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Exploration of Thermal Bridging through Shrub Branches in Alpine Snow

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Key Points:

- The winter ground temperature in a snow-covered alpine area during a cold spell is 1.3°C colder under alders than under nearby grass.
- Using finite element modeling, we demonstrate that this is due to thermal bridging through alder branches.
- Plane-parallel snow layer geometry cannot be used to model ground temperature, soil freezing, and snow metamorphism if shrubs are present.

24 **Abstract**

25 In the high Arctic, thermal bridging through frozen shrub branches has been demonstrated to
26 cool the ground by up to 4°C during cold spells, affecting snow metamorphism and soil carbon
27 and nutrients. In alpine conditions, the thermal conductivity contrast between shrub branches and
28 snow is much less than in the Arctic, so that the importance of thermal bridging is uncertain. We
29 explore this effect by monitoring ground temperature and liquid water content under green alders
30 and under nearby alpine tundra in the Alps. During a January 2022 cold spell, the ground
31 temperature at 5 cm depth under alders is 1.3°C colder than under alpine tundra. Ground water
32 freezing under alders is complete, while water remains liquid under tundra. Finite element
33 simulations reproduce the observed temperature difference between both sites, showing that
34 thermal bridging does affect ground temperature also under Alpine conditions.

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38 **Plain Language Summary**

39 With climate warming, shrubs are expanding in seasonally snow-covered Arctic and alpine areas.
40 In the Arctic, it has been shown that shrubs buried in snow act as thermal bridges between the
41 ground and the atmosphere, so that the ground winter temperature is colder than if thermal
42 effects due to snow only are considered. Thermal bridging is efficient in the Arctic because the
43 thermal conductivity of shrub branches is 30 to 70 times as large as that of snow. In alpine areas,
44 the difference in thermal conductivity between the shrub branches and the snow is much lower,
45 so that the efficiency of thermal bridging by shrubs is uncertain, even though shrub branches are
46 much thicker. We monitored the soil temperature at an Alpine site at a spot with green alders and
47 a nearby spot with herbaceous vegetation. The ground was 1.3°C colder under alders during a
48 cold spell. Using finite element simulations, we show that this is explained by thermal bridging
49 through alder branches. Snow and land surface models must therefore include this process for
50 adequate simulations of the soil temperature, soil freezing and carbon recycling, snow
51 metamorphism and snow physical properties.

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55 **1 Introduction**

56 In snow-covered areas, heat exchanges between the atmosphere and the ground through
57 the snowpack determine winter ground temperature (Domine et al., 2019). Physical snow models
58 describe heat exchanges through snowpacks based on a plane-parallel snow layer geometry. In
59 Arctic and Alpine areas, shrubs are expanding (Anthelme et al., 2003; Wiedmer & Senn-Irlet,
60 2006; Ju & Masek, 2016), inducing changes in snow properties. Shrubs trap blowing snow,
61 increasing snow height (Sturm et al., 2001; Lamare et al., 2023), reducing snow compaction, and
62 favoring the formation of the most thermally-insulating snow type: depth hoar (Domine, Barrere,
63 & Morin, 2016).. Furthermore, shrub branches disrupt the plane-parallel geometry. Recently,
64 thermal bridging through frozen shrub branches buried in snow has been detected in the high
65 Arctic (Domine et al., 2022), enhancing ground cooling in winter, despite widespread depth hoar.
66 Cooling averaged over the November-February period was 1.21°C, but reached 4°C during cold
67 spells. Accurate simulation of the ground temperature by snow models is crucial as it impacts the
68 temperature gradient in the snowpack, which determines metamorphism and snow physical
69 properties. Ground temperature is equally important to land surface models to simulate carbon
70 and nutrient recycling in soils, which considerably slows down when the ground freezes
71 (Saccone et al., 2013).

72 In the Arctic, the thermal conductivity contrast between snow found in shrubs and frozen
73 shrub branches is a factor of 30 to 70. Snow within shrubs is mostly depth hoar with a thermal
74 conductivity of 0.03 to 0.07 $\text{Wm}^{-1}\text{K}^{-1}$ in the Arctic (Domine, Barrere, & Morin, 2016; Domine et
75 al., 2022) while the thermal conductivity of frozen wood is around 2 $\text{Wm}^{-1}\text{K}^{-1}$ (Domine et al.,
76 2022). Therefore, even though high Arctic shrub branches rarely exceed 3 cm in diameter
77 (Sturm et al., 2001; Domine et al., 2022), the thermal conductivity contrast is sufficient for
78 thermal bridging through frozen shrub branches to efficiently cool the ground.

79 Whether thermal bridging also operates in Alpine regions is uncertain because the
80 thermal contrast between alpine snow and the presumably unfrozen alpine shrub branches is
81 much less than in the Arctic. (Morin et al., 2010), (Calonne et al., 2011) and (Riche &
82 Schneebeli, 2013) measured thermal conductivity values from 0.05 to 0.46 $\text{Wm}^{-1}\text{K}^{-1}$ for Alpine
83 snow. These values were however for snow without shrubs, whose effects are therefore not
84 considered.

85 Snow temperature in Alpine regions where shrubs are found seldom drop durably below -
86 10°C (Morin et al., 2010; Morin et al., 2012). At these temperatures, shrub branches probably do
87 not freeze because of physiological freeze resistance (Squeo et al., 1996; Zhang et al., 2016). The
88 axial thermal conductivity of fresh wood is 0.5 to 1 $\text{W m}^{-1} \text{K}^{-1}$, with the higher values more
89 frequent (Turrell et al., 1967; Deliiski, 2013; Lagueta et al., 2015). The thermal contrast between
90 snow and buried shrub branches in Alpine regions is therefore in the range 1 to 20, much less
91 than in the Arctic. Alpine shrub branches are however much bigger than in the Arctic, e.g. green
92 alders (*Alnus alnobetula*) have branches up to 10 cm in diameter (Wiedmer & Senn-Irlet, 2006).
93 The cross-sectional surface area of shrub branches may therefore be at least a factor of 10 greater
94 than in the Arctic, compensating the lower thermal conductivity contrast.

95 Thermal bridging through shrub branches buried in Alpine snow therefore deserves
96 investigation. This preliminary study of the process explores whether a more complete study
97 with extensive instrumental deployment is justified. We report data from the 2021-2022 winter
98 near the Col du Lautaret, French Alps. Using finite element modeling, we conclude that thermal
99 bridging through shrub branches is necessary to explain observations. More detailed studies of
100 thermal bridging in Alpine conditions are therefore warranted.

101 **2 Materials and Methods**

102 2.1 Species and site description

103 The green alder, *Alnus alnobetula*, is a tall deciduous shrub growing up to 5-6 m. It
104 exhibits clonal growth with many ascending branches, which sprout from a horizontal thickened
105 stem. In the Alps, green alders form dense stands in many north-exposed slopes between 1000 m
106 and 2000 m (Richard, 1968; Wiedmer & Senn-Irlet, 2006). The estimated above-ground biomass
107 of dense *Alnus* stands amounts 100 t ha⁻¹ (Richard, 1968), much more than in the Arctic, where
108 values around 10 and 2 t ha⁻¹ have been estimated in the low and high Arctic, respectively
109 (Greaves et al., 2016; Paradis et al., 2016). Over the recent decades, the green alder has been
110 expanding at the expense of formerly grazed grasslands (Figure S1 in supporting information),
111 affecting biodiversity (Anthelme et al., 2003).

112 The study site (45.034750°N, 6.413630°E, 2034 m asl), called Alnus-Nivus, is a north-
113 facing slope dominated by green alders up to 2.5 m tall (Figure 1 and Figure S2 in Supporting
114 Information). It is located within a nature reserve so that placing visible instruments is not
115 permitted. Only buried sensors could be deployed. The site was selected because of the presence
116 of the nearby FR-Clt meteorological station (45.041278°N, 6.410611°E, 2046 m asl, (Gupta et
117 al., 2023)) about 750 m away on a 4° south-facing slope across the valley, where there is no
118 alder, and which is outside the nature reserve. This station is part of the Integrated Carbon
119 Observation System network (<https://www.icos-cp.eu/observations/ecosystem/stations>).

120 2.2 Instruments

121 We placed 5TM temperature and fractional volume water content sensors from Decagon
122 in the ground at 5 and 15 cm depths at two spots: (i) under a green alder, near the emergence of
123 ascending branches, hereafter called ALNUS; and (ii) in a nearby grass patch about 6 m away,
124 hereafter called GRASS. Values of air temperature, wind speed and downwelling longwave
125 radiation measured at FR-Clt are probably reasonably similar to those at Alnus-Nivus. However,
126 downwelling shortwave radiation is significantly different in winter because the site is entirely
127 shaded by mountains. Snow height is higher at Alnus-Nivus. On 31 March 2021, we measured
128 over 1.5 m of snow at both ALNUS and GRASS vs only 0.5 m at the FR-Clt station.

129 2.3 Field measurements

130 On 19 September 2022, we measured the ground thermal conductivity at 5 and 15 cm
131 depths at ALNUS and GRASS using a TP02 heated needle probe from Hukseflux, as described
132 in (Domine et al., 2015). At ALNUS, we counted a total of 35 primary branches at 50 cm height,

133 with a mean diameter of 6.5 cm. No winter measurements were performed because of the
134 avalanche risk.

135 2.4 Finite element model calculations

136 Heat transfer between snow, soil, and shrub branches was simulated with finite element
137 modeling, using the open source ElmerFEM software (Malinen & Råback, 2013), as detailed in
138 (Domine et al., 2022). The shrub geometry used, based on field observations, is shown in Figure
139 2. Branches were constructed only to a height of 1 m, greater than the 0.7m snow height. All
140 branches were 6.5 cm in diameter, the average measured. Secondary branches were omitted. The
141 wood density and specific heat values were 900 kg m^{-3} and $1200 \text{ J kg}^{-1} \text{ K}^{-1}$ (Radmanovic et al.,
142 2014). Since measured soil thermal conductivities were different at ALNUS and GRASS (Table
143 S1 in Supporting Information), we divided the ground between an ALNUS ground with a radius
144 of 0.75 m around the shrub, and a GRASS ground beyond that. The soil comprised three layers:
145 0-8 cm, 8-30 cm, and 30 cm to 10 m (Figure 2 and Table S1). For frozen soil, measured values
146 were multiplied by two (Table S1), following measurements in the Arctic (Domine, Barrere, &
147 Sarrazin, 2016; Domine et al., 2022). The baseline soil volumetric thermal capacity used was 2.6
148 $\times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$, corresponding to a density of 1300 kg m^{-3} and a specific heat of $2000 \text{ J K}^{-1} \text{ kg}^{-1}$.
149 To represent the effect of water phase change on temperature, a Soil Freezing Characteristic
150 Curve (SFCC) was used under the form of an increased apparent thermal capacity (Tubini et al.,
151 2021). In practice, the thermal capacity of the soil was increased near the freezing point,
152 accounting for the extra-energy needed to change the soil temperature just below 0°C , as a
153 fraction of the energy is converted to latent rather than sensible heat. For instance, warming the
154 soil from -1°C to 0°C requires an extra $9.1 \times 10^6 \text{ J m}^{-3}$ of energy, compared to $2.6 \times 10^6 \text{ J m}^{-3}$ if no
155 freezing occurs. The SFCC was derived from water content versus temperature data measured at
156 a tundra site at Bylot Island (Domine, Barrere, & Sarrazin, 2016; Domine et al., 2021). The soil
157 there was silt loam, reasonably similar to that at ALNUS, based on observations on 19
158 September 2022.

159 A time-constant snow height was used for all simulations. The Gmsh software (Geuzaine
160 & Remacle, 2009) was used to generate the finite element mesh. The simulations were run with a
161 30 min time step and forced at the top with the snow surface temperature, obtained from the
162 longwave upwelling radiation measured at FR-Clt, using an emissivity of 1, and with the mean
163 annual air temperature at 10 m depth, 3°C . Simulations outputs used were temperatures in the
164 vicinity (representing ALNUS) and away (representing GRASS) from the alder recorded at 5 and
165 15 cm depths, as shown in the bottom panel of Figure 2.

166 3 Results and discussion

167 3.1 Detection of thermal bridging from observations

168 Permanent snow cover at FR-Clt started on 25 November. Snow height exceeded 10 cm
169 on 2 December 2021 and was 25 cm around 8 December (Figure 3). Snow height then varied
170 between 30 and 70 cm, while the air temperature was often above 0°C and seldom dropped

171 below -10°C (Figure 3). The snow surface temperature dropped below -20°C on 3 December and
172 was often below -15°C . Temperatures are shown in Figure 3 as 24 h running means for clarity.

173 Measured ground temperatures and ground liquid water contents at 5 and 15 cm depths
174 are shown in Figure 4. These data inform us on sensible and latent heat fluxes between the
175 ground and the atmosphere through the snow. Our analysis focuses on the period with permanent
176 snow cover, starting on 1 December 2021.

177 Striking features in Figure 4 include: (1) cooling stages at ALNUS in early January and
178 March (Figure 4a,b), indicating large sensible heat losses at ALNUS, with no sensible heat losses
179 at GRASS; (2) large rapid changes in liquid water content at ALNUS in early December, late
180 December and early January (Figure 4c,d), indicating large latent heat exchanges at ALNUS,
181 with much lower and/or much slower exchanges at GRASS. ALNUS is thus clearly closely
182 coupled to atmospheric temperature changes, while this coupling is much weaker at GRASS.
183 This is consistent with an extra heat transport process existing at ALNUS. We hypothesize that
184 thermal bridging through frozen shrub branches is that process. We detail two selected events.

185 A cold spell started on 4 January 2022 (Figure 3), with the air and snow surface
186 temperatures dropping below 0°C . The daily-averaged snow surface temperature then remained
187 below -5°C during 30 days. Figure 4 shows that at 5 cm depth at GRASS, the liquid water
188 content and the ground temperature remained essentially unchanged throughout January,
189 indicating little sensible or latent heat changes, probably because the limited heat loss through
190 the insulating snowpack was compensated by the upward ground heat flux. At ALNUS however,
191 most of the ground water froze rapidly on 6-7 January, indicating significant latent heat loss.
192 Once most of the water was frozen, the ground temperature dropped below 0°C , and the sensible
193 heat loss is clearly visible in Figures 4a and 4b, starting on 8 January.

194 Warming events also show much faster heat exchanges at ALNUS. The warming spell
195 that started on 28 December led to the melting of essentially all the frozen ground water at
196 ALNUS (Figures 4c,d), while only a small amount of frozen water melted at GRASS. Latent
197 heat exchanges are thus much greater at ALNUS, and these exchanges most likely took place by
198 heat transfer through the shrub branches.

199 Changes are similar at 15 cm depth, albeit slower because of the greater thermal inertia in
200 deeper ground. At GRASS, the ground temperature remained at 0°C , while most of the water
201 remained liquid. At ALNUS on the contrary, most of the water froze during cold spells and the
202 temperature dropped to -0.7°C .

203 The extra sensible and latent heat exchanges at ALNUS at both depths may therefore
204 reasonably be assigned to thermal bridging through snow. We test this hypothesis using finite
205 element calculations.

206 3.2 Confirmation of thermal bridging by simulations

207 Finite element simulations were performed starting on 10 December to avoid the low and
208 variable snow height in early December. Simulations were first performed with 70 cm of snow
209 because we observed thicker snow at Alnus-Nivus than at FR-Clt. We used a snow thermal

210 conductivity value of $0.1 \text{ Wm}^{-1}\text{K}^{-1}$, so that the wood/snow thermal conductivity contrast is a
211 factor of 10. We first performed simulations without shrubs to ensure that the different ground
212 properties at ALNUS and GRASS were not responsible for observations. Ground thermal
213 property differences do result in a cooler ground at ALNUS (Figure 5a), but by only 0.25°C and
214 only for two short periods, insufficient to explain measurements. Figures 5b and 5c reproduce the
215 data of Figure 4 reasonably well, given the simplifications. The GRASS temperatures remain
216 close to 0°C , while those at ALNUS drop during the cold spells, to values identical to those
217 measured. Despite the use of a SFCC for the soil, the zero-curtain effect is not as marked in
218 simulations as in measurements, probably because of differences in SFCCs at Alnus-Nivus and
219 at Bylot. Figures 5a to 5c demonstrate that including thermal bridging through shrub branches
220 adequately simulates results.

221 Since snow height was not measured at Alnus-Nivus, we performed simulations for snow
222 heights of 35 and 140 cm. Results are shown in Figure S3. As expected, thinner snow leads to in
223 general colder ground while thicker snow leads to reduced cooling. However, qualitatively,
224 results are similar, with a better thermal coupling between snow and ground at ALNUS, due to
225 thermal bridging.

226 A higher snow thermal conductivity reduces the relative impact of thermal bridging.
227 Figure S4 in Supplementary Information shows simulations with a snow thermal conductivity of
228 $0.2 \text{ Wm}^{-1}\text{K}^{-1}$. Expectedly, the temperature difference between ALNUS and GRASS decreases,
229 but the general trends are still reasonably reproduced.

230 Branch diameter and thermal conductivity also affect heat exchanges. Figure S5 shows
231 results with 70 cm of snow of thermal conductivity $0.1 \text{ Wm}^{-1}\text{K}^{-1}$, and branches of 32, 65 and 130
232 mm diameter. Obviously, thicker branches increase the temperature difference between ALNUS
233 and GRASS, confirming that thermal bridging strongly affects the temperature at ALNUS.

234 Alternative scenarios to shrub thermal bridging were explored to explain measurements.
235 Reduced snow height at ALNUS would increase atmosphere-ground thermal coupling there. We
236 performed simulations without shrubs, with only 35 cm of snow at ALNUS and snow height
237 increasing to 70 cm towards the edge of the simulation domain (Figure S5). Figure 5d shows that
238 results at ALNUS are in fact reasonably similar to those of Figure 5b. However, daily
239 temperature variations are visible, while they do not appear in the data (Figure 4a) indicating that
240 the thermal insulance of the snowpack is too low to realistically simulate the data. Furthermore,
241 general observations indicate that the effect of shrub on snow height is rather to increase it, not to
242 decrease it (Sturm et al., 2001; Busseau et al., 2017; Lamare et al., 2023). Moreover, snow height
243 was not lower at ALNUS than at GRASS on 31 March 2021. The scenario of Figure 5d therefore
244 appears unrealistic. Thermal bridging through alder branches is therefore the most reasonable
245 explanation for the temperature difference between ALNUS and GRASS, and for the close
246 thermal coupling between ALNUS and the atmosphere.

247 3.3 Upscaled impact and implementation in models

248 We calculated the impact of heat exchange through shrubs at the km scale by assuming a
249 shrub density of one alder per square of $2 \times 2 \text{ m}$. By calculating the spatially-averaged heat flux

250 with and without shrubs, we find that the average thermal insulance decreases from 7 to 5.9 K m⁻¹
251 ²W⁻¹ when shrubs are added. Alders represented in Figure 2, with a 70 cm snowpack, thus
252 increase the heat flux through the snowpack by 15%. It is not possible to translate this directly
253 into a temperature change because in most Alpine areas the soil temperature is usually near 0°C,
254 meaning that latent heat exchanges are important, so that much of the flux will serve to freeze
255 soil water. Soil freezing considerably reduces nutrient recycling and favors carbon accumulation
256 (Saccone et al., 2013). Given that green alders are now quite widespread in the French Alps
257 (Figure S7), the impact may be quite large and deserves evaluation.

258 In snow models, shrub thermal effects may be implemented simply by adjusting the
259 thermal insulance of the snowpack to account for the increased heat flux. A more sophisticated
260 approach would introduce shrubs as an extra domain that thermally couples the atmosphere and
261 the soil. However, shrubs also affect radiation transfer in snowpacks (Belke-Brea et al., 2021),
262 affecting snow temperature and metamorphism. Fully accounting for shrub effects would
263 therefore require significant model modifications. The efforts are probably worthwhile, because
264 shrubs keep expanding and adequate simulations of soil temperature are required for carbon
265 budgets and productivity modeling (Loranty et al., 2018).

266 **4 Conclusion**

267 Field measurements and finite-element simulations lead to the conclusion that ground
268 temperature under green alders is affected by thermal bridging through branches. Relative to the
269 high Arctic, the lower thermal conductivity contrast between snow and branches is compensated
270 by the greater branch cross section; 1095 cm² per simulated shrub here vs 92 cm² in the Arctic
271 (Domine et al., 2022). Thermal bridging through shrub branches buried in snow is therefore
272 probably a general process. Given the ever-greater shrub expansion in seasonally snow-covered
273 areas, this process must be considered in snow physics models to accurately describe the thermal
274 gradient in snowpacks, snow metamorphism and snow physical properties.

275 Thermal bridging also affects the thermal regime of the ground and here causes extensive
276 ground freezing. This strongly affects microbial metabolism and therefore the carbon budget of
277 soils, nutrient recycling and primary productivity (Saccone et al., 2013). These widespread
278 effects justify further detailed study where all relevant meteorological, snow and soil variables
279 are measured.

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287 **Open Research**

288 The meteorological and soil data shown in Figure 3 and 4, as well as the simulation
 289 framework including the shrub mesh of Figure 2, are available on the Zenodo repository at
 290 <https://doi.org/10.5281/zenodo.8057992>, (Domine et al., 2023).
 291

292 **References**

- 293 Anthelme, F., Michalet, R., Barbaro, L., & Brun, J. J. (2003). Environmental and spatial influences of shrub cover
 294 (*Alnus viridis* DC.) on vegetation diversity at the upper treeline in the inner western Alps. *Arctic Antarctic
 295 and Alpine Research*, 35(1), 48-55. [http://dx.doi.org/10.1657/1523-0430\(2003\)035\[0048:Easios\]2.0.Co;2](http://dx.doi.org/10.1657/1523-0430(2003)035[0048:Easios]2.0.Co;2)
- 296 Belke-Brea, M., Domine, F., Picard, G., Barrere, M., & Arnaud, L. (2021). On the influence of erect shrubs on the
 297 irradiance profile in snow. *Biogeosciences*, 18(21), 5851-5869.
 298 <https://bg.copernicus.org/articles/18/5851/2021/>
- 299 Busseau, B.-C., Royer, A., Roy, A., Langlois, A., & Domine, F. (2017). Analysis of snow-vegetation interactions in
 300 the low Arctic-Subarctic transition zone (northeastern Canada). *Physical Geography*, 38(2), 159-175.
 301 <http://dx.doi.org/10.1080/02723646.2017.1283477>
- 302 Calonne, N., Flin, F., Morin, S., Lesaffre, B., du Roscoat, S. R., & Geindreau, C. (2011). Numerical and
 303 experimental investigations of the effective thermal conductivity of snow. *Geophysical Research Letters*,
 304 38, L23501. <Go to ISI>://WOS:000297635100001
- 305 Deliiski, N. (2013). Computation of the wood thermal conductivity during defrosting of the wood. *Wood Research*,
 306 58(4), 637-649. <http://www.woodresearch.sk/wr/201304/13.pdf>
- 307 Domine, F., Barrere, M., & Morin, S. (2016). The growth of shrubs on high Arctic tundra at Bylot Island: impact on
 308 snow physical properties and permafrost thermal regime. *Biogeosciences*, 13(23), 6471-6486.
 309 <http://www.biogeosciences.net/13/6471/2016/>
- 310 Domine, F., Barrere, M., & Sarrazin, D. (2016). Seasonal evolution of the effective thermal conductivity of the snow
 311 and the soil in high Arctic herb tundra at Bylot Island, Canada. *The Cryosphere*, 10(6), 2573-2588.
 312 <http://www.the-cryosphere.net/10/2573/2016/>
- 313 Domine, F., Barrere, M., Sarrazin, D., Morin, S., & Arnaud, L. (2015). Automatic monitoring of the effective
 314 thermal conductivity of snow in a low-Arctic shrub tundra. *The Cryosphere*, 9(3), 1265-1276.
 315 <http://www.the-cryosphere.net/9/1265/2015/>
- 316 Domine, F., Fourteau, K., Choler, P., & Voisin, D. (2023). *Soil and meteorological data, and finite element
 317 simulation framework for heat transfer through shrubs in winter near Lautaret pass, French Alps*. [Dataset]
 318 Zenodo. <https://doi.org/10.5281/zenodo.8057992>
- 319 Domine, F., Fourteau, K., Picard, G., Lackner, G., Sarrazin, D., & Poirier, M. (2022). Permafrost cooled in winter
 320 by thermal bridging through snow-covered shrub branches. *Nature Geoscience*, 15, 5540-5560.
 321 <https://doi.org/10.1038/s41561-022-00979-2>
- 322 Domine, F., Lackner, G., Sarrazin, D., Poirier, M., & Belke-Brea, M. (2021). Meteorological, snow and soil data
 323 (2013–2019) from a herb tundra permafrost site at Bylot Island, Canadian high Arctic, for driving and
 324 testing snow and land surface models. *Earth Syst. Sci. Data*, 13(9), 4331-4348.
 325 <https://essd.copernicus.org/articles/13/4331/2021/>
- 326 Domine, F., Picard, G., Morin, S., Barrere, M., Madore, J.-B., & Langlois, A. (2019). Major Issues in Simulating
 327 Some Arctic Snowpack Properties Using Current Detailed Snow Physics Models: Consequences for the
 328 Thermal Regime and Water Budget of Permafrost. *Journal of Advances in Modeling Earth Systems*, 11(1),
 329 34-44. <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018MS001445>
- 330 Geuzaine, C., & Remacle, J.-F. (2009). Gmsh: A 3-D finite element mesh generator with built-in pre- and post-
 331 processing facilities. *International Journal for Numerical Methods in Engineering*, 79(11), 1309-1331.
 332 <https://onlinelibrary.wiley.com/doi/abs/10.1002/nme.2579>
- 333 Greaves, H. E., Vierling, L. A., Eitel, J. U. H., Boelman, N. T., Magney, T. S., Prager, C. M., & Griffin, K. L.
 334 (2016). High-resolution mapping of aboveground shrub biomass in Arctic tundra using airborne lidar and
 335 imagery. *Remote Sensing of Environment*, 184, 361-373. <http://dx.doi.org/10.1016/j.rse.2016.07.026>
- 336 Gupta, A., Reverdy, A., Cohard, J. M., Hector, B., Descloitres, M., Vandervaere, J. P., et al. (2023). Impact of
 337 distributed meteorological forcing on simulated snow cover and hydrological fluxes over a mid-elevation

- 338 alpine micro-scale catchment. *Hydrology and Earth System Sciences*, 27(1), 191-212.
 339 <https://hess.copernicus.org/articles/27/191/2023/>
- 340 Ju, J. C., & Masek, J. G. (2016). The vegetation greenness trend in Canada and US Alaska from 1984-2012 Landsat
 341 data. *Remote Sensing of Environment*, 176, 1-16. <http://dx.doi.org/10.1016/j.rse.2016.01.001>
- 342 Laguela, S., Bison, P., Peron, F., & Romagnoni, P. (2015). Thermal conductivity measurements on wood materials
 343 with transient plane source technique. *Thermochimica Acta*, 600, 45-51.
 344 <http://dx.doi.org/10.1016/j.tca.2014.11.021>
- 345 Lamare, M., Domine, F., Revuelto, J., Pelletier, M., Arnaud, L., & Picard, G. (2023). Investigating the Role of
 346 Shrub Height and Topography in Snow Accumulation on Low-Arctic Tundra using UAV-Borne Lidar.
 347 *Journal of Hydrometeorology*, 24(5), 835-853. [https://journals.ametsoc.org/view/journals/hydr/24/5/JHM-](https://journals.ametsoc.org/view/journals/hydr/24/5/JHM-D-22-0067.1.xml)
 348 [D-22-0067.1.xml](https://journals.ametsoc.org/view/journals/hydr/24/5/JHM-D-22-0067.1.xml)
- 349 Loranty, M. M., Abbott, B. W., Blok, D., Douglas, T. A., Epstein, H. E., Forbes, B. C., et al. (2018). Reviews and
 350 syntheses: Changing ecosystem influences on soil thermal regimes in northern high-latitude permafrost
 351 regions. *Biogeosciences*, 15(17), 5287-5313. <https://dx.doi.org/10.5194/bg-15-5287-2018>
- 352 Malinen, M., & Råback, P. (2013). Elmer Finite Element Solver for Multiphysics and Multiscale Problems. In I.
 353 Kondov & G. Sutmann (Eds.), *Multiscale Modelling Methods for Applications in Materials Science* (pp.
 354 101–113). Jülich: Forschungszentrum Jülich GmbH.
- 355 Morin, S., Domine, F., Arnaud, L., & Picard, G. (2010). In-situ measurement of the effective thermal conductivity of
 356 snow. *Cold Regions Science and Technology*, 64, 73-80.
 357 <http://dx.doi.org/10.1016/j.coldregions.2010.02.008>
- 358 Morin, S., Lejeune, Y., Lesaffre, B., Panel, J. M., Poncet, D., David, P., & Sudul, M. (2012). An 18-yr long (1993–
 359 2011) snow and meteorological dataset from a mid-altitude mountain site (Col de Porte, France, 1325 m
 360 alt.) for driving and evaluating snowpack models. *Earth Syst. Sci. Data*, 4(1), 13-21. [http://www.earth-syst-](http://www.earth-syst-sci-data.net/4/13/2012/)
 361 [sci-data.net/4/13/2012/](http://www.earth-syst-sci-data.net/4/13/2012/)
- 362 Paradis, M., Lévesque, E., & Boudreau, S. (2016). Greater effect of increasing shrub height on winter versus
 363 summer soil temperature. *Environmental Research Letters*, 11(8), 085005. [http://stacks.iop.org/1748-](http://stacks.iop.org/1748-9326/11/i=8/a=085005)
 364 [9326/11/i=8/a=085005](http://stacks.iop.org/1748-9326/11/i=8/a=085005)
- 365 Radmanovic, K., Dukic, I., & Pervan, S. (2014). Specific Heat Capacity of Wood. *Drvna Industrija*, 65(2), 151-157.
 366 <http://dx.doi.org/10.5552/drind.2014.1333>
- 367 Richard, L. (1968). *Écologie de L'aune Vert (Alnus viridis): Facteurs Climatiques et édaphiques*. Retrieved from
 368 Grenoble: http://ecologie-alpine.ujf-grenoble.fr/articles/DCVA_1968__6__107_0.pdf
- 369 Riche, F., & Schneebeli, M. (2013). Thermal conductivity of snow measured by three independent methods and
 370 anisotropy considerations. *The Cryosphere*, 7(1), 217-227. <http://www.the-cryosphere.net/7/217/2013/>
- 371 Saccone, P., Morin, S., Baptist, F., Bonneville, J.-M., Colace, M.-P., Domine, F., et al. (2013). The effects of
 372 snowpack properties and plant strategies on litter decomposition during winter in subalpine meadows.
 373 *Plant and Soil*, 363, 215-229. <http://dx.doi.org/10.1007/s11104-012-1307-3>
- 374 Squeo, F. A., Rada, F., Garcia, C., Ponce, M., Rojas, A., & Azocar, A. (1996). Cold resistance mechanisms in high
 375 desert Andean plants. *Oecologia*, 105(4), 552-555. <http://dx.doi.org/10.1007/bf00330019>
- 376 Sturm, M., McFadden, J. P., Liston, G. E., Chapin, F. S., Racine, C. H., & Holmgren, J. (2001). Snow-shrub
 377 interactions in Arctic tundra: A hypothesis with climatic implications. *Journal of Climate*, 14(3), 336-344.
 378 [http://dx.doi.org/10.1175/1520-0442\(2001\)014<0336:ssiat>2.0.co;2](http://dx.doi.org/10.1175/1520-0442(2001)014<0336:ssiat>2.0.co;2)
- 379 Tubini, N., Gruber, S., & Rigon, R. (2021). A method for solving heat transfer with phase change in ice or soil that
 380 allows for large time steps while guaranteeing energy conservation. *The Cryosphere*, 15(6), 2541-2568.
 381 <https://tc.copernicus.org/articles/15/2541/2021/>
- 382 Turrell, F. M., Austin, S. W., McNee, D., & Park, W. J. (1967). Thermal Conductivity of Functional Citrus Tree
 383 Wood. *Plant Physiology*, 42(8), 1025-1034.
 384 <http://www.plantphysiol.org/content/plantphysiol/42/8/1025.full.pdf>
- 385 Wiedmer, E., & Senn-Irlet, B. (2006). Biomass and primary productivity of an *Alnus viridis* stand - a case study
 386 from the Schachental valley, Switzerland. *Botanica Helvetica*, 116(1), 55-64.
 387 <http://dx.doi.org/10.1007/s00035-006-0758-7>
- 388 Zhang, Y.-J., Bucci, S. J., Arias, N. S., Scholz, F. G., Hao, G.-Y., Cao, K.-F., & Goldstein, G. (2016). Freezing
 389 resistance in Patagonian woody shrubs: the role of cell wall elasticity and stem vessel size. *Tree*
 390 *Physiology*, 36(8), 1007-1018. <https://doi.org/10.1093/treephys/tpw036>

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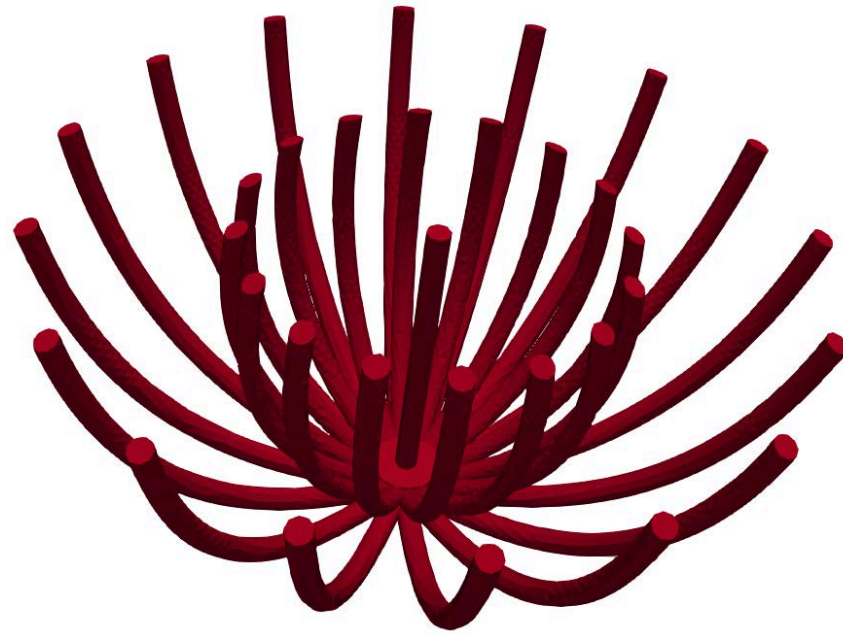
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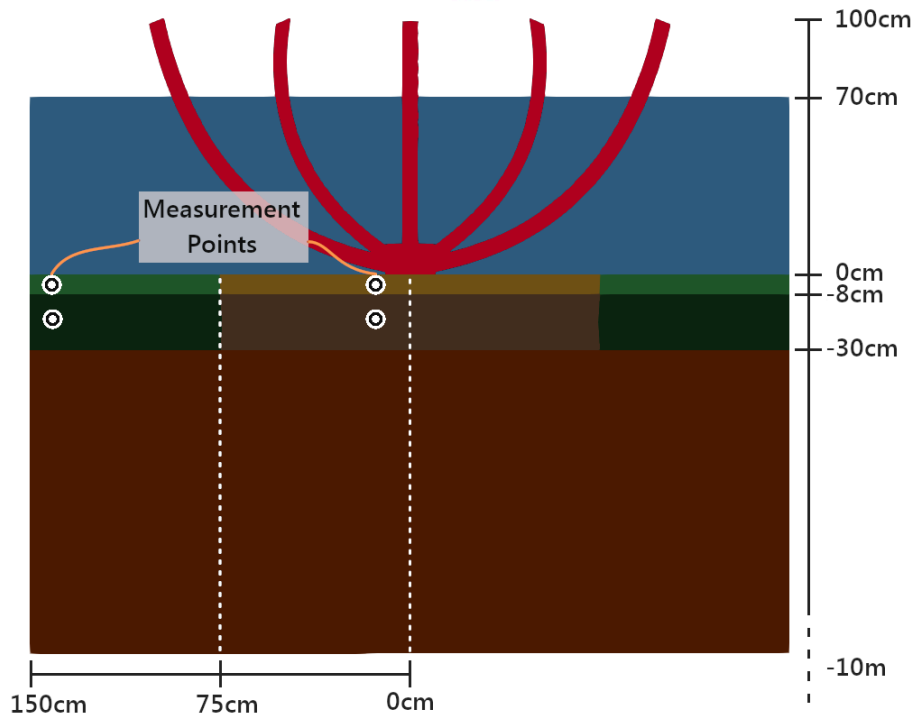
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Figure 1. Map showing the location of the Alnus-Nivus site and of the FR-Clt meteorological station near Col du Lautaret, central French Alps. Maps from <https://en-gb.topographic-map.com/>.



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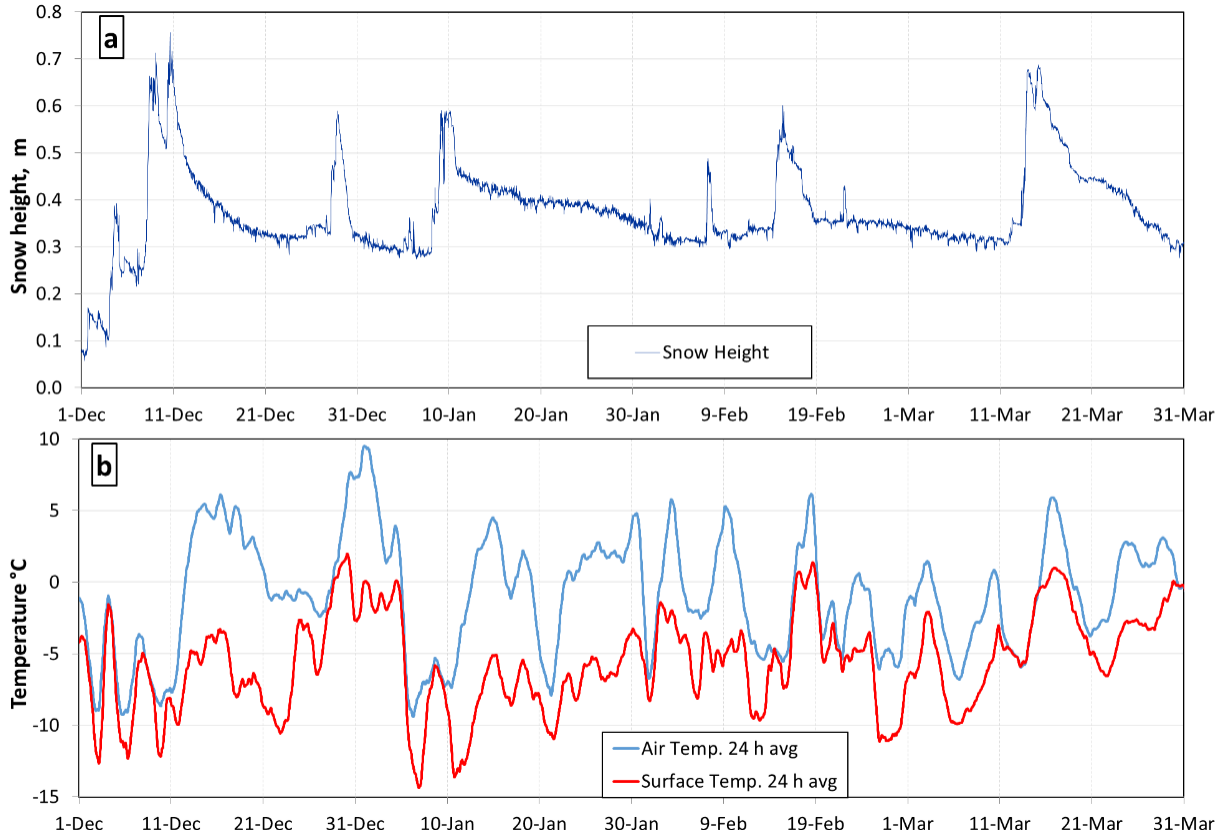
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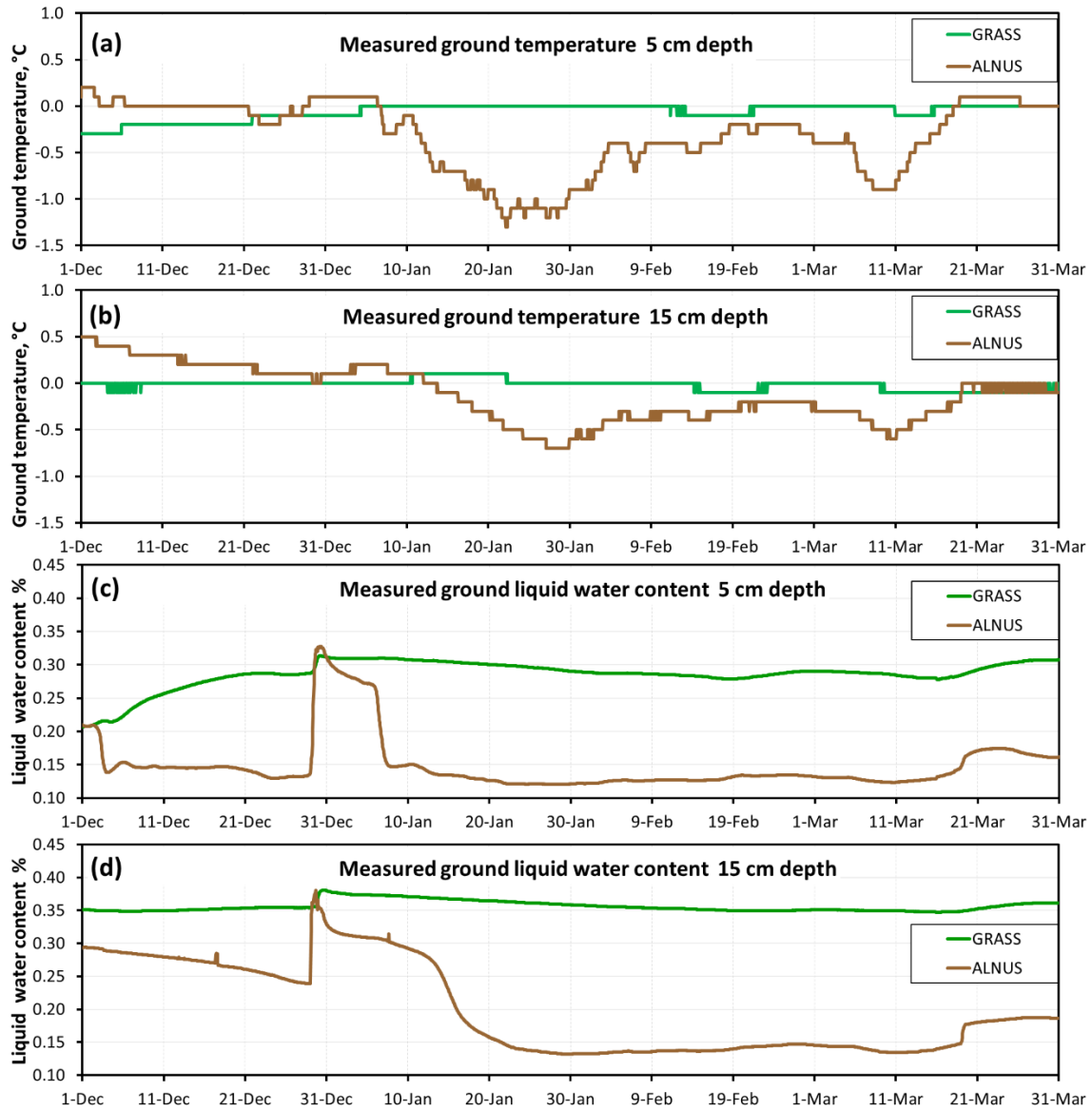
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Figure 2. (Top) Perspective views of the alder mesh used for FEM simulations. Two concentric sets of 16 caudices 6.5 cm in diameter and 1 m high, with one extra central caudice, were used. The central trunk is 20 cm in diameter. (Bottom) Conditions for our baseline simulation. Three soil layers were used. The top two layers had different thermal properties under the alder and under the grass (Table S1). Measurement spots at 5 and 15 cm depths, and 10 and 140 cm from the center are indicated. Snow height was 70 cm.



408 **Figure 3.** Meteorological variables measured at FR-Clt. (a) snow height; (b) 24h running-mean
 409 air and snow surface temperatures.
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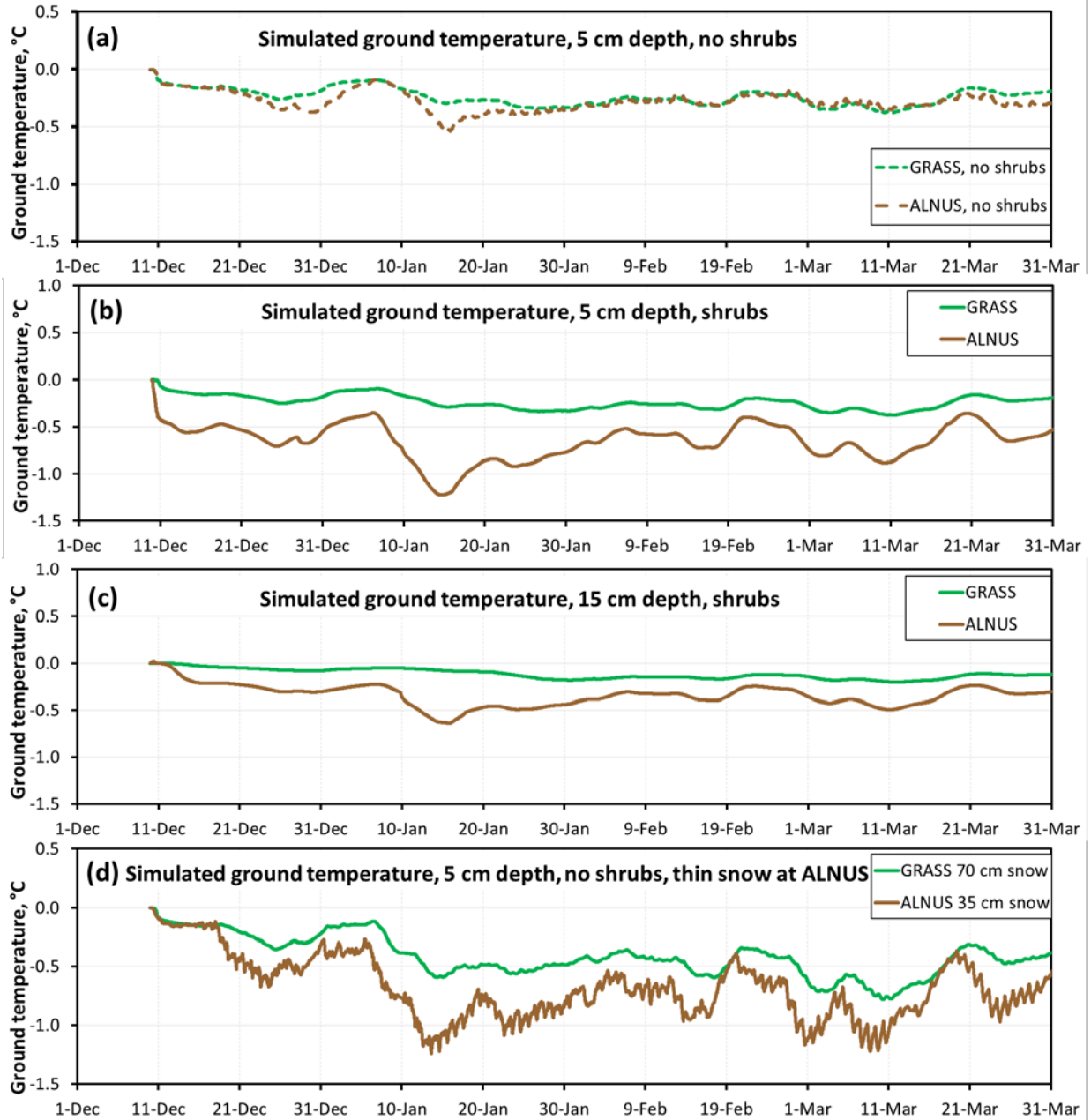


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413 **Figure 4.** Ground temperature and volume liquid water fraction measured under alders (ALNUS)
 414 and in the nearby grass patch (GRASS). (a) temperature at 5 cm depth; (b) at 15 cm depth; (c)
 415 volume liquid water fraction at 5 cm depth; (d) at 15 cm depth.

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 419 **Figure 5.** Ground temperature simulated at ALNUS and GRASS. (a) at 5 cm depth, without
 420 shrubs; (b) at 5 cm depth, with shrubs; (c) at 15 cm depth, with shrubs; (d) at 5 cm depth without
 421 shrubs and with 35 cm of snow at ALNUS and 70 cm of snow at GRASS.

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