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Effects of Silicon Application and Groundwater Level in a Subirrigation System on Yield of a Three-Cut Meadow

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Abstract: The increasing demand for food and animal products makes it important to ensure that animals have sufficient fodder obtained from grassland. Unfortunately, there has been a recent decline in grassland areas, which makes it essential to find solutions to increase the grassland's productivity and the quality of the fodder it yields. One of these solutions may be the use of appropriate irrigation and fertilization. The present study investigated the effect of the foliar application of silicon fertilizer and the groundwater level in a subirrigation system on the yield of a three-cut meadow. Four different experimental plots were used: high groundwater level (HWL), high groundwater level with silicon application (HWL_Si), lower groundwater level (LWL), and lower groundwater level with silicon application (LWL_Si). The analyses showed that silicon significantly reduced the amount of dry matter obtained in each of the three meadow cuts during the year. Furthermore, the plot with a higher groundwater level had an annual yield of 12.69 Mg·ha^{-1}, whereas when silicon was applied to this area, it was 10.43 Mg·ha^{-1} (17.8% reduction in dry matter). A similar trend was noted at lower water levels, in which silicon also caused a dry matter reduction. However, the experiment did not indicate a statistically significant effect of silicon application on plant height and NDVI values. These results show that further research is still needed to better understand silicon's effect on meadow sward.

Keywords: grassland; yield; irrigation; silicon; biodiversity

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1. Introduction

Grasslands play an important role in land areas on Earth. One of their main functions is to provide fodder for animals. Furthermore, grasslands prevent soil erosion, mitigate flooding, locally regulate microclimates, and support biodiversity. They are also valuable regarding landscape value [1,2]. Scientists note that the area of permanent grasslands in Europe has declined in recent decades, so their protection should be prioritized [3]. A major problem is the excessive conversion of permanent grassland to arable land. This change is mainly due to the growing demand for food [4]. However, the reduction in grassland is not only due to the excessive tendency to convert much land into arable fields or forests but also to urban development and new buildings. It has been noted that it will be a sizable challenge to reverse this trend and increase the proportion of grassland worldwide. The problem that needs to be addressed is how to encourage farmers to maintain, or even increase, the share of grassland [5]. It is important, therefore, to look for practices that will allow farmers to improve the yield of these areas and thus increase the financial profits from grasslands. However, it must be remembered that pursuing higher- and higher-quality yields must take place while maintaining the biodiversity of grasslands. The benefits of increased production cannot be achieved by degrading these areas. The research indicates that to achieve the most beneficial economic results, it is necessary to carry out the irrigation and fertilization of meadows at the same time [6].

Previous research shows that using silicon in crops can be a good alternative to chemical fertilizers and crop inputs. Scientists consider the use of silicon (Si) to be an environmentally friendly method of improving growth and alleviating plant stresses. Moreover, Si does not have corrosive or contaminating properties for crops [7]. Plants need Si contained in the soil to grow. Silicon is relatively common in soils however often in silicon dioxide (SiO_2), which is unavailable to them [7]. Thus, an alternative may be providing Si as supplemental crop fertilizer. It has been noted that the foliar application of silicon can be a good solution. It is cheaper and more convenient to apply than soil fertilization [8]. Artryszak and Popielec [9] state that the foliar application of silicon is a relatively new treatment in plant practice in Poland. Their survey showed that among 145 farmers, as many as 38% applied foliar silicon products for the first time only in the 2020/2021 growing season, with only 10% of respondents using this treatment for five or more seasons so far. The most frequently mentioned crops on which silicon was foliar applied were sugar beets, corn, canola, and wheat [9].

In recent years, there has been a marked increase in the number of papers on the research of Si applications on plants. The period spanning the last decade of the 20th century to the present is called the golden age of silicon research. The largest number of scientific articles published in this field came from authors from China, the U.S., and Brazil [10]. Many studies prove silicon's beneficial effects on crops such as rice, wheat, corn, soybeans, barley, sugarcane, tomato, or cucumber. Its application promoted biomass growth and improved quality and yield [11]. Kowalska et al. [7], in their study on silicon application (Adesil and ZumSil fertilizers) in wheat, also noted positive effects on the number of emergences, plant height, the number of ears, and the density of spikes. Saud et al. [12], in an experiment on Kentucky bluegrass (*Poa pratensis* L.) grown in pots, observed that Si application contributed to mitigating the negative effects of drought and higher water use efficiency. They claim that higher photosynthesis, a faster growth rate, and a lower transpiration rate are responsible for this result. A survey conducted in Poland showed that farmers most often use silicon precisely to achieve an improvement in plant health and drought tolerance. Less frequently, responses stated the intention to increase disease resistance or improve yield as the reason for performing this treatment [9]. However, the researchers note that the results of many silicon application studies on plants are inconsistent. The differences obtained often depend on the plant species, genotypes, as well as environmental conditions. Therefore, there is still a need to increase the number and scope of Si application studies to better understand the relationships that occur and to successfully apply silicon to various crops [13].

Silicon fertilization can also affect the quality of groundwater. Silica is a natural component of the soil that affects its structure and plant health. Incorporating silicon into the soil can increase water retention capacity and improve permeability, stability, and structure. Depending on local geological and hydrological conditions, increased silica fertilization may affect silicon concentration in the water. Silicon is usually considered a low-risk substance to human health, animals, plants, and ecosystems. In the right amounts, silicon can be beneficial to aquatic organisms, plants, and microorganisms [14–19]. However, an excess of silicon in groundwater, which is often associated with surface water, can cause undesirable effects. For example, silicon oversaturation can lead to changes in aquatic ecosystems, such as cyanobacterial blooms and reduced water transparency. In addition, excess silicon in drinking water may require different water treatment processes, which can be costly and increase energy consumption [20].

This study aimed to determine the effect of the foliar application of an antitranspirant containing silicon as well as the groundwater level on the yield of a three-cut meadow with a functioning subirrigation system. The research was conducted in two meadow sites: the first was characterized by a higher groundwater level, and the second covered a lower groundwater level (upstream and downstream of the melioration ditch valve). Using two sites made it possible to observe the effect of silicon on meadow plants under different conditions. Moreover, the study verified the research hypothesis that the application of silicon significantly affects meadow yields.

2. Materials and Methods

2.1. Research Area and Experiment Design

The research was conducted in 2021 in a three-cut meadow in the Racot village in Wielkopolska voivodeship in Poland (52°03′47″ N, 16°41′46″ E). The meadow has a subirrigation system, which regulates the area's water management. This system is based on valves located on ditches. These valves make it possible to regulate the amount of water in the ditches and, simultaneously, the groundwater level in the area between the ditches. The location selected for this study is unique in the country, as currently, many of the structures in subirrigation systems are neglected or have been destroyed, making properly functioning systems of this type rare. Scientists emphasize that in Poland, the problem is too little funding and not enough emphasis on the maintenance work of the structures, which results in the deterioration of the condition and functionality of drainage facilities on many meadow sites [21,22]. Moreover, based on archival maps, it was also found that the irrigation system in Racot village in 1976 consisted of as many as 36 km of ditches, whereas in 2000, it was only 12.5 km [23].

In the investigated part of the meadow, water for the subirrigation system is supplied from the nearby Gołębiowski Ditch. Excluding precipitation, this is the only source of water for this meadow. The study area is divided into two research sites. In the first, a high groundwater level (HWL) is maintained, thanks to a closed valve on the ditch, whereas in the second site, the groundwater level is lower (LWL), as the area is located behind the water damming. The valve remained closed for the entire experiment period to maintain the difference in water levels between the test sites.

During the experiment, a HOBO U20L-01 Onset (MA, USA) datalogger was installed in each test site (HWL and LWL) to measure groundwater levels. In addition, the ditch's water level was recorded directly at the damming valve using a datalogger 3001 LTC Solinst (ON, Canada). Moreover, CS-616 reflectometers (Campbell Sci., UT, USA) were installed in each plot at a depth of 20 cm to monitor changes in soil moisture.

Within each site (HWL and LWL), two experimental plots were separated, one control and one with applied silicon. In this way, four different combinations of plots were obtained (HWL, HWL_Si, LWL, LWL_Si). A Polish fertilizer called *Krzemian* by Chemirol was used in this experiment. This product contains orthosilicic acid (2.5%), i.e., silicon in a form that is available and quickly absorbed by plants. Furthermore, this fertilizer includes such micronutrients as boron (B) 0.3%, copper (Cu) 1.0%, molybdenum (Mo) 0.2%, and zinc (Zn) 0.6%. According to the manufacturer's description, this product improves plant vigor and growth. In addition, it strengthens resistance to adverse weather conditions and infection caused by diseases and pests. Moreover, according to the information leaflet, it reduces transpiration. This fact makes this product potentially belong to the broad group of antitranspirants. Currently, the application of antitranspirants in agriculture is becoming increasingly popular. There is also a noticeable increase in the scientific community's interest in researching products of this type [24,25]. The producer of the *Krzemian* fertilizer chosen for this experiment recommends using it on agricultural, vegetable, and fruit crops, including mainly: wheat, barley, rye, triticale, soybean, rapeseed, alfalfa, peas, corn, potatoes, sugar beets, apple, pear, plum, cherry, strawberry, bell pepper, tomato, and cucumber. So far, this product has not been applied to meadows, so in this work, it was chosen to experimentally test its effect on yield and plant parameters. The present measurements are the first attempt to evaluate the application of *Krzemian* in a three-cut meadow with a subirrigation system. This study decided to use the dose provided for cereals due to their membership in the *Poaceae* family, including grass species growing in meadows [26]. The silicon product was applied to selected meadow plots at a rate of 0.8 $L \cdot ha^{-1}$ at the beginning of the growing season in 2021 and ten days after each of the three meadow cuts. In addition, other agrotechnical treatments were carried out according to recommendations on the entire area.

2.2. Scope of Study

2.2.1. Meteorological Monitoring and Analysis

During the experiment, meteorological conditions were monitored through measuring devices installed in the meadow (Campbell Scientific, PM Ecology). Parameters such as precipitation (mm), air temperature (°C), relative humidity (%), photosynthetically active radiation PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$), wind speed ($m \cdot s^{-1}$), and wind direction (°) were measured continuously. Part of the meteorological data were acquired from a station that was installed as part of the technological innovations and system of monitoring, forecasting, and planning of irrigation and drainage for precise water management on the scale of drainage/irrigation system project (INOMEL) BIOSTRATEG3/347837/11/NCBR/2017.

Based on meteorological data, the beginning and end of the vegetation growing season in 2021 were determined using the methodology proposed by Huculak and Makowiec [27]. This method is widely used in studies relating to the territory of Poland [28,29]. It is based on constructing cumulative series of deviations in average daily temperature from the threshold value of 5 °C. The beginning of the growing season is determined by the date after which the cumulative values of successive deviations from 5 °C are exclusively positive, and for the end of the season, they are exclusively negative [30]. Meteorological conditions for the 2021 growing season are presented using a Gaussen–Walter climate diagram with a modification proposed by Łukasiewicz [31]. The Gaussen–Walter diagram makes it possible to present data, including temperature and precipitation, and allows for estimating precipitation excess or deficit [32]. Łukasiewicz's modification includes using a scale of 10 °C = 40 mm of precipitation, which better reflects the actual conditions in Poland and is used by scientists in research [33,34]. Furthermore, pluvio-thermal conditions were characterized for the study area using the Sielianinov hydrothermal coefficient *k* calculated from Equation (1):

$$k = \frac{P}{0.1 \sum t} \quad (1)$$

where:

P—monthly sum of precipitation (mm);

Σt—sum of average daily air temperatures for a given month > 0 °C (°C).

Based on the calculated *k* values, each month of the growing season was classified according to the scale used for Poland (Table 1) [35,36].

Table 1. Classification of conditions according to the Sielianinov hydrothermal coefficient *k* [35,36].

Sielianinow's Hydrothermal Coefficient Value (*k*)	Condition Classification
$k \leq 0.40$	extremely dry (ed)
$0.4 < k \leq 0.7$	very dry (vd)
$0.7 < k \leq 1.0$	dry (d)
$1.0 < k \leq 1.3$	quite dry (qd)
$1.3 < k \leq 1.6$	optimum (o)
$1.6 < k \leq 2.0$	quite wet (qw)
$2.0 < k \leq 2.5$	wet (w)
$2.5 < k \leq 3.0$	very wet (ww)
$k > 3.0$	extremely wet (ew)

Analysis of meteorological conditions for grassland areas is particularly important. For example, Łabędzki [37] notes that grasslands require irrigation in habitats with negative water balance. This means the amount of outflow (runoff and evapotranspiration) outweighs recharge. Moreover, it is indicated that the assessment of the area's irrigation needs in addition to the water balance can be extended to the properties of the soils. Accordingly, several soil analyses were also carried out as part of the present study.

2.2.2. Soil Research

To determine the soil cover and its morphological variation, soil samples were taken from the study area. Soil samples were dried at room temperature and then sieved through a sieve with a mesh size of 2 mm. Only earth fractions (less than 2 mm) were used for further analyses. The following properties were determined in the soil samples prepared as follows:

- Soil texture: The sand fraction was determined by the sieve method, and the finer fraction was determined by Casagrande's hydrometer method in a modification of Prószyński (PN-R-040032). The division into granulometric groups and subgroups was made in accordance with the Soil Science Society of Poland [38];
- Soil organic carbon (SOC) content was determined by dry mineralization using the N/C 3100 JenaAnalytik analyzer. Taking into account the weight of the soil, the obtained result was converted to the C content in $g \cdot kg^{-1}$. Before direct determination, soil samples were sieved through a sieve with a mesh size of 500 µm to separate larger fragments of organic matter (roots and fragments of bark [39]);
- Soil pH: determined by the potentiometric method in two solutions: H_2O and 1 M KCl—with a soil-to-water ratio of 1:1 for mineral samples and 1:10 for organic samples—humus horizon [40];
- Bulk density was determined by the drying-weigh method.

Furthermore, using an evaporation technique based on tensiometer measurements, the water content was determined for the 0–20 cm soil layer at a potential of 10 kPa (pF 2.0). This value corresponds to field water capacity (FWC). The HYPROP measurement system (Meter, WA, USA) was used to determine it.

2.2.3. Biodiversity Research

The following indices were used to assess the differentiation of the examined plots with grass sward:

- Shannon–Wiener index (H′) [41]: one of the most commonly used biodiversity indicators. Its value determines the probability that two individuals drawn from the sample belong to different species (Equation (2)):

$$H' = -\Sigma\ (pi * \log 2\ pi) \tag{2}$$

where:

pi—the proportion of occurrence of each species in a given plot.

This rule is relevant for H′ from 0 to log2 (proportion of species in the sample), where H′ = 0 means no biodiversity, and the maximum value H′ means full biodiversity.

- Simpson's index of diversity (D): describes the variability of species in a selected ecosystem or habitat. It is a normalized value, indicating the probability that two randomly selected individuals from a given set will belong to the same species (Equation (3)). The lower the Simpson index, the greater the biodiversity in a specific ecosystem [42]:

$$D = 1 - \sum pi^2 \tag{3}$$

where:

pi—is the share of occurrence of the i-th species in the population.

Simpson's index value scale: 0 < D < 1, where D = 0 means no diversity, and D = 1 means maximum diversity (each species is represented by one unit).

Sørensen's similarity index, sometimes called the Czekanowski index [43], was also calculated to assess the similarity of the studied plots with the grass sward. The indicator is calculated as the ratio of the number of species present in both sets to the sum of the number of elements in both sets (Equation (4)). This indicator is normalized, and its value always ranges from 0 to 1, where 1 means full similarity, and 0 means no similarity.

$$QS = \frac{2 * C}{A + B} \quad (4)$$

where:

A and B are the numbers of species at sites A and B, respectively, and C is the number of species common to both sites. This expression was extended to compare all analyzed plots with grass sward.

In addition, based on field measurements carried out throughout the growing season, the total species richness of the area was determined using the method proposed by Chao [44,45]. An online tool was used for this purpose: iNEXT (iNterpolation and EXTrapolation—access as of 6 February 2023) [46]. It makes it possible to estimate species diversity using a procedure based on the use of Hill numbers. The tool uses a non-asymptotic approach based on interpolation and extrapolation, which allows for the plotting of integrated curves reflecting species richness. In addition, it also calculates confidence intervals around diversity for rarefied/extrapolated samples. The iNEXT tool, as well as the iNEXT R package, are widely used in much scientific research [47–50].

2.2.4. Plant Parameters

The study monitored plant parameters such as height and Normalized Difference Vegetation Index (NDVI). Plant heights were measured using a hand-held measure each time at 15 locations for each of the four study plots (combinations) (HWL, LWL, HWL_Si, LWL_Si). Moreover, NDVI values were also monitored for each plot. Measurements were made using the SKL 904 SpectroSense2 (Skye Instruments, Llandrindod Wells, UK).

2.2.5. Yield

The yield was assessed three times during the research period—after each cut of the meadow. The cuts took place on dates set by the owner of the property. Each time, plants were cut from each of the four research plots (HWL, LWL, HWL_Si, LWL_Si) in triplicate. Plants in the research plots were cut by hand at a height of 5 cm from 75 × 75 cm areas before mechanical harvesting. All biomass samples were weighed and transported to the laboratory on the same day. The plant samples were dried at 105 °C to obtain the dry matter size. The results were converted to dry matter values per hectare for each plot. The sward was mowed thrice in 2021: 31 May, 14 July, and 30 September.

2.2.6. Statistical Analyses

Statistical analyses of the data obtained were carried out using Statistica (version 13) and R Studio (version 4.2.1). The main objective of the statistical analyses was to verify the hypothesis that the application of silicon and a higher groundwater level significantly affect the yield of the meadow. The study used a two-way ANOVA in which the effects of the two explanatory variables on the response variable were evaluated, respectively, and the model from Equation (5) was used:

$$y_{ikl} = \mu + \alpha_i + \beta_i + (\alpha\beta)_{ij} + e_{ijk} \quad (5)$$

where:

μ—is the overall mean;

α_i—is the effect of the factor of higher groundwater level i (i = 1,2);

β_i—is the effect of the silicon application factor j (= 1,2);

$(\alpha\beta)_{ij}$—is the appropriate interaction of these factors, and e_{ijk}—is error.

Moreover, two heat maps were created using the *heatmaply()* function available in the R package heatmaply, which were proposed for the graphical presentation of the data transformed, respectively, regarding plant height and NDVI index. Finally, data transformation using 'normalize' was applied to enable the comparison and grouping of data of different orders. Cluster analysis made it possible to group the data based on plant heights or NDVI index, respectively, due to all the measurements carried out in 2021, in such a way that the degree of association of plant heights or the NDVI index within one group was the highest, and it was the lowest between groups. Grouping tree diagrams were obtained using Ward's agglomerative method (Ward Hierarchical Clustering) and a measure of Euclidean distance.

3. Results and Discussion

3.1. Meteorological Conditions

Annual precipitation in Racot in 2021 was equal to 539.5 mm. Monthly precipitation and average air temperatures are shown in Table 2. The month with the highest precipitation was July (76.8 mm), which was also the warmest month in the study period (average monthly temperature of 20.9 °C). Conversely, the lowest average monthly temperature occurred in January at −0.3 °C, and the lowest precipitation was recorded in March (19.9 mm).

Table 2. Temperatures and precipitation totals by month in 2021 in the Racot meadow area and total precipitation for the thirty-year period from 1990–2020 in Kościan.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Average monthly temperature in 2021 (°C)	−0.3	−0.2	4.5	6.7	12.6	20.6	20.9	17.7	15.6	10.3	5.5	0.3
Monthly precipitation totals in 2021 (mm)	47	24	20	30	66	53	77	83	21	40	41	38
Average precipitation totals from the period of 1991–2020 for the IMGW-PIB Kościan station (mm)	34	28	36	27	50	56	77	64	39	34	32	32

The 2021 monthly precipitation totals measured at the Racot research area were compared with monthly precipitation totals for the years 1991–2020 from the meteorological station in Kościan, located 5 km from the Racot research plots (Table 2). These data were obtained from the Institute of Meteorology and Water Management National Research Institute (IMGW-PIB). Analyzing the monthly precipitation totals in 2021 against the thirty-year period, it can be seen that in February, March, June, and September, the precipitation was lower than the average for Kościan. On the other hand, in July 2021, the total rainfall was exactly the same as the average value for 1991–2020. However, it should be noted that the precipitation total in 2021 was higher for many months than in earlier years. This is particularly noticeable in the case of August, where as much as 19 mm more precipitation was recorded than for the 1991–2020 average.

The beginning of the growing season for the study area in 2021 was determined to be 24 March 2021, and the end was set for 22 November 2021. Thus, the growing season lasted for 244 days. In order to better illustrate the conditions in the study area during the growing season, a Gaussen–Walter climate diagram was made with the modification proposed by Łukasiewicz [31]. Using the climate diagram makes identifying the periods with a precipitation deficit easy. In Figure 1, it can be noticed that there were two periods of precipitation deficit. The first occurred from the end of May 2021 to the end of July 2021, and the second period of negative climatic water balance values occurred from the end of September to mid-October.

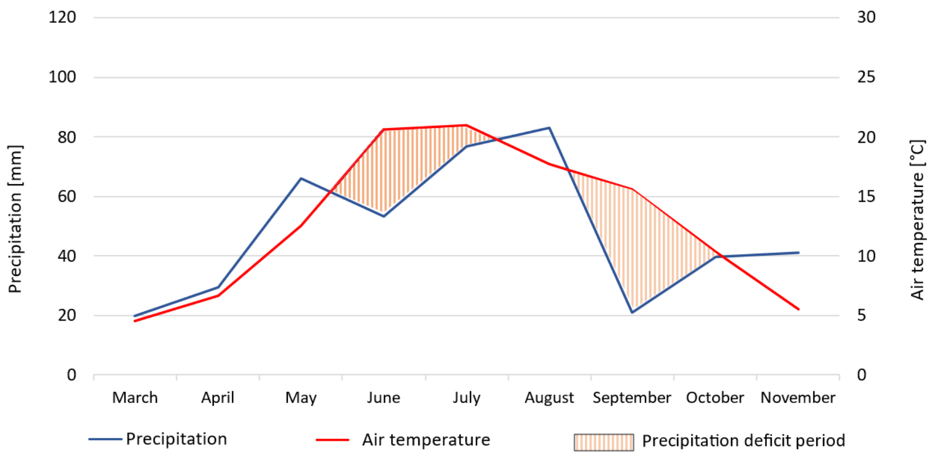

Figure 1. Gaussen–Walter climate diagram with Łukasiewicz modification for the 2021 growing season in Racot.

The characterization of pluvio-thermal conditions carried out using the Sielaninov hydrothermal coefficient *k* coincides with the results obtained from the Gaussen–Walter diagram with Łukasiewicz modification (Figure 1). At the beginning of the growing season (from March to May), the *k* coefficient was 1.4–1.7, which was equivalent to optimal and even quite wet conditions in May (Table 3).

Table 3. Characterization of pluviothermal conditions in the 2021 growing season using the Sielaninov hydrothermal coefficient *k*.

Month	March	April	May	June	July	August	September	October	November
Sielaninov coefficient (*k*)	1.4	1.5	1.7	0.9	1.2	1.5	0.5	1.2	2.5
The month's classification [35]	optimum	optimum	quite wet	dry	quite dry	optimum	very dry	quite dry	wet

The following months, mainly covering the second period of plant growth (June and July), experienced rainfall deficits and were classified as dry and quite dry (Figure 1). On the other hand, September, with a total of 21 mm of precipitation, was very dry. This volume was 18 mm lower than the monthly average for 1991–2020 (Table 2). Thus, it can be concluded that weather conditions for vegetation development were favorable only at the beginning of the growing season (March–May), whereas later, they deteriorated markedly due to precipitation deficits (June–July, September–October). The exception is August, which was classified as optimum. It is worth noting that in November, conditions were also improved (wet); however, this was after the last meadow harvest of that year had already been completed.

3.2. Water and Soil Conditions

3.2.1. Groundwater Table Level

During the growing season, water table levels and soil moisture were continuously monitored in two study sites: one with a higher groundwater level (HWL) and one with a lower groundwater level (LWL). The results are shown in Figure 2. From the beginning of the growing season (24 March 2021) to the first cutting of the meadow (31 May 2021), the groundwater table in the HWL site ranged from a value of 0.13 m below ground level (mbgl) to 0.43 mbgl, whereas the water level in the LWL site was lower, ranging from 0.29 mbgl to 0.68 mbgl. The average difference between the water levels in the studied sites was 0.26 m. During the second regrowth of the meadow (1 June–14 July 2021), the differences were smaller and averaged 0.16 m. It can also be considered that the water table was at a lower level than during the first meadow growth. On the HWL site, it ranged from 0.43–0.85 mbgl, and on LWL, it was 0.65–1.02 mbgl. Moreover, the lowest groundwater levels were recorded during the third regrowth (15 July–30 September 2021). On the HWL site, they varied from 0.32 to 0.92 mbgl, and on the LWL site, they ranged from 0.61 to 1.09 mbgl. The average difference between the plots was 0.19 m.

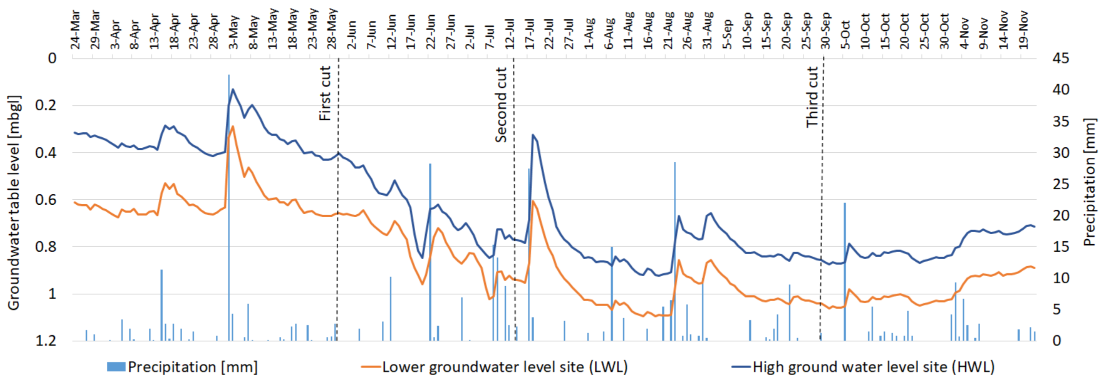

Figure 2. Groundwater levels in 2021 with daily precipitation totals for the measurement sites.

3.2.2. Soil Conditions

The soil research showed that the analyzed meadow area is dominated by soils created of fine-grained loose sands, which form *Mollic Gleysols*. The main material is glacial sand. The granulometric composition of the soil profile representative of the study area is presented in Table 4. Loose sand graining was found in all horizons of the analyzed soil profile. When analyzing the division of sand fractions into individual granulometric subfractions, it was noticed that the average content of very coarse sand (ø 2–1) in soil samples was 5%, coarse sand (ø 1–0.5) accounted for 12%, medium sand (ø 0.5–0.25) 13%, fine sand (ø 0.25–0.1) 36%, and 28% was very fine sand (ø 0.1–0.05). The results confirm the clear layering of well-washed glacial sands caused by soil-forming processes.

Table 4. Granulometric composition of the representative profile in the study area.

Horizon	Depth (cm)	Percentage of Diameter Fraction ø (mm)								Granulometric Group
		>2	2–1	1–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.002	<0.002	
Ap	0–20	12	14	26	22	18	14	7	0	S
C1	20–46	24	6	21	19	30	19	5	0	S
C2gg	46–70	1	0	2	10	51	29	6	2	S
Gg	>70	1	1	0	1	44	51	2	1	S

Note: Ap—humus horizon, C1—parent material, C2gg—parent material with glial features, Gg—gleying horizon, S—sand.

Soil should be perceived as a three-phase system consisting of solid, liquid, and gaseous phases, and the dependencies resulting from the relationship between them determine many soil properties. Therefore, the description of these phase relationships is essential and is most often characterized by soil bulk density (ρc), field density (ρcw), the density of the solid soil phase (ρs), and the porosity coefficient (fc). The conducted density tests for a representative profile showed that ρc ranged from 0.34 g·cm^{-3} in the humus horizon (Ap) to 1.66 g·cm^{-3} in the gleying horizon (Gg). The density ρcw was in the range of 1.03–2.03 g·cm^{-3}, and ρs showed values ranging from 2.26 g·cm^{-3} in the humus horizon to 2.64 g·cm^{-3} in the gleying horizon (Table 5).

Table 5. Summary of dry soil bulk density (ρc), field density (ρcw), solid-phase density (ρs), total porosity (fc), reaction, and C_{org} in a profile representative of the research area.

Horizon	Soil Density (g·cm^{-3})			Porosity Coefficient (cm^3·cm^{-3})	pH Reaction		SOC Content
	ρc	ρcw	ρs	fc	H_2O	KCl	(g·kg^{-1})
Ap	0.34	1.03	2.26	0.85	7.05	6.35	127.5
C1	0.38	1.05	2.26	0.83	7.62	6.94	129.1
C2gg	1.54	1.92	2.64	0.42	7.72	6.49	3.43
Gg	1.66	2.03	2.64	0.37	8.11	7.18	2.7

The pH of the soil, determined in H_2O, ranged from 7.05 in the humus horizon to 8.11 in the gleying horizon. In addition, studies on the content of C_{org} in soils showed that the highest average C_{org} content of 127.5 g·kg^{-1} was recorded in the humus horizon. Detailed results for individual levels are presented in Table 5.

Moreover, during the analysis, one of the basic water and soil characteristics was also determined: field water capacity (FWC), specifying the percentage of water content at a potential of 10 kPa (pF 2.0). The FWC is an essential value for plant cultivation, constituting one of the limits of water potentially available to plants. Therefore, the values determining water availability for vegetation are from pF 2.0 to pF 4.2 (permanent wilting point—PWP). Determining this value is particularly important, because the soil moisture in the root layer, close to the FWC, ensures maximum grassland yield without excessive water consumption for evapotranspiration [51]. For the studied area, the FWC is 49%. This value is presented with soil moisture in the two study sites, HWL and LWL, during the growing season in Figure 3.

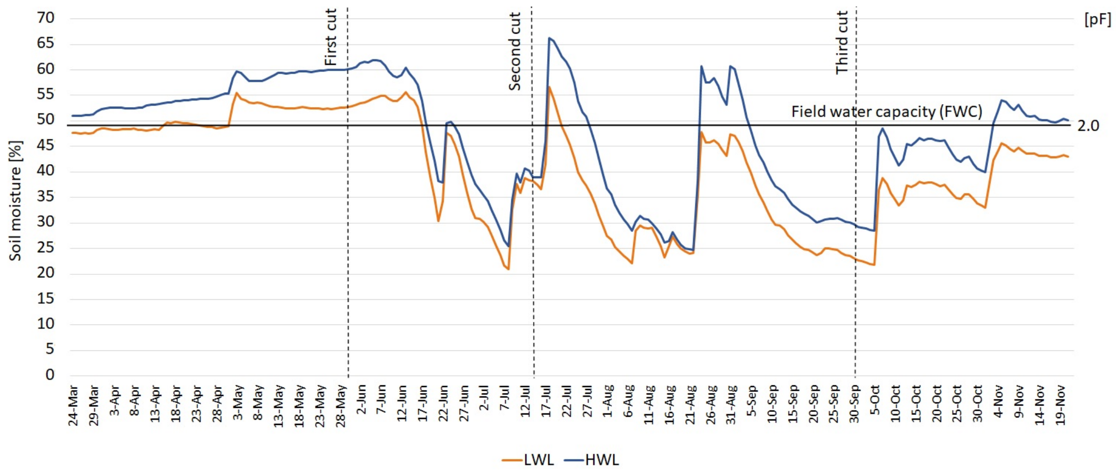

Figure 3. The soil moisture course at the 0–20 cm level in the HWL and LWL sites during the growing season.

When analyzing the course of soil moisture in the growing season, it can be observed that during the entire time of the first grass growth, soil moisture in the HWL site was higher than the value of FWC. On the other hand, in the HWL site, the moisture remained at a level similar to the FWC until the beginning of May, and then exceeded it. During the second regrowth of the meadow, initially, the humidity in both sites was higher than the FWC, whereas in the middle, it dropped sharply below this level and remained below 49% on most days. It is also worth noting that the differences in moisture levels between the

HWL and LWL plots were not as prominent during this period and had similar values at many points. Low moisture levels mainly characterized the third grass regrowth compared to the rest of the growing season. The exceptions were two peaks in mid-July (17.07) and late August (23.08), when there was an increase in moisture content due to the occurrence of abundant daily precipitation (27.5 mm and 28.5 mm, respectively). However, a marked difference in soil moisture between the study plots is evident during this period. At the end of the growing season, soil moisture values in both plots began to increase gradually, reaching values close to the beginning of the growing season.

3.3. Biodiversity

During the study period, 18 taxa (including monocotyledonous and dicotyledonous species) were identified on the analyzed grass sward in all plots containing three repetitions. The number of species depended on the cut. Definitely, the first cut was characterized by the smallest number of identified taxa. Between the second and third cuts, the difference was small in quantity and quality (Table 6). This proves a species rotation in the examined plots during the growing season. However, it should be remembered that the number of species refers to the amount of different plant species present in the cuts, whereas biodiversity takes into account both the number of species and their relative uniformity.

Table 6. List of identified plant species on experimental plots covering all analyzed combinations at individual cuts.

No.	1st Cut	No.	2nd Cut	No.	3rd Cut
1	*Capsella bursa*	1	*Capsella bursa*	1	*Capsella bursa*
2	*Cirsium rivulare*	2	*Carex* sp.	2	*Carex* sp.
3	*Glechoma hederacea*	3	*Chenopodium album*	3	*Chenopodium album*
4	*Lamium album*	4	*Cirsium rivulare*	4	*Cirsium rivulare*
5	*Lamium purpureum*	5	*Elymus repens*	5	*Elymus repens*
6	*Phalaris arundinacea*	6	*Glechoma hederacea*	6	*Galium mollugo*
7	*Poa pratensis*	7	*Lamium album*	7	*Glechoma hederacea*
8	*Ranunculus auricomus*	8	*Lamium purpureum*	8	*Lamium album*
9	*Rumex obtusifolius*	9	*Phalaris arundinacea*	9	*Lamium purpureum*
10	*Stellaria media*	10	*Poa pratensis*	10	*Phalaris arundinacea*
11	*Taraxacum officinale*	11	*Polygonum bistorta*	11	*Poa pratensis*
12	*Veronica chamaedrys*	12	*Ranunculus auricomus*	12	*Polygonum bistorta*
13	*Veronica persica*	13	*Rumex obtusifolius*	13	*Ranunculus auricomus*
		14	*Stellaria media*	14	*Rumex obtusifolius*
		15	*Taraxacum officinale*	15	*Stellaria media*
		16	*Veronica chamaedrys*	16	*Taraxacum officinale*
		17	*Veronica persica*	17	*Veronica chamaedrys*
				18	*Veronica persica*

Differences in the number of taxa were observed in individual plots. The largest number of species was recorded in the first cut in the LWL plot. In this plot, the lowest number of species was recorded in the second cut. The quantitative assessment shows that changes in the number of species in the growing season in the analyzed plots ranged from one to three species, with the third cut being the most uniform in this respect (Table 7).

Table 7. The average number of species in cuts in individual plots with grass sward.

Cut	Plot			
	HWL	HWL_Si	LWL	LWL_Si
1st	4	5	6	5
2nd	3	4	3	4
3rd	3	4	4	4

Comparing the qualitative assessment with the quantitative one, we can see that the number of species does not correlate with the species composition. Despite the largest number of species recorded in the first cut, the total number of identified taxa in plots was the smallest (Table 6). This proves a greater species similarity between some of the plots in the first cut and greater species diversity in combinations in the second and third cuts.

It can be seen that the addition of silicon, together with increased soil moisture, increased the number of species. This can be seen when we compare HWL and HWL_Si plots. The number of species in the first cut for plots with silicon (HWL_Si and LWL_Si) was also higher than the number of species in second and third cuts for these combinations. It can therefore be concluded that the combination of silicon with humidity increases the number of meadow plant species.

When analyzing biodiversity based on the Shannon–Wiener index (H′), it is noted that the following plots, respectively, characterized the greatest species variability: HWL_Si in first cut, LWL_Si in second cut, and LWL in the third cut (Table 8).

Table 8. Results of biodiversity analysis in individual plots in successive cuts (Shannon–Wiener index H′).

Cut	Plot			
	HWL	HWL_Si	LWL	LWL_Si
1st	0.7991	0.9282	0.7518	0.6335
2nd	0.5096	0.6089	0.5644	0.6341
3rd	0.4690	0.6097	0.6876	0.6343
Mean	0.5926	0.7156	0.6679	0.6340

Species inventory and valorization using the Shannon–Wiener index can be used for meadow plants [52–55]. Studies by Magurran [56] on meadow biodiversity in various grassland types indicate that in a eutrophic meadow, the number of registered plant species can reach up to 42, and the value of H′ reaches 4.82. In an oligotrophic meadow, the author of the abovementioned publication identified a maximum of 25 plant species, and the value of H′ was 3.97. The meadow analyzed in the study was eutrophic, but the number of registered species and biodiversity was much lower than in the eutrophic and even oligotrophic meadows studied by Magurran [56].

Research indicates that biodiversity in highland and lowland meadows can vary due to various environmental factors such as sunlight, temperature, humidity, soil composition, and nutrient availability. Highland meadows, which are often less urbanized and less intensively used, show higher biodiversity than lowland meadows, which are often intensively used and dominated by plant monocultures [53,57,58]. The value of the H′ index for mountain meadows may be around 3–3.5. The values of this indicator may vary significantly depending on the region, period, weather conditions, or soil and climatic conditions [59].

The Shannon–Wiener index is an important tool for assessing biodiversity, but it is not the only one. It should be used in conjunction with other assessment methods to obtain a complete picture of biodiversity in permanent grasslands. Therefore, the study also calculated the Simpson's index (D), which describes the biodiversity of various plant communities, including forests, deserts, steppes, sea coasts, lakes, and rivers [60,61]. In forests, the Simpson index can range from 0.1 to 0.9, depending on the number of species of trees, fungi, and other organisms that are present. In deserts, the Simpson index may be lower, ranging from 0.1 to 0.5, due to the harsh environmental conditions and a limited number of species. The Simpson index may be higher in the steppes, ranging from 0.5 to 0.9, due to more favorable environmental conditions and more species of grasses and other plants. On the other hand, on sea coasts, the value of Simpson's index can vary from 0.1 to 0.9, depending on the type of coast, water depth, and other factors.

The results using the Simpson's index (D) confirmed the highest biodiversity of the HWL_Si plot in the first cut (Table 9). In the second cut, the highest biodiversity was recorded in the LWL_Si plot, although, apart from the HWL, in which the lowest biodiversity was recorded, in other cases, the biodiversity was quite even. In the third cut, the highest biodiversity was again observed in the HWL_Si plot. The biggest difference in biodiversity (between HWL_Si and HWL plots) was also recorded here, amounting to 0.1665.

Table 9. Results of biodiversity analysis in individual plots in successive cuts (Simpson's index D).

Cut	Plot			
	HWL	**HWL_Si**	**LWL**	**LWL_Si**
1st	0.4387	0.4792	0.3799	0.3250
2nd	0.2781	0.3236	0.3232	0.3419
3rd	0.2373	0.4038	0.3489	0.3074
Mean	0.3180	0.4022	0.3507	0.3248

Biodiversity analysis using the Shannon–Wiener Index (H′) and Simpson's Index (D) indicates a tendency to increase biodiversity in conditions of increased soil moisture in combination with the silicon used.

In this paper, research was also carried out to determine the total species frequency of occurrences (repetitions) of identified species using the iNEXT online tool (iNterpolation and EXTrapolation) [45]. The results of species frequency for individual research plots are presented in Figure 4. In this chart, two groups of plots are visible: the first includes LWL and LWL_Si, and the second includes HWL and HWL_Si. It can therefore be concluded that the species frequency on LWL and LWL_Si was comparable. A similar situation occurred concerning HWL and HWL_Si. It is worth noting that the groundwater level was a factor shaping the division of the combination into two groups. This confirms the analysis using the Shannon–Wiener index (H′) and Simpson's index (D). A higher frequency of occurrences of identified species of about 14 was noted on LWL and LWL_Si plots. On the other hand, for HWL and HWL_Si, it was lower and reached about 11. However, it should be remembered that overlapping confidence intervals indicate no evidence of significant differences in species frequency between plots. Thus, only a tendency toward forming two groups within the study plots can be observed.

Analyses made using the iNEXT tool indicate that the groundwater level, which translates into soil moisture conditions, is of great importance on the occurrence of specific species and their frequency, because the division into two designated groups is clearly based on the moisture parameter.

To assess the similarity of the studied plots with the grass sward, the Sørensen's similarity index was also calculated, which is often used in ecological studies, including in relation to meadow habitats [62–65]. The values of the Sørensen coefficient for meadows may vary depending on the region and habitat characteristics. The values of this coefficient range from 0 to 1, where 1 means full similarity, and 0 means no similarity.

In the case of the analyzed plots, their differentiation can be noticed. The results confirm the analyses using the Shannon–Wiener index H′ and Simpson's index D indices. It can be seen that the values of the Sørensen coefficient depend on many factors, such as the diversity of plant species, topography and weather, and climatic and soil conditions. In addition, these values are influenced by factors such as irrigation, the degree of fertilization, or the preparations used that affect the growth and development of plants. On average, in three cuts, the plots HWL_Si:HWL, HWL_Si:LWL, and HWL_Si:LWL_Si showed the greatest similarities. This was especially true for the first and third cuts. Nevertheless, differences in similarities between plots depending on the cut are visible (Tables 10–12).

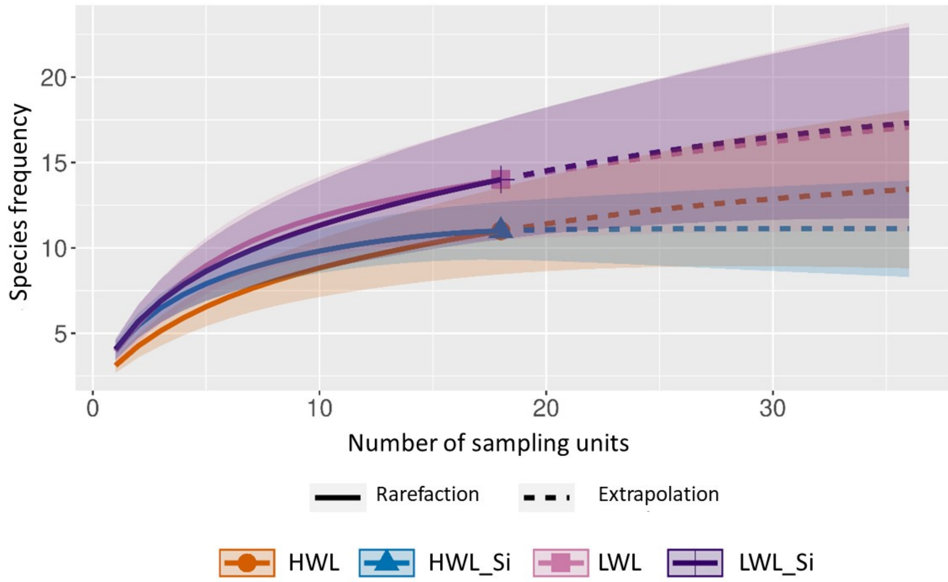

Figure 4. Chao's frequency of identified species occurrence curves for each of the four measurement combinations. Solid lines are rarefaction curves based on sample size, and dashed lines are extrapolation sampling curve. The solid symbols (dots/triangles/squares/dashes) mark the reference samples. The shaded area represents 95% confidence intervals obtained using the bootstrap method on the basis of 100 repetitions.

Table 10. Comparison results in individual plots in the first cut—Sørenson's similarity index.

Plot	HWL	HWL_Si	LWL	LWL_Si
HWL		0.92	0.82	0.86
HWL_Si	0.92		0.92	0.91
LWL	0.82	0.92		0.88
LWL_Si	0.86	0.91	0.88	

Note: Intensity gradient of the feature from the light color denoting the greatest difference to the dark color denoting the smallest difference between the combinations.

Table 11. Comparison results in individual plots in the second cut—Sørenson's similarity index.

Plot	HWL	HWL_Si	LWL	LWL_Si
HWL		0.90	0.86	0.89
HWL_Si	0.90		0.90	0.85
LWL	0.86	0.90		0.95
LWL_Si	0.89	0.85	0.95	

Note: Intensity gradient of the feature from the light color denoting the greatest difference to the dark color denoting the smallest difference between the combinations.

Table 12. Comparison results in individual plots in the third cut—Sørenson's similarity index.

Plot	HWL	HWL_Si	LWL	LWL_Si
HWL		0.96	0.86	0.87
HWL_Si	0.96		0.94	0.97
LWL	0.86	0.94		0.93
LWL_Si	0.87	0.97	0.93	

Note: Intensity gradient of the feature from the light color denoting the greatest difference to the dark color denoting the smallest difference between the combinations.

To sum up, the analyses of the Sørensen coefficient value, as well as the analyses made with the use of iNterpolation and EXTrapolation, indicate that the groundwater level is more important for shaping the diversity indices than fertilization with silicon at the dose adopted in this study.

3.4. Plant Parameters

The final average plant heights obtained for each plot on the cut days is shown in Table 13. In the first cut, the highest value was obtained in the plot with a lower water level (LWL) of 59.9 cm. The lower values on the HWL were most likely contributed by too high a groundwater level and too much soil moisture, which caused plant inhibition. Scientists state that excess water can contribute to a reduction in oxygen content in the soil and thus limit plant growth [66,67]. It should be noted, however, that in the silicon plot with lower groundwater (LWL_Si), the average plant height was lower than at LWL, at 55.5 cm. A similar relationship occurred on the site with a higher water level where a value of (HWL) 54.6 cm was obtained, and the one with silicon (HWL_Si) was 49.5 cm. Thus, it can be seen that in the first cut, the Si application contributed to a decrease in plant height. This trend also occurs in the next cut, but only in the site with a lower groundwater level, where the plot with the antitranspirant (LWL_Si) achieved an average of 4.5 cm lower grass height than LWL (45.1 cm). HWL_Si recorded vegetation 0.5 cm higher than on HWL. During the third cut, the average height was also greater on HWL_Si (36.3 cm) than on HWL (35.4 cm). Thus, the opposite trend from that during the first cut is noticeable. On the other hand, the exact value of 33.9 cm was recorded within the site with lower water levels for both plots (LWL and LWL_Si). Thus, it was concluded that, based on the results obtained, the relationship between plant height and application of the silicon product could not be determined. This is also confirmed by the statistical analyses performed in Statistica (version 13). The obtained measurement results were subjected to a two-way ANOVA analysis of variance to evaluate the effect of a higher water level and silicon application on plant height. The analysis showed that the main factors tested had no significant effect (at $\alpha = 0.05$) on the results obtained, and the interaction between them was not statistically significant. Therefore, it can be concluded that neither silicon application nor a higher water level significantly affected plant heights during the growing season.

Table 13. Average plant heights on the day of each cut (cm).

Plots	1st Cut	2nd Cut	3rd Cut
	31 May 2021	14 July 2021	30 September 2021
high groundwater level (HWL)	54.6	44.5	35.4
high groundwater level + silicon (HWL_Si)	49.5	45.0	36.3
lower groundwater level (LWL)	59.9	45.1	33.9
lower groundwater level + silicon (LWL _Si)	55.5	40.6	33.9

However, when analyzing the final results for individual cuts of the meadow, a noticeable trend shows that the highest average plant height was achieved during the first cut, and the lowest was reached during the third cut for each plot studied. Regardless of the groundwater level and whether it was a plot with or without silicon, the highest result within each combination was recorded during the first period of plant growth, and the lowest was recorded during the last cut.

For further analysis of plant heights for individual plots, heat maps were made in R Studio, considering all measurements taken during the growing season. The measured plant heights were normalized, resulting in a uniform scale from 0 to 1. On the dendrogram (Figure 5), it is noticeable that the most similar plots regarding plant height are HWL and HWL_Si. The second pair with close results is LWL and LWL_Si, although these are less similar to each other than the previous pair. These results are in line with those obtained concerning biodiversity (Figure 4), when it was also noted that the plots form two distinct groups, depending on the groundwater level (higher/lower). It can also be inferred from Figure 5 that high plant height values were common in the HWL_Si and LWL plots. However, if we look at the dates of the measurements, it can be seen that high values for LWL were recorded only in May, June, and early July, that is, during the first and early second growth of the meadow. It is worth noting that during the first growth of the plants, the water table was relatively shallow below ground level (Figure 2) compared to the rest of the growing season. This is why the LWL plot achieved such high heights. At the same time, the lowest values were recorded on HWL_Si among all the plots. This is most likely because the groundwater table and soil moisture were too high, and there was a reduction in the oxygen content of the soil, which hindered the development of vegetation [66,67]. Simultaneously, silicon contributed to a decrease in plant height at this time. It should also be noted that the values obtained depend on the plant species present within the plot and their growth rates during the growing season. In the later part of the growing season (July, August, September), a decrease in the groundwater level was observed, and thus higher values of plant heights were obtained in the HWL plot, where water was maintained throughout the season thanks to a closed valve on the ditch. The LWL_Si plot had lower plant height values, as shown by the dark colors on the heat map.

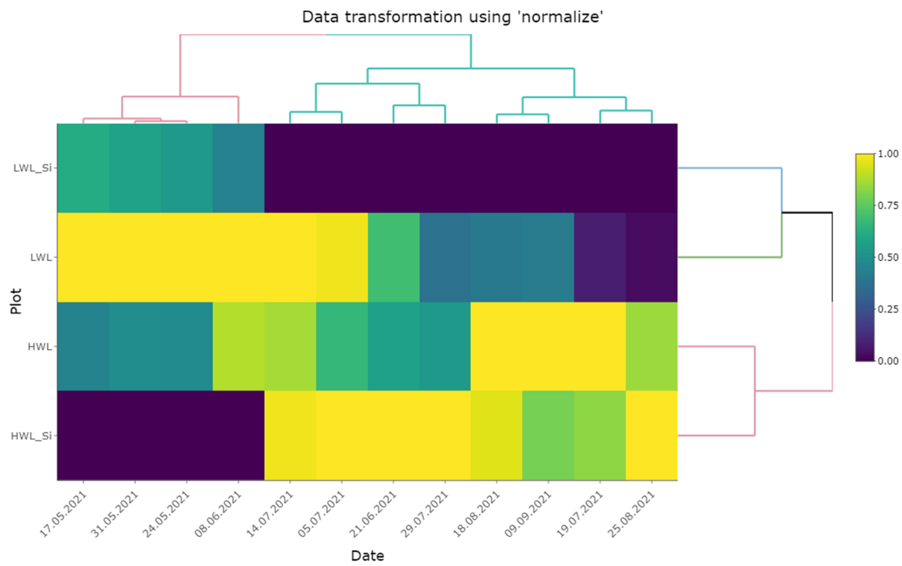

Figure 5. Heat map of the obtained normalized plant heights from individual plots.

The NDVI values obtained from field measurements for individual plots were also analyzed. Again, the results were normalized and presented as a heat map (Figure 6). Considering these values, it is noticeable that the most similar plots regarding NDVI values are HWL and HWL_Si. The second similar pair is LWL and LWL_Si; however, as in the case of plant height, they are less similar to each other than the pair HWL with HWL_Si. These results coincide with the plant heights and the results obtained in the biodiversity analyses (Figure 4), where the formation of two distinct groups was observed within the plots studied. In the case of NDVI values, it can be seen that the highest results were achieved in the HWL plot, where the yellow color on the heat map dominates (Figure 6). Only during the measurement on 19 July 2021 were low values recorded. However, it should be noted that this measurement was made only five days after the sward was cut, hence the NDVI results were lower than on other dates. Looking at the normalized heat map comprehensively, the predominance of darker colors on the LWL and LWL_Si plots can also be seen. Thus, in most cases, the NDVI results obtained on these plots were lower than those on higher groundwater-level plots. This indicates a trend that the groundwater level can positively affect NDVI values. This is consistent with an earlier study by Marín [68], which showed that NDVI values are higher with full turfgrass irrigation than with deficit irrigation. However, it is worth noting that the tendency seen in the heat map was not statistically significant. A two-way ANOVA analysis conducted in Statistica software to highlight the effect of higher groundwater levels and silicon application on the NDVI index did not show a significant effect of the main factors or their interaction on NDVI values at $\alpha = 0.05$.

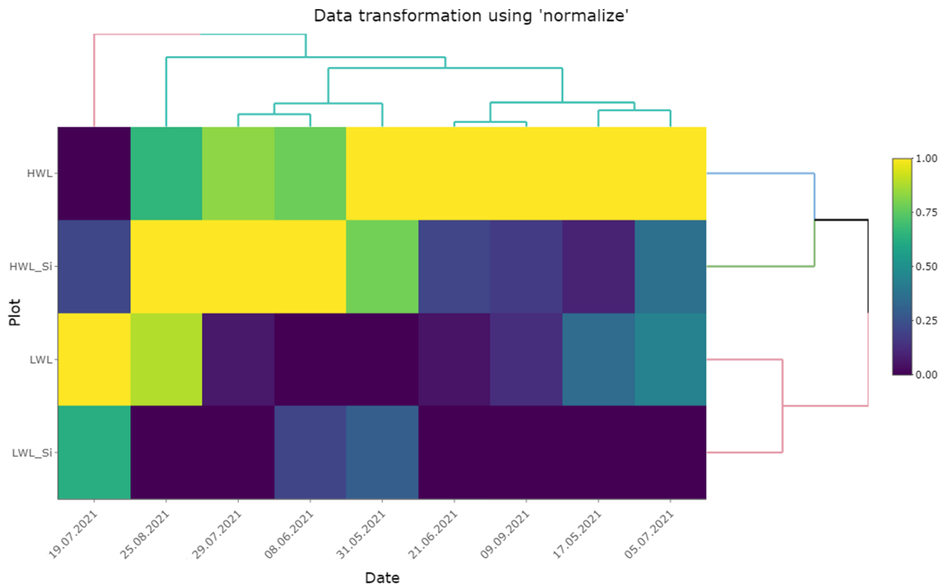

Figure 6. Heat map of the obtained normalized NDVI values from individual plots.

In summary, the studies on plant height and NDVI index showed no significant effect of silicon application and higher groundwater levels in this meadow.

3.5. Yield

Due to the nature of the study area, yield evaluation was carried out three times during the growing season. Therefore, the meadow was cut on 31 May 2021, 14 July 2021, and 30 September 2021. The dry matter results based on which the yield of the meadow was evaluated for each of the four tested plots (HWL, HWL_Si, LWL, LWL_Si) are shown in Figure 7.

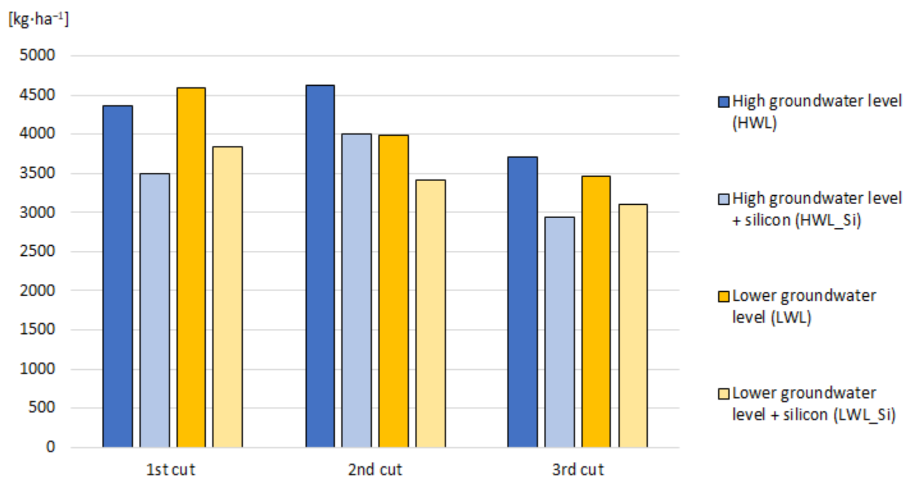

Figure 7. The amount of dry matter obtained in each cut of the meadow [kg·ha^{-1}].

Looking at the dry matter values obtained from each cut, it is possible to see a tendency that the area where silicon was applied received lower yields than the sward area without its application. This relationship is evident in each of the cuts. For example, in the first cutting, the dry matter value achieved from the HWL plot was 4365.39 kg·ha^{-1}, whereas that from HWL_Si was 3489.42 kg·ha^{-1}. The plot fertilized with silicon yielded 20% less (875.97 kg·ha^{-1}). Analyzing the results for the site with lower groundwater levels, a similar relationship can be observed. The dry weight for the LWL plot was 4587.14 kg·ha^{-1}, whereas for LWL_Si, it was 3842.25 kg·ha^{-1} (16% lower yield). The same trend was noted for the second cut; the difference between HWL and HWL_Si was 621.69 kg·ha^{-1}, and between LWL and LWL_Si, it was 582.21 kg·ha^{-1}. In contrast, the dry matter value obtained from the HWL plot in the third September cut was 3706.08 kg·ha^{-1}, and from the HWL_Si plot, it was 2939.83 kg·ha^{-1}. In the site with a lower groundwater level, silicon also decreased dry matter from 3467.47 kg·ha^{-1} (LWL) to 3111.19 kg·ha^{-1} (LWL_Si). Thus, it can be concluded that regardless of the mowing season (first, second, third cut) silicon caused a reduction in yields. This trend is noticeable regardless of the groundwater level.

Analyzing dry matter values across all cuts shows that for each of the four plots, the lowest yields were obtained during the third last cut. This trend is consistent with the results of meadow yields in Poland, where the first cut, regardless of the region, was characterized by the highest values and the last cut by the lowest values [69]. The highest results in the first cut obtained in Racot were influenced by the favorable meteorological conditions in the first months of the growing season. At that time, there were no periods of precipitation deficits (Figure 1), which facilitated vegetation development. The higher dry matter values obtained in the first cut on the site with a lower water level (LWL) than the site with a higher water level (HWL) are most likely the result of too much water on the irrigated plot. During the first half of the first grass growth period, soil moisture values on the LWL were close to the value corresponding to the field water capacity (FWC) (Figure 3). In contrast, on the HWL site, the values were much higher than FWC throughout the first grass growth. The researchers note that at a moisture condition exceeding the PPW of the soil (pF is less than 2.0), there can be excess water and, consequently, insufficient oxygen necessary for proper plant development. It has also been found that soil air in the root zone should constitute 6–8% of the soil volume for meadow plants. Oxygen deficiency contributes to a decrease in the production of growth regulators in the roots and limits their development. There is also a disruption in the nutrient uptake by the roots [67]. Moreover, oxygen deficiency in the soil can cause plants to stunt development and growth, causing yellowing, wilting, and even dying [66]. Szajda [70] notes that the high moisture content of the root layer corresponding to the field water capacity minus 6% of the volume contributes to reduced grass yield and excess water consumption for evapotranspiration [70,71].

During the second grass regrowth (1–15 June), there were precipitation deficits, and conditions in these two months were classified as dry and quite dry. This had the effect of reducing yields compared to the first cut on LWL. The problem of precipitation deficits during the second growth of vegetation in three-cut meadows in Poland, which can limit their productivity, was noted earlier in a study by Dembek et al. [72]. During this growth, it can also be noted that moisture conditions were more favorable in the site with higher water levels, resulting in higher dry matter compared to the LWL site. Despite the relatively unfavorable meteorological conditions, the damming of water in the ditch contributed to an increase in the groundwater level, and the beneficial effect of subirrigation on yield was evident during this period. The results obtained in this cut align with the research of Jurczuk [6], who found that meadow yield increases under the influence of subirrigation are more correlated with soil water conditions than meteorological conditions. Moreover, he notes that the positive effect of subirrigation on yields is particularly pronounced in dry and very dry years.

Analyzing the values obtained in the third cut, it can be seen that, regardless of the combination, they were the lowest of all three cuts in the growing season. These results are consistent with previously published results, which clearly show that the lowest yields characterize the third cut. During the third period of sward growth, the groundwater table was deep below the subsurface, reaching the lowest value over the entire season of 1.09 mbgl for LWL and 0.92 mbgl for HWL (Figure 2). The pluvio-thermal conditions in the meadow's third growth were also unfavorable. In the initial phase of growth (July), they were classified as quite dry, and in September, they were classified as very dry (Table 3). At the same time, September was a month with high precipitation deficits (Figure 1). Low groundwater levels and unfavorable pluvio-thermal conditions contributed to low grass growth and low yields during the third period of sward growth.

Looking at the total yields obtained from the entire year, it can be seen that the highest value was obtained from the high groundwater level (HWL) plot and amounted to 12.69 Mg·ha^{-1}. (Figure 8). From the high groundwater level + silicon (HWL_Si) plot, the annual dry matter volume was 10.43 Mg·ha^{-1}. Comparing these two plots, it can be noted that the Si application caused a 17.8% decrease in yield. Concerning the site with lower groundwater levels, silicon application resulted in a 14% reduction in dry matter (from 12.05 to 10.36 Mg·ha^{-1}). Considering only the groundwater level on an annual basis, the higher water level (HWL) contributed to higher yields on both plots without and with Si application. This is because the dry matter with HWL was 0.64 Mg·ha^{-1} higher than LWL. A similar trend was also noted in an earlier study by Jurczuk [6,73], which showed that it is possible to improve grassland yields due to subirrigation.

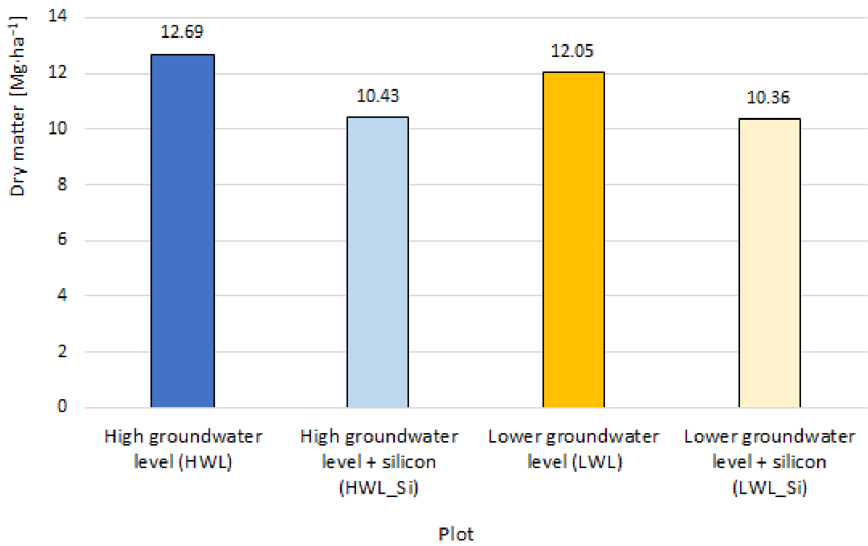

Figure 8. Total dry matter yield over the entire growing season for individual plots [Mg·ha^{-1}].

The positive effect of water management based on controlling water supply using renewed irrigation facilities in a system of subirrigation on the yield from grasslands for the area was also observed by Napierała et al. [74]. However, their results of actual yield values estimated for the area in question using the model are much lower (3.7–7.9 Mg·ha^{-1}) than those obtained in the present study.

To identify significant differences between the yields of each plot in this study, the obtained data on the amount of dry matter from each cutting were subjected to statistical analysis. With the assumptions met (normality of distribution and homogeneity of variance), a two-way ANOVA was performed to analyze the effect of higher groundwater level and silicon application on dry matter. The analysis showed that the interaction between the studied factors was not significant. Therefore, a two-factor analysis was conducted for the main factors. Statistically significant differences (at the $\alpha = 0.05$ level) in dry weight were shown for silicon application (Table 14). These occurred in each of the three cuts studied. Thus, it can be concluded that silicon application contributed to a significant reduction in dry matter in each cut. Moreover, during the second cutting of the meadow, statistically significant differences in the dry matter were also observed concerning the higher groundwater level. In this case, it can be concluded that the higher water level significantly increased yields during the second cut.

Table 14. Two-way ANOVA results for dry matter.

Factor	Degrees of Freedom	First Cut		Second Cut		Third Cut	
		F	*p*-Value	F	*p*-Value	F	*p*-Value
Higher groundwater level	1	1.25	0.292	5.50	0.044 *	0.03	0.874
Silicon application	1	9.97	0.012 *	5.37	0.046 *	7.38	0.024 *

Note: * Statistically significant differences at the $p < 0.05$.

Radkowski et al. [75] also conducted research on silicon application's effect on the meadow. Species such as *Lolium perenne*, *Festuca pratensis*, *Dactylis glomerata*, *Poa pratensis*, *Festuca rubra*, *Phleum pratense*, *Trifolium pratense* L., *Taraxacum officinale coll.*, as well as *Achillea millefolium* L. dominated the area of their experiment. Radkowski et al. [75] found no statistically significant effect of foliar silicon application on dry matter yield. However, when we look at their results, a trend is noticeable in that Si caused a decrease in dry matter values. In the control plot, they obtained a value of 5.96 Mg·ha^{-1}, whereas when silicon fertilizer Optysil was applied at a rate of 0.5 dm^3·ha^{-1}, the dry matter yield was 5.26 Mg·ha^{-1}, and at a rate of 0.8 dm^3·ha^{-1}, it was 5.66 Mg·ha^{-1}. Thus, a reduction in dry matter yield can be seen, which was also noted in this study. However, Mastalerczuk et al. [76] obtained different results in their study showing the positive effect of foliar application of fertilizers with silicon on the yield of the grass–clover sward. However, it should be noted that in the study in question, different fertilizers were used than in the present study. In addition, different doses were used, amounting to 4 kg·ha^{-1} for Herbagreen fertilizer and 1 l·ha^{-1} for Optysil, respectively. Moreover, during each grass sward growth, the fertilizers were applied twice (4 and 2 weeks before each harvesting), whereas in the present experiment in this paper, they were applied once for each grass sward growth. Differences in the results obtained may also be due to the presence of other species. The study by Mastalerczuk et al. [76] was conducted on a prepared grass–clover mixture with the following composition: *Lolium perenne* L., cv. Solen, *Trifolium pratense* L., cv. Nike and *Trifolium repens* L., cv. Grasslands Huia. The different results may also be due to the different abilities of meadow plants to accumulate silicon. However, in previous studies on the grain yield of *Phleum pratense* L., a positive effect of foliar application of fertilizer with silicon (Optysil) was noted, significantly increasing this parameter. It was also reported that the obtained grains were larger and showed a higher germination capacity than the control seeds [77]. Studies were also conducted on two grass–legume mixtures, consisting of *Dactylis glomerata*, *Festulolium braunii*, and *Trifolium pratense* or *Medicago x varia*, and a grass mixture—*Dactylis glomerata*, *Festulolium braunii*, and *Lolium perenne*—including the effect of silicon (Herbagreen fertilizers, Optysil) on botanical composition and nutritional value. They showed that botanical composition changed during the measurements, but mainly due to weather conditions and plant competitiveness. The effect of silicon application on botanical composition was slight [78]. Moreover, other studies have shown no clear effect of foliar application of these fertilizers on the botanical composition of grass–clover swards containing *Lolium perenne* L., cv. Solen, *Trifolium pratense* L., cv. Nike, *Trifolium repens* L., and cv. Grasslands Huia [76]. On the other hand, the results obtained by Radkowski et al. [75] show that the foliar application of Optisil influenced the botanical composition of pasture flora and thus improved the nutritive value of ensiled feed.

Borawska-Jarmułowicz et al. [78] state that previous measurements of silicon fertilization of grass–legume mixture swards do not provide conclusive results. The present study partially confirms this conclusion, as no unequivocal effect of silicon application was observed on the meadow's plant height and NDVI value. Statistically significant differences were noted only in the case of yield, in which there was a significant decrease in the amount of dry matter obtained after Si application. However, it should be noted that these results refer to a selected silicon-containing product (*Krzemian*) and one specific dose (0.8 l·ha^{-1} in each cut), and the work published to date does not indicate a clear trend on this issue. Therefore, it is recommended that further research be continued to obtain broader results for applying different doses and other silicon-enriched products. Tripathi et al. [10], in their review of silicon, state that very limited information is currently known to determine the optimal amounts of Si needed for better plant growth at particular developmental stages. This topic should also be expanded on in future studies. The author also notes that there is still too little current knowledge to fully understand the role of Si in plant biology. The researchers also state that to date, few studies have been conducted on the effect of silicon fertilization on the nutritive value of individual grass and legume species and the quality of the sward of mixtures applied to grasslands [78]. The effect of silicon on the quality and nutritive value of grasses is a good direction for measurements in the future, which will enable a better understanding of the interaction of silicon application with plant response. Increasing measurement data in this area and yield experiments will allow for a comprehensive evaluation of silicon's effect on grasslands. The present study is a step towards expanding the knowledge of the impact of Si application in three-cut meadows and its effect on yield.

4. Conclusions

This study demonstrates that the application of silicon significantly reduced the dry matter obtained in individual cuts from a three-cut meadow. Over the whole year, it contributed to a yield reduction of 17.8% in the plot with higher groundwater levels and 14% in the plot with lower groundwater levels. Furthermore, in the case of plant height and the NDVI index, no conclusive results were recorded to construct firm conclusions regarding the effect of foliar silicon application on these parameters. However, it should be remembered that these results apply to the selected silicon product and a single applied dose. This experiment also noted a trend that subirrigation could have a positive effect on yield. However, it seems that maintaining damming at a constant level in the ditch is not the best solution for irrigating grasslands. Instead, damming should be regulated to manage grassland more efficiently to keep water tables at the appropriate level under meteorological conditions. This will ensure optimum soil moisture for the plants for their proper development and abundant yields.

The analyses concerning biodiversity show that the addition of silicon in the dose used in this work, along with simultaneously increased soil moisture, which resulted from a higher level of groundwater and more favorable moisture parameters in the soil in spring, could contribute to an increase in the number of species and biodiversity. A greater number of species in the meadow, including dicotyledonous plants, may contribute to the palatability of the sward and, simultaneously, its consumption by animals. This may translate directly into an increase in production effects. Detailed research shows that water has a decisive influence on the increase in biodiversity. Silicon is less important to biodiversity, although it improves phytosociological indicators at the dose used in the experiment. This shows that changes in moisture conditions in the context of climate change, including temperature increases or transpiration, can significantly reduce the diversity in grasslands and limit silicon fertilization's effectiveness in meadows and pastures.

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