Instruments and Methods
Comparison of density cutters for snow profile observations

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ABSTRACT. An investigation was made to estimate the variance, measurement errors and sampling error in currently accepted practices for manual snow density measurement carried out as part of snow profile observations using the available variety of density cutters. A field experiment in dry snow conditions was conducted using a randomized block design to account for layer spatial variability. Cutter types included a 500 cm^3 aluminium tube, 200 and 100 cm^3 stainless-steel box types, 200 cm^3 stainless-steel wedge types and a 100 cm^3 stainless-steel tube. Without accounting for variation due to weighing devices, the range of values for 'accepted practice' determined in this study included variation within individual cutters of 0.8–6.2%, variation between cutters of 3–12%, variation between cutter means and layer means of 2–7%, and under-sampling errors of 0–2%. The results of a statistical analysis suggest that snow density measurements taken using various density cutters are significantly different from each other. Without adjustment for under-sampling, and given that the mean of all measurements is the accepted true value of the layer density, variation exclusively between cutter types provides 'accepted practice' measurements that are within 11% of the true density.

INTRODUCTION

Snow densities are observed when conducting a full snow profile (McClung and Schaerer, 2006). These are commonly accomplished using small density cutters to sample individual layers; however, electronic probes have recently been introduced to perform the same task, as well as that of sampling total snow water equivalent. Several density cutter types are available, two of which have been introduced during the past 20 years and are widely available. The sole prior analysis of density cutters, conducted as part of the San Juan Avalanche Project (Carroll, 1977), compared the then newly introduced 200 and 100 cm^3 stainless-steel box-type density cutters with the classic 500 cm^3 aluminium tube. This study was undertaken to establish a value range for 'accepted practice' based on the various available density cutters used in snow profile observation.

There exists very limited guidance for estimation of error present in the standard method of measuring snow density in the field. Bader (1954) estimated the maximum measurement error for a 500 cm^3 tube-shaped density cutter at 0.25% and 1% for fine-grained and coarse-grained snow respectively. A 10% combined sampling and weighing error in repeated density measurements with a 100 cm^3 density cutter was described by Harper and Bradford (2003) during a small-area spatial density investigation on an Alaskan glacier. Peterson and Brown (1975) validated earlier estimation of an over-sampling bias of up to 12% for snow survey devices used in total snowpack snow water equivalent measurement (e.g. Mount Rose samplers).

When densities are utilized in published studies, accuracy is often not addressed other than in statements such as 'measurements were made according to observation standards' (e.g. Schweizer and Jamieson, 2001). However, specified techniques for density sampling described in current North American avalanche, weather and snow observation standards (CAA, 2002; Greene and others, 2004) provide only limited technique direction:

> Use wedge-type or smaller cutters for thin layers, larger volume cutters for depth hoar,
>
> Insert horizontally in the center of the layer, vertically if layer thickness exceeds cutter width, and in the pit side-wall for angled slopes.

Less guidance is available regarding observation quality, with the only reference being to snow density competency or confidence (SDC) that describes sample quality as: (1) good sample, (2) some loss of snow, (3) full sample not possible because too low for cohesion or too hard to sample (McMurdo Dry Valleys Long-Term Ecological Research (LTER), http://huey.colorado.edu/LTER/datasets/glaciers/glsnwdns.html 2000).

DENSITY CUTTER TYPES

Several density kits are commercially available and currently being used. There are others that are no longer purchasable. There are different styles of cutters for taking volume samples as well as different weighing devices. The 'standard' 500 cm^3 tube was originally described in English by Seligman (1936), and the sampling technique published in 1939 (Bader, 1954). This cutter is commonly referred to as the Swiss or SIPRE (US Army Snow, Ice, and Permafrost Research Establishment) cutter and sometimes the CRREL (Cold Regions Research and Engineering Laboratory) cutter. It is easily constructed from tube aluminium stock with one end sharpened chisel-like. The box-type cutter design originated at the Institute for Low Temperature Science, Japan, and was manufactured in the USA by Hydro-Tech as the Taylor–LaChapelle density kit (Fig. 1, left). The wedge-

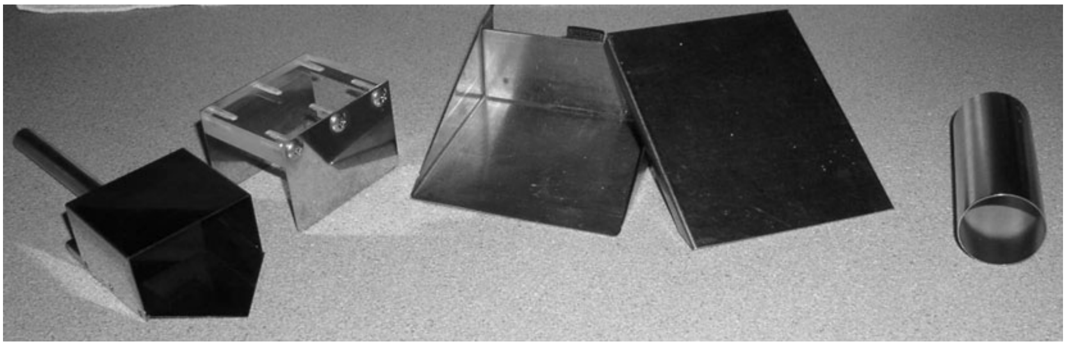

Fig. 1. Various types of density cutters tested for variance. Left to right: box (Hydro-Tech 100 cm^3), wedge (Snow Research Associates 200 cm^3) and tube (Wasatch Touring 100 cm^3).

type or rip cutter design is attributed to R.I. Perla and is presently manufactured by Snowmetrics in the USA. The wedge-type cutter tested was made by Snow Research Associates (SRA) and is no longer available (Fig. 1, middle). The Wasatch Touring density kit with a small, 100 cm^3 tube-type cutter (Fig. 1, right) was designed by S. Rosso and can be obtained through numerous sources worldwide. Specifications of the cutters are summarized in Table 1.

EXPERIMENTAL DESIGN

The experimental design was formulated to represent the general snowpack conditions under which densities are taken when conducting a snow profile associated with avalanche-potential observations. It varied from a standard profile layout in that a horizontal area of a selected layer was exposed so that we could take multiple samples at the same vertical position within the layer.

A random block experimental design was chosen to focus measured effect on the density cutter and to remove horizontal variability between sample areas (blocks). In a random blocking, the order in which the sample is taken (i.e. in which a cutter is used) is randomized for each block. The layer was then sampled with multiple blocks. The data are then analyzed using a one-way analysis of variance (ANOVA). The null hypothesis tested is: the mean density resulting from each cutter is the same.

A practice sampling day was conducted to assess technique and measurement equipment prior to the actual data collection. Data for analysis were collected in a flat area adjacent to the Parks Canada Mount Fidelity Station study plot (1905 m a.s.l.) in Glacier Park, British Columbia.

Data were collected over three field days: 15 and 17 February 2006 and 29 March 2006. On each day, a rectangular pit was excavated in a previously undisturbed location such that the working area was to the south of a deeper trench for the operator to stand in (the standing area) (Fig. 2 (i)). The working area consisted of a small horizontal bench cleared perpendicular to the standing area and exposing the top plane (approximately 70 cm wide by 130 cm across) of the layer to be sampled. Each block (dashed rectangles in Fig. 2) was approximately 70 cm wide (away from the trench), 10 cm across and 15 cm thick. The layer was removed to the left of the area to be sampled so that the long edge of the block to be sampled was exposed for the insertion of the sample cutters (Fig. 2 (ii)). This edge was re-prepared for each block. This was repeated for deeper layers by further excavating the standing trench and clearing a new working area below the previous one.

Each block included one sample per cutter, working from closest to the standing trench away (southwards). Sequencing of cutters within the block was randomized. Blocks progressed left to right along the same layer plane into a section undisturbed by the previous block. In cutting and removing a sample, substandard samples (e.g. visible volume loss or non-removable extraneous snow, SDC2) were discarded and the sampling was repeated until an adequate sample was obtained, before moving on to the next cutter in the sequence. The same experienced individual took all samples and measurements.

The tested density kits come with a variety of scales for measuring the sample mass: hanging and dial mechanical spring scales, digital scales and, in the case of the Wasatch Touring model, a custom-made balance device. To isolate

Table 1. Specifications and characteristics of density cutters tested in the randomized block analysis.

Cutter	Symbol used in Table 2 and Fig. 3	Type	Measured volume	Tare at −9°C	Width	Diameter	Height	Length	Cutting edge
			cm^3	g	cm	cm	cm	cm	
Hydro-Tech 100	Small square ▫	Box	99	71	6		5.5	3	Yes
Hydro-Tech 200	Large square □	Box	197	88.5	7		4.7	6	Yes
SIPRE 500	Large circle ○	Tube	485	490		5.63		19.5	Yes
SRA 200	Triangle △	Wedge	208	172	10		4.1	1	Yes (on cutting plate)
Wasatch Touring 100	Small circle ◦	Tube	99	47.5		3.71		9.2	No

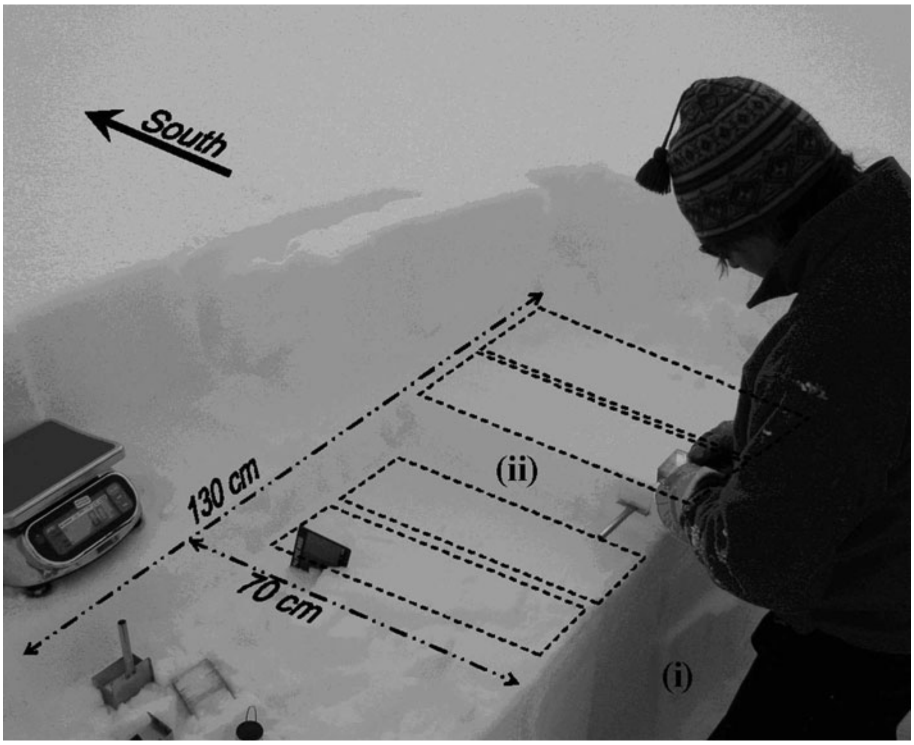

Fig. 2. Photo of the work area layout showing the standing trench (i) and the bench area divided into sample blocks. Rectangles outlined with dashed lines represent the location of four sample blocks, the two on the left having been completed. The first sample in the random sequence is being taken from the third sample block; (ii) indicates the prepared (vertical) edge of the block into which the cutters are pushed horizontally.

measurement error and compare cutters (rather than the scales), an appropriate digital bench scale was used for all experimental measurements (A&D Weighing model SK-WP). The scale was stainless steel, portable, waterproof, measured up to 1000 g at a 0.5 g resolution with accuracy of ±1 g, in an operating environment of –10 to 40°C, and had a calibration accuracy of ±0.1 g.

All the cutters were pushed horizontally from the left of the long axis of the block layout into the layer being measured, as seen in Figure 2, to the right of (ii). This ensured we were sampling as close to the same stratigraphy as possible, with vertical variation the same across each sample. The box-type cutters are supplied with a close-fitting cap that slices the sample down both open ends of the cutter and snugly encloses the cutter. The wedge-type cutter has a sliding plate that slices the sample from the surrounding material as it is inserted along the open top edge of the cutter. Often this squeezed the cutter out of the sample area, leaving a less than complete volume in the cutter. The tube-type cutters require using a flat metal piece such as a crystal screen or spatula to cut away material from both open ends. There is regular opportunity for low-density snow to fall out of these when removing them for weighing.

Layers for sampling were selected, based on a visual observation of homogeneity, at least 10 cm (and preferably 15 cm or more) thick. Table 2 summarizes the characteristics of each layer. On 15 February, the base of sample layer 1 was 33 cm down from the surface and consisted of small rounds (size 0.25–0.5 mm), with limited evidence of past faceting on the larger sizes. The layer thickness was 12 cm. The wind was calm and the air temperature ranged from –9.3°C at the start to –11.3°C near the end of data collection. Eight blocks were sampled.

On 17 February, two sets of 12 blocks were sampled in the same manner. The upper 12 blocks (layer 2) sampled were centered in a layer 5–15 cm down from the surface. This layer consisted of decomposing fragments (size 1–2 mm) with some faceting. The second set of 12 blocks (layer 3) was

Table 2. Summary of sample layer characteristics. Grain shape abbreviations follow 1990 International Association for Cryospheric Sciences classification (Colbeck and others, 1990): RG: round grains; FC: faceted crystals; DF: decomposing and fragmented precipitation particles

Layer	Number of blocks	*N*	Layer mean density kg m^{-3}	Grain shape	Size mm	Layer thickness cm
1	8	40	195	RG & FC	0.25–0.5	12
2	12	60	119	DF & FC	1–2	10
3	12	60	255	RG	0.5	36
4	6	30	151	RG	1	17
5	6	30	345	RG	0.25–0.5	20

Table 3. Summary of measurement error and cutter under-sampling error estimates

Density cutter	Weight measurement accuracy	Weight accuracy as % of measurement	Cutter under-sampling error	
	$kg\,m^{-3}$		$kg\,m^{-3}$	%
Hydro-Tech 100	±4	±1 to 4	2–8	–2
Hydro-Tech 200	±2	±1 to 2	2–7	–2
SIPRE	±0.8	±1	1–5	–1
SRA	±2	±1 to 2	2–8	–2
Wasatch Touring	±4	±1 to 4	1–5	–1

taken from a thick layer, and sample centers were 57 cm below the surface.

Two sets of six blocks were sampled on 29 March. The first set (layer 4) was taken directly above an old crust 17.5 cm down from the surface. This layer consisted of round grains, 0.5 mm in size and visibly rounding during grain identification (+3.1°C air temperature). The second set of eight (layer 5) was taken 67 cm from the surface and represented the most heterogeneous layer sampled. It consisted of moderately necked rounds, 0.5 mm in size with no observable change occurring (–3.2°C layer temperature).

Snow density competency or confidence (McMurdo Dry Valleys LTER, http://huey.colorado.edu/LTER/datasets/glaciers/glsnwds.html 2000) that describes sample quality was not recorded for these data, based on field technique that all samples were SDC1.

WEIGHT-MEASUREMENT AND SAMPLING ERROR

A component of the analysis was estimation of measurement and sampling error. The weight measurement error was assumed to be the variation of density measurements resulting from the scale accuracy over the sampled range of densities. A Monte Carlo simulation was run 100 times for 100 randomly assigned errors within the stated scale accuracy, resulting in the estimated measurement errors shown in Table 3.

Additionally, a potential under-sampling error was assumed and calculated using a 0, 1 or 2 mm randomly assigned volume reduction at the open ends or top of the cutter. The under-sampling error was estimated using a similarly iterated Monte Carlo simulation. This was also done for the range of density measurements taken during the analysis and resulted in the estimated under-sampling errors shown in Table 3. It is assumed this nominal under-sampling occurs for SDC1 observation quality samples.

Interpretation of these estimates is not straightforward; the estimated sampling errors do not include the likelihood of under-sampling based on the relative ease of making an accurate measurement. Though the box cutters have the larger error (–2%), their design makes under-sampling very unlikely (i.e. 0%), which was supported by experience. The wedge cutter often under-sampled due to displacement of the cutter as the cutting plate neared the thin leading edge of the wedge. The tube cutters, although percentage errors are smaller, also regularly under-sampled due to the manner in which the snow is cut from the ends of a horizontally inserted tube. Combination of these observations and sampling-error estimates therefore results in the error-bar values associated with the scale used (see Table 4).

Table 4. Under-sampling and weight-measurement error values representing SDC1 for tested cutters when used with the experiment-specific scale

Density cutter	Under-sampling and weight errors
	%
Hydro-Tech 100	±4
Hydro-Tech 200	±2
SIPRE	–2 to +1
SRA	–4 to +2
Wasatch Touring	–5 to +4

ANALYSIS

Statistical analyses were performed using the JMP IN ® Version 5.1 software package (Sall and others, 2003). The layers described above were analyzed ($N = 220$) and F-test results compared for an alpha level of 0.05. In three of the five layers, results suggested that the cutters were significantly different. Initial results also indicated blocking was not necessary in three of the five layers. Recalculation of ANOVA results for those layers did not change the outcomes (Table 5).

The right portion of Table 5 shows the ranges between cutter density means for each layer as well as the ranges between cutter density means and the mean layer densities. The coefficients of variation are expressed as percentages of the mean layer density. The greatest difference between cutter density means is 3–12%. The range of greatest cutter mean density to the mean layer densities is 2–7%.

All pairs were tested using the Tukey–Kramer honestly significant difference to assess the risk of committing a type I error in the analyses. The results are shown in Table 6, which summarizes the cutters that were suggested to be significantly different from others. In this table, cutters not connected by the same letter (A, B, C, etc.) within a layer were significantly different from the letter-connected sets. There was no threshold or pattern evident in the differences (e.g. 200 cm^3 or tubular cutters always fell into the same groupings). However, in all cases where the cutters were significantly different, both the small box and small tube cutters were not different from the large tube.

ANOVA assumes the variances are equal within the treatments. Four statistical tests (O'Brien's, Brown–Forsythe, Levene's, and Bartlett's) were applied to each layer analysis to evaluate this assumption. Only in layer 1 do two of these tests suggest unequal variances. Application of the Welch ANOVA (which weights observations by an amount inversely proportional to the variance) supported rejection of the null hypothesis for layer 1.

The results summarized in the rightmost two columns of Table 5 are expanded in Table 7 illustrating the variances for each cutter within the sampled layer. The coefficients of variation expressed as percentages of the mean layer density from Table 7 are combined with similarly expressed values for the variances between the cutter density means and the sample means (Table 5) to provide an expression of relative error shown in Figure 3.

Table 5. Result summary of random-block, one-way ANOVA ($N = 220$) for density cutters at $\alpha = 0.05$. The asterisk (*) indicates layers where the null hypothesis was rejected

Layer	Number of blocks	N	Prob > F		Null hypothesis result	Greatest density difference between cutter means	Greatest cutter-to-cutter difference as % of layer mean density	Layer mean density	Greatest density difference between cutter mean and layer mean	Greatest cutter and layer difference as % of layer mean density
			Cutter	Block						
						kg m^{-3}		kg m^{-3}	kg m^{-3}	
1*	8	40	0.0088	0.0747	Cutters significantly different	9.21	5	195	5.8	3
2*	12	60	0.0006	0.0002	Cutters significantly different	9.5	8	119	5.4	5
3	12	60	0.0701	0.1117	Unable to reject null	7.6	3	255	4.8	2
4*	6	30	<0.0001	0.1078	Cutters significantly different	18.7	12	151	10.2	7
5	6	30	0.1431	0.4196	Unable to reject null	24.9	7	345	13.4	4

DISCUSSION

Carroll (1977) used a two-way ANOVA to address random effects by operators. Fifty samples per cutter per layer for three homogeneous layers were analyzed ($N = 150$). Five operators recorded ten samples each cutter per layer. We assume that different weighing devices were used for the tube cutter versus the box cutters based on knowledge of the scale supplied with the box-type cutter kit and the weight characteristics of the tube cutter. In this study, we used a random block sample design to remove horizontal layer variability prior to a one-way ANOVA to determine the expected range of measured values using available density cutters. We recorded 30–60 samples per layer over five layers ($N = 220$) utilizing only one operator and one scale.

Whereas Carroll (1977) found insufficient evidence in all three layers to suggest significant difference in cutter type, we found that in three out of five layers sampled, the density cutters were significantly different. In his analysis, Carroll did find significant evidence that operator effect existed in the upper and lower layers at the 0.01 alpha level, which he attributed to grain type and associated measurement difficulties that required greater experience.

We attribute our findings to the vertical variation in layers where grain type represents early and transitional stages of metamorphism such as precipitation particles, decomposing fragments, and early stages of rounds at a layer scale.

As stated, all cutters were pushed horizontally into the snow. Field experience during this study suggests that the following practices are used for layers with multiple grain forms or early in the metamorphic process (precipitation particles or decomposing or fragmented particles):

> When a wedge-shaped density cutter is inserted horizontally (top of wedge sloping from the top at the front to the bottom at the back and the bottom parallel to the layering), 75% of the measured volume is in the lower half of the measurement, providing a vertically biased sample. When it is rotated 90° and inserted with the bottom and top of the wedge plumb, any layering bias is removed. This is reflected in the description by the current manufacturer of wedge cutters.
>
> A similar condition exists when using tube density cutters. They should be inserted with the cylinder axis vertical, cutting down through the layer to a pre-placed metal spatula or snow crystal card. This will provide a sample with less variance than inserting horizontally. Density of thin layers that do not fill the tube cutter can be calculated using the equation for volume of a cylinder.

CONCLUSIONS

In application as performed for dry snow profiles, snow density measurements taken by various density cutters may be significantly different, though there are expected ranges of precision. A conclusion can be made solely on the value ranges presented by the investigation without taking into account various reasons for the differences (e.g. stage of densification or mixture of metamorphism states).

Table 6. Summary of layers 1, 2 and 4 where null hypothesis (that cutter density measurements are equal) was rejected. In this table, cutters not connected by the same letter (A, B, C, etc.) within a layer were significantly different from the letter-connected sets (e.g. in layer 1, the Hydro-Tech 200 was significantly different from the other four cutters, and the Wasatch and Hydro-Tech 100 cutters were significantly different from the others)

	Layer 1		Layer 2			Layer 4	
Hydro-Tech 100	A			D			G
Hydro-Tech 200		B			E	F	
SIPRE	A	B	C	D	E		G
SRA	A	B	C			F	
Wasatch	A		C	D	E		G

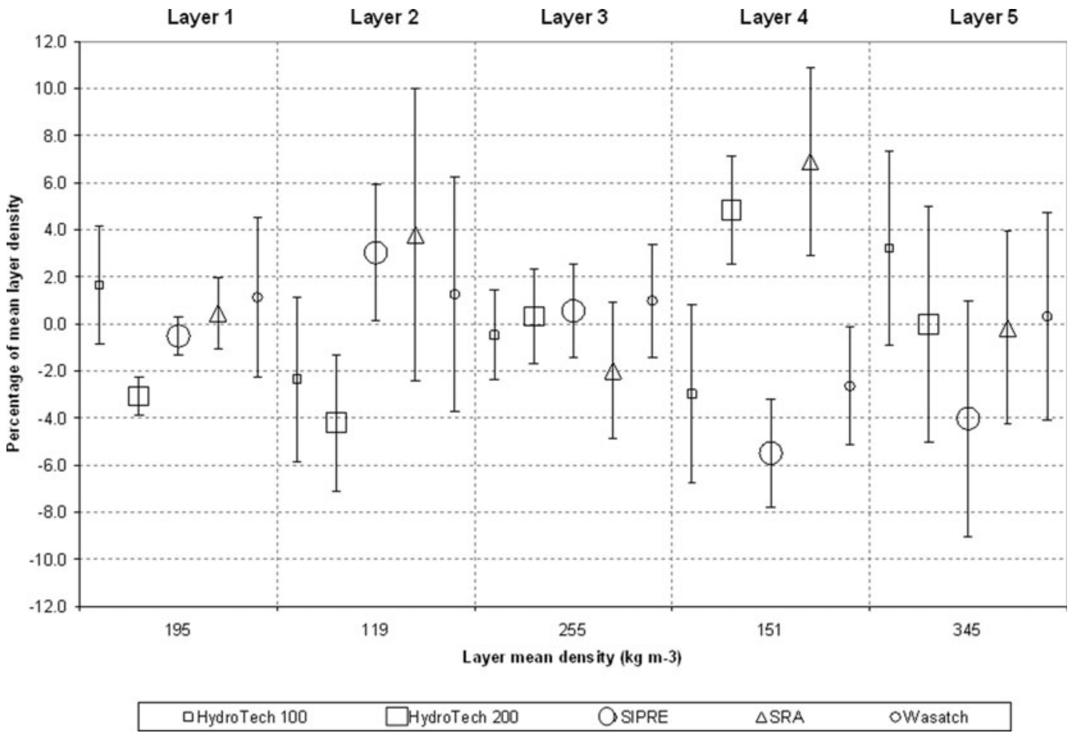

Fig. 3. Graphic summary of relative errors for density cutters, not including weighing and under-sampling errors. A graphic symbol described in Table 1 provides visual representation of cutter type and relative size (e.g. small square for small box cutter, large square for large box cutter, and triangle for wedge cutter). This symbol representing the cutter mean for the layer is positioned relative to the layer density mean.

Results shown in Table 4 suggest that for layers greater than 10 cm and less than 30 cm thick, larger box-type and tube-type density cutters provide results with less error than smaller cutters or wedge-type cutters.

Without accounting for variation due to weighing devices, the 'accepted' range of density measurements includes variation within individual cutters of 0.8–6.2%, variation between cutters of 3–12%, variation between cutter means and layer means of 2–7%, and potential under-sampling errors of 0–2%. The variations within individual cutters attached to the variations between cutter means and layer means are shown in Figure 3 illustrating the relative error of each cutter against the sampled layers. Interpretation of Figure 3 suggests that given the mean of all samples is accepted to be the true value of the measured layer density, variation exclusively between cutter types provides 'accepted practice' measurements that are within 11% of the true density.

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Table 7. Summary of variances and coefficients of variation expressed as a percentage of mean layer densities for cutter measurements within layers. The asterisk (*) indicates layers where the null hypothesis was rejected

	Hydro-Tech 100		Hydro-Tech 200		SIPRE		SRA		Wasatch	
Layer	Cutter std dev. kg m^{-3}	as % of layer mean density	Cutter std dev. kg m^{-3}	as % of layer mean density	Cutter std dev. kg m^{-3}	as % of layer mean density	Cutter std dev. kg m^{-3}	as % of layer mean density	Cutter std dev. kg m^{-3}	as % of layer mean density
1*	4.9	2.5	4.3	2.2	1.5	0.8	3.0	1.5	6.7	3.4
2*	4.2	3.5	4.1	3.4	3.4	2.9	7.4	6.2	6.0	5.0
3	4.9	1.9	6.5	2.5	5.2	2.0	7.4	2.9	6.2	2.4
4*	5.7	3.8	3.7	2.5	3.5	2.3	6.0	4.0	3.8	2.5
5	14.3	4.1	6.1	1.8	17.4	5.0	14	4.1	15.3	4.4

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