Comparison of the SnowHydro snow sampler with existing snow tube designs in southwestern Alberta, Canada

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ABSTRACT

Snow tube samplers are the primary method of measuring snow water equivalent (SWE) in the field as they are considerably less destructive to the snowpack, and faster to use than traditional snow pit techniques. This study evaluates the performance of three commonly used snow tube designs: standard federal, meteorological service of Canada (MSC), and snowhydro. The standard federal and MSC have previously been extensively tested; however, the snowhydro snow sampler is a new design that has not yet undergone error analysis in the literature. We compared the three designs under shallow, highly stratified snow conditions common to our research area, which are not well represented in the previous studies, and in both forested and clearcut conditions. All samplers were observed to under measure SWE relative to snow pit measurements, in contrast to previous literature. We found that the snowhydro outperformed the other two designs in terms of coring performance, and produced more consistent SWE measurements. We recommend against using the SWE scale provided with the standard federal due to the variability it introduces to SWE measurements in favour of bagging samples for later weighing on a calibrated balance. Although this is the first study to quantify the performance of the snowhydro sampler, additional studies under varying snow conditions are required to adequately quantify sampling errors.

Keywords: snow, snow measurement, snow tubes, mountain snow, southwestern Alberta

INTRODUCTION

Snow water equivalent (SWE) is the most important property when measuring snow in the field, and is calculated from measurements of snow depth and density collected via snow surveys (Adams and Barr, 1974; Pomeroy and Gray, 1995). Snow surveys along snow courses and using snow tube samplers are typically favoured for spatially distributed SWE measurements as this method is less destructive to the snowpack and less time consuming than snow pit measurements (Church, 1933; Adams and Barr, 1974; Goodison *et al.*, 1987; Woo, 1997). Snow courses are transects that have been designed to allow repeated measurements of snow properties to monitor temporal changes in snow accumulation. Permanently marked sampling points ensure that subsequent sampling occurs in a well-defined area to minimize the effects of confounding factors such as topography and vegetation cover (Goodison *et al.*, 1981; Woo, 1997).

Three snow tubes commonly used in Canada were examined in this study (in order of age): Standard Federal, Meteorological Service of Canada (MSC), and SnowHydro (Fig. 1, Table 1).

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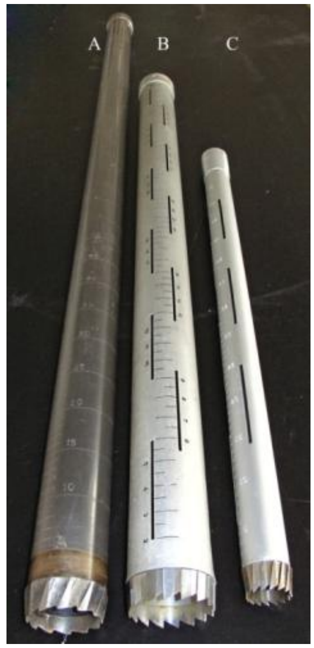

Figure 1. Snow tubes used in this study: A: SnowHydro, B: MSC, C: Standard Federal (one section).

Table 1 Technical specifications of snow tubes used in this study (after Goodison *et al.*, 1981; SnowHydro, 2004).

	Standard Federal	MSC	SnowHydro
Material	Aluminum	Aluminum or Lexan	Lexan
Tube Length (m)	0.76 (each section)	1.1	1.6
I.D. of cutter (cm)	3.772	7.051	6.185
Cutter teeth (#)	8 or 16	16	12
Depth of snow that can be sampled (m)	≥ 5.0	1.0	1.6

The Standard Federal is an example of a small diameter sampler, designed for deep, alpine snowpacks where the small diameter aids sampling (Fig. 2). It dates from the 1930's and is both the oldest snow tube design and the most widely used sampler in North America, primarily in the western mountain ranges (Clyde, 1932; Beaumont, 1967; Goodison *et al.*, 1981; Woo, 1997). The current Federal design is based on the Mt. Rose sampler, designed in 1908 by J.E. Church, which was modified in the 1930's by G.D. Clyde to reduce the diameter. Although the terms Mt. Rose and Standard Federal are often used interchangeably in the literature, they refer to the original and current designs, respectively (Clyde, 1932). The Standard Federal has a modular design that allows the surveyor to add sections for sampling snowpacks up to 5 m deep, and is available with both an 8- and a 16-tooth steel cutter design, with the latter being the most common. It is used in conjunction with a specially calibrated spring scale that reads in units of SWE: given the cutter diameter, 1 cm of SWE will weigh ~11.2 g, allowing simple calibration of the scale (Clyde, 1931; Clyde, 1932; Bindon, 1964).

Figure 2. Comparison of inner diameter of snow tubes used in this study: MSC, SnowHydro, Standard Federal. A 5 cm tall surveying target is provided for scale.

The MSC, and SnowHydro tubes are examples of large diameter tubes, designed for shallower snow conditions where larger snow cores increase the accuracy of measurements. The MSC snow tube was designed by the Meteorological Service of Canada specifically for use in snowpacks on the prairies or in eastern Canada that are generally < 1.0 m deep (Bindon, 1964; Goodison, 1978; Goodison *et al.*, 1981). The MSC has a steel 16-tooth cutter similar in design to the Standard Federal 16-tooth cutter. It may be used in conjunction with a SWE scale, although one was not available for this study. The SnowHydro is a relatively new design fabricated by Matt Sturm's SnowHydro company in Fairbanks, AK. It has a fixed length of 1.6 m and is constructed of clear Lexan, eliminating the need for observation slots. The SnowHydro has a 12-tooth cutter and is similar in design to the Standard Federal (SnowHydro, 2004).

Extensive studies were completed in the 1960's and 1970's to characterize the errors involved in sampling with snow tubes (Bindon, 1964; Freeman, 1965; Work *et al.*, 1965; Beaumont, 1967; Peterson and Brown, 1975; Goodison, 1978; Farnes *et al.*, 1982; see Table 2). These studies examined the effect of snow tube and cutter design on the accuracy of tube measurements under a variety of snow conditions. The most significant sources of error were found to be the presence/absence of slots in the tube, and cutter design and maintenance.

In a comparison between a slotted and non-slotted Standard Federal in deep snow conditions (>2 m), the slotted sampler measured 109 mm greater SWE (Beaumont and Work, 1963). Significantly, the measurement error of the Standard Federal increased as snow density approached 250 kg m^{-3}. This is likely due to the twisting action required to penetrate a dense snowpack, which allows the slots to 'shave' snow into the tube (Beaumont and Work, 1963; Peterson and Brown, 1975; Goodison *et al.*, 1981). Non-slotted tubes (e.g. SnowHydro) do not have this problem.

The design and maintenance of the cutter may influence the amount of snow collected in the tube (Bindon, 1964; Work *et al.*, 1965). A portion of the SWE overestimation observed with the Standard Federal can be attributed to the cutter design, which tends to force excess snow into the tube (Work *et al.*, 1965).

Table 2 Average % error of common snow tube designs. See Farnes *et al.* (1982) for detailed testing results (data from Bindon, 1964; Freeman, 1965; Work *et al.*, 1965; Beaumont, 1967; Peterson and Brown, 1975; Goodison, 1978; Farnes *et al.*, 1982). Notes: NT = Not Tested; SnowHydro is not included as it has never been tested.

Study	Location	Average % Error		
		Standard Federal (slotted)	***Standard Federal (non-slotted)***	***MSC***
Bindon (1964)	Mount Forest, Ontario, Canada	6	NT	NT
Freeman (1965)	Mt. Hood, Oregon, U.S.A.	9.8	11.3	NT
Work *et al.* (1965)	Mt. Hood, Oregon, U.S.A.	10.5	NT	NT
Work *et al.* (1965)	Alaska, U.S.A.	8.2	10	NT
Beaumont (1967)	Mt. Hood, Oregon, U.S.A.	11.2	10.8	NT
Peterson and Brown (1975)	California, U.S.A.	9	NT	NT
Goodison (1978)	southern Ontario, Canada	4.6	NT	6
Farnes *et al.* (1982)	Alaska, U.S.A.	10	NT	7

A sharp, well maintained cutter allows for cleaner separation of the core from the snowpack, thus reducing SWE overestimation by up to half (Bindon, 1964; Beaumont, 1967). The number of cutter teeth may also influence tube performance. Generally, cutters with fewer, larger teeth tend to break crust or ice layers into larger chunks, which may jam a small diameter tube and cause snow ploughing (i.e., pushing snow away from the tube opening before it can be collected) and snowpack under-sampling. A cutter with more, smaller teeth is less likely to experience this issue, although smaller teeth require greater effort to cut hard layers (Bindon, 1964).

A well-maintained cutter with sharp teeth will minimize the downward force required to cut through hard layers, and reduce the possibility of collapsing the underlying snow. Snow surveyors typically attempt to collect a core that is ≥ 80% of the measured snow depth. This ensures that snow is not lost due to snow ploughing or that excess snow has not been collected as this may be difficult to quantify with a collapsed snow core. Collection of a soil plug with the snow core provides further confidence that the entire snowpack has been sampled, and helps with core retention in the tube (BC Ministry of Environment, 1981).

We compare the relative performance of the SnowHydro, Standard Federal, and MSC snow tubes under the snowpack conditions encountered in the Crowsnest Pass. Standard Federal and MSC results are compared with previous research to assess differing performance under these conditions; however, to our knowledge this is the first analysis of the SnowHydro design in comparison with the other snow tubes.

Although the Standard Federal and MSC tubes have previously undergone error analyses, these studies have primarily been conducted at Mt. Hood, Oregon, a maritime climate with deep, rain-on-snow dominated snowpacks producing high SWE (Work *et al.*, 1965; Lillquist and Walker, 2006), and in southern Ontario, a continental climate with shallow, highly stratified snowpacks typically < 1 m deep (Adams, 1976; Goodison, 1978). We re-assess the performance of each sampler given the snow conditions particular to our study site (Crowsnest Pass, southwestern Alberta), where a dry continental climate results in a shallower snowpack, but mid-winter melt due to frequent chinook events creates a highly stratified snowpack. In addition, the SnowHydro design is relatively new and has therefore not undergone a rigorous analysis of its sampling error. As we primarily use this sampler in our field campaign, error information is required to determine data quality.

STUDY AREA

Fieldwork was completed in the Star Creek watershed, Crowsnest Pass, Alberta, Canada (Fig. 3).

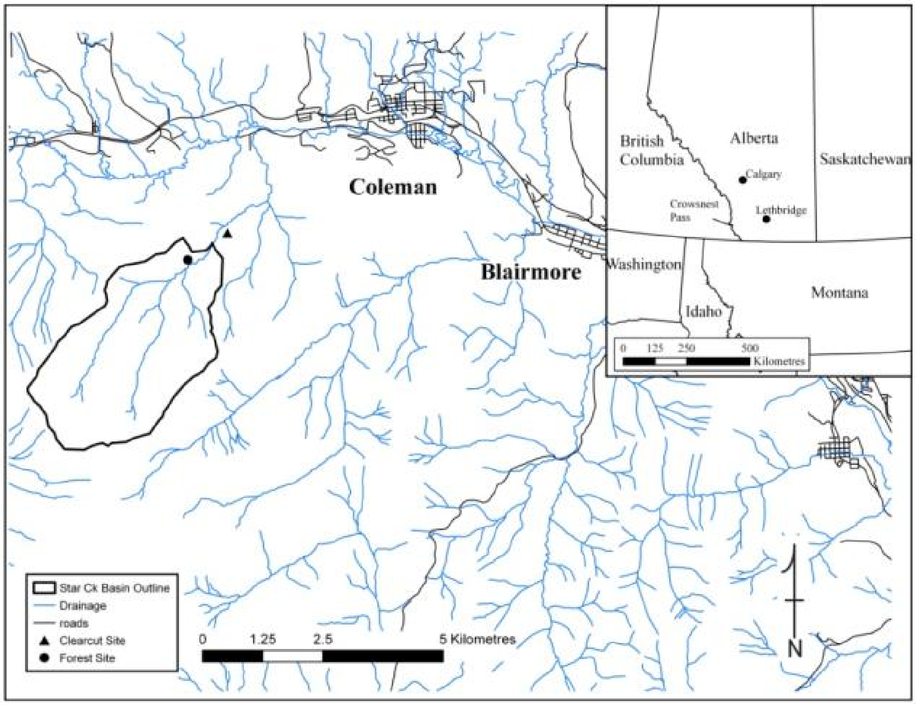

Figure 3. Location of sampling grids with respect to Star Creek watershed and the Crowsnest Pass.

Vegetation cover in the watershed consists of montane forest below elevations of 1900 m (Fig. 4). At lower elevations (< 1700 m), the forest is dominated by lodgepole pine (*Pinus contorta* var. *latifolia*) and Engelmann spruce (*Picea engelmannii*) with interspersed clonal stands of trembling aspen (*Populus tremuloides*). At mid-elevations (1700 – 1900 m), subalpine forest dominates with a combination of subalpine fir (*Abies lasiocarpa*) and Engelmann and white spruce (*Picea glauca*). Above 1900 m elevation, alpine meadows consisting of low grasses and coniferous shrubs, talus slopes, and bare rock are characteristic (Silins *et al.*, 2009).

The study area is characterized by a cold, temperate continental climate (Nkemdirim, 1996). Precipitation is highly interannually variable with strong topographic gradients. Average precipitation is 882 mm annually, ~50% of which falls as rain (Silins *et al.*, 2009; Environment Canada, 2011). Unlike other Rocky Mountain basins with similar topography located along the Continental Divide, significant rain events are common during the winter and spring months (December to May) (Silins *et al.*, 2009).

The 30-year average annual precipitation and air temperature record from Environment Canada's weather station in Coleman (Environment Canada, 2011) (Fig. 5) indicates that rain may account for 20 – 45% of mean monthly precipitation during winter. Air temperatures can be well above 0°C during winter months, which results in average winter air temperatures > -7°C. While Environment Canada's weather station is at an elevation of 1341 m, ~100 m lower than the minimum elevation in the study area; it provides key information on long-term climate patterns. This region of Alberta also experiences frequent winter chinook activity, with an average of 48 – 50 chinook days per winter, potentially resulting in high rates of mid-winter melt (Nkemdirim, 1996).

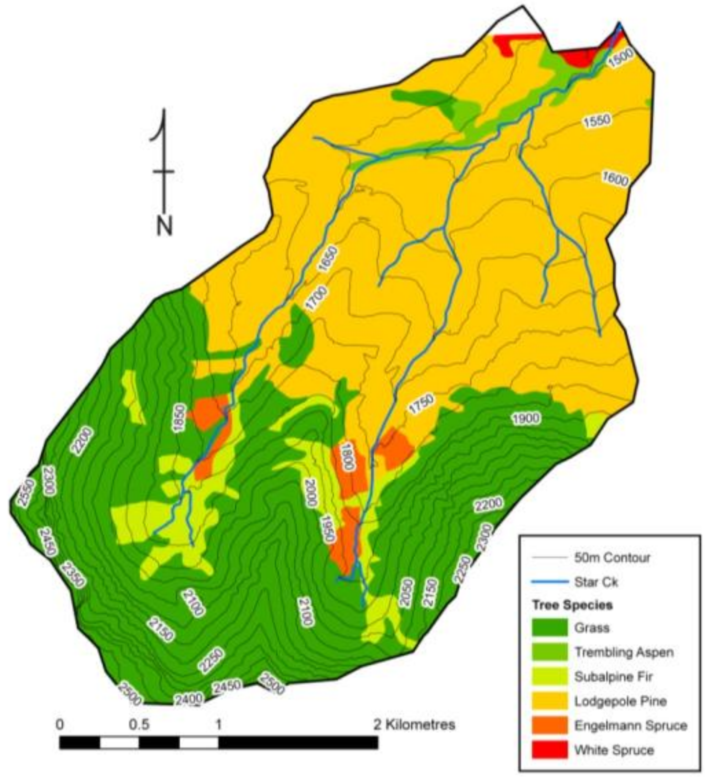

Figure 4. Distribution of vegetation species within Star Creek (Alberta Vegetation Index data provided by Alberta Sustainable Resource Development, Forest Management Branch).

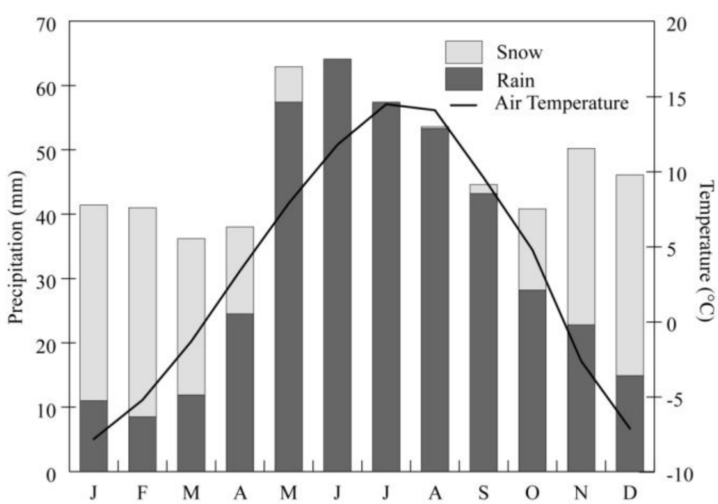

Figure 5. 30-year (1971 – 2000) monthly average precipitation and air temperature from Environment Canada's station at Coleman, Alberta. The station is located approximately 7 km NE of Star Creek, and 100 m below the minimum elevation of the watershed (modified from Silins et al., 2009 with additional data from Environment Canada, 2010).

Two snow survey grids with 36 permanently marked sampling points spaced at 5 m intervals were established within the watershed to capture within- and between-stand variability in each of the two vegetation cover types that dominate the larger study watershed (Fig. 6). The first grid was located in a clearcut just north east of the Star Creek watershed boundary, and the second grid was established in a homogeneous mature lodgepole pine stand (Fig. 7a, b). The sites are ~1 km apart, both are level, and have an elevation difference of 50 m.

The clearcut site is highly wind-exposed and thus had potential for high rates of wind transport; however, the sampling grid was sheltered from the prevailing wind by a mature pine stand ~100 m west of the grid location. Wind conditions may, however, contribute to snow compaction and wind slab development in this area. Additionally, the lack of forest canopy allows for maximum incoming solar radiation, which may form solar crusts and melt/freeze layers. These factors may result in considerable snowpack stratification, potentially creating challenging sampling conditions. Despite the potential for greater wind transport and higher melt rates, snow depths will be greater in this site than the forest, as there is no canopy to intercept incoming snow.

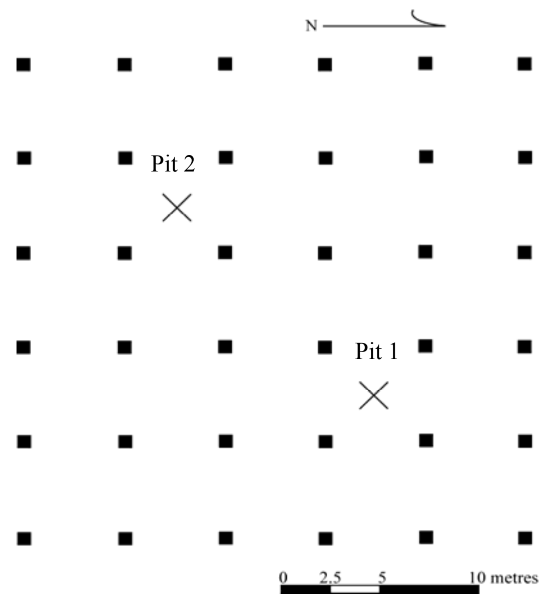

Figure 6. Schematic of the snow survey grids, both of which were oriented in approximately the same direction. Snow pits (noted by X) were located away from the edge of the grid to provide representative measurements of snow conditions encountered in the grid.

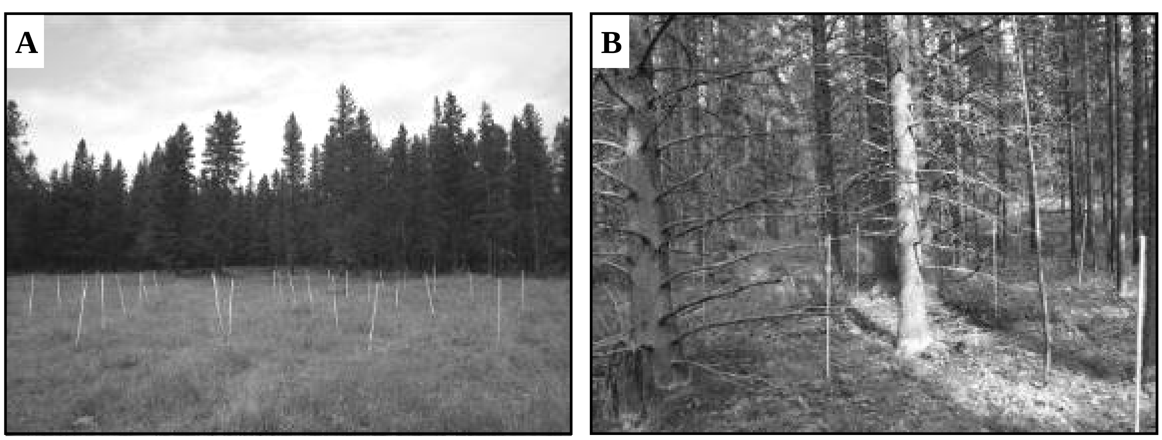

Figure 7. Sample grids: A: clearcut site; and B: mature forest site.

While the forest site is highly sheltered from wind and solar radiation, the forest canopy creates a mosaic of sun-lit and shaded areas that can potentially cause high variability in snowpack properties within the grid. Snow depth is likely to be shallower in sun-lit areas, and have higher density due to melting effects caused by exposure to direct solar radiation (Ellis *et al.*, 2011). This grid is exposed to high longwave fluxes from the surrounding tree stems, resulting in differential melt rates with proximity to tree trunks, and subsequent effects on snow depth, density, and SWE in these areas (Pomeroy *et al.*, 2009). This site is also subject to internal ice layer formation due to canopy drip of melting intercepted snow (Schmidt *et al.*, 1988; Schmidt and Gluns, 1991; Storck *et al.*, 2002). Interception is very important relative to the clearcut, thus lower snow depths are expected in this site.

METHODS

Sampling Strategy

Snow measurements were completed on March 21 – 22, 2011. Snow cores were collected with each of the three samplers at each of the 36 sampling points at each study site, ensuring a snow core of at least 80% of the measured snow depth was collected (BC Ministry of Environment, 1981). Snow depth was also measured at each sample point using a graduated probe (cm). Cores were placed in numbered, pre-weighed plastic bags, and then weighed on a calibrated Denver Instrument MXX-2001 balance with 2000 g capacity and 0.1 g resolution. Snow density was calculated from Eq. 1, with individual bag weights used to tare the total sample weights.

$$\rho_s = \frac{m_{Sample}}{\left(\pi \times \left(R_{Cutter}\right)^2 \times d_s\right)} \tag{1}$$

where ρ_s is the density of the snow sample (g cm^{-3}), R_{Cutter} is the inside radius of the cutter on the snow tube (cm), d_s is snow depth measured from the snowtube (cm), and m_{Sample} is the mass of the sample corrected for sample bag weight (g).

SWE was then calculated from Eq. 2:

$$SWE = d_s \frac{\rho_s}{\rho_w} \tag{2}$$

where d_s is the measured snow depth (cm), ρ_s is the density of the snow sample (g cm^{-3}), and ρ_w is the density of water (1 g cm^{-3}).

As noted previously, the Standard Federal tube includes a spring balance that reads in units of SWE. This balance was also used to measure SWE (termed *Cradle SWE*) prior to bagging and weighing the sample. As the balance weighs the tube and snow sample together, the initial weight (in SWE) of the empty tube was recorded. Filled tubes were then weighed and the empty tube weight used to tare the weight to obtain the sample SWE. The weight of the empty tube was recorded repeatedly throughout the test to account for any snow or ice build-up inside the tube caused by thermal changes.

Two snow pits were dug at each site using standard techniques (cf. Adams and Barr, 1974). The pits were located within the grid to characterize snowpack structure and temperature, and collect high-resolution measurements of snow density (Fig. 6). Density samples were extracted from the pit face in a vertical profile using a 250 cm^3 cutter (Snowmetrics, Ft. Collins, CO). Samples were placed in numbered, pre-weighed plastic bags and weighed on a calibrated balance (Denver Instruments MXX-2001). Density was calculated as:

$$\rho_s = \frac{m_{Sample}}{V_{Sample}} \tag{3}$$

where ρ_s is snow density (g cm^{-3}), m_{Sample} is the mass of the snow sample corrected for sample bag weight (g), and V_{Sample} is the volume of the density cutter (cm^3). Within each stand, snowpack densities from both snowpits were averaged, and Eq. 2 was used, along with depth measurements from the graduated probe at each sampling stake, to calculate SWE (termed *Pit SWE*). As snow pits provide the most accurate measure of snowpack density, this value was used as a relative control against which snow tube results were compared (Woo, 1997).

Data analysis

Data were plotted with notched box plots using SYSTAT 13 (Chambers Software, Chicago, IL). Notches that overlap between boxes indicate that median values are not statistically different at $p = 0.05$ (Chambers *et al.*, 1983). Data were then analyzed with Statistica DataMiner software (StatSoft, Tulsa, OK) to calculate descriptive statistics, test normality using a Shapiro-Wilks' W test (Shapiro *et al.*, 1968), and test for homogeneity of variances using Levene's test (Quinn and Keough, 2002). A one-way analysis of variance (ANOVA) was run to quantify differences between samplers and sampling locations (Quinn and Keough, 2002). If a statistically significant difference between samplers was detected a Tukey's Honestly Squared Difference (HSD) post-hoc test was performed to determine which sampling techniques were statistically different (all tests at $p < 0.05$) (Duncan, 1955; Quinn and Keough, 2002).

Anomalous results for Cradle SWE were observed between the mature forest and the clearcut. Thus, the spring scale calibration was tested in the lab using two techniques: (1) converting the SWE measurement from the scale to weight in grams, and comparing that value with the core weight measured with the electronic balance; and, (2) weighing known masses of water on the spring scale at different scale temperatures. These masses spanned the weight range of the spring scale, while the temperature of the scale started at room temperature, and was cooled in three stages to -25°C. Once the scale had equilibrated at each new temperature, the control weights were measured and recorded.

RESULTS

Mature forest stand

Weather on the day of sampling was clear and sunny with an air temperature of 5°C. Mean snow depth at the site was 52.5 ± 6.4 cm, and the mean *Pit SWE* for this grid was 13.5 ± 1.7 cm. The snowpack was characterised by three main crystal types: (1) highly metamorphosed snow with large, rounded irregular crystals with no faceting (3 – 4 mm) (stage II-B-2, Sommerfeld and LaChapelle, 1970) below ~19 cm above ground level (AGL); (2) consolidated fined grained snow (1 – 2 mm, stage I-A) between 19 – 23 cm AGL; and, (3) highly consolidated fine-grained, stellar crystals (< 1 mm) (stage I-A) in the upper half (above ~ 35 cm AGL). A 3 cm thick ice layer located at ~30 cm AGL was observed in both pits, and is attributed to canopy drip from a previous melt episode. A melt/freeze crust was also present at ~43 cm AGL. These layers caused significant sampling problems, including jamming and snow ploughing, only with the Standard Federal. Thus, resampling at most points to achieve a core ≥ 80% of measured snow depth was required. Free water was present at all depths, and mean snowpack temperature was -2°C (Fig. 8).

Snowpack structure was similar between pits below 45 cm AGL (Fig. 8). The base of both pits was characterized by coarse, granular snow (3 – 4 mm), which was ~10 cm thicker in Pit 1. At 18 – 22 cm AGL, snow crystals were smaller and more consolidated (1 – 2 mm), and crystals at 20 – 25 cm AGL were a highly consolidated wind slab. These consolidated layers were overlain by an ice layer at 30 – 33 cm AGL, above which there was a layer of highly consolidated snow (1 – 2 mm) at 33 – 43 cm AGL. A melt/freeze crust was located at 43 – 48 cm AGL, and formed the surface of Pit 2, which was located under dense forest canopy. At Pit 1, located in a small clearing (~20 m wide), there was an additional 22 cm of highly metamorphosed, coarse grained snow (3 – 4 mm) above this crust, caused by increased accumulation due to reduced canopy interception.

All layers described above were encountered at similar heights AGL across the stand when performing snow tube measurements, indicating that the pits were representative of snow conditions across this plot. Sample data from this site were normally distributed with homogeneous variances, thus meeting the assumptions required to use parametric statistics.

In the mature forest, all snow tubes underestimated SWE, while *Cradle SWE* overestimated SWE (Table 3; Figure 9). Relative to mean *Pit SWE*, the SnowHydro measured 12.7 ± 1.6 cm (93.5%), the Standard Federal 13.2 ± 1.8 cm (97.2%), *Cradle SWE* 15.8 ± 2.1 cm (116%), and the MSC 12.35 ± 2.1 cm (91.3%). The Cradle and MSC produced the most variable measurements of SWE across this stand, with the greatest range of values. The range of values from the MSC was approximately twice that of the SnowHydro and the Standard Federal. A one-way ANOVA indicated a significant difference between all samplers and *Pit SWE* (p = 0.00). The Tukey HSD post-hoc test indicated that none of the snow tubes were statistically different from *Pit SWE*, but *Cradle SWE* was statistically different from all other techniques (Table 4).

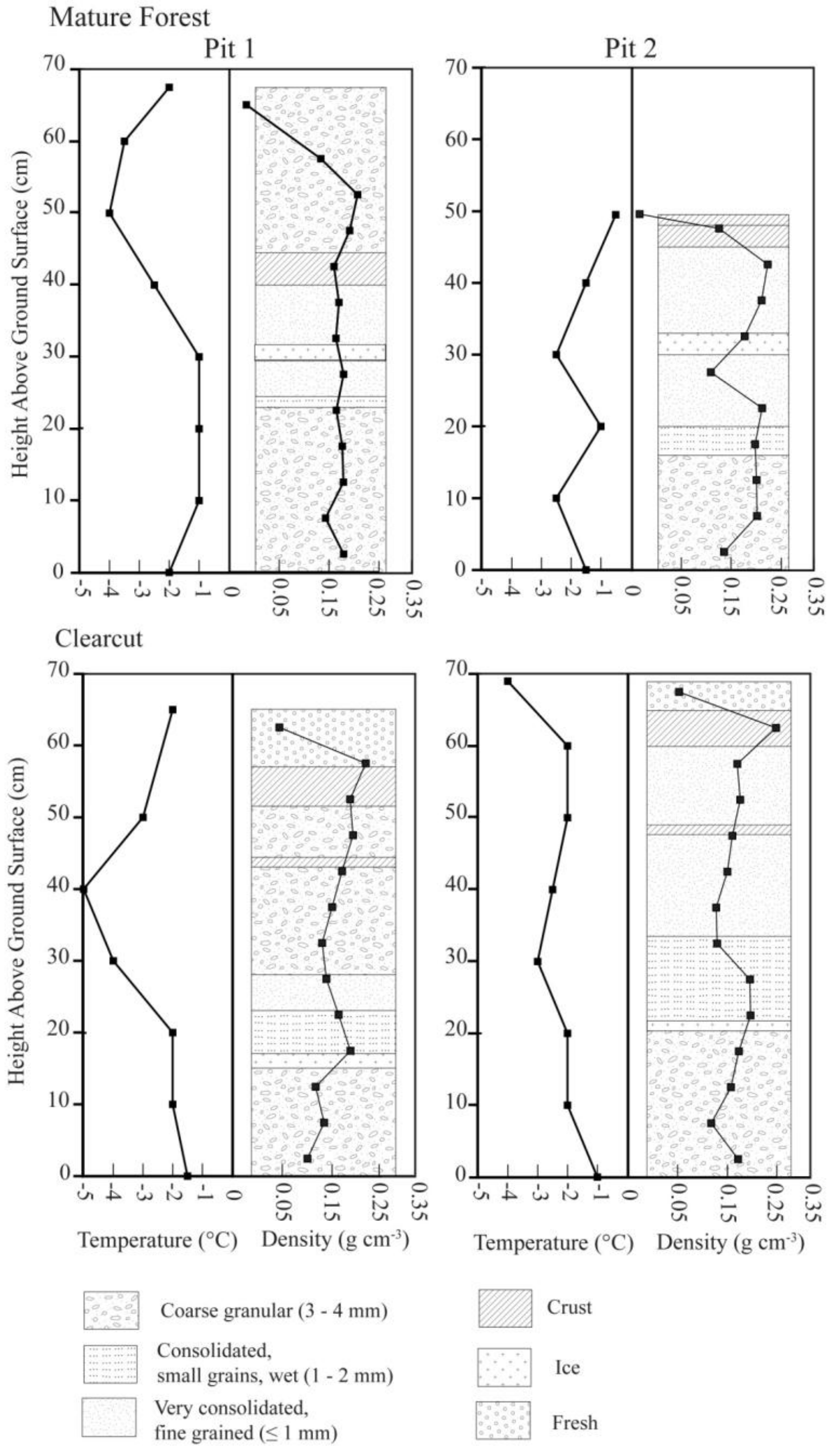

Figure 8. Snow pit temperature and density profiles and structure for mature forest site, and clearcut site.

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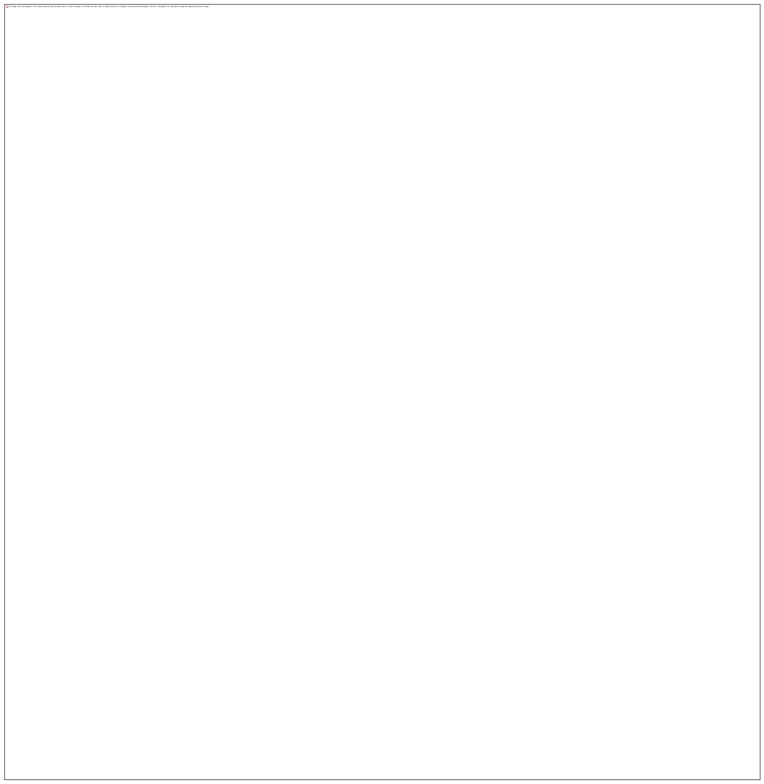

Figure 9. Notched box plots of snow data collected from the mature forest and clearcut stands. Boxes show 25th and 75th percentiles, the notch represents the median value, and bars represent non-outlier maximum and minimum values. Overlapping notches indicate that the median values are not statistically different. Sample size is $n = 36$ for each sampler.

Table 3 Descriptive statistics for *Pit SWE* and all samplers in the mature forest site.

	Pit SWE	**SnowHydro**	**Standard Federal**	***Cradle SWE***	**MSC**
Mean SWE (cm)	13.5	12.7	13.2	15.8	12.4
Median SWE (cm)	13.6	12.5	13.1	16	12.4
Min SWE (cm)	10.8	10.0	10.36	12	4.7
Max SWE (cm)	17.1	15.8	17.5	20	15.6
Standard Deviation (cm)	1.7	1.6	1.8	2.1	2.1
Standard Error (cm)	0.3	0.3	0.3	0.3	0.4

Table 4 Summary of results from a Tukey's HSD post-hoc test for the mature forest site. Bold cells are significantly different at $p < 0.05$.

Snow tube	**SnowHydro**	**Standard Federal**	***Cradle SWE***	**MSC**	***Pit SWE***
SnowHydro		0.78	**0.00**	0.96	0.25
Standard Federal	0.78		**0.00**	0.35	0.91
Cradle SWE	**0.00**	**0.00**		**0.00**	**0.00**
MSC	0.96	0.35	**0.00**		0.05
Pit SWE	0.25	0.91	**0.00**	0.05	

Clearcut

Weather on the day of the clearcut survey was overcast with very light snow and air temperature of 0°C. Mean snow depth in the clearcut site was 67.0 ± 3.5 cm and mean SWE for this grid was 17.3 ± 0.9 cm. The snowpack was characterised by highly metamorphosed, rounded, irregular crystals with no faceting (3 – 4 mm; stage II-B-2) in the lower 15 – 20 cm of the snowpack. This layer was separated from an overlying consolidated layer of small fine grained, stellar crystals (1 – 2 mm; stage I-A) by a 1 – 2 cm thick ice lens located at 25 cm depth. This lens created challenging sampling conditions, often resulting in collapsed snow cores that were significantly less than 80% of the depth; thus multiple attempts were required to extract a valid core at each point. Another hard layer of wind slab at ~50 cm AGL, consisting of small rounded crystals (1 – 2 mm), had less of an effect on sampling. The top 5 cm of the snowpack was fresh, low density snow that accumulated overnight between surveys, but was of low density and so had little effect on total SWE. Free water was present at all levels of the snowpack, and mean pack temperature was -3°C. The ground surface was covered in logging slash, creating problems with core retention in snow tubes as it was difficult to obtain a soil core. Despite identical average snow densities, *Pit SWE* varied by 2.5 cm between Pits 1 and 2 due to a 5 cm difference in snow depth (Fig. 8).

Snowpack structure was very similar between pits, with the exception of a layer of coarse granular (3 – 4 mm) snow at 38 – 51 cm AGL in Pit 1. In Pit 2, this range of depths was composed of consolidated, fine grained snow (stellar crystals, ~1 mm). A crust mid-way through these layers was encountered in both pits. The two primary hard layers identified in Fig. 4.6 (43 – 46 cm; 16 – 20 cm AGL), were consistently observed across the plot within that depth range, indicating that the pits were representative of snow conditions across this plot. Sample data from this site were normally distributed with homogeneous variances, thus the assumptions required to use parametric statistics were fulfilled.

At this site, both the Standard Federal and Cradle SWE values were virtually identical to *Pit SWE*, but the SnowHydro and MSC tubes underestimated SWE (Table 5; Fig. 9). Relative to mean *Pit SWE*, the SnowHydro measured 15.4 ± 1.6 cm (88.6%), the Standard Federal 17.5 ± 1.6 cm (101%), *Cradle SWE* 17.1 ± 1.6 cm (98.8%), and the MSC 16.1 ± 1.8 cm (93.2%). Ranges and standard deviations from all sampling methods were similar in this stand, in contrast to the mature forest. A one-way ANOVA showed a significant difference between sampling techniques (p = 0.00) (Fig. 9). Tukey's HSD post-hoc test showed that the Standard Federal and Cradle SWE were not significantly different from *Pit SWE*, while the MSC and SnowHydro were (Table 6).

Table 5 Descriptive statistics for *Pit SWE* and all samplers in the clearcut site.

	Pit SWE	**SnowHydro**	**Standard Federal**	***Cradle SWE***	**MSC**
Mean SWE (cm)	17.3	15.4	17.5	17.1	16.1
Median SWE (cm)	17.4	15.4	17.5	17	16.1
Min SWE (cm)	15.1	12.0	13.4	13	11.8
Max SWE (cm)	18.9	19.5	21.4	21	19.0
Standard Deviation (cm)	0.9	1.6	1.6	1.6	1.8
Standard Error (cm)	0.2	0.3	0.3	0.3	0.3

Table 6 Summary of results from a Tukey's HSD post-hoc test for the clearcut site. Bold cells are significantly different at $p < 0.05$.

Snow tube	SnowHydro	Standard Federal	*Cradle SWE*	MSC	*Pit SWE*
SnowHydro		**0.00**	**0.00**	0.19	**0.00**
Standard Federal	**0.00**		0.84	**0.00**	0.99
Cradle SWE	**0.00**	0.84		0.06	0.98
MSC	0.19	**0.00**	0.06		**0.01**
Pit SWE	**0.00**	0.99	0.98	**0.01**	

Calibration of the Standard Federal spring scale

We expected that *Cradle SWE* measurements would produce similar errors between sites, as the response of the spring scale should be independent of site and snow conditions. However, in the mature forest, the cradle weight (in grams) was consistently higher than the core weight, while in the clearcut the two were comparable (Fig. 10).

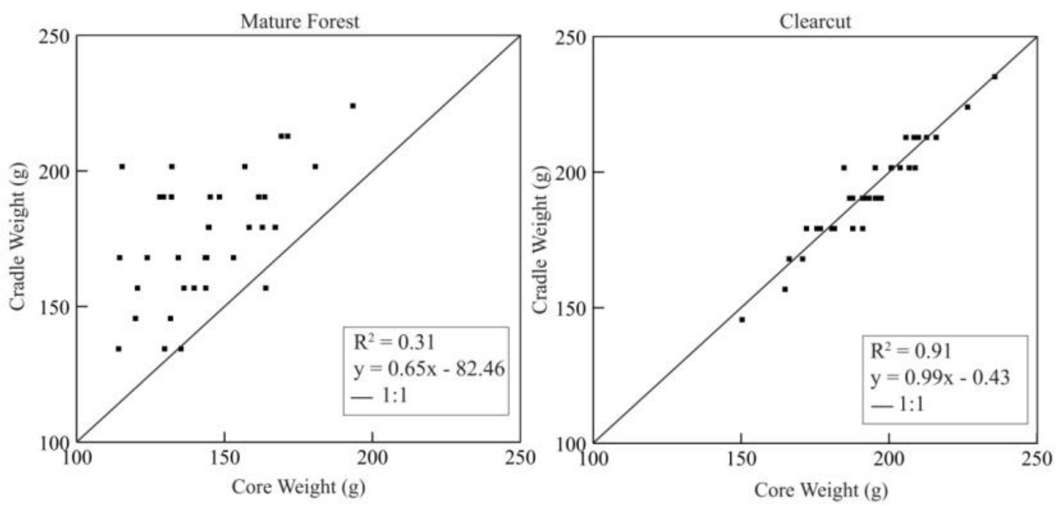

Figure 10. Comparison of core weights measured on an electronic balance with tube weights produced by the Standard Federal spring scale. Solid line represents 1:1 relationship, equation is for linear regression line, which is statistically significant at both sites.

While the spring scale is independent of site and snow conditions, it may be sensitive to air temperature. Air temperatures differed by only ~7°C between surveys, but the plots in Fig. 10 suggest considerable thermal drift in the scale over this small temperature range. Testing control weights at various scale temperatures confirmed this thermal drift (Fig. 11).

The temperature response of the scale varies depending on scale temperature and weight being measured. Overall, the scale consistently underweighs by up to 5%, with the greatest error observed at the low range of the scale and increasing accuracy with increasing weight. At the low range of the scale, the differences in weight accuracy are greatest between 20°C and 0°C, with a ~1.5% reduction in accuracy between the two. However, below 0°C scale accuracy remains consistent. At the mid-range, there is a ~0.75% increase in accuracy between 20°C and 0°C, but accuracy declines by this same amount at temperatures below 0°C. For the lower high range weight (3024 g), accuracy improved by ~1.5% between 20°C and 0°C, and then stabilized at ~ 98% below 0°C. At the highest range (3161 g) the scale produces the greatest accuracy at 20°C, and then drops as scale temperature decreases. The accuracy then stabilizes ~ 0.5% lower at a temperature of -18°C.

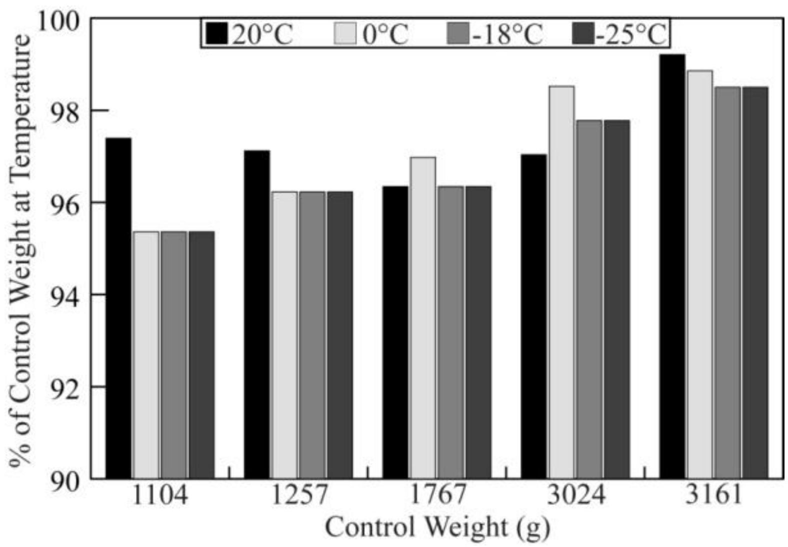

Figure 11. Plot of temperature response of Standard Federal spring scale over a 45°C temperature range.

DISCUSSION

Qualitatively, the performance of the three tubes was quite different. In both sites, the MSC and SnowHydro retained snow cores more consistently than the Standard Federal. The MSC and SnowHydro tubes generally did not collapse the snow profile when encountering hard layers, because their larger diameter better resisted blockage. This resulted in the MSC and SnowHydro regularly extracting cores that were ≥ 90% and ≥ 88% of snow depth, respectively. This, combined with the ability to retain cores, meant that both tubes collected a useable sample on the first attempt without requiring resampling, thus significantly increasing sampling speed. By contrast, the Standard Federal could only extract cores of ~80% of snow depth, due largely to the snow profile collapsing when hard layers were encountered. Multiple attempts were required to collect these cores, significantly increasing the time required to sample the grid. This is attributed to the small inner diameter of the tube, which tended to jam easily. These conditions were observed at both study sites, although all samplers had slightly more difficulty in the clearcut. The latter is due to the logging slash that was integrated into the base of the snowpack, which often prevented cutting a soil plug, or produced areas of weak snow structure that disintegrated as the tube was extracted.

The conditions encountered in this study are likely not ideal conditions for the Federal. This snow tube is specifically designed to sample deep, wind hardened snowpacks in contrast to the shallow, highly metamorphosed snow conditions encountered here. These conditions are characteristic of an early-spring snowpack, but are commonly encountered in the Crowsnest Pass throughout the winter due to frequent chinook events and resultant mid-winter melting. However, in unrelated sampling performed earlier in 2011, when the snowpack was highly consolidated with little internal stratification, the Federal tube worked very well, regularly collecting valid snow cores on the first attempt and resisting jamming. Significant snowpack metamorphism following this sampling date resulted in a number of hard layers underlain by soft, granular layers. These metamorphic processes created challenging sampling conditions for the Standard Federal during this study, as jamming was highly likely.

SWE values measured with the Federal tube were more consistent across stands than the MSC, with lower standard deviations. The MSC was only slightly more variable because it had the most difficultly retaining cores and required resampling. However, in both stands the SnowHydro produced the lowest standard deviations in SWE that were closest to *Pit SWE*. This suggests that its design produces more consistent measurements than the other designs under these snow conditions. Overall, greater standard deviations observed in the mature forest stand were likely due to the greater variability in snow depth and density produced by the mosaic of sun-lit and shaded areas across the plot. Measurement variability is reduced between samplers in the clearcut because snow depth and density were more homogeneous across that plot. There was little shelter in the clearcut plot, thus ensuring that the snowpack was uniformly exposed to meteorological processes. In this plot, the large-diameter tubes had slightly more trouble retaining cores due to the depth hoar layer at the base of the pack, which fell out as the tube was extracted or collapsed when the tube encountered an overlying hard layer. This problem was common to all samplers. Frozen ground contributed to difficulty retaining soil plugs, in addition to issues due to the presence of logging slash. However, there is no statistical reason why the two large-diameter snow tubes should be different from *Pit SWE* and the Standard Federal in this plot.

In contrast to previous work, significant overestimation of SWE with the Standard Federal and MSC samplers was not observed in this test (see Table 2). Rather, the MSC underestimated by approximately the same magnitude as the overestimates reported by Goodison (1978) and Farnes *et al.* (1982). Standard Federal measurements were virtually identical to *Pit SWE*, rather than the ~10% overestimate usually reported (Table 2). Statistical results show that the SnowHydro is not significantly different than *Pit SWE* under the mature forest canopy. However, individual SWE measurements at each stake were underestimated by 6 – 12%, a similar magnitude of measurement error reported for other samplers in other studies.

Sturm *et al.* (2010) report consistent under-measurement of SWE for surveys across the region from Manitoba to Alaska. They highlight a number of potential sources of under measurement, particularly the type of snow being sampled. Snow jamming the tube due to internal stratification may cause snow to be pushed away from – rather than entering – the tube. Thus, the stratification observed in this study may have contributed to the observed under-measurement.

Snowpack structure is critical for sampler selection. The snowpack in this study was most similar to the snowpacks reported for studies completed in southern Ontario. We measured SWE ranging from 13-17 cm SWE, while SWE measured in southern Ontario commonly ranged between 5-18 cm (Bindon, 1964; Goodison, 1978; Farnes *et al.*, 1982). Snowpack stratification was similar to that reported in the literature regarding testing in southern Ontario. In contrast, studies performed at Mt. Hood recorded 20 – 120 cm SWE, and had less stratification than we observed (Work *et al.*, 1965; Beaumont, 1967).

The lab test showed that the spring scale consistently under-weighs samples by ~50 g. Although this may be insignificant when sampling deep, dense snowpacks, this under-measurement becomes increasingly important when shallow or low-density snowpacks are measured. We hypothesize that the variability in the forest measurements is caused by a shift to a lower spring rate (i.e., less force required to activate the spring) caused by higher air temperatures. In this state, the scale is more sensitive to vibrations and thus the surveyor is more likely to read the scale incorrectly as it oscillates between values. Despite the scale weighing more accurately at higher temperatures, oscillation may cause reading errors of ±4 cm SWE; even greater if samples are collected in windy conditions. At lower air temperatures the spring stiffens and becomes more resistant to oscillation, and reduces human error in reading. This allows the scale to quickly settle on a value, though this value is likely not as accurate as would be expected at higher temperatures (up to – 5% depending on weight). The large variability seen on the warmer day can, therefore, probably be attributed to the oscillation in the scale and associated reading errors. Although these errors may cancel out over the course of a field season, this testing highlights the potential for significant measurement error when using the spring scale.

Bray (1973) notes that scale calibration drifts through time and thus should be checked frequently; however, there is inherent error involved in using a spring scale to measure SWE (Sturm *et al.*, 2010). Over-measurement errors of SWE, similar to those found in this study, were reported by Bray (1973) under similar weather conditions to those encountered on the forest survey day. He was able to correct his measurements by calibrating the spring scale, after which it produced similar results to weighing bagged samples. Calibration of the scale may also drift through time due to rough handling or fatigue in the spring. We found that under the colder conditions encountered in the clearcut, spring scale vs. bag weights were very comparable.

Therefore, we do not recommend that the Standard Federal be used under conditions similar to those observed in this study (i.e., snowpacks with significant internal stratification) due to issues with jamming and snow ploughing. Having the spring scale to directly measure SWE in the field is very useful, especially if long transects, deep snowpacks, or significant numbers of sampling points are measured at once. However, caution must be exercised when using this scale to ensure that it is not affected by wind, and calibration curves based on temperature should be developed and used. It should be noted that a similar scale is commonly used with the MSC, and any spring scale with sufficient capacity and resolution could be adapted for use with the SnowHydro.

The SnowHydro performed very well under the sampling conditions encountered in this study. The large diameter resisted plugging with hard layers, and prevented cores from collapsing. The Lexan construction better resists heat transfer from handling than the aluminum construction of the MSC and Standard Federal, reducing snow and ice build-up inside the tube. While the SnowHydro is slightly more cumbersome than the modular design of the Standard Federal, its performance offsets that limitation.

CONCLUSIONS

This study re-evaluated the performance of two existing snow tube designs, and compared them to a new design that had not yet been tested. While the magnitude of the error for the existing designs was in the same range as previous work, they were in the opposite direction: measurements tended to under- rather than over-estimate SWE. In the mature forest plot, the three samplers collected statistically identical measurements to the snow pits, which are considered the most accurate method of determining SWE. In the clearcut, only the Standard Federal measurements were statistically similar to pit measurements, but SWE underestimates were < 10% for all samplers. The Standard Federal also consistently produced the lowest error relative to *Pit SWE*, in contrast to the literature.

Qualitatively, the larger diameter tubes allowed for faster sampling because valid cores were typically extracted on the first try, whereas the small diameter Standard Federal typically required multiple attempts. Comparing the two large-diameter tubes, the SnowHydro and MSC, we recommend the SnowHydro due to its ability to sample greater snow depths, its Lexan construction that allows examination of the core, and lower heat transmission from handling.

Additional snow conditions should be assessed for snow tube performance. This study only investigated early-spring snow conditions where the pack was nearly isothermal and exhibited strong internal stratification, and at only one elevation. To provide a better understanding of the performance of the SnowHydro snow tube, a wider range of conditions need to be assessed. This could include conditions such as cold, mid-winter snowpacks, and late spring isothermal packs. This could be expanded to include snowpacks in different elevation ranges (i.e., alpine snowpacks), where different internal snowpack processes and external meteorological controls operate on snowpack structure.

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