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Influence of Slope Aspect and Vegetation on the Soil Moisture Response to Snowmelt in the German Alps

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Abstract: Snow, especially in mountainous regions, plays a major role acting as a quasi-reservoir, as it gradually releases fresh water during the melting season and thereby fills rivers, lakes, and groundwater aquifers. For vegetation and irrigation, the timing of the snowmelt is crucial. Therefore, it is necessary to understand how snowmelt varies under different local conditions. While differences in slope aspect and vegetation (individually) were linked to differences in snow accumulation and ablation, this study connects the two and describes their influence on the soil moisture response to snowmelt. This research focuses on the catchment of the "Brunnenkopfhütte" (BKH) in Bavaria, southern Germany, where an automatic weather station (AWS) has operated since 2016. In addition, soil temperature and moisture monitoring systems in the surrounding area on a south aspect slope on an open field (SO), on a south aspect slope in the forest (SF), and a north aspect slope in the forest (NF) have operated since 2020. On snow-free days in winter, the soil temperature at the SF site was on average 1 °C lower than on the open site. At the NF site, this soil temperature difference increased to 2.3 °C. At the same time, for a 1 °C increase in the air temperature, the soil temperature increases by 0.35 °C at the NF site. In addition, at this site, snow cover disappeared approximately one week later than on the south aspect slopes. Snow cover at the SF site disappeared even earlier than at the SO site. Finally, a significant difference in the soil moisture response was found between the sites. While the vegetation cover dampens the magnitude of the soil moisture increases, at the NF site, no sharp increases in soil moisture were observed.

Keywords: snowmelt; soil moisture; soil temperature; vegetation; exposure; winter regime

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1. Introduction

Snow is an important water storage and acts as a quasi-natural reservoir of fresh water during winter. In mountainous regions all over the world, snow provides a steady supply of water during the melting season. Snow that melts in spring and summer fills rivers and lakes and recharges groundwater aquifers [1]. The melting season in particular was highlighted by Lana-Renault et al., who showed that a two-month snowmelt period contributed almost 50% of the total annual runoff of the central Spanish Pyrenees [2]. At a global scale, catchments, which are primarily fed by snowmelt, are responsible for the production of approximately 60% of the world's freshwater runoff [3]. This water is used for irrigation in arid and semi-arid regions and provides necessary resources for multiple ecosystems, especially in forests, where the timing of snowmelt is crucial for plant growth, breeding patterns of animals, and the overall health of the surrounding ecosystems [4]. Therefore, changes in snow dynamics can have a significant impact on these ecosystems. With increasing air temperatures, especially in the northern hemisphere, it is important to understand how hydrological processes in winter will be affected [5,6]. Various studies have observed a decline in available freshwater due to rising temperatures over the last 20 to 30 years [7,8]. However, other studies reported that trends in aridity change depending on the observed time frame. Wetlands on the American continent became wetter from 1948 to 1979 and dryer from 1980 to 2008. For African drylands, the opposite was observed [9].

Winter regimes and snow conditions vary on a temporal scale throughout different years but also on a spatial scale in a catchment. Topographical characteristics, like slope aspect and degree, have been reported to have a vast influence on both snow depth and persistence. López-Moreno et al. found that south-facing slopes have lower maximum snow accumulation, shorter snow cover times, and are more sensitive to warming [10]. Saydi et al. came to the same conclusion by observing higher snow cover rates at north aspect slopes. They added that the increase in the slope gradient leads to a decrease in snow cover in winter [11]. Therefore, efforts have been made to integrate the local influence of aspect into snow distribution models [12] and into snowmelt runoff models [13].

Snow conditions directly influence the soil conditions, like soil temperature and soil moisture. Soils having a snow cover of >10 cm show temperatures of around 0 °C, because of the insulation effect of the snowpack [14,15]. In extreme cases, the difference between the air and soil temperature can be up to 20 °C in winter [16]. In contrast, for the soil to freeze, the air temperature needs to be below −3 °C for a longer snow-free period [17]. The soil temperature is an important factor controlling belowground processes like decomposition [18,19] and the distribution of nutrition [20]. Furthermore, the soil temperature was found to be a very important factor controlling the growth of vegetation [21]. Since soil temperature measurements are much less common than air temperature measurements, efforts have been made to estimate the soil temperature from air temperature data [18]. Previous studies observed a 1:1 relation between the air and soil temperature in the snow-free period [22].

In addition, the vegetation has an effect on the air–soil temperature relationship. During winter, the soil temperature in forest-covered areas is higher than that of grasslands soil under snow-free conditions [23]. Snow depth is affected by vegetation too. Musselman et al. found in a subalpine forest that vegetation interception leads to a 47% smaller snow water equivalent and 54% faster ablation of the snow in open sites [24]. A number of studies have improved the models to simulate snow accumulation and ablation inside forests [25–27]. They found that a fine-scaled digital surface model of the area is needed to estimate the canopy interception [26] and that the efficiency of the interception decreases after a maximum value of precipitation is exceeded [27].

The soil acts as both a storage and transportation medium for water, as snowmelt water infiltrates and moves in the soil. Harpold et al. found that the peak soil moisture corresponded to the disappearance of the snow cover [28]. Delayed snowmelt, flowing from the forest to grassland, was found by Lopez et al. [29]. In general, snowmelt starting in spring releases water gradually into the ground. The study by Webb et al. examined the evolution of flow paths on different slope aspects and discovered that meltwater runoff on the north slope is more prevalent [30]. However, to our knowledge, no study has looked into the combined influence of aspect and vegetation cover on the soil moisture response to snowmelt.

While in the Ammergauer Alps snowmelt water is not relevant for irrigation in agriculture, the region is a national protected habitat, which is home to a variety of plants and animals. Several studies were conducted in the vicinity of Brunnenkopfhütte, the area of this study, such as Ewald et al. (2018), which found over 200 plant species, some of which are exclusive to this area [31]; a study about the re-grazing of an abandoned Alp by Vidal et al. [32]; and finally, the work of Ismail et al., in which they extensively described the process of snowmelt in this area [5]. However, none of these studies have examined the response of soil moisture to snowmelt in this region. The current study, in contrast, investigates the influence of the slope aspect and vegetation cover on (1) the relationship of the air temperature and soil temperature in the snow-free season, (2) the duration of snow cover, and (3) the soil moisture response to snowmelt.

2. Materials and Methods

2.1. Study Site

The Brunnenkopfhütte (BKH) is located in the Ammergauer Alps in southern Germany. It is part of the Dreisäulerbach catchment, which is located in between 47°34′55″–47°35′05″ North and 10°56′40″–10°57′07″ East [33]. While the catchment spans from 900 m.a.s.l. to 1768 m.a.s.l. in elevation, the BKH is located at 1603 m.a.s.l. The climate of the BKH is characterized by an annual average air temperature of 5.75 °C and an average annual precipitation of 1972.5 mm. Table 1 shows the monthly average temperature and precipitation.

Table 1. Monthly average temperature and precipitation data at Brunnenkopfhütte (November 2016–May 2023).

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T [°C]	−2.21	−0.54	0.85	3.49	7.06	12.75	13.61	13.70	9.67	8.00	2.75	−0.02
P [mm]	154.3	119.3	124.8	125.3	243.9	158.6	233.0	245.1	177.9	148.6	89.6	152.1

In November 2016, an automatic weather station (AWS) was installed close to the BKH. For soil moisture monitoring, three measurement sites were selected and installed in October 2020: at a south aspect slope on an open field (SO), a south aspect slope in the forest (SF), and a north aspect slope in the forest (NF) (Figure 1). All northern slopes without forest cover are very steep, which made it impossible to establish a north slope site without forest cover in the vicinity of the BKH. Air temperature, precipitation, snow depth, and snow water equivalent data were collected by the AWS and are available from October 2016 to May 2023. Soil temperature and soil moisture data were collected at the three different study sites and span from October 2020 to May 2023.

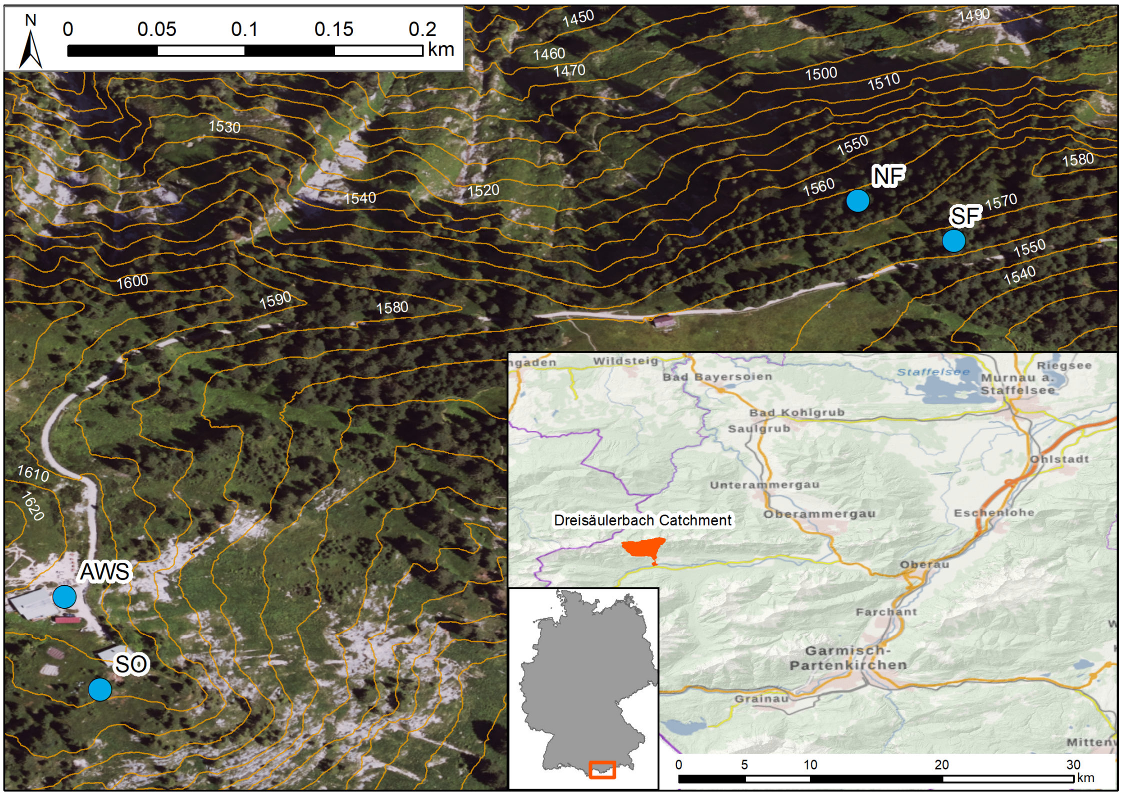

Figure 1. Research area at the Brunnenkopfhütte (BKH) with an automatic weather station (AWS), south aspect open site (SO), south aspect forest site (SF), and north aspect forest site (NF) within the Dreisäulerbach catchment. Source of maps: Bayrische Vermessungsverwaltung [34].

Soil moisture monitoring sites

The SO site is located close to the BKH on a 24° south slope covered by grass at 1592 m.a.s.l. and is slightly lower in elevation than the BKH. The soil texture found at this site is mainly sand (Su2). After 5 cm of organic material, there is a horizon of brown soil over a C-Horizon of calcareous soil (Dolomite stone). According to the Umweltatlas Bayern (The Umweltatlas Bayern is an open-source web service of the land Bavaria. It provides maps of several geo- and environmental data), the soil type can be described as Rezina and brown soil from grus-sand to silt (Ah, cC) [35], with an average field capacity of 15% SO [35].

The SF and NF sites are located about 400 m north-east of the station in a spruce tree forest, with a canopy cover of 74% and 92%, respectively [36]. SF is placed on a 29° south slope, while NF is oriented northward of the mountain ridge on a 27° slope. The leading soil texture at both sites is loamy sand (Su3), while the soil type is Ah, cC [35]. At the SF site, 2 cm of organic cover material is followed by 16 cm of brown soil. At NF, 3 cm of organic material was found. The A-horizon was 14 cm thick and made of brown soil. From 16 to 26 cm below ground level, bulks of clay are found [35]. In the following horizon, considerable amounts of roots and increasing clay are present in the soil. According to [35], the field capacity is 14% on average both at NF and SF. Table 2 gives an overview of the site characteristics.

Table 2. Characteristics of the soil moisture measurement sites: south aspect open (SO), south aspect forest (SF), and north aspect forest (NF). (Soil texture stands for Su2: Sand; Su3: Loamy sand. Soil type stands for Ah, cC: Rezina and brown soil from grus-sand to silt).

Spot	Elevation	Aspect	Slope Angle	Vegetation	Canopy Cover [1]	Soil Texture	Soil Type [2]
SO	1592 m.a.s.l.	S	24°	Grass	0%	Su2	Ah, cC
SF	1564 m.a.s.l.	S	29°	Spruce	74%	Su3	Ah, cC
NF	1562 m.a.s.l.	N	27°	Spruce	92%	Su3	Ah, cC

[1] Source: European Environment Agency [36]. [2] Source: Umweltatlas Bayern [35].

2.2. Data

The AWS monitors the climate parameters: air temperature, relative humidity solar radiation, and wind speed and direction throughout the year. In addition, snow water equivalent and snow depth are measured in the winter season. While a temporal resolution of 10 min was provided by the AWS, hourly values were calculated to match the other observations and measurements in this study. Table 3 summarizes the data that were used in this study. In the following, we explain the acquisition of the data.

Table 3. Utilized data.

Variable	Abbreviation	Unit	Available Time	Monitoring Site
Air Temperature	T_{Air}	°C	2016–2023	AWS
Soil Temperature	T_{Soil}	°C	2020–2023 [1]	SO, SF, and NF
Precipitation	P	mm	2016–2023	AWS
Snow Water Equivalent	SWE	mm	2016–2023 [1]	AWS
Snow Depth	d_{snow}	cm	2016–2023 [1]	AWS
Soil Moisture	θ_v	m^3/m^3	2020–2023 [1]	SO, SF, and NF

[1] Measurements began in October and ended in May of each year.

Temperature

The 10 min measurements of the air temperature sensor (Sommer, Carrum Downs, Austria) at the AWS at the BKH (Figure 2) were aggregated to a 1 h time series. The air temperature was available from November 2016 to May 2023. Soil temperature data were collected by 12-bit Temperature Smart Sensors (Hobo, Annapolis Junction, MD, USA) at the three sites. SO and SF featured two soil temperature sensors, while NF featured three soil temperature sensors for redundancy. All soil temperature sensors were placed just below surface with the goal of detecting the existence of snow cover and potential soil freezing. In contrast to the air temperature, soil temperature data were stored on built-in dataloggers in situ, from which the data were read and saved twice a year.

Figure 2. Automatic weather station (AWS) at the Brunnenkopfhütte at 1603 m.a.s.l.

Precipitation

The installed precipitation gauge was not shielded and heated and lead to rain under-catch in summer due to wind and both snow under- and over-catch in winter because of temporary snow caps on the gauge. Similar issues have been observed in other places too [37]. Since not all data were available, the precipitation was filled and reconstructed from the Radolan service and data of Pürschling station (5.5 km distance to the BKH). Every precipitation event at an air temperature above 3 °C was considered rain. For air temperature values smaller than 3 °C, in the case of the snow depth increasing, the precipitation was considered snow; otherwise, it was considered as rain.

Snow depth and Snow Water Equivalent (SWE)

The snow depth was measured by an ultrasonic distance sensor of the AWS. The snow water equivalent (SWE) describes the amount of water in [mm] that is contained in the snow column. It was measured by the snow scale of the AWS, which has a measurement area (A) of 1 m^2 and is surrounded by 6 additional plates in order to reduce the effect of stress and ice-bridges in the snowpack. With a water density (ρ_{water}) equal to ~1000 kg × m^{-3}, the measured value of snow weight (m_{snow}) in kg equals the value of SWE in mm:

$$SWE[\text{mm}] = \frac{\frac{m_{snow}[\text{kg}]}{A[\text{m}^2]}}{\rho_{water}\left[\frac{\text{kg}}{\text{m}^3}\right]} = \frac{\frac{m_{snow}[\text{kg}]}{1[\text{m}^2]}}{1000\left[\frac{\text{kg}}{\text{m}^3}\right]} = m_{snow}\left[10^{-3}\text{m}\right] = m_{snow}[\text{mm}] \tag{1}$$

Soil Moisture

The soil moisture was measured by 28 *EC5 Soil Moisture Smart Sensors* at the three measurement sites in the area around the BKH station. The *ECH2OTM Sensor* measures the volumetric water content in m^3/m^3 using the electric capacitance of the surrounding medium [38]. At each site, data at four different depths were collected with the aim of analyzing how precipitation or snowmelt water infiltrates the different soil horizons. In order to prevent data losses, two dataloggers were installed at the SO and SF sites and three at NF. At SO, the soil moisture sensors were located at 5 cm, 12 cm, 18 cm, and 23 cm below the ground surface. At SF, the installation depths of the soil moisture sensors were 4 cm, 10 cm, 19 cm, and 26 cm. Finally, for NF, the soil moisture sensors sat at 8 cm, 14 cm, 18 cm, and 24 cm belowground.

3. Results

3.1. Winter Regime

At the BKH, snow starts to accumulate in November. During the period of 2016–2023 the first snow occurred on average on November 12 $\pm$ 9 days. In 2021, the earliest snowfall occurred on November 3, while the latest was observed in 2018 on November 28. The last day of snowmelt usually occurred at the beginning of May, with the exception of April 13 in 2022.

During the observed period, a high annual variability in the time of occurrence and height of the snow depth peak was observed. In 2019, a snow depth peak of 108 cm occurred on December 11. In contrast, in the following season, the snow depth peaked at 140 cm on March 21 in 2021. In the winter seasons from 2016 to 2023, the snow depth peak varied from 104 cm (February 2022) to more than 160 cm (January 2018). The latter occurred in the winter season of 2017/18 and rose over the measuring capabilities of the station. Therefore, a difference in the maximum snow depth of at least 56 cm was observed (Table 4). From 2016 to 2023, the average snow depth peak was 128 cm.

Table 4. Snow seasons at the Brunnenkopfhütte.

Season	First Snow Day	Date of Max. Snow	Max. Snow Depth [cm]	Last Snow Day [1]
2016/17	2016-11-13	2017-03-08	108	2017-05-08
2017/18	2017-11-06	2018-01-25 [2]	>160 [2]	2018-05-06
2018/19	2018-11-28	2019-02-04	159	2019-05-06
2019/20	2019-11-06	2019-12-11	108	2020-05-03
2020/21	2020-11-21	2021-03-21	140	2021-05-09
2021/22	2021-11-03	2022-02-16	104	2022-04-13
2022/23	2022-11-06	2023-04-17	113	2023-05-01

[1] Measurements began in October and ended in May. [2] In the winter of 2017/18, the snow depth exceeded the measuring scale and was much higher than 160 cm.

Within a given snow season, it is not uncommon in the Ammergauer Alps to have days without snow cover due to warmer periods. In this area, ephemeral snow cover is present in November and December, while permanent snow cover typically occurs from January to March/April. New snow is sometimes observed in late April or early May after the permanent snow cover has melted. Overall, in the observed years from 2016 to 2023, the timing and amount of snow cover did vary but without a notable trend at the BKH station (Figure 3).

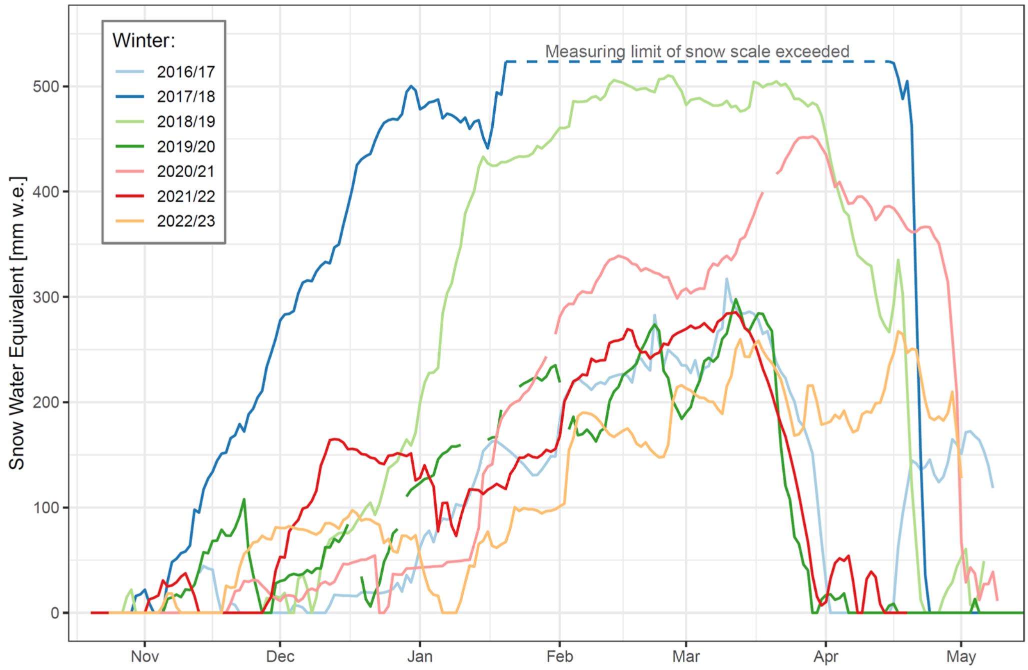

Figure 3. Snow water equivalent observations at the Brunnenkopfhütte station. In the winter of 2017/18, the snow depth and weight exceeded the values of the measurement scale.

3.2. Air and Soil Temperatures

In order to investigate the general impact of the vegetation cover at the study sites, and as a proxy for the energy differences at the measurements sites, the relation of the air and soil temperatures was analyzed. Due to the insulation effect of snow, only the air temperature and soil temperature of days without snow cover were used for this regression. To compare seasonal effects, the data of the summer months of June, July, August, and September of 2021 and 2022 were analyzed before looking into the cooler months of October, November, April, and May of the years ranging from 2020 to 2023. December, January, February, and March were not considered due to the snow cover during these months and, consequently, the soil temperatures near 0 °C.

All sites showed a strong relationship between air and soil temperatures. In addition, the scatter patterns were similar over the two snow-free seasons for each site (Figures 4 and 5). During summer, at all sites, the relationship between the air temperature and soil temperature was stronger due to more days with higher solar radiation. At the SO site, the mean soil temperature of 13.8 °C was higher than the average air temperature of 12.4 °C. The SF site showed the strongest relation, with a slope of 0.71 and an intercept with the y-axis at 3.5 °C. The average soil temperature at SF was 12.4 °C. With an average soil temperature of 9.9 °C in the summer months, the NF site had the lowest soil temperatures. The same holds true for the slope of 0.32 at NF (Figure 4).

During the cooler months, the mean air temperature was 7 °C and the mean soil temperature at SO was 7.8 °C during snow-free days. The slope of the trend line for SO was 0.5. The trend lines' intercept was at 4.36 °C. On average, the soil temperatures at SF and NF were 1 °C and 2.3 °C lower than at SO with 6.8 °C and 5.5 °C, respectively. The soil temperature at SF showed the strongest relation to the air temperature, with a slope of 0.65. The SF's trend line intercept of 2.2 °C corresponded with the lower average temperature. In contrast, the slope of the trend line at NF was 0.34 and an intercept of 3.14 °C. This was the weakest response to the air temperature of the three sites (Figure 5).

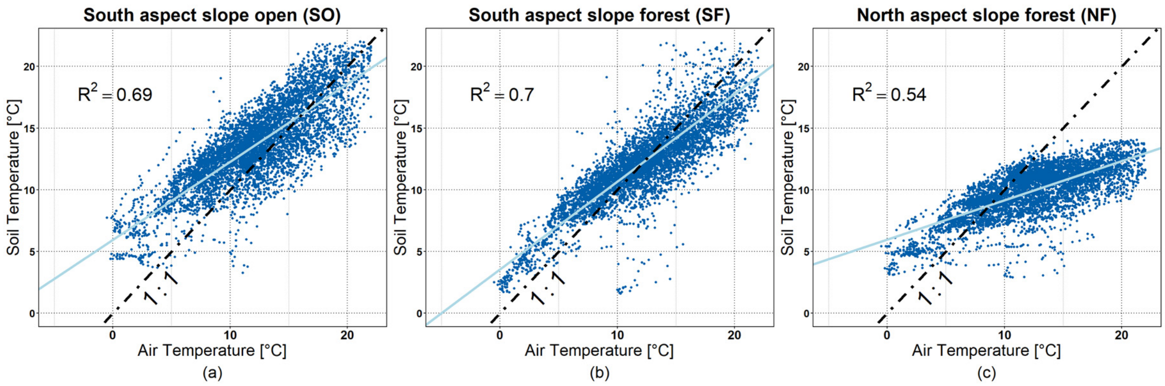

Figure 4. Scatter plot of the air and soil temperature data in the months of June, July, August, and September in the years from 2021 and 2022. (**a**) scatter plot of SO site, (**b**) scatter plot of SF site and (**c**) scatter plot of NF site.

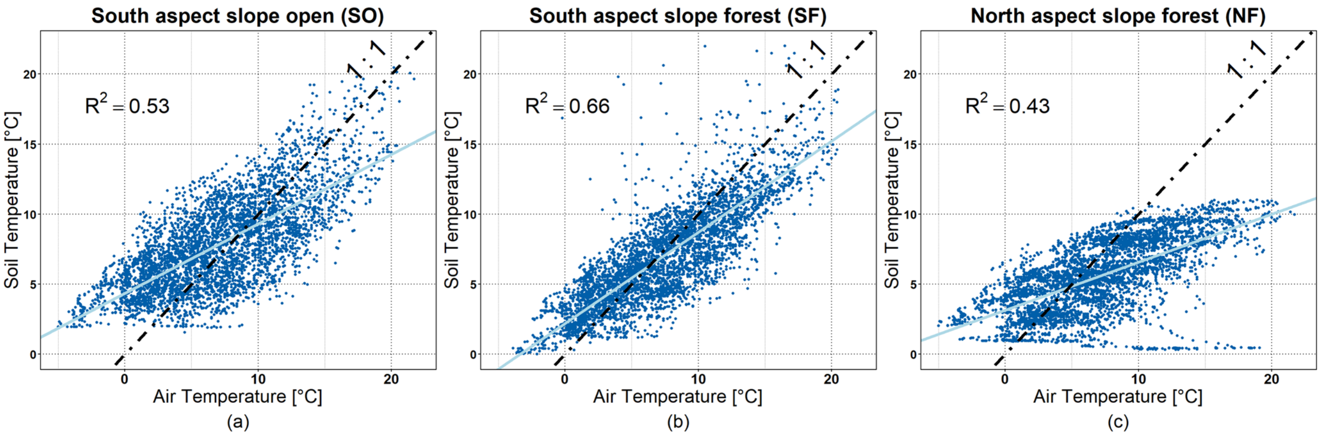

Figure 5. Scatter plot of the air and soil temperature data of snow-free days in the months of October, November, April, and May in the years from 2020 to 2023. (**a**) scatter plot of SO site, (**b**) scatter plot of SF site and (**c**) scatter plot of NF site.

These results show that the vegetation cover leads to a lower average soil temperature at the NF and SF study sites in comparison to the SO site. In addition, the aspect of the NF site leads to a weaker response of the soil temperature to the air temperature (Figures 4 and 5) compared to the south slope sites. While all trend line slopes were higher in summer, the three sites showed comparable characteristics in relation to each other. The strongest correlation of the air and soil temperatures was observed at the SF site, while the weakest correlation was observed at the NF site.

3.3. Snow Cover

Given the absence of continuous measurements of snow conditions in the NF and SF forest sites, the soil temperature was employed to ascertain the presence of snow cover. The insulating effect of the snow cover resulted in a reduction in the diurnal fluctuations in the soil temperature, which can be observed in the time series (Figure 6). This approach allowed for the determination of the snow cover period at NF and SF. The onset of snow cover at the AWS was accompanied by a 10-day decline in the soil temperature at all sites, which remained between 1 and 1.6 °C for the duration of the snow cover.

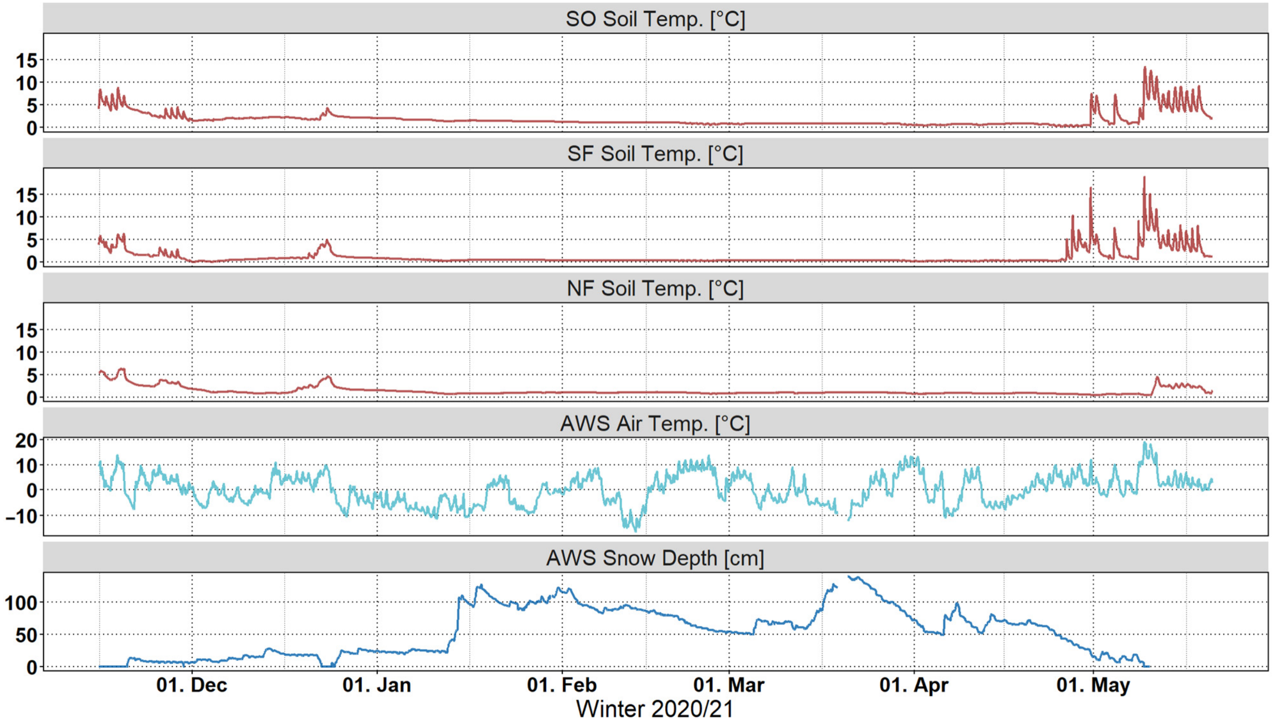

Figure 6. Soil temperature variability at the SO, SF, and NF sites before, during, and after the 2020/21 snow season.

In the winter season of 2020/21, a snow-free window occurred from 22 December to 25 December. Four days prior to this, the soil temperature at NF began to follow the air temperature, indicating that the snow cover at NF melted more quickly than at the AWS. A similar pattern was observed at site SF site, where the soil temperature began to follow the diurnal air temperature fluctuation from 20 December onward. This observation can be attributed to the lower snow accumulation observed at the sites under forest cover. In contrast, at the end of the winter season, the order in which soil moisture fluctuations occurred at the three sites changed. The soil temperature at the SO and SF sites exhibited fluctuations in accordance with the air temperature when the snow depth at the AWS approached 0 cm. In the 2020/21 season, the SF site began approximately seven days earlier than the SO site. Moreover, the SF site exhibited higher soil temperatures than the SO site (Figure 6). In contrast, the NF site exhibited a delay in the soil temperature response in each observed year. While the 2020/21 season is the most striking example of this phenomenon, it is also evident in the other years of soil temperature measurements. In the 2021/22 season, fluctuations in the soil temperature at the SO and SF sites began to occur simultaneously (Figure A1), while the NF site showed a one-week lag. Finally, at the end of the 2022/23 season, the soil temperature at the SF site exhibited fluctuations approximately seven days prior to that at the SO site and 10 days prior to that at the NF site (Figure A2). This observation can be attributed to the combined influence of shading by the vegetation and the northern aspect. By the end of the season, the aspect had a significant influence on the delay of snowmelt. While snow depths were relatively small at the beginning of winter, at the end of the melting season, it took more time to melt the snowpack at the NF site due to the energy-buffering effect of the north aspect.

3.4. Soil Moisture Response

Percolating snowmelt is the main contribution to soil moisture increases in winter at the BKH, and it can be divided between early and late snowmelt. As mentioned before, the snow cover is not persistent throughout the winter season. In particular, early snowfall in November and December melts quickly because of its shallow depth and positive monthly mean air temperatures. In the cases of early, non-persistent snow cover, the snow depth was less than 30 cm and the SWE was below 100 mm.

While at SO, early snowmelt can be identified, at SF and NF, it was more difficult to distinguish due to smaller responses of the soil moisture. Late snowmelt typically occurs between the end of March and the beginning of May. It is characterized by a stair-like melting curve and a highly saturated snowpack. On average, snow started melting at around 6 am with the first sunlight and continued for about 6 to 9 h. The SWE at this time was greater than 150 mm. For the SO site, the decrease in the snow depth was coupled with increases in the soil moisture.

The snowmelt ranged between 5 and 20 mm d^{-1} at the end of the season, with extreme daily melting reaching nearly 50 mm d^{-1} decrease in SWE. Most of the snowmelt happened in April and May, when the air temperature rose and insolation was strong. At SO, a delay of 2 to 6 h in soil moisture increases after the start of the daily melting was observed. However, no correlation was found between the amount of snowmelt and the delay in the start of soil moisture increases. The soil moisture increased for 1 to 3 h before slowly declining to field capacity. All layers at SO responded at the same time to the snowmelt. Due to the temporal resolution of 30 min and the shallow soil horizons, it was not possible to measure any delay between the horizons (Figure 7). This is because the penetration of snowmelt water takes less time than the temporal resolution.

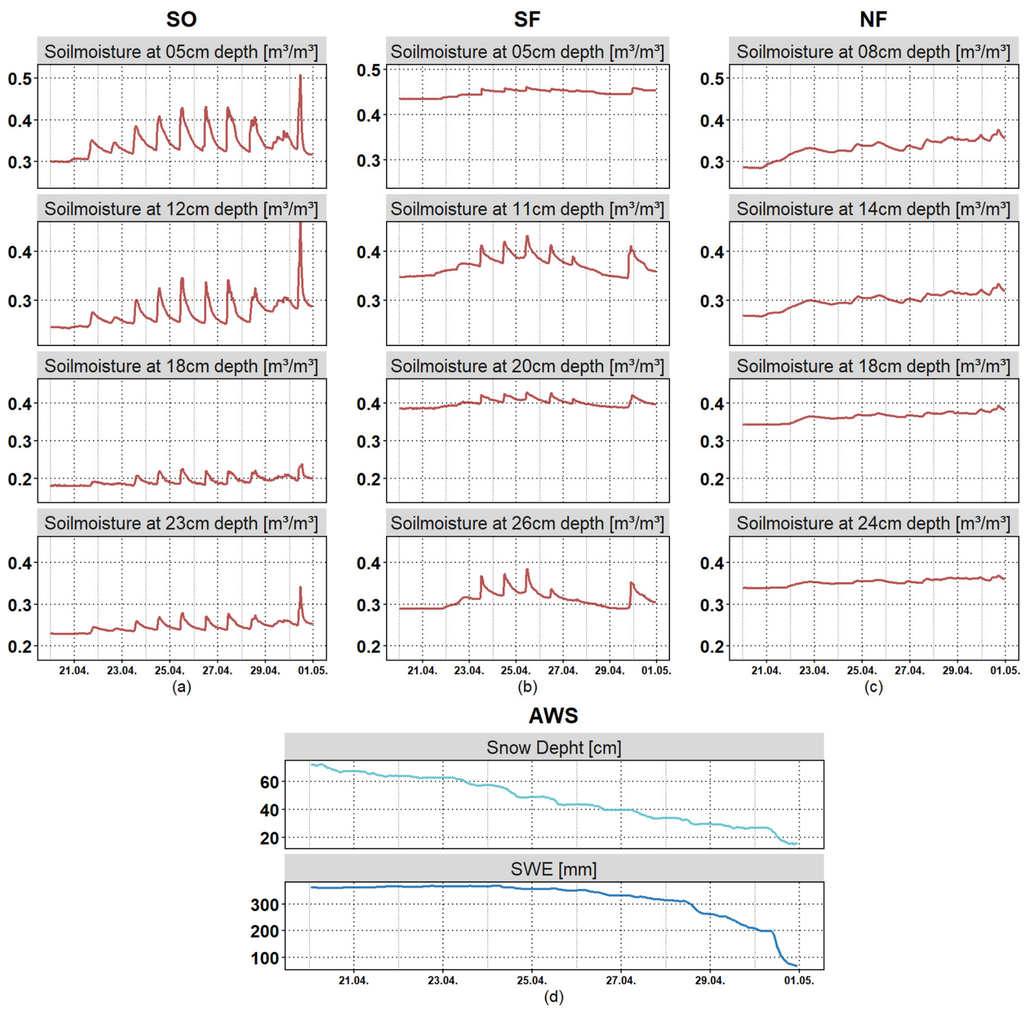

Figure 7. Soil response to snowmelt events at the end of the winter season of April 2021 at the south aspect slope on an open field (SO) (**a**), the south aspect slope in a forest (SF) (**b**), and the north aspect slope in a forest (NF) (**c**). Panel (**d**) shows the snow depth and SWE measured at the automatic weather station.

The SF site shows soil moisture responses similar to those observed at SO. Early and late snowmelt can be clearly separated, with the latter showing the above-mentioned stair-like melting pattern. Soil moisture increases were recorded with a delay of 2 to 6 h after the start of the daily snowmelt, which began usually between 6 am and 8 am. In comparison, the soil moisture increase happened faster than that at site SO, lasting for 1 to 2 h.

At the NF site, the soil moisture response to rain or snowmelt was drastically different. In general, the delay and duration of soil moisture increases were much higher than those at SO. After a snowmelt event, the soil moisture increased for 8 h on average, though increases of 12 h to a maximum of 15 h were observed. In addition, no sharp peaks were measured but rather a steady increase before the start of the decline of 5 to 12 h, which was significantly longer than the time observed at SO (Figure 7). This can be explained by the dampening effect of the forest and the north-facing slope condition of NF.

The influence of the forest leads to less snow accumulation on this site. In addition, the reduced energy because of the shading of vegetation and topography delays the snowmelt further. For these very small amounts of snowmelt, only the moisture in the upper layers increases. These patterns suggest that the southern orientation of the slope plays a more important role than the covering vegetation.

4. Discussion

This study demonstrated the influence of the north aspect on the relationship between the air temperature and soil temperature, the differences in snow ablation at the three sites, and the differences in the soil moisture response to snowmelt. In the following sections, these results are discussed individually and compared to results from other studies. Finally, the results are contextualized within the interannual variability in snow conditions at the research site.

Soil temperature

To test the potential energy differences at the three study sites, the air temperature measured at AWS was compared to the soil temperatures at each site. This analysis showed a significant dampening effect of the vegetation on the soil temperature, which is in agreement with previous studies [39,40]. Müller et al., in particular, showed a significant interaction between the soil temperature and vegetation patterns, which caused differences in soil temperatures inside and outside of dense forests due to its shading [40]. The observations at the BKH lead to the same conclusion and show that, on average, the soil temperatures in the forest are 1.3 to 3.7 °C lower than in the open field. In addition, the influence of the air temperature on the soil temperature at the northern slope in the forest at the NF site was even weaker. The mean soil temperature on the north aspect slope (NF) was smaller than on the southern forest site (SF). The sites differed in steepness of the regression line (0.43 and 0.76, respectively) too. In addition to the shading by the vegetation, the aspect significantly influences the net radiation and surface temperature, as also shown by Pomeroy et al. [41].

Snow cover

This study found that the soils at the three sites did not freeze as measured by the soil temperatures and the visible soil moisture response to various events in winter. This is supported by Kraft et al., who reported soil temperatures to reach near and above 0 °C during winter in a previous study [39]. This is caused by the insulation effect of the snowpack [14,15]. Kankaanpää et al. have shown the major variability in the local snow depth in mountainous areas [42]. Likewise, due to the varying vegetation cover and exposition to the north and south of the measurement sites at the BKH, high variability in snow depths values was expected. Since, in this study, the snow conditions at the forest sites were not monitored, the soil temperature fluctuation was used to deduce the period of snow cover at each site. The insulation effect of the snow cover led to an almost constant soil temperature of about 1 °C during snow cover at all three sites. The analysis of the soil temperature showed that, in the beginning of the winter season, the snow cover at the SF site disappeared faster than that at the open site (SO). The reason for this is the interception of the snow by the dense vegetation at the NF and SF sites, which results in a smaller snow depth on the ground, as shown by Musselman et al. [24]. Various studies found that the sublimation of snow intercepted by canopy is the primary factor for snow losses in the forest [43,44]. Therefore, the canopy coverages of 74% and 92% at the SF and NF sites, respectively, led to significantly less snow accumulation at these sites.

In contrast, at the end of the winter season, the soil temperature at the northern aspect site in the forest is the last one to respond to the diurnal air temperature fluctuation. An explanation for this is the previously explained dampening effect on the northern aspect site. As it was shown, the NF site had a lower correlation of the air temperature and soil temperature. At this site, almost no energy from direct solar radiation is available due to the shading of both vegetation and topography, resulting in a delayed ablation of the snow cover. Similar effects of delayed snowmelt at a northern aspect have also been documented in previous studies [10,41]. In contrast, the site on the south slope inside the forest was first to show fluctuations in the soil temperature at the end of the snow season in all three years. Snow at the SF site melted about one week earlier than at the SO site (Figure 6). This can be explained by the lower snow accumulation, which was reported to be 30 to 45% less under the forest cover by Pomeroy et al. [45]. In addition, the highest correlation of the air temperature and soil temperature suggests a warmer microclimate at the SF site. This is supported by the study of Roth et al., who described the earlier snow ablation in low- and mid-altitude forests compared to open sites due to increased longwave radiation inside the forest [46]. One exception to this observation was observed during the 2021/22 season, when the soil temperature at both SO and SF sites exhibited fluctuations at approximately the same time (Figure A1). Early and slow snow ablation in the beginning of April 2022 may have caused the simultaneous disappearance of snow at the two southern sites (Figure 3). The late and steep SWE decreasing at the end of April and beginning of May seemed to cause an earlier snow disappearance at the SF site, although more seasons have to be monitored to validate this conclusion.

The importance of snow cover for ecosystems has been highlighted in previous studies [47,48]. Guan et al. linked the start of vegetation growth to snow depth in spring [49]. However, earlier snowmelt could be an advantage for understory vegetation [48]. In contrast, in areas where snow is not persistent throughout the winter, the air temperature becomes the driving factor for vegetation growth [50,51]. Future studies could investigate the differences in the vegetation development at the three sites in relation to the findings of this study.

Soil moisture

At the BKH, no freezing of the soil was observed at any of the measurement sites. Blankinship et al. concluded that the timing of snowmelt only affects shallow soils [52]. The same effect was observed at the BKH, where shallow soil is predominant and all layers were found to respond without any noticeable delay to snowmelt events. In addition, the shallow soil horizon at the BKH made comparisons to infiltration models, like the one established by Bai et al., difficult [53]. The findings of this study show the influence of aspect and vegetation on the response of the soil moisture to snowmelt. In contrast to the vegetation at SF, which had a dampening effect on the response, the northern orientation of NF resulted in a temporal delay and significant lower intensity of the soil moisture response. It is likely that this difference in soil moisture response is caused by a smaller snow accumulation in the forest [24] and slower ablation rates on the north aspect slope [11].

In future studies, soil moisture conditions in summer need to be studied in detail, linking the available water with the status of vegetation to find insights into the dynamics of the ecosystem at the BKH, like previous studies did in mountainous regions [20]. After all, soil moisture plays an important role in the growth and the regeneration of plants [40]. In addition, in periods without snowmelt events, the soil moisture content remained nearly constant, which might be explained by the low or non-existent demand of water by vegetation in winter.

A wider installment of low-cost soil moisture sensors could contribute to a better understanding of the spatial development of soil moisture. Recent research has combined those sensors with artificial intelligence models that improved the field performance of these low-cost sensors and produced good fitting after calibration [54,55]. Even though there are small variations in soil characteristics in the European Alps on a broader scale [56], small-scale differences can be quite drastic and lead to a heterogeneous pattern of observed soil moisture [57], which is an additional reason to improve soil moisture monitoring.

This study found interannual variability in the conditions of winter hydrology at the Brunnenkopfhütte during the observed period spanning from 2016 to 2023. On the other hand, due to the short observation time, no trend regarding snow accumulation was observed. Therefore, the time from October 2020 to May 2023, in which soil moisture was monitored, was considered to be common regarding the snow conditions. However, the 2020/21 season showed the largest snow accumulation of these three years. Peak SWE in late March, like in 2021, was followed by a sharp decline in SWE at the end of April. In spring of 2022, the snow disappeared by mid-April, in contrast to the following year, in which the snow cover was persistent until the beginning of May. As mentioned before, this period is too short for predicting trends for the near future in this area. Therefore, longer in situ observations are needed in this area in order to make better predictions for future climate scenarios and putting the analyzed seasons into a broader context.

In addition, this study was limited in the knowledge of the true snow conditions at the three measurement sites. The absolute value of snow depth in the three sites could not be measured for this study. At the SO site, there may be a different snow regime than at the BKH station, because of the special topography close to the hut, which occasionally caused accumulation by snowdrifts at the AWS. Especially in the forest-covered sites (NF and SF), the true snow depth is expected to be lower due to the dense vegetation (tree canopies) and consequently smaller SWE. Data of this conditions would help to interpret and support the findings of this study better. Finally, a fourth study site located on a north aspect slope would help to further evaluate the influences of aspect and vegetation on snowmelt. Snow depth measurement with an automated setup of an outdoor camera, a measuring rod, and a neural network could help to acquire these data [33].

5. Conclusions

This study looked into the influence of slope aspect and vegetation on the soil moisture response to snowmelt in the area around the Brunnenkopfhütte, located in the southern German Alps and aimed to contribute to a better understanding of the local differences in snow accumulation and ablation in alpine areas. In the observed period from 2016 to 2023, the interannual variability in the snow conditions was observed. It was shown that the slope aspect and vegetation influenced soil temperatures in the snow-free seasons. While vegetation cover leads to a lower soil temperature on average, the northern slope causes a weaker relation between the soil temperature and air temperature. In winter, under vegetation, less snow accumulates and melts faster in warmer periods in the beginning of winter. At the end of the season, the snow cover on the northern slope melts slower. Finally, both aspect and vegetation influence the response of the soil moisture to snowmelt. The amplitude of the soil moisture response was significantly smaller at the southern slope in the forest than in the open field. At the northern site under tree cover, almost no daily peaks in soil moisture could be measured and the increase in soil moisture showed a significant delay each day of the melting season. Potential differences in water availability on the north and south slope after snowmelt could be investigated in future studies. In conclusion, the most significant factor influencing snow accumulation is vegetation cover, while slope aspect exerts a more pronounced influence on snow ablation, on the air–soil temperature relationship, and the soil moisture response to snowmelt at the BKH.

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Appendix A

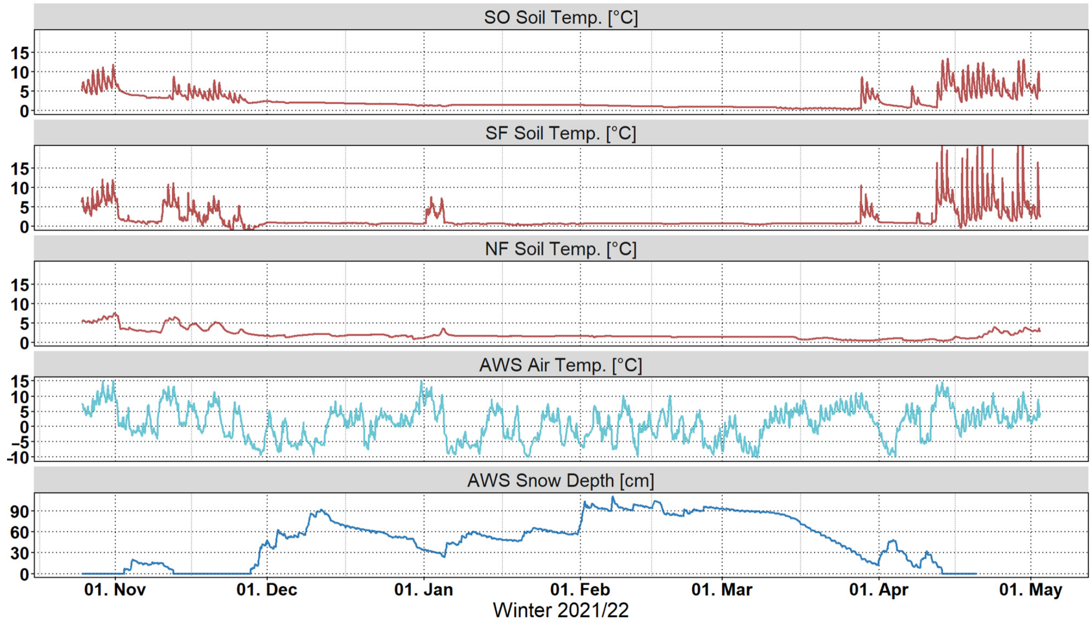

Figure A1. Soil temperature variability at the SO, SF, and NF sites before, during, and after the 2021/22 snow season.

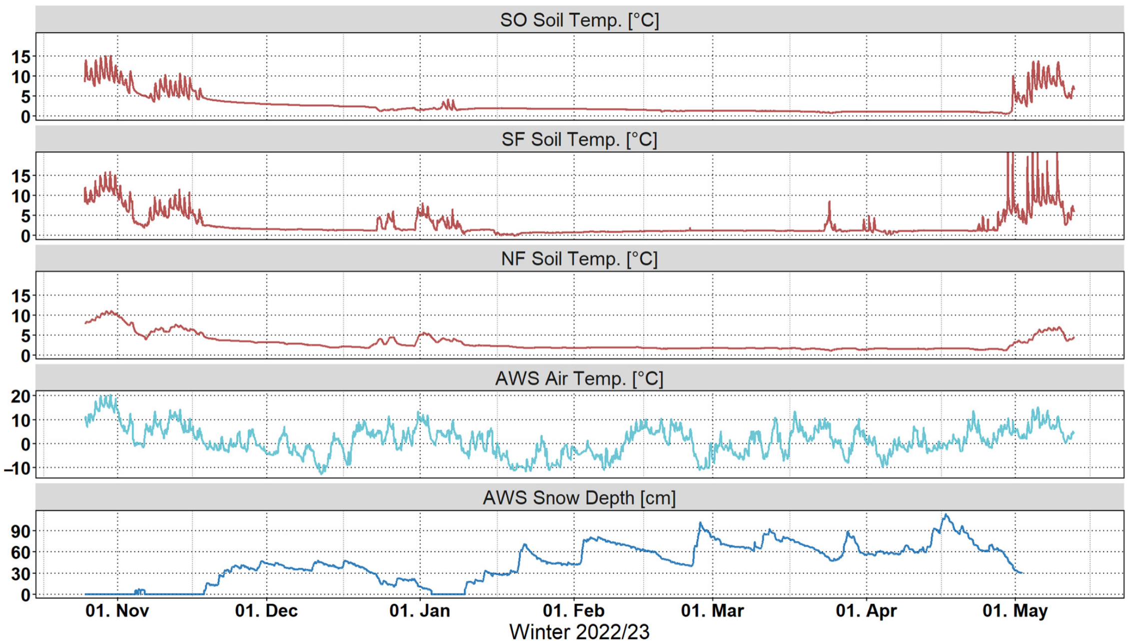

Figure A2. Soil temperature variability at the SO, SF, and NF sites before, during, and after the 2022/23 snow season.

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