a regional scale, it is difficult to apply them for site-specific N management since a particular landscape is often featured with complex spatial variation of available soil water and organic matter (Pan et al., 2008). The spatial variation of soil water can have other important environmental and economic implications. Nutrient volatilization and leaching losses were found to be affected by spatial and temporal variation of soil water through various physiochemical and biological processes (Fenn and Fossner, 1981; Fenn and Miyamoto, 1981; Ferm, 1988; Liu et al., 2007). Studies also showed that greater spatial variations of available soil water caused greater variation of crop yield and crop quality associated with protein content (Daniels et al., 1987; Wright et al., 1990; Afyuni et al., 1993; Sadler et al., 1995; Bongiovanni et al., 2007; Huggins, 2008). Elevated protein content of wheat improves the crop quality and therefore increases the profitability (Jørgensen and Jørgensen, 2007; Bongiovanni et al., 2007).

The spatial variation of soil water may occur in many ways and are impacted by complicated site specific climatic, topographic, soil and management factors (Sinai et al., 1981; Afyuni et al., 1993). Pan et al. (2008) proposed several possible mechanisms, including uneven snow redistribution and accumulation due to over-winter drifting and melting. It is intuitive that soil water tends to derive from topographically high area and accumulate at topographically low area. Yet there is limited knowledge about how various management practices affect the spatial variation of soil water storage.

Studies indicated that, compared to conventional tillage (CT), no-tillage (NT) retained more soil water in the traditional winter wheat cropping regions of the Southern Plains (Dao, 1993; Sharpley and Smith, 1994; Baumhardt and Jones, 2002), in the inland PNW hilly dryland farming regions (Fuentes et al., 2003; Qiu et al., 2008), and in Canadian prairies (Cutforth and McConkey, 1997). CT practices, on the other hand, retained less soil water due in part to elevated surface runoff. Studies in the Southern Great Plains showed that CT practices could cause significant redistribution of precipitation with elevated surface runoff compared to conservation tillage (Sharpley and Smith, 1994; Shipitalo et al., 2000; Truman et al., 2003). McCool et al. (2006) compared several conservation tillage practices to the traditional control treatment, Continuous tilled bare fallow (CTBF), using 18 years of data, and reported that under the continuous NT winter wheat (WW/WW-

NT) practice, runoff was only 11.8% of that under the CTBF.

In the Northern Great Plains and Canadian Prairies snow accounts for 20–30% of the annual precipitation or 250–500 mm (McCool et al., 2003). In the Palouse region of the inland PNW, 50–70% of precipitation occurs during the primary period of soil water recharge from October to March (Oregon Climate Service, 2008). Snow accounts for nearly one-third of the total precipitation during this period (NCDC, Station # 456789, 2008a). Snow drifting is one of the important precipitation redistribution processes and wind-driven snow translocation was reported to create snow depths that vary by a factor of ten or more over short distances in Arctic tundra (Liston and Sturm, 1998). Factors influencing snow drifting include the wind field, topography, surface conditions (vegetation, crop residues, roughness from tillage) and precipitation (Liston and Sturm, 1998). Terrain with bush vegetation tends to hold more snow in place during the winter than bare ground. Increasing shrub abundance may increase snow depth by 10–25% in Arctic tundra (Liston and Sturm, 1998; Sturm et al., 2001; Sturm et al., 2005).

Similar to bush vegetation, the presence of surface residues, especially standing stubble, enhances snow capture in winter (Benoit et al., 1986; Cox et al., 1986). Snow depth and soil water were compared between strips with stubble heights of 39–60 cm and 15–20 cm over 10 years in Saskatchwan, Canada (Campbell et al., 1992). The treatment of high stubble resulted in an average of 10-cm greater snow depth and 16% greater water infiltration than the treatment with shorter stubble. Smika et al. (1966) reported based on a four-year study in Northern Great Plain that a field with standing residue trapped more snow and gained 5.2 cm soil water during the winter season, whereas a field with fall incorporation tillage lost 0.3 cm soil water on average in the 1-m soil profile due to less trapped snow. Similar results were also reported by others (Staple et al., 1960; Aase et al., 1980; Nielsen, 1998).

Snow accumulation and snowmelt runoff can be an important water redistribution mechanism that impacts soil water recharge (Hiemstra et al., 2002). Attaining a better understanding of the factors that influence snow capture and retention in agricultural landscapes is important to evaluate the impacts of residue management practices on soil water storage and its spatial variation. The purpose of this study was to evaluate the impact of two contrasting tillage practices with different surface residue conditions, namely NT and CT, on snow accumulation and redistribution as well as the spatial variation of soil water storage on a field scale.

Methodology

Site description

The study was conducted on two adjacent farms located 10 km north of Pullman, WA: the Washington State University Cook Agronomy Farm (CAF), and the Clark Farm, a private farm. Both farms have hilly topography typical of the Palouse region with soils in the Palouse-Naff-Thatuna association consisting of Latah (Fine, mixed, mesic Xeric Argialbolls), Palouse (Fine-silty, mixed, mesic Pachic Ultic Haploxerolls), Thatuna (Fine-silty, mixed, mesic Xeric Oxyaquic Argialbolls), and Naff (Fine-silty, mixed, mesic ultic Argixerolls) silt loams (USDA NRCS, 2008). The CAF has been under continuous NT since 1999 with winter wheat harvested in the fall of 2007 immediately before the initiation of this study. Tillage history records prior to 2007 were not available for the Clark Farm but for the study period, the field was conventionally fall-tilled in 2007 leaving little surface residue or roughness.

A weather station was operated at the CAF during the study period, with precipitation, solar radiation, air temperature, wind speed and direction measured in every 5-min but averaged and recorded in hourly interval.

Field snow monitoring and sampling

Field surveys of snow depth and snow density were conducted following several schemes. An extensive survey was first carried out on January 10, 2008 on a 25.6-ha field, including 12.0 ha located in the southeastern portion of the CAF and 13.6 ha along the northwest edge of the Clark Farm. This survey aimed to assess the spatial variation of snow across the topographical positions from valley to ridge top and from south- to north-facing slopes (Fig. 1). The overall aspects of the two farms were slightly different, with the Clark Farm having more south- to southwest- and northwest-facing slopes than the CAF exhibiting mainly south- and north-facing slopes (Fig. 1). Two smaller areas (4.4 and 4.1 ha in the CAF and Clark Farm, respectively), both south-facing and encompassing a ridge top, shoulder, and valley, were chosen for a series of detailed measurements of snow depth and density (Fig. 1). These two smaller areas contained very similar soils both with Naff silt loam soil at ridge tops and Palouse silt loam at south slopes. In addition, a snow survey was made along a ridge in the CAF where several tillage treatments resulted in different standing stubble heights. This survey was to determine the effects of residue height on snow holding capacity (Fig. 1). The timing of these surveys was illustrated in Fig. 2, together with fresh snow fall and on-the-ground snow depth as well as air temperature from a nearby National Climatic Data Center (NCDC) weather station (NCDC Station #456789, 2008a).

Stratified random sampling points were pre-determined from a GIS site map using the Hawth's tool extension in the ArcGIS software program (ESRI, Inc., 2007) for the survey of the larger field. The field was divided into 50 m×50 m grid by N–S and W–E transects, and a random location within each grid was chosen by the GIS program, resulting in a total of 267 points for the two farms. The survey was conducted on January 10–11, 2008, by navigating an All-Terrain Vehicle (Ontario Drive and Gear Ltd., New Hamburg, Ontario, Canada) directed by a field GPS receiver to the pre-determined sampling locations. A few points were mistakenly missed and the survey resulted in 260 snow depth observation points in total (111 in the CAF, 149 in the Clark Farm). Additionally, fifty-two observation points (18 in CAF and 34 in Clark Farm) were added to capture the abrupt changes in snow depth in shoulder areas. These points were not used, however, for snow depth evaluation since they were not randomly chosen. The snow depth at each location was manually measured to the closest 0.5 cm using a ruler. Eighteen percent of the 260 points (47 points) were randomly selected using the aforementioned GIS program for snow-density measurements.

The majority of the snow-density samples were taken with a clear plastic tube (3.72 cm diameter) pushed to the bottom of the snow pack. Snow surrounding the tube was removed and the snow in the tube was carefully transferred into a labeled zip-closed plastic bag. Out of the 47 snow-density sampling points, five had a snow depth exceeding 0.7 m. For these points, multiple samples in 0.3-m intervals starting from the snow surface were taken at the middle of each interval using soil sample rings (4.75-cm diameter and 5.0 cm in height). The snow samples were allowed to melt at room temperature (23 °C) to obtain the snow water equivalent (SWE, the column height of the liquid water corresponding to the same diameter as the sampler) and the snow density was calculated as the ratio of the SWE to the measured snow depth. Three sampling locations at the Clark Farm were found bare and there was no snow for sampling.

Twenty-five sampling points on the CAF and 22 on the Clark Farm were randomly chosen for the two smaller south-facing areas using the same GIS program. Eight surveys of snow depth were conducted via snow-shoeing during the period of January 28 to February 14, 2008; each survey lasted 4–8 hrs as weather permitted. The eight surveys captured one major snow event for the season (Fig. 2). Snow density sampling was also conducted in three out of the eight surveys.

The survey along the ridge top route was completed on Jan. 15, 2008 during a small snow event. Snow depth was observed at 50 points and snow density samples were taken from 13 locations (eight from south-facing, and five from north-facing, slopes).

Residue measurement

The height of standing residue was measured for all the observation points for snow depth within the large field, the smaller area, and the surveyed ridge top within the CAF. In addition, the amount of residue (separated into standing stubble and flat residue in the CAF, and grossly for the conventionally-tilled Clark Farm) was measured for the two smaller areas. The residue measurements were conducted during April 8–18 after the snow had melted and the field was accessible.

Soil water content sampling

The 47 points on the two smaller areas were sampled on May 13, 2008 to 1.5-m depth (unless an impenetrable obstruction was encountered) with a Giddings soil sampling machine (Giddings Machine Company, Windsor, CO) mounted on a John Deere 350 crawler. The soil cores were cut into 0.3-m pieces and each piece was taken as one sample. At the time of sampling, the Clark Farm had been tilled and the surface soil was dry. One extra sample within the top 5 cm was taken at each sampling location at the Clark Farm. The gravimetric soil water content was determined by measuring the weight of a soil sample prior to, and after, oven-drying at 105 °C for 24 hr and the weight of the soil can.

Statistics analysis

Non-parametric Wilcoxon rank-sum tests were performed using SAS (SAS Institute Inc., 2004) to determine differences in snow depth and soil water storage between the CT and NT treatments. These tests (significance level $\alpha = 0.05$) were made for data pooled by treatment or categorized by topographic position within a treatment, namely, ridge top, south- or north-facing slope, and valley. The Wilcoxon rank-sum test (nonparametric alternative to the two-sample *t*-test) was used due to the non-normal distribution of snow depth and soil water.

Results and Discussion

Snow depth and snow redistribution

The extensive snow depth survey conducted on January 10, 2008 revealed that the snow depth on the NT treatment (CAF) ranged 11–99 cm, averaging 29 cm with a standard deviation of 10 cm, whereas the snow depth on the CT treatment (Clark Farm) ranged 0–143 cm, averaging 22 cm with a standard deviation of 18 cm. The nonparametric Wilcoxon rank-sum tests indicated significant statistical differences between the two farms overall and for every topographic position except the north slope (Table 1). The shallower average snow depth on the CT treatment (22 cm vs. 29 cm in the NT) suggests that snow has drifted out of the Clark Farm to neighboring farms.

Snow pack was shallower on the ridge top and south-facing slopes and deeper on the north-facing slopes and valleys for both treatments (Table 1). The snow pack surveyed on January 10, 2008 was an accumulation from several snow falls with the first starting on January 6, and followed by another two on January 9 and 10 (Fig. 2). During the five-day period, wind blew dominantly from W or WSW with hourly average speed ranging from 4.5 to over 6.7 m s^{-1} for nearly half of the time (insert of Fig. 3). A NCDC weather station located 5 km south of the study site recorded similar wind directions, and, in addition, periodic gusts of 10.7–13.4 m s^{-1} (NCDC, Station# 94129, 2008c). The dominant westerly wind tended to blow snow to the east-, north- and northwest-facing slopes where deeper snow was found for both the NT and CT fields (Fig. 3). The snow depth was much more variable in CT compared to NT (Fig. 3). A short period (2 hr) of NE and NNE wind at the speed of 4.5–6.7 m s^{-1} recorded on January 9, 2008 was responsible for the snow accumulation on the southwest-facing slopes in the Clark Farm. Overall, the wind from W or WSW was slightly unfavorable to the snow accumulation in the Clark Farm since it had larger south-facing slope areas (Fig. 1). However, when comparing only south-facing slopes and ridge tops, we still found that the NT retained substantially more snow (by 10–12 cm) than the CT (Table 1). The ridge top area was always covered by snow in the NT but was oftentimes found bare in the CT at the time of maximum snow accumulation. These results corroborated the positive effects of standing residue on snow holding in the areas subject to snow drift. Much greater spatial variation of snow depth was found in the CT treatment, with a standard deviation of snow depth greater than that of the NT for every topographic location (Table 1).

The snow survey on the two smaller, south-facing slopes during January 28 to February 14, 2008 showed similar results. Ridge tops retained the least amount of snow and valley areas retained the thickest snow pack for both the CT and NT. However, snow depths were considerably shallower in all topographic locations (Fig. 4a,b) and the spatial variation was much greater in the CT than in the NT (Fig. 4c,d). At the maximum snow accumulation (Feb 4–9, 2008), the snow depth in the CT was 10–14 cm shallower on the ridge top and south-facing slope than in the NT. The last two observations on February 12 and 14, 2008 showed a much faster snowmelt in the CT due to its shallower snow pack compared to the NT.

The greater snow drift in the CT could have several implications. First, the resultant greater spatial variation of snow depth may result in greater variation of cross-farm soil water, particularly, for the bare ridge top area, little snow would be available for recharging soil water through infiltration. Second, the excessive snow accumulation at certain areas of the CT, oftentimes a north-facing slope, would cause large snowmelt runoff as well as water erosion and agrochemical transport. Such phenomenon has indeed been observed in the CT fields in the Palouse region of the PNW (Greer et al., 2006; McCool et al., 2006). Third, lack of the insulation from the snow cover and residue layer in the CT can often result in prolonged duration of low soil temperature and frost responsible for injury of winter crops (Benoit et al., 1986; Cox et al., 1986). Consequently, patchy snow cover with variable depth in the CT may lead to variable soil temperature and frost depth across the field, thus delaying spring growth of crops in certain areas.

Snow holding capacity

Ridge tops are areas prone to snow drift regardless of wind direction as long as the wind speed reaches a certain threshold. Snow depths observed on the ridge top in the NT on January 15, 2008 indicated that the snow amount held in this field was closely related to the height of the standing stubble (Fig. 5a). That the snow depth was shallower than the residue height might be attributed to the relative small snow event with less snow on the ground compared to other events (Fig. 2).

Snow depths were also positively related to the residue height in the NT treatment for the event of January 10, 2008 (Fig. 5b). The snow depth (ranging 11–99 cm with an average of 29 cm) was mostly deeper than the residue height (ranging 9–33 cm with an average of 21 cm). This event was larger than the event on January 15, 2008, with a wind speed of 4.5–6.7 m s^{-1}. Snow depths on the ridge top and south-facing slopes mostly followed the 1:1 line, and the snow holding capacity mirrored the residue height for a winter wheat residue structure with a row width of 25 cm and average standing residue of 159 g m^{-2} in spring time.

In the Palouse region of the PNW, snow fall and melt are frequent throughout the winter. Historical records (NCDC Stations #456789 2008a and NCDC Station #106152, 2008b) indicated that 68–75% of snow-on-the-ground events lasted for less than five days and in 74–88% of the time when snow was on the ground, the snow depth was less than 21 cm (the average standing residue height observed in the CAF). Therefore, the snow holding capacity of the NT residue at the study site would not be fully filled most of the winter time. The snow held by the residue is potentially available for subsequent sublimation, melting and infiltration across the field, rather than drifting away to accumulate on shoulders or valley areas as in the CT treatment.

Snow density and SWE

Measured snow density of the snow pack exhibited high variation, with a range of 0.11–0.46 g cm^{-3} for all samples from five surveys (Table 2). Substantial variation of snow density has been reported in numerous previous studies. The density of freshly fallen snow was found to vary by one order of magnitude (Judson and Doesken, 2000; Kay, 2006). For the Palouse area of the PNW, the density of the new fallen snow mostly varied between 0.01and 0.3 g cm^{-3} with a mode of 0.08 g cm^{-3} based on 36 years of climatic data for 1958–1993 (NCDC, Station# 456789, 2008a). Snow density is typically subject to continuous change affected by multiple factors throughout the processes of compaction, recrystallization and densification (Marshall et al., 1999; Kay, 2006).

There was no clear relationship between average snow density (when only profile-averaged density was sampled) and the overall thickness of snow pack (Fig. 6a), likely due to the complicated process involving several snow events with drifting and melting. However, snow density did increase linearly with depth when incremental samples were taken (Fig. 6b).

There was also no definite association between average snow density and topographic locations although in two of the five surveys snow appeared to be denser on the north slope in the NT (Table 2). The two surveys in the NT on January 11 and 15, 2008 showed that average snow density between the north- and south-facing slopes was significantly different (*Z*-scores of −2.001 and 2.712, *P*-values of 0.007 and 0.045). A cold west wind (see Fig. 2 for air temperature) before the January 15, 2008 survey appeared to have caused the recrystallization of the snow on the north-facing slope and the formation of a crust on which one could walk during the survey, whereas snow on the south slope was puffy. The other surveys, however, showed relatively uniform snow density (0.19–0.22 g cm^{-3}) across the NT (Table 2). The survey on the CT on January 11, 2008 also exhibited no difference between the north- and south-facing slopes (*Z*-score −0.423, *P*-value 0.672). In addition, the Wilcoxon rank-sum test for this survey indicated that there was no significant difference in average snow density between the two treatments of CT and NT (*Z*-score 1.714, *P*-value of 0.087).

SWE was the lowest on the ridge tops, and highest in the valleys and on the north-facing slopes for the two treatments regardless of surface residue conditions (Table 3). The range of the SWE, averaged for each topographic location (Table 3), was wider in the CT (1.1–18.1 cm) than in the NT (3.4–14.0 cm), indicating the greater spatial variation in the former. The Wilcoxon rank-sum tests did not detect significant difference in the mean SWE between the two treatments with data pooled or categorized by topographic positions with *Z*-score ranging from −1.04 to 1.64, and *P*-value ranging from 0.10 to 0.50.

Soil water and spatial variation

Soil sampling results showed that soil water was the lowest at ridge tops and increased through south-facing slopes to valley areas for both treatments (Table 4). Except for the valley, soil water was significantly higher in the NT than in the CT (Table 4). Soil water content in the valleys of the two treatments showed no significant difference (*Z*-score 0.42, *P*-value 0.68). Furthermore, soil water content had much smaller variation among topographic positions in the NT (–4.3% to 5.7% departure from average) than in the CT (–6.0 to 16.7% departure from average) (Table 4). In other words, more snow was deprived from the ridge top and slopes and then transported to other locations and, resulting in significant spatial variation of soil water in the CT.

Measurement of soil water along a 1.5-m profile further corroborated the larger spatial variation in soil water distribution in the CT. Soil water content along the whole vertical profile of the CT was significantly higher at the valley area than at the ridge top and south-facing slope (Fig. 7), and higher than the soil water content at all three locations of the NT except for the top soil layer (0–0.3m). Field observation revealed that ponding and surface runoff in the valley area due to snowmelt on the north-facing slope lasted much longer in the CT than in the NT. On the other hand, soil water under NT was relatively uniform at the 0.65–1.5 m depth among topographic locations (Fig. 7), and was higher in the south-facing slope and valley, compared to the CT. In addition, average soil water of additional surface soil samples taken at the Clark Farm was only 0.096 g g^{-1}, demonstrating that the surface soil under the CT was subject to considerably higher evaporative loss in early spring than in the NT (Fig. 7).

Summary and Conclusions

Snow depths in a series of snow survey events observed during the 2007–2008 winter season exhibited large spatial variation across the hilly field of two farms under NT and CT, respectively. The least amount of snow was found on the ridge top and south-facing slopes for both the NT and CT treatments since the dominant wind was from the west and southwest during the study period. On the ridge tops and south-facing slopes where snow was subject to the greatest drift, the NT field with a 9–33 cm standing stubble retained 10–12cm more snow for one event and 10–14 cm more snow for another, compared to the CT field. The CT field was often found bare, while this was not the case for the NT field. The snow depth was not significantly different between the two treatments on north-facing slopes where snow tended to accumulate. Snow depth was positively correlated to residue height and snow-holding capacity equaled to the residue height if there was enough snow.

The average density of the on-the-ground snow was highly variable across the field and did not appear to be associated with a particular topographic location, but increased with depth. SWE followed the same pattern of snow depth and was lower on the ridge top and south-facing slope and higher on north-facing slope and valleys. Spatial variation of SWE was greater in the CT than in the NT, although no statistical difference was found between the mean SWE of the two treatments.

Recharge of soil water in the spring was the lowest at the ridge tops, and highest in the valleys, yet such variation was much smaller in the NT (-4.3% to 5.7% departure from average) than in the CT (-6.0 to 16.7% departure from average). Although many factors may have contributed to the difference in spring soil water, we believe that, surface residue, especially standing residue, contributed to the high soil water storage and smaller spatial variation in the NT, likely through enhanced snow holding, infiltration of rain and snowmelt and reduced evaporation from the ridge top and south-facing slope.

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Table 1

Snow depth (cm) observed on the NT (CAF) and the CT (Clark Farm) and statistical tests

	NT			CT			Wilcoxon rank-sum tests	
	Range	Average	Std. dev	Range	Average	Std. dev	*Z*-score	*P*-value
South slope	21–37	28 (28) [a]	4	7–50	18 (50)	8	6.03	<0.0001
Ridge top	11–32	23 (25)	5	0–22	11(33)	7	5.44	<0.0001
North slope	20–99	32 (32)	13	12–99	33 (33)	24	1.79	0.0742
Valley	21–67	33 (26)	10	12–143	28 (33)	22	3.66	0.0003
Overall	11–99	29 (111)	10	0–143	22 (149)	18	8.17	<0.0001

[a] Shown in parentheses is the sample size

Table 2

The range and mean of snow pack density (g cm^{-3}) at different topographical locations of the NT (CAF) and CT (Clark Farm) treatments

Treatment	Observation time	Ridge top	South slope	Valley	North slope
CT	Jan, 11, 2008	N/A	0.21–0.46	0.13–0.30	0.23–0.34
		0.40 (1) [a]	0.29 (6)	0.22 (6)	0.29 (8)
NT	Jan. 11, 2008	0.18–0.23	0.18–0.32	0.20–0.35	0.21–0.40
		0.21 (2) [b]	0.22 (7)	0.27 (5)	0.27 (10)
	Jan. 15, 2008		0.12–0.21		0.19–0.35
		NS [c]	0.15 (8)	NS	0.31 (5)
	Jan. 30, 2008	0.12–0.23	0.17–0.25	0.17–0.24	NS
		0.20 (11)	0.20 (9)	0.20 (5)	
	Feb. 2, 2008	0.13–0.22	0.14–0.23	0.13–0.23	NS
		0.20 (11)	0.19 (8)	0.19 (5)	
	Feb. 5, 2008	0.18–0.33	0.11–0.25	0.15–0.23	NS
		0.22 (11)	0.20 (6)	0.20 (5)	

[a] Three of the four proposed sampling points were found bare and no snow samples were available.

[b] Shown in parentheses is the sample size.

[c] Not sampled.

Table 3

Snow water equivalent (SWE, cm) at different topographical locations of the NT (CAF) and CT (Clark Farm) treatments

Treatment	Observation time	Ridge top	South slope	Valley	North slope
CT	Jan. 11, 2008	1.1 (4) [a]	2.2 (7)	9.9 (5)	18.1 (9)
NT	Jan, 11, 2008	3.6 (2) [b]	3.4 (6)	6.6 (6)	14.0 (8)
	Jan. 30, 2008	4.4 (11)	5.9 (9)	6.5 (5)	NS [c]
	Feb. 2, 2008	5.1 (11)	7.2 (8)	8.6 (5)	NS
	Feb. 5, 2008	5.5 (11)	6.3 (6)	9.3 (5)	NS

[a] Three out of four of proposed sampling locations were found bare of snow.

[b] Shown in parentheses is the sample size.

[c] Not sampled.

Table 4

Gravimetric soil water in top 1.5 m soil and its spatial variations among different topographical locations of the NT (CAF) and CT (Clark Farm) treatments

	NT			CT		
	Soil water ($g\ g^{-1}$)	Std dev	CV (%) [c]	Soil water ($g\ g^{-1}$)	Std dev	CV (%)
Ridge top	0.226 (11) [a]	0.016	−4.3	0.205 (5)	0.009	−6.0
South slope	0.240 (9)	0.025	2.0	0.208 (12)	0.009	−4.5
Valley	0.249 (5)	0.009	5.7	0.254 (5)	0.028	16.7
Average	0.236 (25)	0.021		0.218 (22)	0.025	

[a] Shown in parentheses is the sample size.

[b] Standard deviation

[c] Spatial variation of soil water at a specific location was calculated by comparing with average water content, CV (coefficient of variation) = (soil water at specific location − average soil water)/average soil water ×100%.

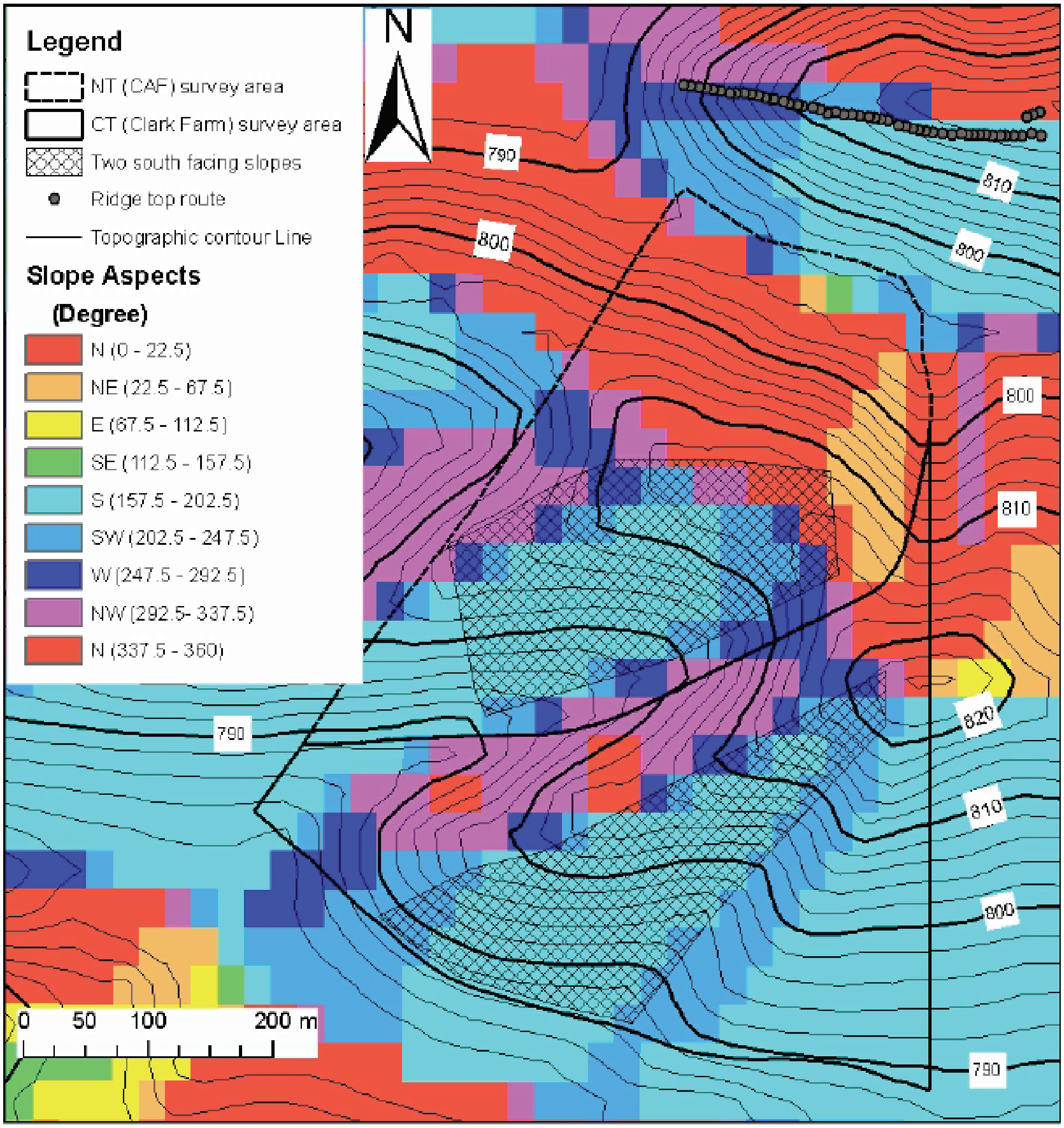

Fig. 1 The snow survey areas and route at the NT (CAF) and CT (Clark Farm), Pullman, WA.

The topographic contour interval is 2 m.

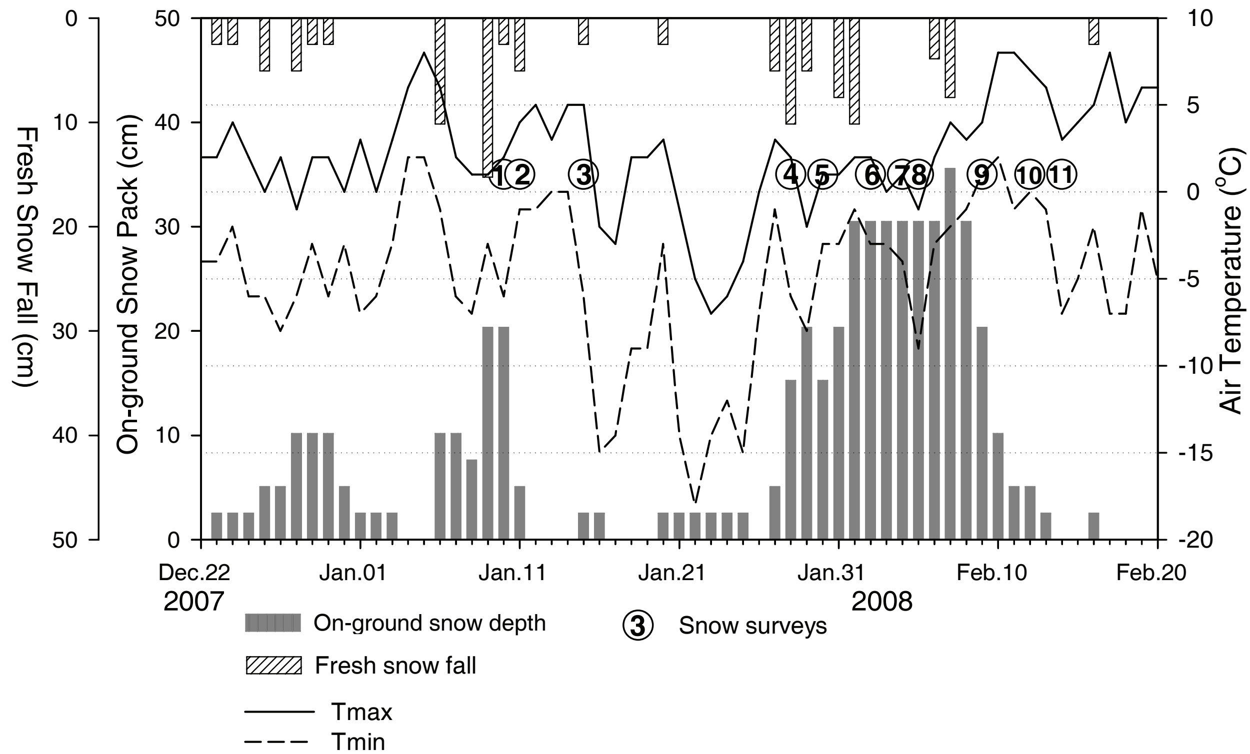

Fig. 2. Major snow-on-ground events in Palouse area (based on NCDC station # 456789, Pullman 2NW) and 11 field snow surveys of this study at CAF and Clark Farms, Pullman, WA, First and second survey were done for the larger domain. Third was for the ridge top route, and 4–11th were for the two smaller areas.

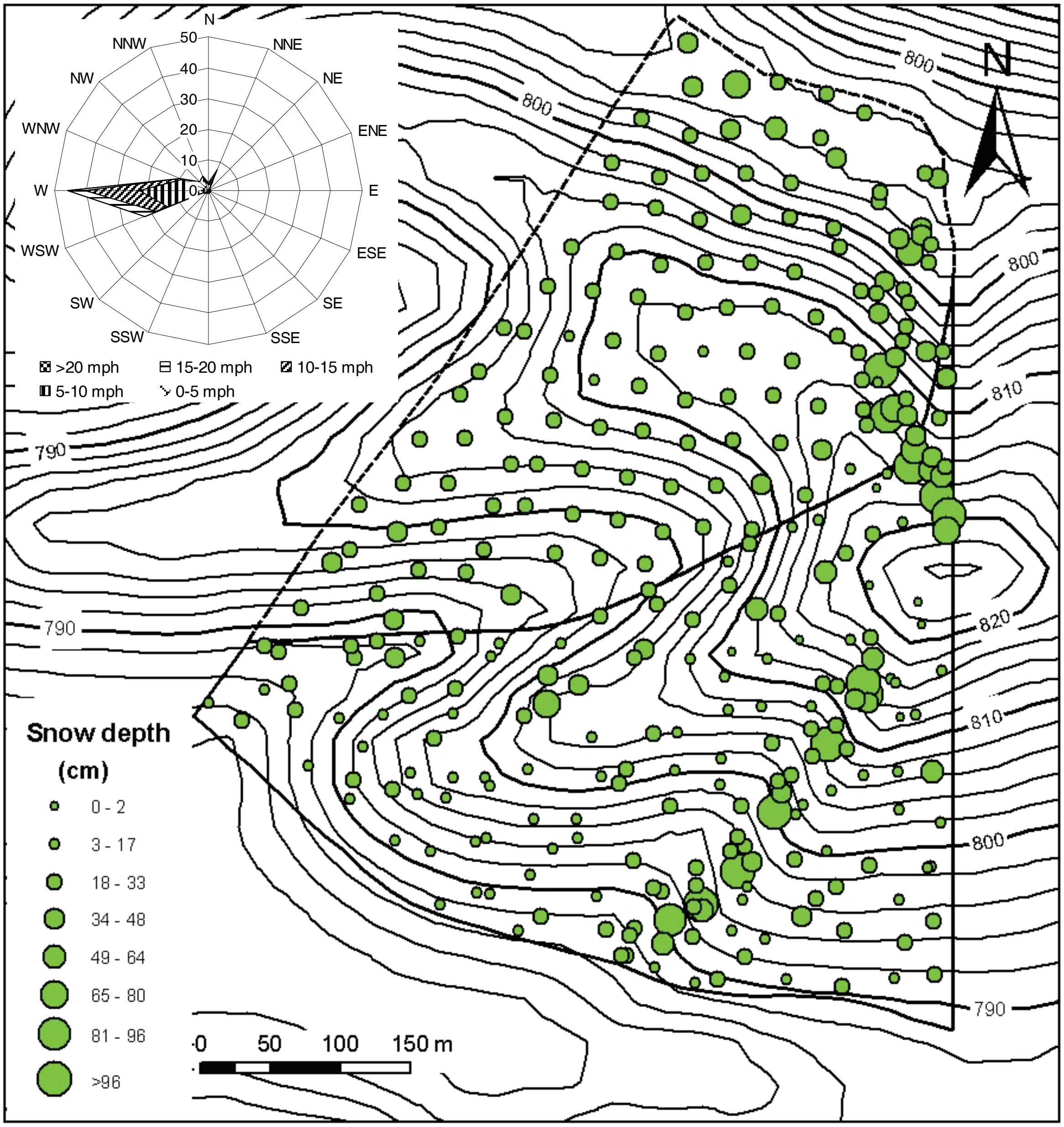

Fig. 3. Snow depth on Jan. 10 2008 in NT (CAF) and CT (Clark Farm), classified with mean (25.1cm) ± 0.5, 1.5, 2.5 ……times of standard deviation (15.6 cm). The insert is the windrose based on data for Jan. 6–10, 2008 from the weather station installed at the CAF.

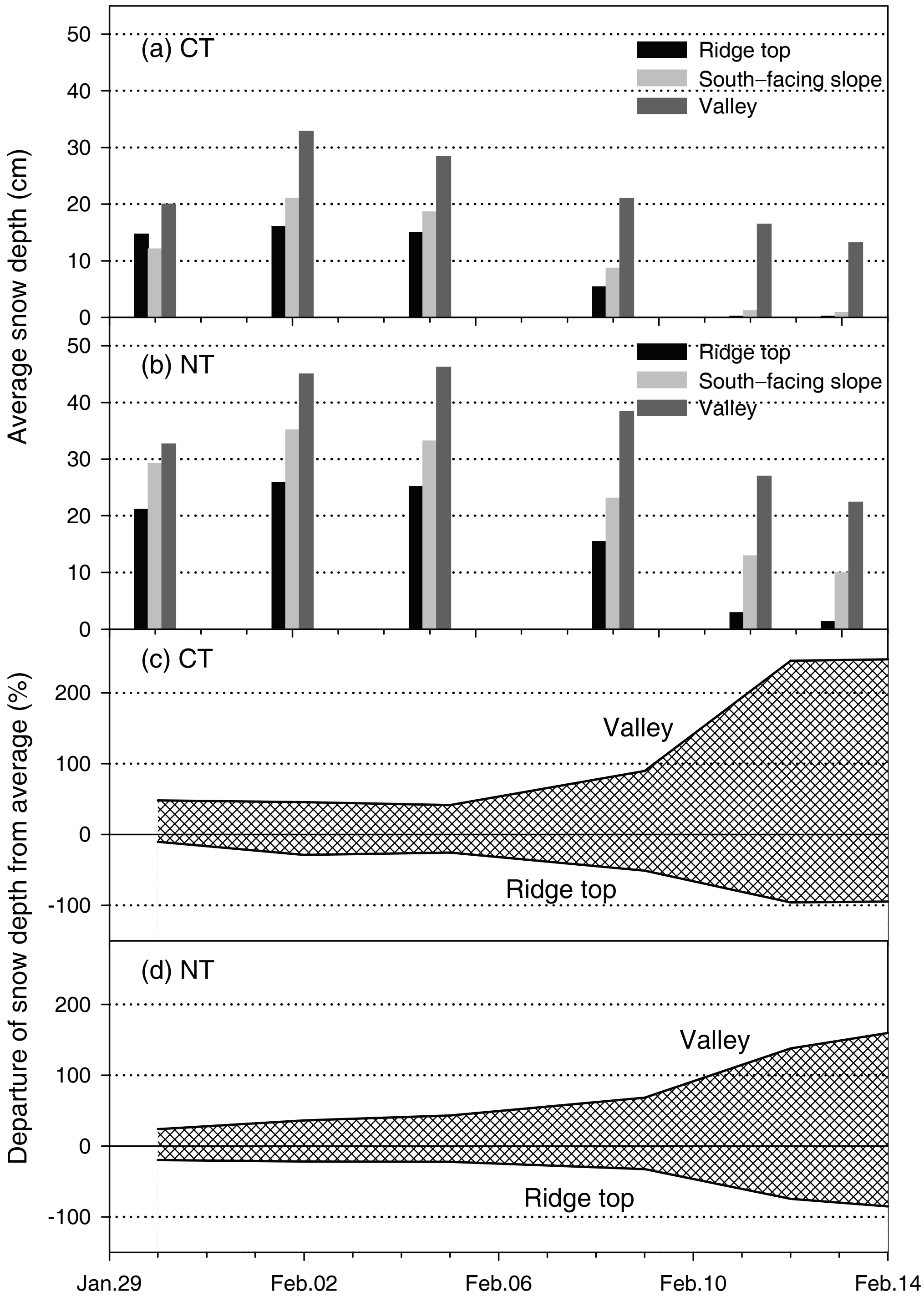

Fig. 4. Average snow depth observed during Jan. 29–Feb. 14, 2008 (a) under CT (Clark Farm), (b) under NT (CAF), (c) Departure of snow depth at ridge top and valley from the average for CT, (d) Departure of snow depth at ridge top and valley from the average for NT.

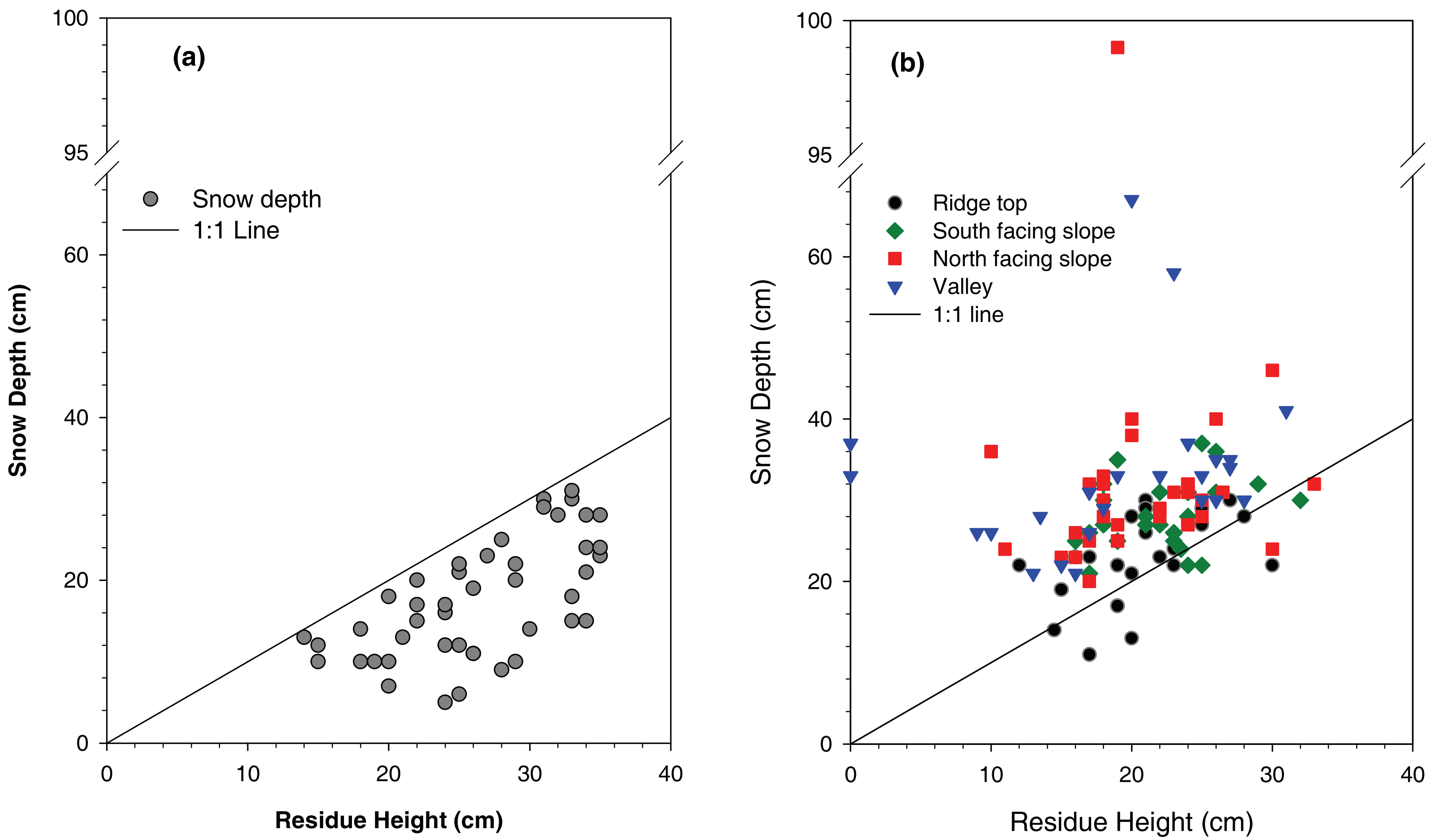

Fig. 5. Snow depth observed at (a) ridge top route on Jan. 15, 2008, and (b) different subsections on Jan. 10, 2008, at the CAF (under NT), Pullman WA.

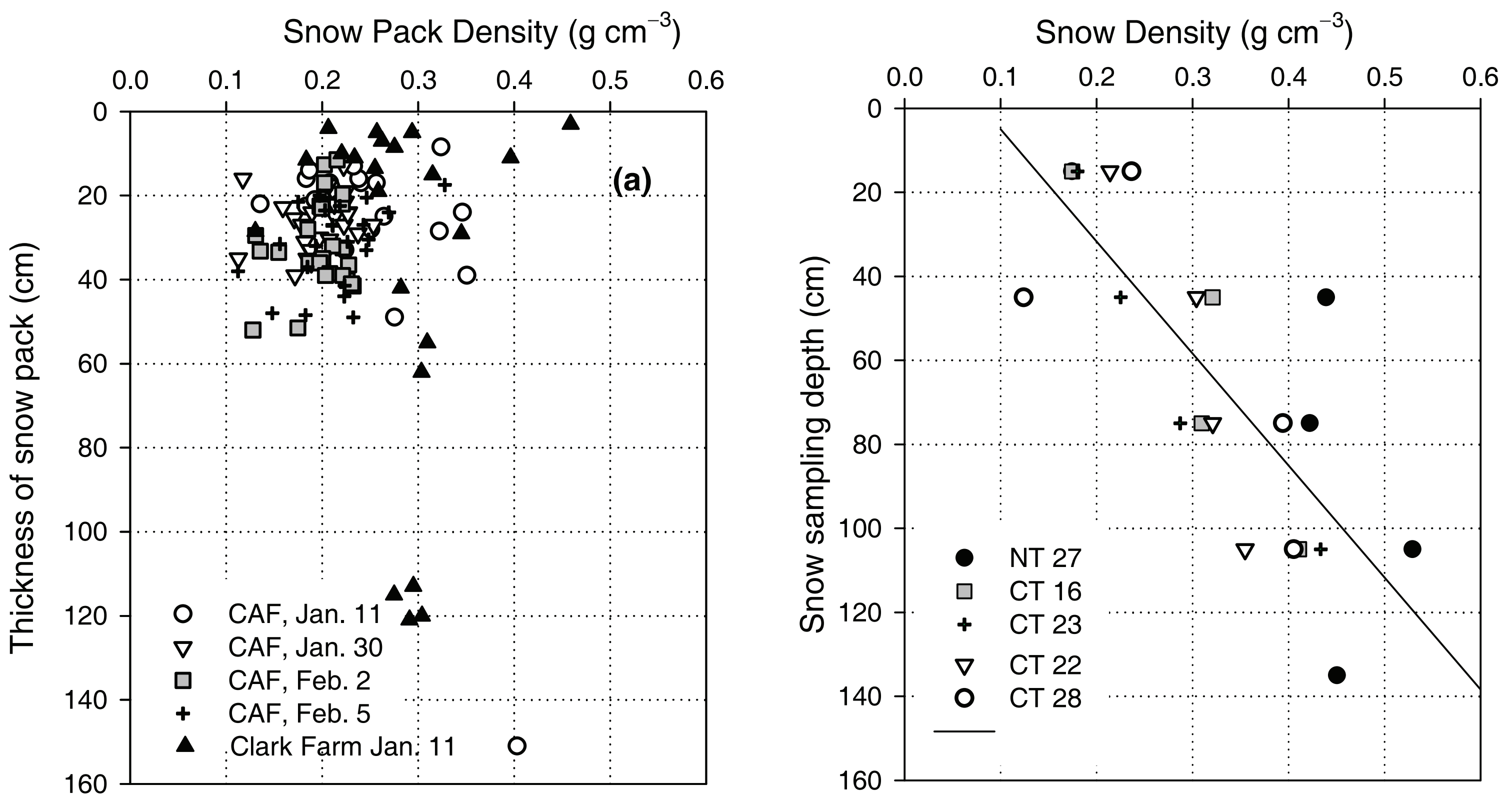

Fig. 6. Snow density sampled in 2008 in CAF (under NT) and Clark Farm (under CT), (a) Average over the entire snow pack, (b) Incremental value with depth.

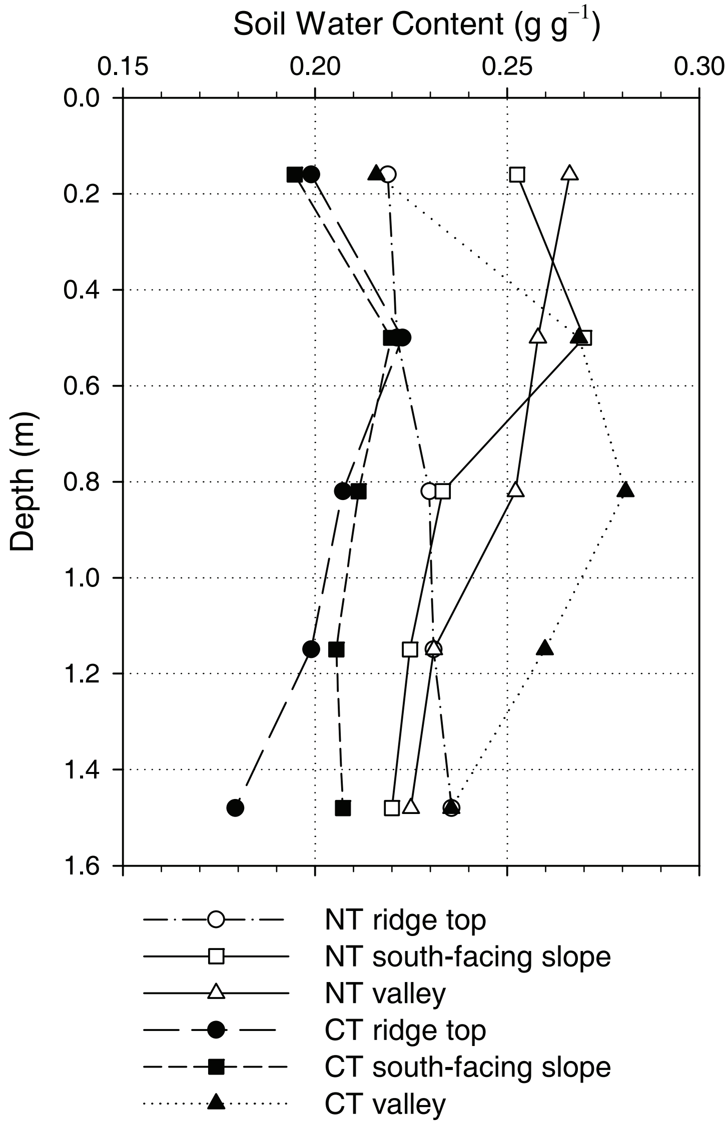

Fig. 7. Soil water content in spring 2008 for NT (CAF) and CT (Clark Farm), averaged over each topographical locations.