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THE IMPACT OF DIFFERENT MANAGEMENT PRACTICES ON SOIL TEMPERATURE AND MOISTURE LEVELS IN SEMI-NATURAL MOUNTAIN GRASSLAND

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ABSTRACT

Aim of the study

The study aimed to assess the impact of various grassland management practices, such as mowing with biomass removal, mulching, and compost application, on the seasonal dynamics of surface soil temperature and soil profile moisture in semi-natural mountain meadows. Understanding these effects is essential for evaluating alternative management strategies that could help maintain biodiversity and ecosystem services, while reducing maintenance costs in low-productivity grasslands.

Material and methods

The experiment was conducted in 2021 on a semi-natural grassland in the Pieniny Mountains. Treatments involved mowing, mulching, compost application. Soil moisture was measured bi-weekly at the depth of 10, 20, 30, and 40 cm using a soil-profile probe. Soil temperature at 5 cm depth was recorded automatically.

Results and conclusions

Soil moisture increased with depth, reaching its lowest and most variable values in the 10-cm layer. The greatest differences in moisture levels across the treatments occurred between May and July: the compost treatment showed the highest levels of moisture in the upper soil layers. In deeper layers, however, management effects were negligible. From late summer onwards, moisture content became similar across all treatments. Soil temperature was highest in the mown plots and lowest in the compost treatment, particularly from May to mid-August. Mulching produced only minor effects on both soil temperature and moisture, likely due to the small amount of mulch used. Compost had the strongest influence through increased biomass accumulation. Mulching had a limited impact and could be used for conserving low-productivity grasslands, but it could also have adverse effects under high-biomass conditions. Biomass quantity is a key driver in shaping soil thermal and moisture regimes, which in turn may influence species composition in the long term.

Keywords: compost, nature protection, mulch, grassland conservation management, grassland vegetation

INTRODUCTION

Traditionally managed semi-natural meadows are a hallmark of the Carpathian cultural landscape. In terms of biodiversity, they host some of the richest plant communities and provide multiple ecosystem services, including those important for the abiotic environment, such as erosion control and increased water retention (Bengtsson et al., 2019). However, their role in agricultural production is diminishing

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today due to low yields and the limited fodder value of the sward. Nevertheless, traditional management, often combined with moderate grazing, remains essential for maintaining their rich and distinctive plant and animal species composition (Shipley et al., 2024).

In protected areas (Tokarczyk, 2018) and within agri-environmental payment schemes (Báldi et al., 2013; Batary et al., 2015), traditional management is most often replaced by mowing and biomass removal. However, as livestock farming is in decline in many regions, especially in mountain areas, there is a lack of demand for fodder. This means that the utilisation of cut biomass is becoming an increasingly significant issue. Consequently, there is a need to identify cost-effective solutions for maintaining such grassland communities.

One possible approach is mulching which involves distributing various covering materials across the soil surface (Iqbal et al., 2020). This practice is primarily used on arable land and in perennial crops. Its main functions include reducing evaporation, stabilising soil temperature, increasing the capacity of soil to hold water, and suppressing weed growth (El-Beltagi et al., 2022). Mulching on permanent grasslands consists of mowing and shredding the vegetation, leaving it to decompose naturally on the surface (Moog et al., 2002). Research on the use of mulching in the management of semi-natural meadows and grasslands has been conducted in many countries (Moog et al., 2002; Fiala, 2007; Mašková et al., 2009; Doležal et al., 2011; Hensgen et al., 2016; Pavlů et al., 2016). Leaving cut biomass on the surface is also commonly practiced in the maintenance of urban and domestic lawns (Grégoire et al., 2022). An alternative approach is to collect the biomass, compost it outside the meadow, and, after partial decomposition, spread the compost back onto the site. In agriculture and horticulture, compost serves as both a fertilizer and as a mulching material (El-Beltagi et al., 2022).

Biomass left on the soil surface influences vegetation directly, by affecting plant growth and development, and indirectly, by modifying soil thermal and moisture conditions (Facelli and Pickett, 1991). Management practices that do not involve annual biomass removal can alter abiotic parameters such as nutrient availability, soil temperature, and moisture, thereby affecting the functioning of biocenosis and the multifunctionality of ecosystem services of temperate grasslands (Richter et al., 2024).

The effects that mulch layers have on soil thermal and moisture conditions are well documented in the literature, although the majority of studies focus on agricultural crops (El-Beltagi et al., 2022). In contrast, research on the use of mulch or compost in permanent grasslands is primarily focused on changes in vegetation composition, examining the effects of these treatments on soil temperature and moisture far less frequently. Yet, changes in the regimes of soil thermal and moisture affect the rate of organic-matter decomposition and mineralisation of different organic materials, influence the development of soil micro- and macrofauna, regulate soil water content and its availability to plants (Onwuka, 2016). Consequently, these changes may lead to alterations in plant species composition.

The overall objective of the experiment was to evaluate the feasibility of replacing mowing and biomass removal with alternative active conservation measures while maintaining the composition of vegetation species. This study sought to compare the seasonal dynamics of surface soil temperature and soil profile moisture during the growing season under different grassland management treatments with those observed under mowing with biomass removal, which served as a reference for management practice.

METHODOLOGY

The experiment was conducted from 2015 to 2021 on a semi-natural mountain meadow located in the Majerz glade in the Pieniny National Park (Polish Carpathians). Situated at an elevation of 640 m a.s.l., the site has a slope of 10° and an eastern exposure. The Pieniny region is characterized by a temperate mountain climate. The long-term mean annual precipitation amounts to 755 mm, while the long-term mean annual air temperature is 6.3°C. In 2021, the total annual precipitation reached 811 mm, and the mean annual air temperature was 7.5°C. Therefore, it can be concluded that the meteorological conditions in the analyzed year did not differ significantly from the long-term

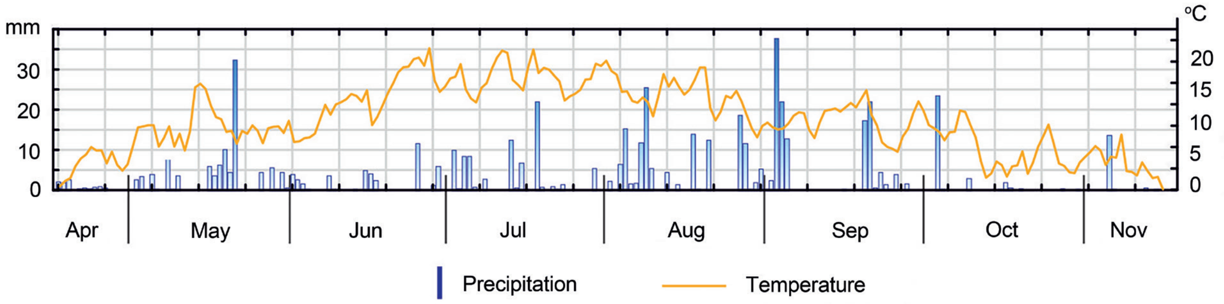

Fig. 1. Total daily precipitation and average daily air temperature in the period April–November 2021 (Source: own elaboration)

averages. Precipitation and air temperature during the study period were recorded using automatic sensors located 500 m from the experimental area at a height of 2 m. The meteorological conditions are shown in Figure 1. The plant community was a mountain grassland belonging to the Arrhenatherion alliance (habitat type 6520 according to the Natura 2000 classification). Prior to the establishment of the experiment, biomass yield was approximately 3.5 t · ha^{-1} (Zarzycki et al., 2024).

The experimental design consisted of three treatments: 1) mowing with biomass removal (the reference management practice), 2) mulching (mowing and shredding the vegetation and leaving it on the surface), and 3) compost application. Experimental plots of 100 m^2 were arranged in three replicates. Mulching and mowing were performed annually at the beginning of August, while compost was applied in 2015, 2017, and 2019. Compost was produced both from biomass collected from grasslands (2015 and 2019) and from forest nursery residue containing legume plants (2017). Wet compost was applied at a rate of 9 t · ha^{-1}, but its chemical composition varied from year to year. The levels of the applied macroelements are presented in Table 1. In 2021, from April to November, soil moisture measurements were conducted at approximately two-week intervals (13 sampling dates). Measurements were taken at depths of 10, 20, 30, and 40 cm using a Delta-T PR2 soil profile probe. Soil temperature was automatically recorded every 15 minutes at a depth of 5 cm in all plots using HOBO Data Loggers. For further analyses, mean values from the three replicates for each treatment were used.

Table 1. Levels of the applied macroelements in compost fertilizer in each year (kg · ha^{-1})

Element	2015	2017	2019
N	28	66	29
P	9	10	20
K	28	49	35

RESULTS

In the sixth year of the experiment (2021), floristic analyses and assessments of biomass were conducted. The last application of compost had occurred in 2019, so by 2021 the material had fully decomposed, limiting its effect to enhancing soil nutrient availability. The biomass was significantly higher in the compost treatment than in the mown and mulched treatments. Species–treatment associations were identified using PCA ordination (Fig. 2). Species associated with mowing and mulching, represented by *Anthoxanthum odoratum* and *Pimpinella saxifraga*, formed one group, whereas tall grass species, such as *Dactylis glomerata*, *Phleum pratense*, and *Alopecurus pratensis*, associated with compost application, formed a separate group. Detailed results of these analyses are presented in a separate publication (Zarzycki et al., 2024).

During the study period (April–November 2021), the highest mean soil moisture (41.7%) was recorded at a depth of 40 cm. At 30 cm, the mean moisture was 34.8%, at 20 cm, it was 29.7%, and the lowest

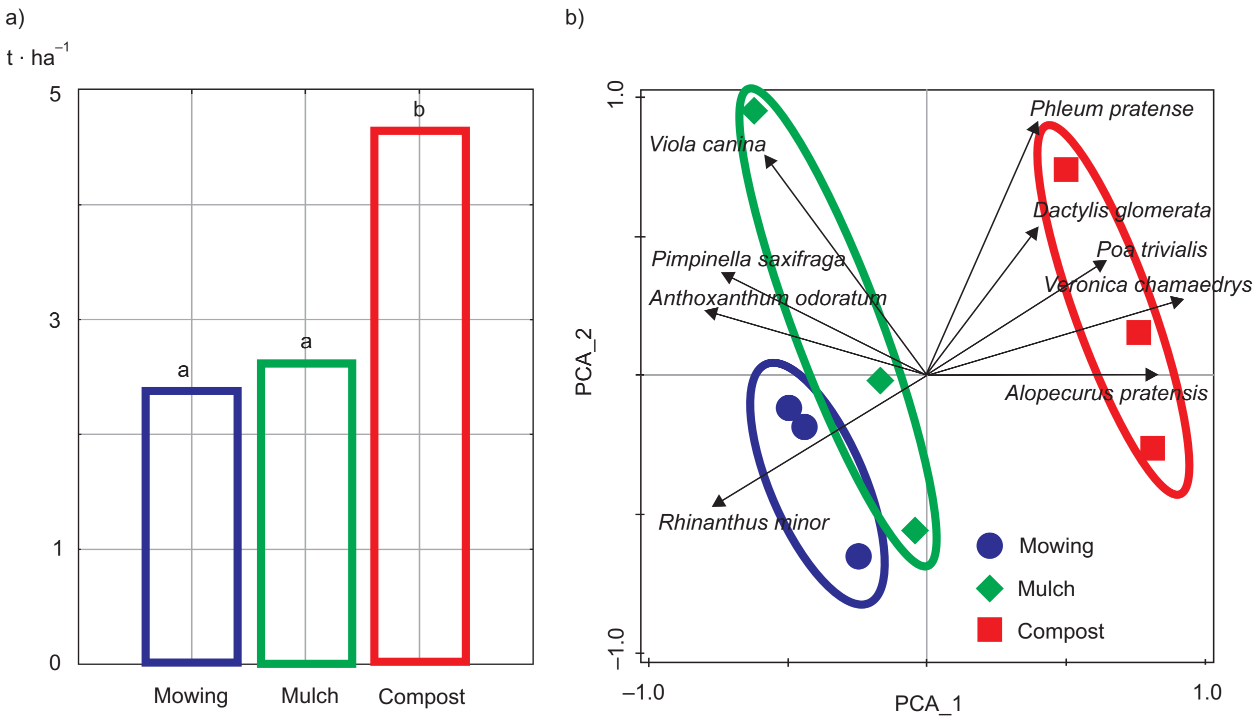

Fig. 2. Vegetation in 2021: a) Dry matter biomass in different treatments (means marked with different letters differ significantly, Tuckey test, $p < 0.05$); b) Ordering of plots based on species composition (PCA analysis) (Source: own elaboration)

value occurred at 10 cm (20.2%) (Table 2). A similar pattern of moisture differentiation among depths was observed at each measurement date. Variability between measurement dates, expressed as the coefficient of variation, was lowest at 40 cm (5.9%) and highest at 10 cm (33.7%) (Table 2).

The greatest differences, both among measurement dates and between the surface layer (10 cm) and the 40-cm layer, were observed from mid-June to the end of August. From September to early November, soil moisture remained relatively stable at all depths (Fig. 3). The mean soil moisture across the profile was lowest under mowing, with the exception of the 30 cm depth (Table 2). The effect of management type on soil moisture was most pronounced at depths of 10 and 20 cm, where the moisture content was consistently higher in the mulch treatment than in the mown treatment throughout the study period. At depths of 30 and 40 cm, soil moisture during spring was slightly higher in the mulch and compost treatments than in the mown treatment. However, later in the study period, it was lower in the compost treatment than in the mown treatment. Soil moisture dynamics in the mown treatment were closer to those in the compost treatment than to those in the mulch treatment (Fig. 4). During the analysed period (April–November 2021), the highest mean soil temperature (14.84°C) was observed in the mown treatment, whereas the lowest (14.08°C) occurred in the compost treatment (Table 3). Soil temperature in the compost and mulch treatment plots was lower than in the mown treatment, particularly from mid-May to mid-August, when the sward was cut. The diurnal temperature amplitudes were even more pronounced in the mulch and compost treatments than in the mown plots during this period (Fig. 5).

Table 2. Descriptive statistics of soil moisture (%) depending on the type of use and depth in the soil profile in the period April–November 2021

		Mean		Minimun		Maximum		Coefficient of variation (%)	
Treatment	Depth (cm)	for depth	for treatment	for depth	for treatment	for depth	for treatment	for depth	for treatment
Mowing			18.56		10.11		27.98		33.5
Compost	10	20.17	19.29	9.36	9.36	32.1	28.63	33.7	37.3
Mulch			22.66		11.41		32.13		29.7
Mowing			27.80		21.80		31.79		11.8
Compost	20	29.70	30.39	21.8	22.64	34.4	34.39	12.4	12.8
Mulch			30.92		25.07		33.61		10.5
Mowing			34.93		31.77		39.20		5.7
Compost	30	34.81	35.93	28.7	31.87	39.7	39.74	7.6	7.2
Mulch			33.56		28.66		37.30		8.7
Mowing			40.67		36.80		47.50		5.9
Compost	40	41.66	42.71	36.8	40.43	49.0	48.98	5.9	5.1
Mulch			41.58		37.50		46.80		6.1

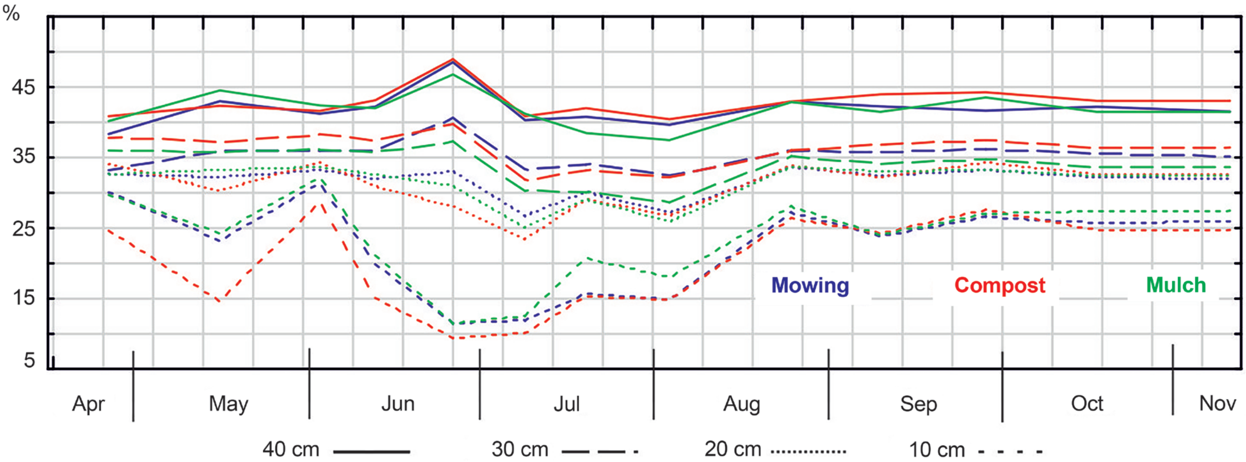

Fig. 3. The course of changes in moisture in the soil profile in the period April–November 2021 (Source: own elaboration)

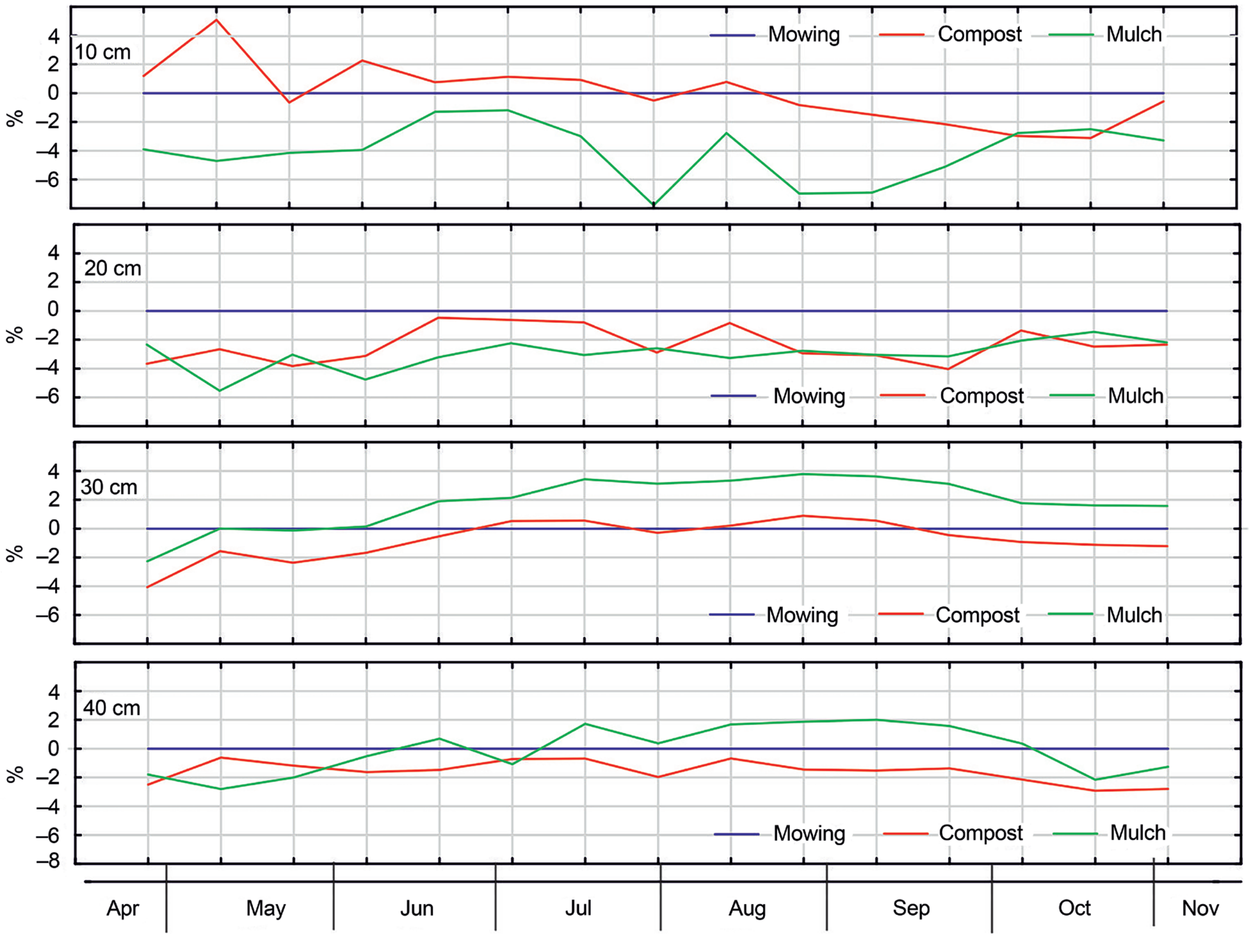

Fig. 4. Differences between soil moisture in the mown treatment, adopted as the reference level ("0"), and soil moisture in the mulch and compost treatments at different depths of the soil profile (Source: own elaboration)

Table 3. Descriptive statistics of soil temperature (°C) at a depth of 5 cm depending on the type of management in the period April–November 2021 and mean for each month

	Year					Month							
Treatment						Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
	Mean	Min	Max	Range	Coeff. of variation	Mean							
Mowing	14.8	2.4	25.1	22.7	38.2	7.0	13.4	19.8	21.7	18.5	15.1	9.1	5.4
Compost	14.1	2.3	23.4	21.1	36.9	6.7	12.8	18.1	20.2	17.6	14.8	8.5	5.3
Mulch	14.5	2.5	24.1	21.6	37.6	6.7	12.8	19.0	20.9	18.2	14.9	8.9	5.2

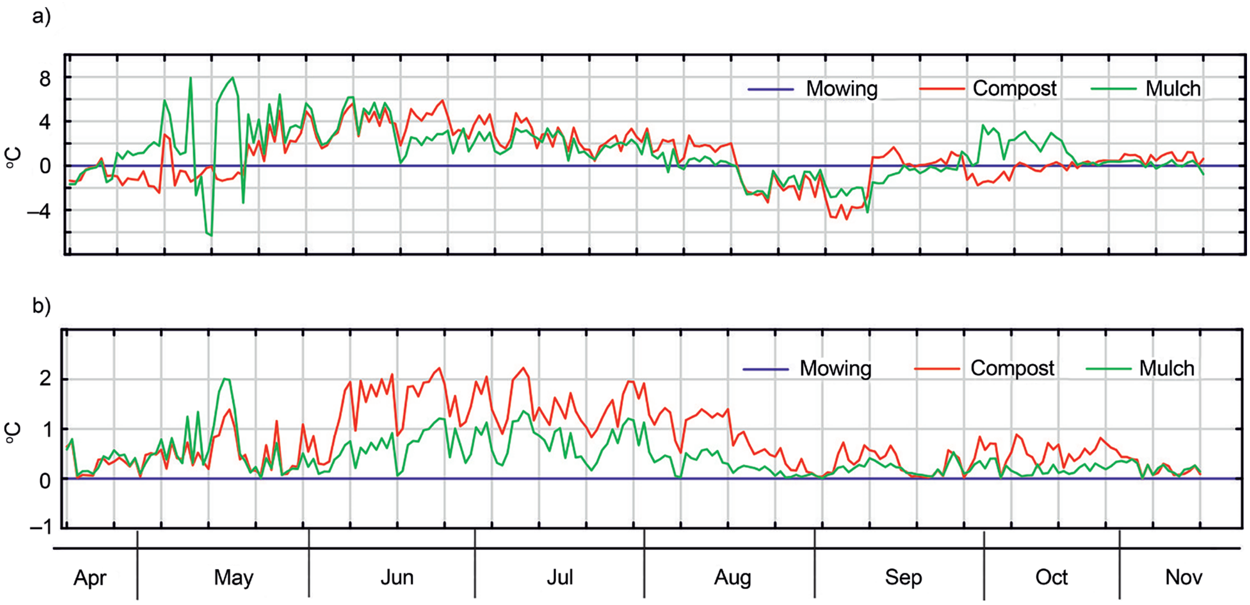

Fig. 5. Differences between: a) soil temperature in the mown treatment, adopted as the reference level ("0"), and soil temperature in the mulch and compost treatments; b) the diurnal soil temperature amplitude in the mown treatment, adopted as the reference level ("0"), and the diurnal soil temperature amplitude in the mulch and compost treatment (Source: own elaboration)

DISCUSSION

The average soil moisture was lowest in the surface layer and increased with depth throughout the soil profile. This layer also exhibited the greatest variability in moisture, as indicated by the coefficient of variation of mean moisture, which decreased with depth. Soil moisture depends on the balance between water inputs and losses, as well as retention properties of soil water (Yu et al., 2018; Dai et al., 2022). Precipitation primarily increases the moisture content of the upper soil layer, while changes in deeper layers occur gradually and with a delay mainly determined by soil properties (Zhang et al., 2020; Dai et al., 2022). Moisture losses are primarily driven by evaporation from the soil and vegetation. Evaporation intensity is strongly influenced by air temperature and the temperature of the surface soil layer. During summer, when temperatures, and thus evaporation, reach their highest levels, soil moisture is at its lowest. Evaporation from plant surfaces also depends on temperature, particularly on leaf area, which is linked to biomass levels (Misztal, 2011; Yu et al., 2018). Variation in the moisture content of the upper soil layer has been observed in differently managed grassland communities in England, though this only applied to communities subjected to long-term uniform management (Bond et al., 2021). In grasslands, the majority of root biomass is concentrated in the upper soil layer, making it the primary source of water uptake. Therefore, during the spring–summer period in our experiment, the lowest moisture was recorded in the 10-cm and 20-cm layers, a pattern also reported by Mostowik et al. (2023). During this time, the highest moisture levels in these layers were found in the mulched treatment. Dead organic matter increases soil moisture (Chen et al., 2024). In our study, although the amount of mulch was small, it nonetheless contributed to higher moisture levels. In agricultural systems, surface application of organic material (mulch) reduces water losses (El-Beltagi et al., 2022), which is why this practice is especially common in arid regions. From mid-August, after cutting, no differences in soil moisture between treatments were observed. Due to low temperatures and reduced leaf area, evaporation at this time of year is minimal, and the effect of mulch on evaporation was negligible. Similarly, Kvitek et al. (1998) found no impact of mulching on soil moisture in a permanent grassland.

Soil temperature fluctuates over time in response to heat exchange with the atmosphere, for which responsible such processes as solar radiation, conduction, convection, evaporation, and the influence of vegetation (Lehnert, 2014). However, the primary drivers are solar radiation and air temperature. In our study, the temperature of the surface soil layer was highest from May to July, when solar radiation and air temperatures reach their annual peaks – a phenomenon commonly observed in Poland (Bryś, 2008; Szyga-Pluta, 2022). During this period, management's influence on soil temperature was also the greatest. Mean temperatures and, especially, diurnal temperature amplitudes were lowest under the compost treatment, where biomass levels were highest. Vegetation absorbs a large proportion of solar radiation during the day, thereby reducing surface heating. At night, vegetation retains some of the energy moving upward from deeper soil layers, preventing excessive heat loss from the substrate (Wojkowski and Skowera, 2017; Facelli and Pickett, 1991; Bryś, 2008). Dense vegetation limits soil-surface heating (Guimarães-Steinicke et al., 2021), partly because increased transpiration exerts a cooling effect. This is particularly evident in spring and early summer, when canopy growth is fastest. Biomass quantity is therefore crucial for shaping soil thermal conditions. Small differences in mean daily temperature or diurnal range were found between the mown and mulched treatments. Although mulching is sometimes used in agriculture to reduce soil heating (Facelli and Pickett, 1991), this phenomenon primarily occurse when bare soil is covered with a substantial layer of organic material (Chen et al., 2024). In our experiment, however, the amount of mulch was small and had partially decomposed by spring, so it had little effect on thermal conditions. The influence of management disappeared from mid-August onwards due to the removal of biomass from the mown and compost treatments after cutting. The remaining mulch did not affect soil temperature because of its small quantity and lower solar radiation during this late-season period. Similarly, Kvitek et al. (1998) reported no effect of mulching on soil temperature in a grassland.

Changes in soil thermal and moisture conditions induced by management may influence species composition in semi-natural grasslands, given that grassland vegetation consists of multiple species with differing thermal and moisture requirements (Jung et al., 2020). Consequently, shifts in dominance structure are often observed between years, depending on weather conditions (Hejcman et al., 2010; Gaisler et al., 2019). Over longer timescales, changes in soil thermal and moisture regimes relative to traditional management practices may alter plant species composition indirectly by modifying soil processes. For example, differences in soil temperature can affect microbial activity and the development of certain invertebrates (Hou et al., 2020), influencing the rate of organic matter mineralization and, ultimately, nutrient availability (Grzyb et al., 2020). The germination of many plant species is triggered by specific soil temperature and moisture conditions (Zhang et al., 2020). Seeds buried in the soil detect their burial depth through light penetration and diurnal temperature fluctuations, thus avoiding germination deep in the soil (Saatkamp et al., 2011). Variation in diurnal temperature ranges, such as observed in spring during the germination period, may influence germination rates differently among species (Wang et al., 2020).

CONCLUSIONS

1. The mulching treatment only had a small influence on soil temperature and moisture.
2. The application of compost, through its effect on increasing plant biomass, reduced the moisture and temperature of the upper soil layer during the period of fastest plant growth (June to August).
3. Mulching may be useful for the active conservation of low-productivity grassland communities.
4. The amount and characteristics of biomass are the main factors affecting changes in soil moisture and thermal conditions, thereby influencing species composition.

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WPŁYW RÓŻNYCH PRAKTYK ZARZĄDZANIA NA TEMPERATURĘ GLEBY I POZIOM WILGOTNOŚCI W PÓŁNATURALNYCH ŁĄKACH GÓRSKICH

ABSTRAKT

Cel badania

Celem badania była ocena wpływu różnych praktyk zarządzania łąkami, takich jak koszenie z usuwaniem biomasy, pokrywanie ściółką i stosowanie kompostu, na sezonowe zmiany temperatury powierzchniowej gleby oraz wilgotności profilu glebowego w półnaturalnych łąkach górskich. Poznanie tych zjawisk jest niezbędne do oceny alternatywnych strategii zarządzania, które mogłyby pomóc w utrzymaniu różnorodności biologicznej i usług ekosystemowych, przy jednoczesnym obniżeniu kosztów utrzymania łąk o niskiej wydajności.

Materiały i metody

Eksperyment przeprowadzono w 2021 roku na półnaturalnych łąkach w Pieninach. Zabiegi obejmowały koszenie, pokrywanie ściółką oraz stosowanie kompostu. Wilgotność gleby mierzono co dwa tygodnie na głębokości 10, 20, 30 i 40 cm za pomocą sondy do badania profilu glebowego. Temperaturę gleby na głębokości 5 cm rejestrowano automatycznie.

Wyniki i wnioski

Wilgotność gleby rosła wraz z głębokością, wykazując najniższe i najbardziej zmienne wartości w warstwie o grubości 10 cm. Największe różnice w poziomie wilgotności między poszczególnymi zabiegami wystąpiły między majem a lipcem: w przypadku kompostu najwyższy poziom wilgotności odnotowano w górnych warstwach gleby. W głębszych warstwach wpływ zabiegów był jednak znikomy. Od późnego lata poziom wilgotności w przypadku wszystkich zabiegów pozostawał zbliżony. Temperatura gleby była najwyższa na koszonych działkach, a najniższa na działkach kompostowanych, szczególnie od maja do połowy sierpnia. Ściółkowanie miało jedynie niewielki wpływ zarówno na temperaturę, jak i wilgotność gleby, prawdopodobnie ze względu na niewielką ilość zastosowanej ściółki. Największy wpływ miał kompost, dzięki zwiększonemu akumulowaniu biomasy. Ściółkowanie miało ograniczony wpływ i mogłoby być stosowane do ochrony użytków zielonych o niskiej produktywności, ale mogłoby również wywierać niekorzystny wpływ przy wysokim poziomie biomasy. Ilość biomasy jest kluczowym czynnikiem kształtującym reżimy termiczne i wilgotnościowe gleby, co z kolei może wpływać na skład gatunkowy w perspektywie długoterminowej.

Słowa kluczowe: kompost, ochrona przyrody, ściółka, zarządzanie ochroną łąk, roślinność łąkowa