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A Novel Method for Monitoring Above- and Belowground Microclimates in Mountain Ecosystems Year-Round

Raphael S. von Büren[1,2] | Michael Zehnder[3,4,5] | Jonathan von Oppen[2] | Christian Rossi[1] | Sonja Wipf[1,3,5] | Sabine Rumpf[2]

[1]Department of Research and Monitoring, Swiss National Park, Zernez, Switzerland | [2]Department of Environmental Sciences, University of Basel, Basel, Switzerland | [3]Mountain Ecosystems Group, WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland | [4]Institute of Integrative Biology, ETH Zurich, Zurich, Switzerland | [5]Climate Change, Extremes and Natural Hazards in Alpine Regions Research Centre CERC, Davos Dorf, Switzerland

Correspondence: Raphael S. von Büren (raphael.vonbueren@nationalpark.ch)

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ABSTRACT

Aim: The role of microclimate in influencing range limits and vegetation shifts, especially in topographically heterogeneous mountain ecosystems, has gained attention in recent years. However, disturbance by large animals and snow pressure complicate reliable year-round time series of microclimatic measurements near the soil surface, calling for more robust logger setups.

Location: Swiss Alps.

Methods: We presented a novel, low-cost, and effective method to monitor above- and belowground microclimate in mountain environments year-round that withstands large animals and snow pressure and is suitable for remote areas. Specifically, we customized the widely used TOMST TMS-4 data loggers and tested their functionality and reliability in a factorial field experiment as well as in a regional-scale field study in heterogeneous mountain terrain.

Results: We found that standard TMS-4 loggers were frequently destroyed by snow creep or snow pressure over winter, but customized loggers remained intact. In addition, camera-trap footage demonstrated that only customized loggers were efficiently protected against large mammals, such as wolves, foxes, red deer, and chamois. The customization of loggers had ecologically negligible effects on the recorded above- and belowground microclimate.

Conclusions: With this method, we enable combined monitoring of air, surface, and soil temperatures as well as soil moisture in alpine environments throughout the year, and thus the collection of crucial microclimatic variables for research in mountain ecosystems.

Sonja Wipf and Sabine Rumpf share last authorship.

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1 | Introduction

Climate warming shifts species' ranges to higher elevations (Pauli et al. 2012; Rumpf et al. 2018; Vitasse et al. 2021) and alters community compositions (Steinbauer et al. 2018) by fostering thermophilic species (Gottfried et al. 2012), local extinctions (Dullinger et al. 2012), and biotic homogenization (Britton et al. 2009). In mountainous terrain, pronounced topographic heterogeneity and variable seasonal snow cover create a diverse array of microhabitats with contrasting microclimates, which can exhibit differences comparable to those found across large elevational or latitudinal gradients (Scherrer and Körner 2010). These microhabitats are not captured by weather stations that commonly measure at 2 m above the ground and typically kilometers apart (Larcher and Wagner 2011; Scherrer et al. 2011; Löffler and Pape 2020; von Büren and Hiltbrunner 2022). Yet, these microhabitats may provide potential microrefugia for cold-adapted species as air temperatures rise (Scherrer and Körner 2011) through so-called microclimatic buffering (Suggitt et al. 2018; Jiménez-Alfaro et al. 2024). Microclimate acts in various ways upon plants (Körner and Hiltbrunner 2018; Kemppinen et al. 2024), but the most relevant mechanisms in alpine environments are assumed to be related to snowmelt (Möhl et al. 2022), growing season temperature and length (Bürli et al. 2021; Körner 2021), and low winter temperatures in the absence of snow cover (Choler 2018; Niittynen et al. 2020; von Büren and Hiltbrunner 2022).

Although microclimatic conditions drive species distributions and biodiversity in alpine environments, they are rarely incorporated into ecological studies because of a lack of reliable in situ data across larger spatial scales. In recent years, however, efforts have increased to complement macroclimatic with microclimatic data (De Frenne et al. 2024; Kemppinen et al. 2024), and microclimatology is an emerging discipline that continues to gain attention in alpine ecology (e.g., Scherrer and Körner 2010; Kulonen et al. 2018; Chytrý et al. 2024). While decades ago, microclimatic measurements in mountain areas involved complicated experimental methods (Lüdi 1966; Cernusca 1976), for example, mean temperature measurements through the inversion of sucrose (Pallmann and Frei 1943), the development of compact logging devices greatly increased the feasibility and replication of microclimatic measurements. Moreover, coordinated research initiatives such as *MEB—Microclimate Ecology & Biogeography* (formerly SoilTemp; Lembrechts et al. 2022) gather microclimate data globally and contribute to upscaling and predicting microclimatic conditions as well as their changes. At the same time, such initiatives highlight the need for standardized and harmonized measurement methods.

In mountainous environments, microclimatic measurements are typically restricted to either the soil for year-round data (e.g., Pauli et al. 2015) or the snow-free period for aboveground data (e.g., von Oppen et al. 2022), as snow pressure, strong winds, ice abrasion, rock fall, and large animals (e.g., cattle, wild ungulates, large predators) often disturb aboveground measurement devices, such as the widely used TMS-4 (TOMST) data loggers (Wild et al. 2019). There is hence a lack of aboveground—as well as combined above- and belowground—microclimate data during fall, winter, and spring in snow-dominated environments (but see Aalto et al. 2022; Tyystjärvi et al. 2024 for an exception from the Finnish tundra). However, such year-round time series are crucial to accurately characterize the local climatic conditions that the typically short-statured alpine plants are experiencing and which are strongly decoupled from free-air temperatures derived from weather stations due to, for example, snow cover, radiation, or wind (Körner and Hiltbrunner 2018). This is particularly the case just after snowmelt when organs and life stages pivotal for growth and survival (e.g., buds, shoots, and seedlings) can be exposed to short-term extreme events such as (radiation) frost (Marcante et al. 2012; Palacio et al. 2015). Combined above- and belowground time series can capture such events and help to determine thermal range limits of plant species in situ, for example, due to freezing damage (Larcher et al. 2010; von Büren and Hiltbrunner 2022). Yet, the distribution of alpine plant species is not linked to a general freezing resistance. Indeed, the decisive plant organs and tissues have differing freezing resistances (von Büren and Hiltbrunner 2022) and relevant temperatures thus need to be measured belowground for roots, at the soil surface for graminoids' meristems and leaf rosettes, and in the air for leaves and flowers. Combined above- and belowground measurements are therefore crucial to accurately predict range shifts of alpine plant species and improve the accuracy of species distribution models (Lembrechts et al. 2019). In addition, such time series can identify site-specific controlling factors of the local microclimate, such as topography (Tyystjärvi et al. 2024) or vegetation structure (Cernusca 1976; von Oppen et al. 2022), and enable characterizing microclimatic effects on plant–plant (Schweiger et al. 2015), plant–animal (Høye et al. 2021), or plant–soil microbe interactions (Frindte et al. 2019) as well as on nutrient (Chen et al. 2018) and carbon cycling (Sturm et al. 2001; Shaver et al. 2006). Yet, currently available methods do not allow for reliable, disturbance-proof above- and belowground microclimate measurements in mountain environments throughout the entire year.

TMS-4 loggers are currently one of the most widely used devices for microclimatic above- and belowground measurements (see table S1 in De Frenne et al. 2024) because of their affordability compared to expensive scientific-grade thermocouples (Maclean et al. 2021). Yet, in three unpublished previous field studies with standard TMS-4 loggers in the Swiss Alps, many loggers were pulled out or ruptured at the soil surface after only 1 year in the field. The most prominent stressors were assumed to be wild or domesticated animals and snow pressure. Logger loss rates ranged from 30% ($n = 30$) to 22% ($n = 32$) in the snow-rich winter of 2020/21 to 10% ($n = 29$) in the very snow-poor winter of 2022/23. While rupture at the soil surface likely resulted primarily from snow pressure, displacement could be caused by either stressor. Even among the "unruptured" loggers, many had damaged top-shields, which compromised the reliability of air temperature measurements. These findings indicate that standard TMS-4 loggers are currently unsuitable for year-round use in alpine terrain.

Here, we present a low-cost customization of TMS-4 loggers that allows for year-round monitoring of air, surface, and soil temperatures as well as soil moisture. With this novel customization, we contribute to facilitating and improving year-round measurements of microclimate in remote and steep mountain ecosystems with seasonal snow cover and large domesticated or wild animals, and thus help to close the knowledge gap of combined above- and belowground time series during the pivotal time for plant growth and survival in alpine environments. We tested this customization in a multi-site approach to assess its reliability to protect the loggers in steep and snow-dominated mountain environments and quantified whether and how the amendments affected the microclimatic measurements.

2 | Materials and Methods

2.1 | Logger Customization

To measure year-round above- and belowground microclimate, we customized the widely used TMS-4 data loggers (TOMST, Czech Republic), which measure air (at canopy-level of alpine vegetation 15 cm aboveground), surface (2 cm above ground), and soil temperature (8 cm belowground; 0.0625 K resolution, ±0.5 K uncertainty) as well as soil moisture (Wild et al. 2019). To increase their physical robustness, we covered the topshield and ring of the logger with transparent adhesive tape to prevent it from breaking, without influencing the passive ventilation of the air sensor. The green belowground blade of the loggers is flat, and its orientation within the soil might thus have an additional effect on the stability and durability of the loggers. We therefore installed the loggers with their blades parallel to the slope direction, lowering the risk of rupture by snow creep. To protect the logger from animal damage, a robust, cylindrical 1.3-cm metal wire mesh cage was closely fitted around each logger and closed to form an upward-pointing wedge shape at the top to distribute snow pressure from above. This cage was secured with three tent pegs pushed into the ground at different angles. To further increase the stability of the logger against downward pressure from creeping or sliding snow, a wooden post (ca. 40 × 5 × 5 cm/0.5 kg) functioning as a wedge was positioned 5 cm upslope and attached to the logger's cage with a metal wire, with one corner facing upslope and tilted by 10°–20° toward the slope (Figure 1). Due to material availability, we acquired loggers with both single and double topshields for our experiments, but we recommend the more stable double topshields as well as the newly available TMS-4 extreme version for increased physical robustness.

2.2 | Effectiveness of Customization

We evaluated the effectiveness of the logger customization with a factorial field experiment and a regional-scale field study in the Swiss Alps, a mountain range with short summers and long seasonal winter snow cover. The weather station "Weissfluhjoch" within our study region (2691 m a.s.l., 46°49′60″ N/9°48′23″ E) records on average 8.9 months per year with snow depths of > 1 cm and 6.9 months with > 50 cm, 9.4 m of annual snow accumulation, a mean temperature of −7.8°C and 6.2°C in January and July, respectively, and 255 days with minimum temperatures below 0°C (data 1991–2020; MeteoSchweiz 2024).

We assessed the robustness of our logger customization in a factorial field experiment. To this end, we installed 12 TMS-4 loggers with double topshields in September 2023 within a radius of 5 m in a subalpine, south-exposed grassland slope at 1870 m a.s.l. with a 30° inclination in the Swiss National Park (46°39′56.8″ N/10°12′51.9″ E). Six of the loggers were customized as described above, the other six served as controls. Additionally, we assessed the effect of the orientation of the flat, green belowground blade by installing half of the customized loggers and half of the controls with this blade oriented parallel to the slope direction, and the other half with this blade oriented perpendicular to it. To monitor disturbances by large mammals and to document whether the customization led to snow accumulation around or on top of the loggers, we set up two camera traps at 1 m height next to the loggers: one captured an image every hour, while the other was motion-activated. In May 2024, we quantified logger damages and read out the camera trap images and microclimatic measurements.

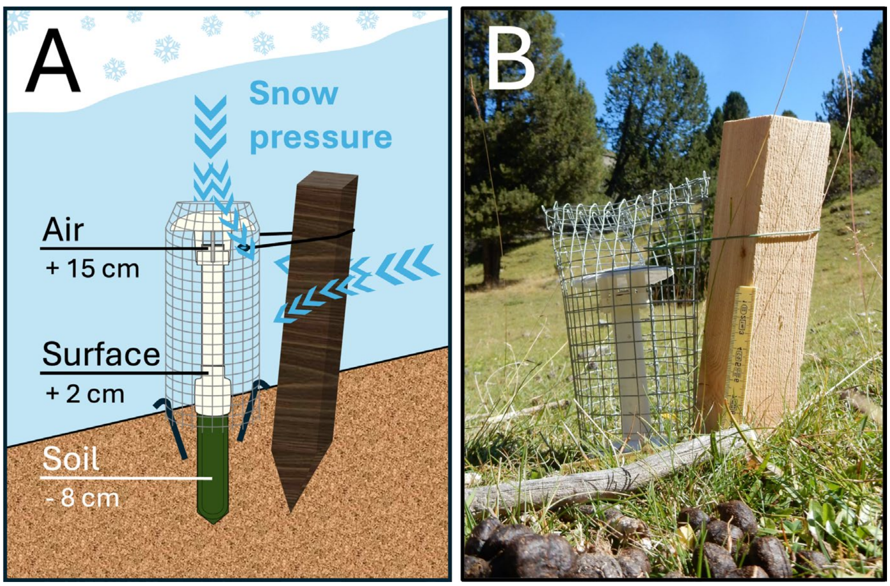

FIGURE 1 | Overview of logger customization. (A) Schematic of customized TMS-4 logger setup during winter covered by snow with indication of temperature sensors (air, surface, soil) as well as moisture sensor (soil), and (B) example photograph during summer. The wooden post functions as a wedge against snow pressure (blue arrows), and wire mesh against large mammals. Photo: Raphael S. von Büren.

To assess the effectiveness of logger customization across larger spatial scales with varying environmental conditions, we additionally conducted a regional-scale field study. For this purpose, we evaluated damages of 113 loggers (91 customized, 22 uncustomized; all with single topshields) from two independent research projects. The loggers were installed in summer 2023 within a radius of 30 km in topographically heterogeneous subalpine and alpine environments with seasonal snow cover in the Swiss Alps, between 1680 and 3150 m a.s.l., and on slopes with inclinations ranging from 0° to 45°. Of the 113 loggers, 11 (4 customized/7 uncustomized) were within extensively managed cow and sheep pastures, 15 (7/8) in unmanaged subalpine and alpine areas (< 2500 m a.s.l.), 16 (8/8) in remote environments at high elevations (> 2500 m a.s.l.), and 71 (all customized) in subalpine and alpine areas in the strictly protected Swiss National Park with a high number of wild animals, such as red deer (10 animals/km^2), chamois (8 animals/km^2), and a wolf pack (Figure 2; Swiss National Park 2024). After 1 year in the field during the snow-rich winter of 2023/24 with many glide-snow avalanches in the region, we assessed damages to the loggers and evaluated the effectiveness of the logger customization in summer 2024.

2.3 | Impact of Customization on Microclimate Measurements

To assess any potential influence of the customization on microclimate measurements, we used the temperature readings of the factorial field experiment of the period before snow cover when all loggers were still intact (i.e., 20 September to 20 November 2023). One uncustomized logger was damaged by a wolf after snowmelt, and all temperature data were lost. Therefore, the sample size was reduced to 11 loggers (6 customized, 5 uncustomized).

2.4 | Data Analyses

We cleaned the data, performed all statistical analyses, and created the figures with the statistical software R, version 4.4.1 (R Core Team 2024).

To quantify the effectiveness of the customization, logger rupture rates and the rates of broken topshields were calculated for the factorial field experiment with 12 loggers and the regional-scale field study with 113 loggers. Camera trap footage was manually reviewed to identify animals damaging the loggers and to evaluate whether the customization led to snow accumulation around or on top of the loggers.

To assess the potential impact of customization on temperature readings in the factorial experiment, we compared daily mean, minimum, and maximum air, surface, and soil temperatures between customized and uncustomized loggers. The temperature raw data were processed with the R package *myClim* (Man et al. 2023): Gap filling was performed with the function "mc_prep_fillNA," employing linear interpolation between the first and last recorded values, with a maximum gap size of eight consecutive NAs (equivalent to 2 h at 15-min measurement intervals). Daily mean, 5th percentile (=minimum), and 95th percentile (=maximum) temperatures were calculated using the function "mc_agg." The 5th and 95th percentiles were used instead of absolute minima and maxima to reduce the leverage effect of potential measurement errors (i.e., outliers) and improve robustness. Finally, to test for differences in temperature readings between customized and uncustomized loggers, we applied Welch's two-sample *t*-tests using the function "t.test."

3 | Results

3.1 | Effectiveness of Customization

Our factorial field experiment confirmed the effectiveness of the customization, as all six customized loggers remained fully intact, including all double topshields. By contrast, all six uncustomized standard loggers were damaged after eight winter months in the field. The two camera traps installed next to the loggers were fully covered by snow, indicating that snow depth exceeded 1 m. The camera trap footage further revealed that the main damaging factors to the loggers were snow pressure ($n = 5$) and disturbance by a wolf ($n = 1$; Figure 3). Besides wolves, the camera traps recorded foxes, red deer, and chamois approaching both customized and uncustomized loggers, but no human

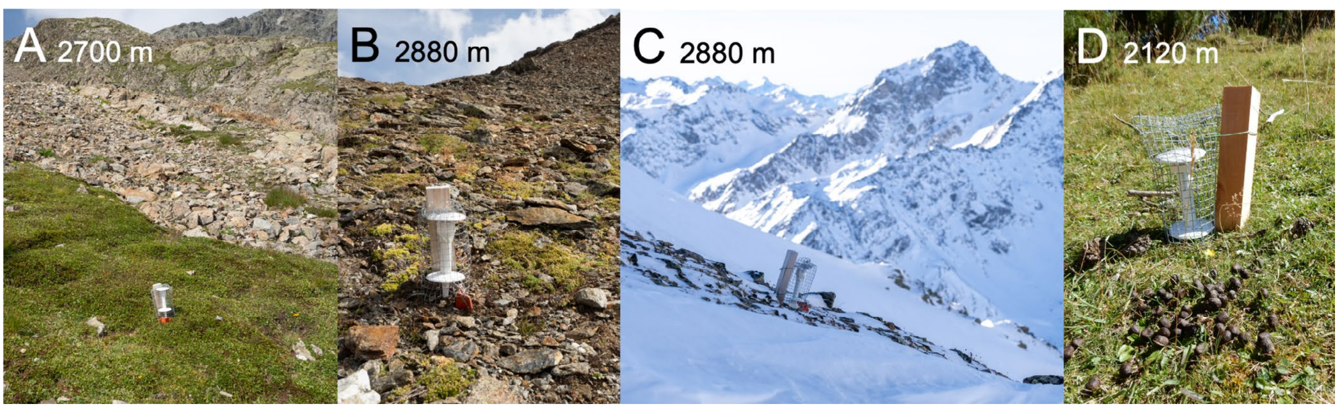

FIGURE 2 | Customized loggers of the regional-scale field study in remote mountain areas in the Swiss Alps. Panels depict examples within a (A) steep alpine snowbed, a wind-exposed ridge during (B) summer and (C) winter, and (D) a strictly protected area (Swiss National Park) with large wild animal populations. Photos: Raphael S. von Büren & Michael Zehnder.

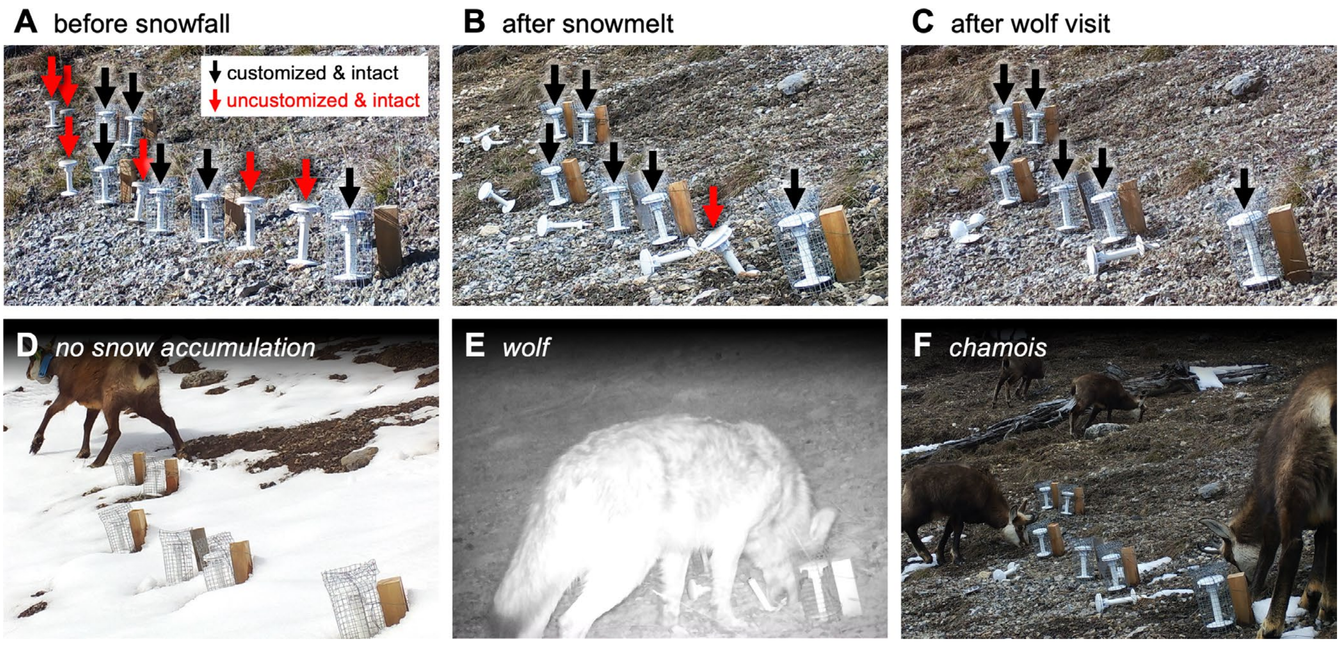

FIGURE 3 | Factorial field experiment to assess the effectiveness of the logger customization (Swiss Alps, south-exposed, 30° steep, 1870 m a.s.l.). (A) Intact experimental setup with six customized (black arrows) and six uncustomized (red arrows) TMS-4 loggers in September 2023 before snowfall. (B) Only one of the six uncustomized loggers survived the snow pressure during winter (> 1 m snow height) and remained intact (arrows indicate intact loggers), but (C) was destroyed by a wolf later on. (D) Logger customization did not result in snow accumulation. (E, F) Examples of wild animals visiting the experiment. Photos: Raphael S. von Büren (camera trap).

disturbances. The three uncustomized loggers that were installed with the green blade perpendicular to the slope direction were ruptured by snow pressure, while those with the blade parallel to the slope did not rupture but were pulled out by snow pressure or by the wolf. The camera traps revealed that the customization did not lead to snow accumulation around or on top of the loggers and did thus not influence the timing of snow-in and snowmelt (Figure 3D).

Our regional-scale field study across a larger spatial scale with increased environmental heterogeneity equally demonstrated substantially higher rupture rates for uncustomized loggers (10 of 22, i.e., 45%) than for customized loggers (4 of 91, i.e., 4%) after 1 year in the field. In addition, the topshield damage rates of unruptured loggers were also substantially higher for uncustomized loggers. Sixty-four percent of the uncustomized loggers but only 20% of the customized loggers had at least partially damaged single topshields.

3.2 | Impact of Customization on Microclimate Measurements

Logger customization had a slight cooling effect on the measured air temperatures, but there was limited evidence of such an effect on surface and soil temperatures (Table 1). The largest effect was observed on daily maximum air temperatures, which were on average 0.4 K lower at customized loggers compared to uncustomized ones. However, even between the uncustomized loggers, temperature differences of similar magnitude (0.14–0.73 K) were observed within the very small area of the experimental setup (Figure 3A; Appendix S1).

4 | Discussion

The novel customized logger setup presented here enables the year-round measurement of air, surface, and soil microclimate data in high mountain environments with high reliability. Although our field studies took place during a winter with heavy snowfall and frequent glide-snow avalanches, the rupture rate of customized loggers was more than 10 times lower than that of uncustomized loggers (4% vs. 45%). This underscores the robustness of our setup to ensure data acquisition and equipment survival in regions with material-adverse environmental conditions and is particularly relevant in remote areas, where data continuity is often compromised (e.g., Krab et al. 2018; Prather et al. 2020; von Oppen et al. 2022) and material damages invoke high logistical effort and costs. Independent of customization, we recommend the use of loggers with double topshields because a considerable number of single topshields were damaged in the regional-scale field study, potentially causing radiation bias affecting the air sensor. In contrast, none of the double topshields used in customized loggers in the factorial experiment were damaged. We believe this supports the robustness of the double-shield design, although we acknowledge that the factorial experiment was restricted to a single location in the field, while single-shielded loggers were deployed across a much wider range of conditions.

The most prominent advantage of our customization is that it enables the measurement of not only soil but also surface and air temperatures year-round (Figure 4), despite snow creep or animal disturbances. To date, year-round microclimate research in alpine areas typically relies solely on soil (e.g., Lundquist

TABLE 1 | Impact of logger customization on temperatures measured between 20 September and 20 November 2023.

		Daily mean temperature	Daily maximum temperature	Daily minimum temperature
Air	Effect size	**−0.22 K**	**−0.40 K**	**−0.16 K**
	95% CI	−0.35, −0.10	−0.63, −0.17	−0.30, −0.02
	df	7.37	6.51	8.99
	t value	4.22	4.21	2.60
	p	0.004	0.005	0.03
Surface	Effect size	−0.06 K	−0.27 K	−0.04
	95% CI	−0.24, 0.12	−0.56, 0.02	−0.33, 0.26
	df	7.69	6.37	8.39
	t value	0.80	2.26	0.29
	p	0.45	0.06	0.78
Soil	Effect size	−0.14	−0.03	−0.23
	95% CI	−0.29, 0.01	−0.43, 0.36	−0.48, 0.03
	df	7.70	8.57	5.69
	t value	2.13	0.18	2.16
	p	0.07	0.86	0.08

Note: Negative effect sizes indicate that customized loggers recorded lower temperatures than uncustomized loggers. Significant effect sizes are highlighted in bold. 95% confidence interval (95% CI), degrees of freedom (df), *t* and *p* values are derived from Welch's two sample *t*-tests.

and Lott 2008; Pauli et al. 2015) or rock surface temperatures (Gruber et al. 2003). Yet, air temperature minima 15 cm above the ground were on average 1.9 K lower than surface minima and 5.6 K lower than soil minima in our study (Appendix S2). These temperature differences would correspond to an elevational shift of 380 and 1120 m, respectively, based on a lapse rate of 0.5 K per 100 m for minimum temperatures (Kollas et al. 2014). Thus, the temperature experienced by the leaf tips during a nightly cold spell was on average similar to that experienced by the roots of a plant at a more than 1000 m higher elevation, which explains why leaves generally exhibit a higher freezing resistance than roots (Sakai and Larcher 1987). These differences are even exacerbated for heat accumulation, which can differ by more than 10 K between different vertical layers of alpine *Carex curvula* vegetation during a warm summer day (Cernusca 1976). Consequently, using only soil temperatures bears the risk that the magnitude, timing, duration, and velocity of extreme events such as nightly cold spells or daily heat accumulation are underestimated for aboveground plant organs critical for growth and survival (Körner and Hiltbrunner 2018). Knowing which organ's resistance to freezing events or heat accumulation limits a plant species' survival is essential to determine which temperature should be measured (von Büren and Hiltbrunner 2022), ideally year-round, but might differ between co-occurring species. This challenge can be solved with the here presented logger customization as it enables the simultaneous measurement of air, surface, and soil temperatures year-round, including during snow-covered periods, in steep areas, and in areas with risk of disturbance by animals.

Besides ecological advantages, our customization has several logistical and financial advantages. First, it is smaller, lighter, and more specifically designed to alleviate snow pressure than the large wire cage proposed by Wild et al. (2019) to protect TMS-4 loggers from wild boar and deer. Therefore, it can be brought and installed with less effort in remote and steep areas. Ten loggers, including wire mesh and wooden posts, weigh approximately 7 kg and can be carried by one person. In addition, the customization and data loggers are comparatively low-cost and well suited for large-scale studies lasting several months to years, as the loggers' battery life and memory capacity are sufficient for nearly 15 years (with a data acquisition interval of 15 min; Wild et al. 2019), potentially with a slightly reduced operational duration in alpine areas due to faster battery drainage under low temperatures. Both protective structures and the logger topshields can be easily and affordably repaired in the field or repurposed for other projects. Last, TMS-4 loggers are widely used around the globe (Lembrechts et al. 2022; table S1 in De Frenne et al. 2024), and their applicability in harsh mountain environments, and generally in areas with high disturbances (e.g., from cattle), widens the scope of temperature records while ensuring comparability to other data sets. When uploading microclimatic data derived from customized loggers to databases such as *MEB—Microclimate Ecology & Biogeography* (formerly SoilTemp; Lembrechts et al. 2022), it is advisable to ensure full transparency by stating in the metadata that the loggers were customized according to the present study to improve stability and durability in the field.

Customized loggers recorded slightly lower air but not surface or soil temperatures than standard loggers, potentially due to shading from the mesh wire cage or the wooden post. However, this cooling effect was smaller than both the logger uncertainty specified by the manufacturer (±0.5 K; Wild et al. 2019) and the

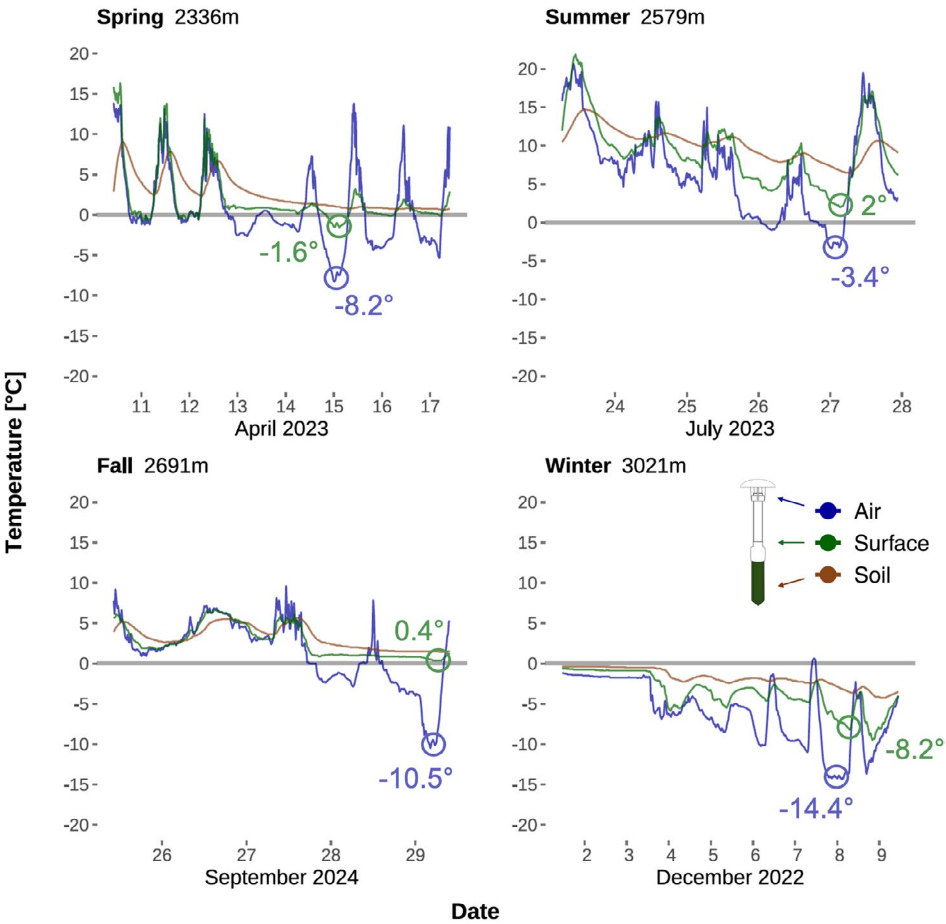

FIGURE 4 | Logger customization enables year-round measurements of above- and belowground microclimate in high mountain environments, including, for instance, the layer-specific perception of cold spells, as exemplarily illustrated here with data from four different locations in our regional-scale field study. This logger setup is particularly relevant, as recording only soil temperatures does not fully reflect the temperature conditions that different parts of a plant actually experience.

local, small-scale microclimatic variability between standard loggers (Appendix S1). Yet, although the temperature resolution of TMS-4 loggers is fairly high (0.0625 K), they cannot compete with expensive scientific-grade thermocouples (Maclean et al. 2021). Hence, one still must accept to a certain degree the trade-off between logger durability, sensor location(s) (above- and/or belowground), measurement reliability, resource efficiency, and number of datapoints. Depending on the research question and study site, one should carefully think about "the right" measurement device and consider the accompanying limitations (De Frenne et al. 2024).

Besides the most appropriate sensor location and measurement device, one must think about the most relevant period extracted from microclimatic measurements for data analyses (Körner and Hiltbrunner 2018). For example, closed alpine grassland is growth-limited by mean temperatures during the growing season (Bürli et al. 2021). Cold spells during the growing season are commonly accompanied by slight snowfall (e.g., Figure 4—spring and fall), which protects roots, graminoid meristems', rosettes, and prostrate plants from low temperatures. Freezing damages occur therefore primarily to erect plants or plant organs that protrude above the snow cover and have limited time for frost hardening. Larcher et al. (2010) observed freezing damages during two sudden cold spells in July 2007 at reproductive shoots and flowers, but not at the leaves close to the ground. A single clear, cold night without insulating snow cover may expose tissues to critically low temperatures and locally eradicate a plant species. Such a night may determine the local vegetation composition for the next centuries in the case of extremely long-lived, clonal alpine foundation species (De Witte et al. 2012; von Büren and Hiltbrunner 2022). The currently continuously decreasing snow cover (Rumpf et al. 2022) will likely increase the incidence rate of such extreme events and may increase projected local extinction events of mountain plant species in the future (Engler et al. 2011; Dullinger et al. 2012).

5 | Conclusion

Despite the increasing attention to microclimatology in vegetation science and global change biology, measuring microclimate reliably is still challenging (Maclean et al. 2021) and particularly so in harsh, remote, and material-adverse environments. The cost-effective TMS-4 logger customization presented here ensured continuous measurements during periods of increased risk of disturbance by snow and wildlife. It therefore represents a reliable method for monitoring year-round air, surface, and soil temperatures in alpine environments.

Author Contributions

R.S.v.B. conceived the research idea; R.S.v.B. designed and performed the factorial field experiment; R.S.v.B., M.Z., and C.R. collected field data; R.S.v.B., with contributions from M.Z., performed statistical analyses; R.S.v.B., with input from all authors, interpreted the results and wrote the paper.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

For reproducibility, relevant data and R code are archived at https://doi.org/10.5281/zenodo.16994183.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Local microclimatic heterogeneity. Temperature variation among the five uncustomized loggers of the factorial field experiment, located within < 5 m (difference between "coldest" and "warmest" logger). **Table S2:** Differences in the magnitude and timing of mean nightly air, surface, and soil minima. See Figure S2 for the empirical data. **Figure S2:** Nightly minima of air, surface, and soil temperatures. Annual air, surface, and soil temperature minima in snow-free nights and their timing, measured by 42 TMS-4 loggers in the Swiss Alps ($n = 31{,}348$). Crosses are centered on overall means and bar lengths indicate standard deviations.