



1 **Brief communication: Comparison of in-situ ephemeral snow**
2 **depth measurements over a mixed-use temperate forest**
3 **landscape**

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5 Holly Proulx¹, Jennifer M. Jacobs^{1,2}, Elizabeth A. Burakowski², Eunsang Cho^{3,4}, Adam G.
6 Hunsaker^{1,2}, Franklin B. Sullivan², Michael Palace^{2,5}, Cameron Wagner¹

7 ¹Department of Civil and Environmental Engineering, University of New Hampshire, Durham, NH, 03824, USA

8 ²Earth Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New
9 Hampshire, Durham, NH, 03824, USA

10 ³Hydrological Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA

11 ⁴Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA

12 ⁵Department of Earth Sciences, University of New Hampshire, Durham, NH, 03824, USA

13 *Correspondence to:* Jennifer M. Jacobs (Jennifer.jacobs@unh.edu)

14 **Abstract.** The accuracy and precision of snow depth measurements depend on the measuring device and the
15 conditions of the site and snowpack in which it is being used. This study compares collocated snow depth
16 measurements from a magnaprobe snow depth probe and a Federal snow tube in an ephemeral snow environment.
17 We conducted three snow depth sampling campaigns from December 2020 to February 2021 that included 39
18 open field, coniferous, mixed, and deciduous forest sampling sites in Durham, New Hampshire, United States.
19 For all sampling campaigns and land cover types with a total of 936 paired observations, the magnaprobe snow
20 depth measurements were consistently deeper than the snow tube. There was a 12% average difference between
21 the magnaprobe (14.9 cm) and snow tube (13.2 cm) average snow depths with a greater difference in the forest
22 (1.9 cm) than the field (1.3 cm). This study suggests that snow depth measurements using a Federal snow tube
23 can avoid overprobing with an ephemeral snowpack in forested environment.

24
25 **Short Summary.** This study compares snow depth measurements from two manual instruments in a field and
26 forest. Snow depths measured using a magnaprobe were typically 1 to 3 cm deeper than those measured using a
27 snow tube. These differences were greater in the forest than the field.

28 **1 Introduction**

29 Snow depth is one of the easier snowpack properties to measure in the field and is an observation that can be
30 measured relatively precisely without considerable expertise or expense. Hundreds of snow depth measurements
31 can readily be taken in a single day and automated samplers can substantially increase that number (Sturm and
32 Holmgren 2018). In-situ snow depth observations can be measured manually or automatically. While automated
33 measurements are increasing in use (Bongio et al. 2021; Kinar and Pomeroy 2015; Kopp et al. 2019), in-situ
34 measurements remain the mainstay of data collection research and operations (Kinar and Pomeroy 2015; Pirazzini
35 et al. 2018). Manual in-situ snow depth measurements are typically made using snow stakes, rulers, or narrow
36 diameter snow probes (Kinar and Pomeroy 2015; Pirazzini et al. 2018). Snow tube samplers, which have been in
37 use since the 1930s, also measure snow depth. The magnaprobe, an automatic snow depth probe that records snow



38 depth and GPS measurements, has considerably increased the number of georeferenced snow depth observations
39 that can be made in a single day and is used extensively for snow depth research campaigns (Sturm and Holmgren
40 2018; Walker et al. 2020). Measurement variability and errors are sometimes reduced by repeating the
41 measurement, typically three times (Leppänen et al. 2016). Because snow depth is assumed to have greater spatial
42 variability than snow density (Elder et al. 1998), a snow survey often makes numerous snow depth measurements
43 per snow density measurement then combines to obtain snow water equivalent (SWE) (López-Moreno et al. 2013).
44

45 SWE measurement errors associated with snow tube samplers are relatively well understood and characterized.
46 Known issues include biases as compared to snow pit measurements (Dixon and Boon, 2012; Farnes et al., 1983;
47 Goodison, 1978; Sturm et al., 2010), accuracies around +/- 5% to 10% for an individual instrument, and
48 differences among SWE from different snow tube models (e.g., the Meteorological Service of Canada, the Federal
49 or Mt. Rose, the Adirondack, and the Snow-Hydro) that can exceed 10% (Farnes et al. 1983). Less is understood
50 about the errors in snow depth measurements. Lopez-Moreno et al.'s (2020) comparison of nine snow core
51 samplers found that snow depths were relatively consistent when taken over a paved surface. However, over
52 uneven ground, the snow depth differences among samplers was much greater and replicate snow depth
53 measurements had larger variability as compared to the snow density. The magnaprobe, which measures snow
54 depth with a precision of less than 0.1 mm, has the potential for low biases if its basket settles into soft surface
55 snow, but those biases are typically less than 1 cm (Sturm and Holmgren 2018). When the rod penetrates the
56 substrate (over-probing), the error depends on the ground surface and the operation. Solid or frozen ground
57 surfaces have negligible over-probing, but unfrozen natural surfaces may have considerable penetration (Derry et
58 al. 2009) with biases on the order of 5 to 10 cm (Berezovskaya and Kane 2007; Sturm and Holmgren 2018). These
59 errors can have profound effects on SWE estimates in shallow snow environments and represent a challenge for
60 error accounting in hydrological modelling.

61

62 The goal of this brief study is to determine 1) if the magnitude of the snow depth measurements using a
63 magnaprobe and a Federal tube are significantly different in an ephemeral snow environment with shallow snow
64 and 2) if the differences vary by land cover type. We hypothesize that the snow depth measurements from the
65 magnaprobe will be deeper than those from the snow tube. This hypothesis is based on the understood errors and
66 biases associated with each the magnaprobe and the Federal tube, including the smaller surface area of the probe
67 which allows for greater penetration through snowpacks and leaf litter. Three snow depth sampling campaigns
68 were conducted from December 2020 to March 2021 over field and forest plots at Thompson Farm in Durham,
69 New Hampshire, USA.

70 **2 Site, Methods, and Data**

71 **2.1 Study Site**

72 This study was conducted at the University of New Hampshire's Thompson Farm Research Observatory in
73 southeast New Hampshire, United States (N 43.11°, W 70.95°, 35 m above sea level, ASL). The site has mixed
74 hardwood forest and open field land covers (Perron et al. 2004) that are characteristic of the region (Fig. 1). The
75 agricultural fields are managed pasture grass with unmown grass in local areas. The deciduous, mixed, and



76 coniferous forest is composed primarily of white pine (*Pinus strobus*), northern red oak (*Quercus rubra*), red
77 maple (*Acer rubrum*), shagbark hickory (*Carya ovata*), and white oak (*Quercus alba*) (Perron et al. 2004). The
78 forest soils are classified as Hollis/Charlton very stony fine sandy loam and well-drained; field soils are
79 characterized as Scantic silt-loam and poorly drained.

80

81 In-situ sampling was conducted at 39 sites located along three parallel transects (**Fig. 1**). The approximately 145
82 m long transects were laid out from east to west. The transects were separated by approximately 10 m, north to
83 south. From east to west, each transect started in the open field area, then transitioned to the coniferous, then
84 mixed, and finally, deciduous forested areas. Each of the three transects had 13 sampling sites; four sites were in
85 the open field area, three in the coniferous forest, three in the mixed forest, and three in the deciduous forest,
86 which were each marked with a stake. The stake locations were geolocated using a Trimble® Geo7X GNSS
87 Positioning Unit and Zephyr™ antenna with an estimated horizontal uncertainty of 2.51 cm (standard deviation
88 0.95 cm) and 4.17 cm (standard deviation 4.60 cm) for the field and forest, respectively, after differential
89 correction. Three soil frost tubes were located in the field approximately 25 m south of the field transect and
90 another three in the forest about 100 m southwest of the study area.

91 **2.2 In-Situ Sampling Methods**

92 Snow depth was measured using a magnaprobe and a Federal snow sampler, also known as a snow tube. The
93 Federal snow tube with its long operational history (Clyde 1932) served as a historical reference against the
94 magnaprobe. A magnaprobe consists of an avalanche probe-like rod of about 1.5 m in length that contains a
95 magnetostrictive device and a sliding magnetic disk-shaped basket with a 25 cm diameter. The rod has a 1.27 cm
96 diameter with an affixed tip that tapers to a point to help penetrate ice layers. The magnaprobe was operated by
97 inserting the pole into a snowpack until the tip of the pole reached the ground surface, allowing the basket to slide
98 down to float on top of the snow. A handheld portable keypad connected to a datalogger recorded the snow depth
99 between the tip of the pole and the bottom of the basket.

100

101 A Federal snow sampler is an aluminium tube, about 76 cm in length with a 4.13 cm inner diameter, that is used
102 to measure snow depth and SWE (Clyde 1932). To measure snow depth, the snow tube was inserted vertically
103 into the snowpack until it reached the ground, and a depth was read at eye level. Snow depth was recorded to the
104 nearest 0.5 cm. To measure snow density, the snow tube was then lifted out of the snowpack, using a spatula as
105 needed to ensure that snow did not fall out of the tube. The snow and snow tube were weighed using a digital
106 hanging scale (CCi HS-6 Electronic Scale, 2-gram resolution).

107

108 Sampling campaigns were conducted on 18 December 2020, 4 February 2021, and 24 February 2021. A total of
109 936 paired magnaprobe and Federal snow tube snow depth observations were collected during the three sampling
110 campaigns. At each of the 39 sampling locations, nine measurements were made in a 1x1 m area. At each location,
111 a 1x1 m square polyvinyl chloride (PVC) grid was placed on the snow surface with one vertex located coincident
112 with a stake. The orientation of two adjacent sides of the grid was recorded using a compass. Nine magnaprobe
113 depth measurements were made at an approximately even spacing within the grid. Immediately after the
114 magnaprobe measurements, snow tube snow depth measurements were made at the same nine locations by



115 positioning the snow tube directly over each magnaprobe sampling location. At a 10th location within each 1x1 m
116 grid, the snow tube was used to make a snow density measurement. For the 24 February 2021 campaign, after the
117 magnaprobe measurements were completed for the two northern transects, the instrument was transferred to a
118 new operator who made measurements on the southernmost transect (Transect 1). Transect 1 data for that date
119 were removed from the analysis because the QA/QC process identified notable errors for observations from that
120 transect.

121

122 Moultrie Wingscapes Birdcam Pro Field Cameras were used to capture images of the snowpack every 15 minutes
123 relative to a 1.5 meter marked PVC pole following the method used in NASA's 2020 SnowEx field camera
124 campaign in Grand Mesa, CO (personal communication, 16 November 2020). Three cameras were used; one was
125 in the open field, one was in the coniferous forest, and one was in the deciduous forest (**Fig. 1**). Snow depth was
126 derived by manual inspection of the photos and recorded to the nearest cm.

127 **2.3 Ancillary Soils and Vegetation Cover Data**

128 Daily soil frost depth data were collected at field and forest locations at the Thompson Farm Research Observatory
129 using Cold Regions Research and Engineering Laboratory style frost tubes (Gandahl 1957). The frost tubes have
130 flexible, polyethylene inner tubing filled with methylene blue dye whose color change is easy to differentiate
131 when extruded from ice. The outer tubing consists of PVC pipe installed between 0.4 to 0.5 m below the soil
132 surface. The field and forest sites each had three soil frost tubes.

133

134 Leaf litter depth was measured on 2 April 2021 after the spring snowmelt. The leaf litter depth was measured at
135 each snow depth sample location. Sampling was conducted using a PVC collar or round ring that is 8 cm in depth
136 and 10 cm in diameter (Kaspari and Yanoviak 2008). The collar was placed in the leaf litter and was pushed down
137 until it was through the leaf litter layer. If sticks or larger stones were in the way, they were either carefully
138 removed or the collar was moved slightly to an adjacent location. Measurements were taken using a wooden ruler
139 at four cardinal points in the collar. The four measurements were recorded and their average to the nearest cm
140 was used as the final litter depth. The range of leaf litter depths measured in the forest using the collar was typically
141 3 to 7 cm with an average leaf litter depth of 3.9 cm.

142 **3 Results**

143 The three sampling campaigns, 18 December 2020, 4 February 2021, and 24 February 2021, all had shallow
144 snowpacks. The snowpacks had similar depths, between 10 and 15 cm, on the three sampling dates with modestly
145 deeper snow in the field than the forest. The deepest snow was on 4 February 2021 with 15 cm in the field and
146 9.3 cm in the forest. Between the 18 December and the 4 February sampling campaigns, there was a melt event
147 in which the entire 10 cm snowpack on 18 December ablated. The next significant snowfall event (15 cm) occurred
148 on 1 February 2021. The snowpack experienced little additional accumulation or ablation between 4 February and
149 24 February. The 4 February (0.15 g/cm³) and 24 February (0.20– 0.24 g/cm³) snowpack density values were
150 higher than those in December (~ 0.10 g/cm³). There were shallow soil frost depths (< 4 cm) during the early



151 winter 18 December campaign in the forest and the field. Deeper soil frost depths of 15.1 cm in the field and 5.9
152 cm in the forest occurred on 4 February 2021, with similar soil frost conditions on 24 February 2021.

153 **3.1 Magnaprobe vs. Snow Tube**

154 The full experiment yielded individual 936 pairs of snow depth measurements from the snow tube and the
155 magnaprobe (**Fig. 2a**). For the comparison between measurement techniques, the orthogonal Deming regression
156 method was applied to consider measurement errors in both variables. Overall, there was moderate agreement (R
157 $= 0.74$) between the two datasets for all three sampling campaigns (**Table S1**). The snow depths measured by the
158 magnaprobe (14.9 cm average snow depth) were deeper than the snow tube (13.2 cm average snow depth) with
159 an overall bias of 1.7 cm. The magnaprobe snow depth was at least 0.5 cm deeper than the snow tube in 74% of
160 the 936 measurement pairs. Only 6.3% of the pairs had snow tube snow depths exceeding magnaprobe snow
161 depths by 0.5 cm or more. Conversely, 7.4% of the pairs' magnaprobe snow depths were over 5.0 cm deeper than
162 the snow tube. In eight pairs of measurements, when the magnaprobe measured snow depth greater than 15 cm,
163 the magnaprobe snow depths were more than double the snow tube snow depth.

164

165 The majority of the nine sampling locations in each grid had magnaprobe snow depth values that were deeper than
166 those measured using the snow tube. For all the grids, an average of 8.7, 7.7, and 7.0 out of the nine sampling
167 locations had deeper magnaprobe snow depths on 18 December 2020, 4 and 24 February 2021, respectively. As
168 hypothesized, the magnaprobe snow depth values were significantly greater than those measured using the snow
169 tube for 39 and 31 of the 39 sampling locations on 18 December 2020 and 4 February 2021, respectively, but only
170 11 out of the 26 sampling locations on 24 February 2021. The mean differences were 2.3, 1.4, and 1.6 cm, with
171 root mean square difference (RMSD) values of 3.0, 2.3, and 3.3 cm, on 18 December 2020, 4 and 24 February
172 2021, respectively, which is on the order of 15 to 25% of the overall depth observed during these campaigns.
173 Despite the biases, the average within cell snow depth variability was nearly identical for the magnaprobe and the
174 snow tube in the field (1.3 cm standard deviation for the magnaprobe). In the forest, the Magaprobe's 2.0 cm
175 within-cell standard deviation modestly exceeded the snow tube's 1.5 cm standard deviation. A slightly reduced
176 agreement was found on 24 February when there was a 1 to 4 cm thick ice layer at the bottom of the snowpack in
177 local depressions.

178

179 The overall agreement between the snow tube and magnaprobe was better when the nine measurements within a
180 single 1x1 m grid cell were averaged at each of the sampling locations (**Fig. 2b** and **Table S1**). There is a notable
181 improvement in grid cell statistics, and the correlation is stronger (overall $R = 0.87$), with slopes closer to one,
182 intercepts closer to zero, and the RMSD values reduced to 2.5 cm or less. Although averaging has no impact on
183 the overall bias, the range of differences among pairs narrowed. The difference between the magnaprobe and the
184 snow tube is typically constrained to less than 3 cm with a limited number of outliers. The magnaprobe snow
185 depth was at least 0.5 cm deeper than the snow tube in almost all grid cells (86.7%), but only three grid cells had
186 differences greater than 5 cm. Among the grid averaged magnaprobe snow depths, there were no instances in
187 which there was a doubling of snow depth when compared to the snow tube measurements.



188 **3.2 Magnaprobe vs. Snow Tube by Land type**

189 The magnaprobe and snow tube snow depths differ by land type, with the field having deeper snow and more
190 spatial variability than the forest land types (**Fig. 3**). Among the three forest types, the deepest snow was in the
191 deciduous-dominated forest, with mixed and coniferous forest having similar snow depths. The mean difference
192 between the magnaprobe and snow tube snow depths is a modest 1.3 cm in the field and 1.9 cm in the forest, with
193 differences of 1.9, 2.0, and 1.9 cm in the deciduous, mixed, and coniferous land types, respectively. However, the
194 differences between the magnaprobe and snow tube snow depths in the forest were higher on 18 December (2.5
195 cm), than on 4 February, and 24 February, 1.7, and 1.4 cm, respectively. Based on t-test results, the magnaprobe
196 measured significantly deeper snow depth compared to the snow tube in both the field and the forest regardless
197 of whether individual locations (p-value < 0.001) or grid cell average snow depths (p-value = 0.02) were used.
198 Based on Welch's adjusted ANOVA test, there are no significant differences in over-probing among forest land
199 types (p-value = 0.24). The RMSD values between the magnaprobe and snow tube snow depths are 3.0 cm (2.3
200 cm) and 2.5 cm (2.0 cm) for the forest and field sampling sites (grid average values), respectively. Thus, the
201 sampling method has a different impact in the field than the forest and the RMSD and bias values provide an
202 indicator of the different errors associated with in-situ measurements based on land type when used for model or
203 remote sensing validation.

204 **4 Discussion and Suggestions**

205 This study quantifies the differences between snow depth measurements made with a magnaprobe and with a
206 snow tube. The differences seem to be primarily associated with greater over-probing by the magnaprobe into
207 vegetation/organic layers and thawed soils. The result was that the magnaprobe snow depth measurements were
208 higher than snow tube measurements, with a greater difference in the forest than in the field. An average of 5 cm
209 bias occurred in the tundra mat during the Cold Land Processes Experiment (CLPX) Alaska campaign (Sturm
210 and Holmgren 2018). Also in the open tundra environment found a 7.6 cm average over-probe penetration for
211 approximately 40 cm deep snow (Canada 2018). Berezovskaya and Kane (2007) also noted over-probing of 5 to
212 9 cm with a magnaprobe as compared to a snow tube found a bias in northern Alaska for snow depths between 29
213 and 48 cm. In this study, the over-probing, 1.3 cm in the field and a 1.9 cm in the forest, was less than previous
214 studies probably due to the lower range of snow depth and different surface conditions as compared to previous
215 studies.

216

217 We also agree with Lopez-Moreno et al.'s (2020) finding that it is important to understand the snowpack and land
218 conditions for which an individual sampler was designed to select the most appropriate sampler. Understanding
219 leaf litter or vegetation depths and underlying soils may potentially reduce and help to account for the over-probing
220 errors of magnaprobe snow depth measurements. Sturm and Holmgren (2018) suggested that operators need to
221 learn to push a magnaprobe through snow, yet not penetrate it too deeply into underlying vegetation/organic layers
222 by developing a sense for the base of the snowpack. This recommendation may be difficult to implement (e.g.,
223 over soft vegetation) where the probe easily penetrates the vegetation and problematic if multiple operators apply
224 a different amounts of force (Berezovskaya and Kane 2007). If operators over-probe into the base of the (frozen)
225 soils, one option is to consistently measure the depths in the same way (which would be snow depth *plus*



226 vegetation) and then subtract typical vegetation depths in the study area from the depths. When leaf litter is
227 evident, penetration into the organic layer should also be considered. In this study, we found that the 2.0 cm snow
228 depth differences were approximately half of the end of winter forest leaf litter depth (3.9 cm).

229

230 As observed in this study, leaf litter and soil frost may differentially impact in-situ snow depth sampling methods.
231 The earliest sampling campaign had limited soil frost and likely reduced litter compaction. Distinct contributions
232 of forest leaf litter depth to magnaprobe and snow tube snow depths may occur because the narrow magnaprobe
233 fully penetrates the leaf litter and the larger diameter snow tube only partially penetrates the litter, or the
234 magnaprobe may only partially penetrate the leaf litter but the snow tube does not break through the leaf litter.
235 Partial penetration of the magnaprobe into the leaf litter layer (i.e., over-probing) may vary by the freeze-thaw
236 state of the duff layer and/or mineral soil layers beneath the leaf litter layer. The horizontally aligned, matted leaf
237 litter could also limit snow tube penetration. High spatial variability of leaf litter depth could also be a factor,
238 though this was not quantified here. Thus, the increased differences among in-situ methods in forested areas
239 observed in this study point to the particular importance of in-situ validation in forested areas and, more generally,
240 sampling with multiple methods in an area with a nonuniform underlying substrate.

241

242 In summary, there are three major suggestions from this work below.

- 243 1) With an ephemeral snowpack in forested environment, snow depth measurements using a Federal
244 snow tube likely avoid over-probing that can frequently occur when a magnaprobe is used.
- 245 2) The use of the average of multiple point samples within a grid is recommended instead of single
246 measurements, because the average of multiple point samples can reduce the point-to-point variability
247 and spatial representativeness errors.
- 248 3) Measurements of vegetation, leaf litter, and soil frost can help to account for the errors of in-situ snow
249 depth observations, particularly when using a magnaprobe.

250

251 **5 Conclusion**

252 Manual in-situ sampling snow depth measurements can be made quickly and easily, but making consistent,
253 representative, and unbiased measurements can be challenging when the surface is irregular, vegetation/organic
254 layers and unfrozen soils result in over-probing, and the leaf litter compacts during the winter. This study
255 quantified the differences between snow depth measurements made with a magnaprobe and a Federal snow tube
256 in a mixed-use temperate forest landscape with ephemeral snowpack. For all sampling campaigns and land cover
257 types, the magnaprobe snow depth measurements (mean 14.9 cm) were usually, but not always deeper than the
258 snow tube measurements (13.2 cm) and had a 1.7 cm or 12% average difference. Biases were significantly higher
259 in the forest (1.9 cm) than the field (1.3 cm). The difference between the two instruments was 50% higher in early
260 winter campaign than the later campaigns. The differences among measurement techniques in this present study
261 reflect the current study area, surface conditions for a single season, and the operation of the instruments by this
262 project team. Further studies to understand the errors from in-situ sampling using snow probe are warranted in
263 various snow environments with different vegetation and soil conditions to provide guidance on best practices for
264 using in-situ snow probe datasets under conditions when over-probing is likely.



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270 depth sampling. Christina Herrick for post-processing GPS data.

271 Data Availability

272 The in-situ snow observations are available in supporting information.

273 Author Contributions

274 HP, JJ, EB, AH, FS, MP, and EC designed the research. HP, CW, JJ, AH, FS, MP, EB, and EC conducted field
275 work to obtain lidar and/or in-situ snow observations. HP, CW, JJ, EB, AH, and MP performed the analysis.
276 HP, EC, and AH produced the figures. HP, JJ, EB, and EC wrote the initial draft. All authors contributed to
277 manuscript review and editing.

278 Competing Interests

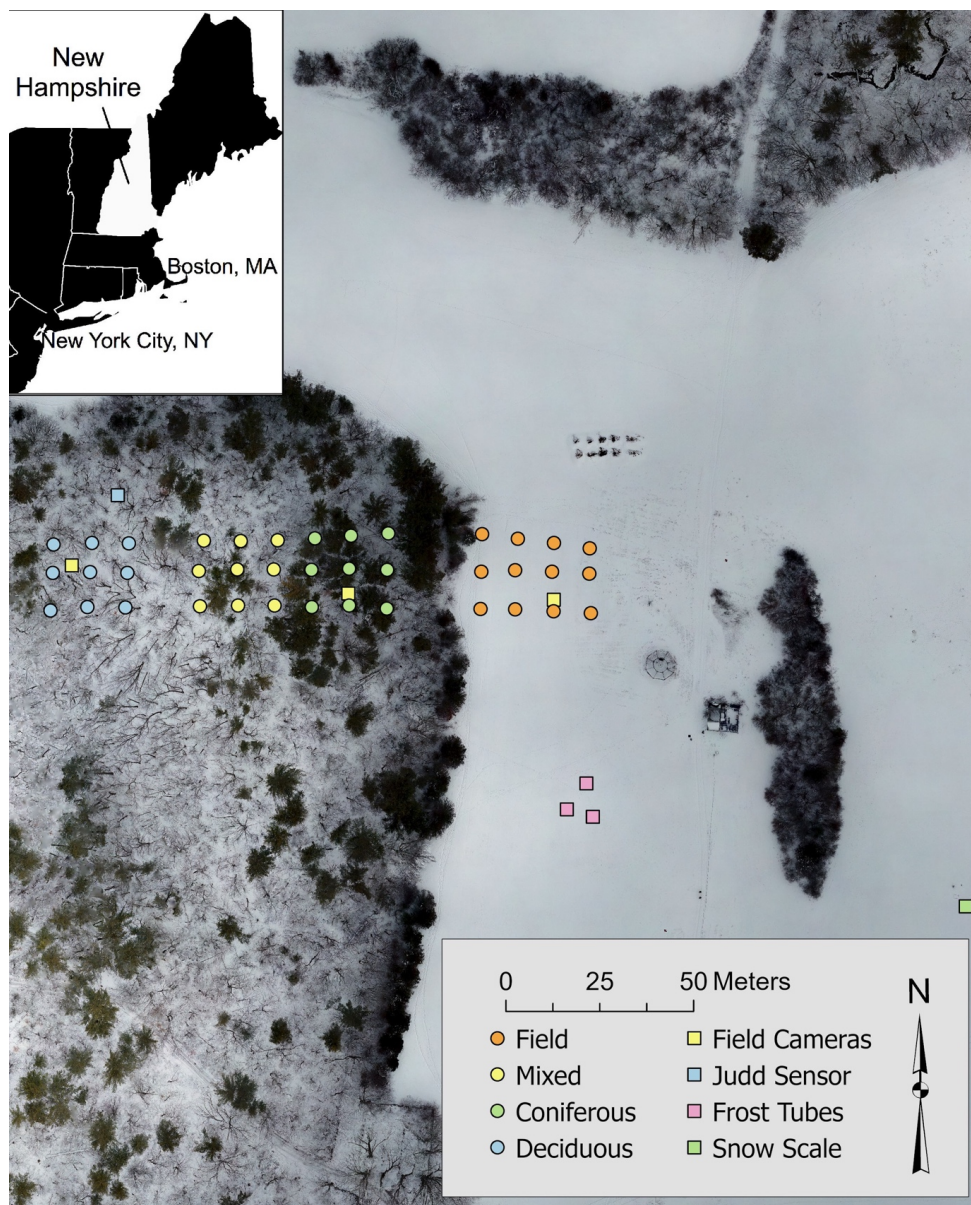
279 The authors declare that they have no conflict of interest.

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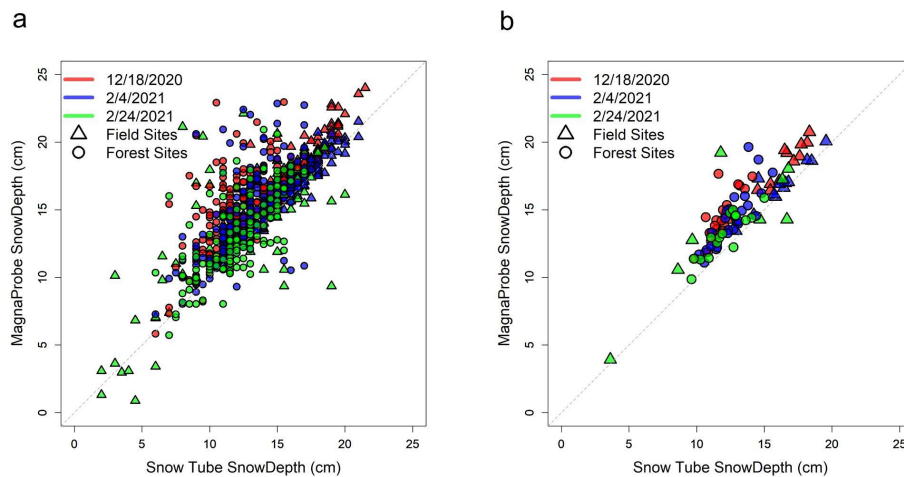
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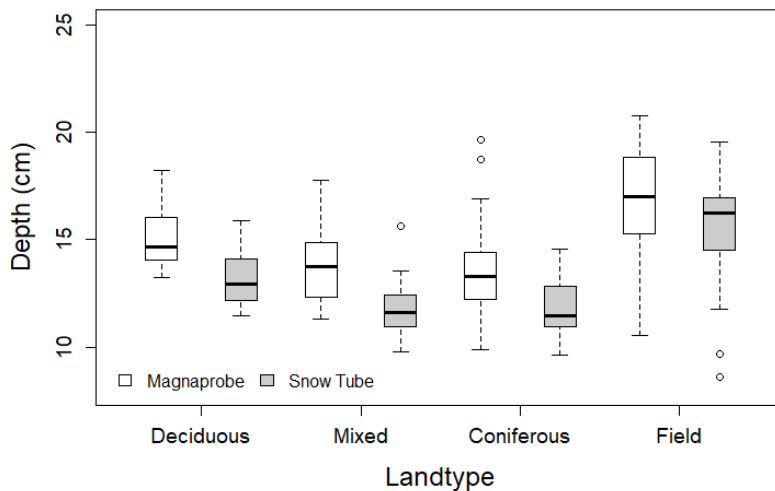
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318 **Figure 1:** The 4 February 2021 aerial optical image of Thompson Farm, Durham NH, USA showing both forest
319 and field region with snow sampling sites in the field, coniferous, mixed, and deciduous forested areas as well as
320 the locations of the CRREL soil frost tubes; and field cameras.



321
322 **Figure 2:** Comparison of snow depths measured by magnaprobe and snow tube for the three sampling campaigns
323 using (a) the sampling individual points ($n = 936$) and (b) using grid cell average values ($n=104$).



324
325 **Figure 3:** Boxplots of snow depths by land type measured by the magnaprobe and the snow tube for the three
326 sampling campaigns using the grid cell average values.

327