

Article

Evaluation of the Durability and Viability of Selected Forage Grass Species on Degraded Soil Under Silicon Application

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Abstract

Soil degradation is largely caused by human activity, and its severity can be exacerbated by unfavourable weather conditions. Selected species form a durable, compact cover that improves soil physical properties and limits degradation. The study included four single-species sowings of forage grasses: *Dactylis glomerata*, *Festuca arundinacea*, *Festulolium braunii*, and *Lolium perenne*. A plant growth enhancer containing silicon nanoparticles was foliar-applied at two levels: no Si and Si. Soil water properties, plant cover, chlorophyll content, leaf area index (LAI), light transmittance (T), aboveground biomass, and weed infestation were measured to evaluate plant viability and durability from 2018 to 2023. The research showed that after six years of utilization by mowing, *D. glomerata* and *F. arundinacea*, due to the greater durability of the plant cover and a stable share in the sward, were better suited to cultivation on degraded soil than *F. braunii* and *L. perenne*. Silicon increased grass species yield, plant–soil cover, chlorophyll content, and LAI while it reduced T. The Si application had the strongest effect on the monocultures of *F. arundinacea* and *D. glomerata*, particularly for DM (increased by 17.5 and 19.1%, respectively) and LAI (increased by 24.4 and 19.8%, respectively). Given the benefits of using silicon in plant fertilisation, further research is recommended, particularly on grass species used to revitalise heavily transformed and degraded soils.

Keywords: *Dactylis glomerata*; *Festuca arundinacea*; *Festulolium braunii*; *Lolium perenne*; monoculture; persistence; silicon nanoparticles



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1. Introduction

Degraded soils (including acidified, dried-out, low in organic matter, with disturbed water relations, and post-extraction soils) create particularly difficult conditions for maintaining the sustainability of grassland management. Under such conditions, biological traits of grass species, such as root depth, tolerance to drought and acidification, tolerance to periodic flooding, and the ability to regenerate after environmental stresses, are of significant importance. One of the most important factors determining the efficiency of grassland management is the ability of grass species to maintain adequate ground cover, productivity, and utility value over many years without the need for restoration. Due to rising production costs, the need to limit expenses, and the intensifying effects of climate change, the durability of meadow and pasture use is becoming increasingly important [1].

Research conducted in recent years indicates that the durability of grasses is a trait dependent on the interaction between the plant's genotype and environmental conditions. Among environmental factors, water availability is the most important for the longevity of grasses [2]. Grassland management practices like rational grazing and mowing, appropriate fertilisation, and the maintenance of high soil quality also have a significant impact [1,3]. One of the fundamental determinants of durability is the genetic potential of the species and variety. Different species of forage grasses vary in their ability to regenerate after defoliation, their tolerance to drought, low temperatures, and other stress factors, which influences their durability and suitability for use in various habitat conditions [4–7].

A significant amount of attention is directed towards *Lolium perenne* (L.), which is characterized by its high nutritional value; however, in numerous regions worldwide, it demonstrates limited resilience to unfavorable growing conditions, especially water shortage [8–10]. Its usefulness for the utilization of degraded soils results from its rapid surface cover, developed root system, and ability to provide phytostabilisation and phytoremediation of pollutants [11,12]. *Festulolium* constitutes a group of interspecific hybrids between the genera *Lolium* and *Festuca*. Modern cultivars of *x Festulolium* Asch. & Graebn. show significantly greater tolerance to drought and environmental stresses than *L. perenne*, while maintaining a high nutritional value [13]. On degraded soils, it can serve as a compromise between productivity and durability, surpassing *L. perenne* in terms of surface cover retention. *Festuca arundinacea* (Schreb.) is currently recognised as one of the most resilient cool-season grass species in terms of tolerance to environmental stresses. It has a deep root system and high tolerance to drought and periodic flooding, soil acidification, and moderate salinity [8,14]. In degraded areas and on marginal soils, the species maintains productivity better than most other forage grasses [15]. *Dactylis glomerata* (L.) is considered one of the most durable forage grass species under conditions of limited water availability [6]. It is characterized by a well-developed root system and the ability to regenerate rapidly after drought [14]. In studies of the durability of perennial grasses in drought-prone sites, it was classified as a species with high durability, often higher than *F. arundinacea* [7]. An additional argument supporting the use of *D. glomerata* on degraded soils is the observation of plant succession on post-mining areas. This species effectively colonised reclaimed post-extraction surfaces, which demonstrates its high adaptive capacity [16,17].

The longevity of grass species in swards is largely determined by the interdependence among the soil's chemical properties (particularly pH and nutrient availability), physical structure (aggregate stability and porosity), and water-holding capacity. High soil fertility and optimal physical properties promote root development and microbial activity, stabilising the botanical composition of the sward [18,19]. Agricultural practices such as sustainable fertilisation and moderate grazing or mowing are crucial for maintaining these soil factors and, consequently, for species durability. Conversely, improper use—especially excessive nitrogen fertilisation—can degrade soil structure and reduce species longevity [20].

In addition to the basic nutritional components of fertilisation, there has been increasing interest in recent years in elements that support plant growth and enhance tolerance to adverse environmental conditions. Silicon (Si), although not classified as an essential nutrient, has been shown to be a beneficial element that strengthens plant immunity by regulating physiological, biochemical, and agrotechnical processes [21]. Silicon acts at multiple levels—from regulating photosynthesis, through modifications to cell wall structure, to the molecular control of transporters and enzymes, which translates into improved absorption and utilization of nutrients by plants [22,23]. Recent studies emphasise silicon's ability to modulate growth, enhance stress tolerance, and optimise feed quality, making

it a promising element for improving the durability of forage grasses under changing environmental conditions [24–26].

2. Materials and Methods

2.1. Experimental Design and Management

The field experiment was conducted in central Europe at the crop plant collection of the Warsaw University of Life Sciences (52°09′40.0″ N 21°03′12.7″ E) from 2018 to 2023. The research was carried out on agriculturally managed soil classified as light soil in an urbanized area, surrounded by urban development. Before management began, the area was a weed-fallow field that was mown once a year, with the cut biomass left on the surface. The soil exhibited an alkaline pH ($\text{pH}_{\text{KCl}} = 7.4$). It was characterized by a relatively high total organic carbon (TOC) content of 14.61 g/kg and a carbon to nitrogen (C/N) ratio of 15.38. The nutrients available to plants, specifically phosphorus (P), potassium (K), and magnesium (Mg), were extracted using the Mehlich-3 method. The soil had a low level of available phosphorus (51.6 mg/kg), an average amount of potassium (135.3 mg/kg), and a very high magnesium content (111.5 mg/kg). The following NPK fertilization was applied: nitrogen 180 kg/ha (before each regrowth), potassium 99.6 kg/ha (in spring and after the first regrowth), phosphorus 35.2 kg/ha (in a single dose in spring). The soil had a relatively high bulk density (1.45 g/cm^3). Significant soil clumping and susceptibility to dusting were also observed. Aggregate fractions smaller than 0.25 mm and larger than 10 mm constituted a significant share of the soil structure, accounting for 20.0% and 18.1%, respectively.

The study included the following forage grass species in single-species sowings: *Dactylis glomerata* (L.) cv. Bepro, *Festuca arundinacea* (Schreb.) cv. Odys, *Festulolium braunii* (K. Richter) A. Camus (initial hybrid combination: *Festuca pratensis* x *Lolium multiflorum*) cv. Sulino, and *Lolium perenne* (L.) cv. Gagat. Grass seeds were obtained from Danko Hodowla Roślin Sp. z o.o. z/s in Choryń (cvs. Odys, Sulino, Gagat) as well as from Hodowla Roślin Grunwald Sp. z o.o. IHAR Group (cv. Berta). The grasses were sown in autumn 2017 in a pure stand, in rows spaced 10 cm apart, at a dose of 21 (*D. glomerata*), 36 (*F. arundinacea*), 40 (*F. braunii*), and 30 (*L. perenne*) kg/ha. The second factor in the experiment was foliar application of silicon (Si) in the form of the plant growth supplement NanoFYT Si (AGRA GROUP, a.s., Střelské Hoštice, Czech Republic). The preparation has a liquid consistency and contains silicon in the form of hydrated nanoparticles (20.0% [m/m] SiO_2) approximately 15 nm in size. Two levels of silicon application were used: no silicon fertilization (no Si) and silicon fertilization (Si) at 0.5 L/ha, diluted in 150 L/ha of water, applied twice, 14 days and 7 days before each mowing. A plant growth supplement containing Si was applied according to the manufacturer's recommendations.

The sward was mown two or three times during the growing season, depending on hydrothermal conditions. In 2018 and 2019, two cuts were made, whereas in the following years (2020, 2022, and 2023), three cuts were made.

2.2. Meteorological Conditions

Basic meteorological data were measured at the research site's meteorological station (Figure 1). The first two years (2018 and 2019) and the fifth year of research (2022) were relatively dry, with average precipitation totals lower than the multi-year average (535.3 mm for 2000–2023) by approximately 126, 151, and 96 mm, respectively. Conversely, the third and sixth years (2020 and 2023) were wetter, with precipitation sums exceeding the multi-year average by 60 and 39 mm, respectively. At the same time, the average annual air temperature in the analyzed years was higher than the multi-year average temperature (9.5°C) by approximately 0.5°C in 2022 and 1.6°C in 2019.

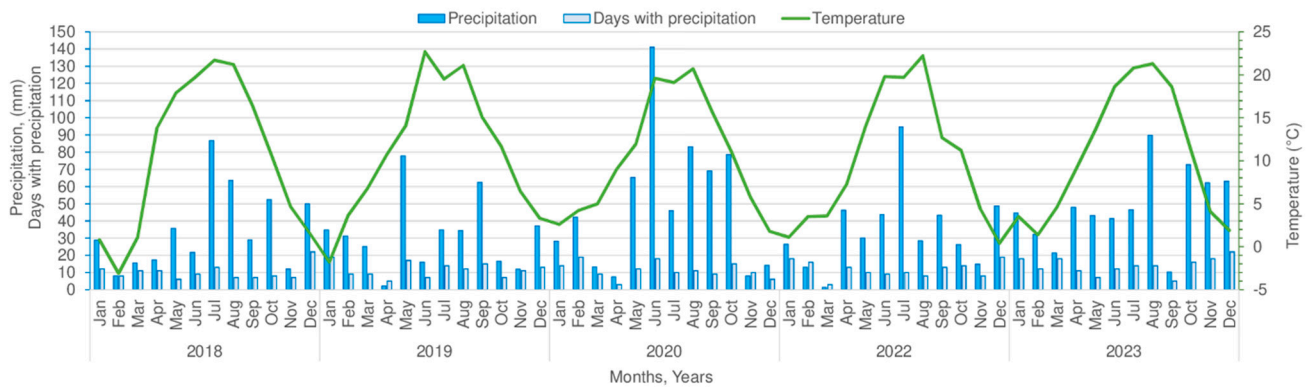


Figure 1. Sum of precipitation (mm), number of days with precipitation, and average air temperature (°C) during the study period in the years 2018–2023.

2.3. Soil Properties and Sward Parameters

To assess soil water conditions, soil samples that preserved their structure were collected from the middle layer (0–30 cm) of each single-species sowing and placed into 100 cm³ cylinders. The following soil properties were evaluated: bulk density (BD) using the Kopecký cylinder, capillary water capacity (CWC), as well as water capacities at pF = 2.4 (field capacity—FC) and pF = 4.2 (permanent wilting point—PWP) measured in pressure chambers (Moisture Retention Curve Systems, Soilmoisture Equipment Corp., Goleta, CA, USA) employing standardized reference methods [27]. The available water capacity (AWC) of the plants was calculated as the difference between the field capacity (pF = 2.4) and the permanent wilting point (pF = 4.2). All features were evaluated during the initial year (2018) and in the sixth year (2023) of utilization.

Degree of soil cover with plants (PC; %), aboveground air-dry plant biomass (DM; Mg/ha) and the share of sown and unsown species in the sward (%) were measured to evaluate the durability of the tested grass species. Annual yields were calculated from the sward DM in each monoculture, based on the following regrowths. The botanical-weight method was used to assess weed infestation, involving the collection of 500 g plant samples, followed by sorting, drying, and weighing individual sward components. The percentage of sown species and the percentage of weeds were determined, with a division into monocotyledonous and dicotyledonous plants. Species were also identified among weeds. The evaluation was carried out across all replicates and for each regrowth during the study years.

Plant viability was assessed by measuring relative chlorophyll content (SPAD units), determined using a SPAD-502 meter (SPAD readings) (Minolta Camera Co., Osaka, Japan). The AccuPAR LP-80 system (Meter Group, Inc., Pullman, WA, USA) was used to determine the leaf area index (LAI), defined as the ratio of the total leaf area to the soil area, and the light transmittance coefficient (T), the value of which is the ratio of PAR measurements taken below the plant canopy to PAR measurements taken above the plant canopy. Chlorophyll content and plant canopy architecture indices (LAI and T) were obtained twice in each regrowth: 7 days before and on the day of each mowing. Measurements (three per plot) were taken in the morning between 8.00 and 10.00 a.m., in accordance with the device manufacturer's standard protocol.

2.4. Statistical Analyses

The experiment was executed employing a randomized block design with three replicates. Experimental data were analyzed using multivariate analysis of variance by Statistica 14.3.0.6 1984–2025 © software (Statsoft, Inc., Tulsa, OK, USA). The Tukey HSD test was used to assess the significance of mean differences at the 0.05 level. The year

was included in the statistical model as a fixed factor, as the analysis was restricted to the six years covered by the experiment. Experimental plots within blocks were treated as the experimental units, with repeated observations collected from the same plots over consecutive years. Results are presented as means, and significant differences among them are indicated by different letters. The relationships among all tested parameters and the multivariate differences between them and the conditions of silicon application in grass monocultures were evaluated using principal component analysis (PCA). Pearson correlation coefficients (PCC) were calculated to measure the strength and direction of linear relationships among the tested parameters. Coefficients were considered statistically significant at $p \leq 0.05$.

3. Results

3.1. Soil Properties

The studies found that the analyzed soil properties changed over six years of use, depending on the grass species cultivated and the applied silicon (Si) treatment. In 2018, the soil had higher CWC, FC, and PWP values than in 2023 (Table 1). At the same time, applying Si increased the values of these features. Regardless of other factors, grass monocultures affected the soil's water properties. Sowings of *F. braunii* and *D. glomerata* positively affected CWC and FC, but also increased PWP. The soil under *F. arundinacea* cultivation was characterized by significantly lower FC and PWP values than those of the other crops.

Table 1. Mean values of soil properties and results of ANOVA (p -values) presenting main effects and the interactions for analyzed variables: year (A), species (B) and silicon application (C).

Factors		BD g/cm ³	CWC v/v, %	FC v/v, %	PWP v/v, %	AWC v/v, %
Year (A)	2018	1.450 ^a	37.11 ^b	20.91 ^b	12.49 ^b	8.21 ^a
	2023	1.453 ^a	31.50 ^a	19.56 ^a	11.04 ^a	8.19 ^a
Species (B)	<i>D. glomerata</i>	1.431 ^a	34.69 ^b	20.38 ^b	11.77 ^b	8.39 ^a
	<i>F. arundinacea</i>	1.443 ^{ab}	34.10 ^{ab}	19.19 ^a	10.40 ^a	8.42 ^a
	<i>F. braunii</i>	1.455 ^{ab}	34.88 ^b	20.30 ^b	12.47 ^b	7.66 ^a
	<i>L. perenne</i>	1.476 ^b	33.56 ^a	21.08 ^b	12.42 ^b	8.32 ^a
Si application (C)	No Si	1.445 ^a	33.90 ^a	19.97 ^a	11.39 ^a	8.21 ^a
	Si	1.458 ^a	34.71 ^b	20.51 ^b	12.14 ^b	8.19 ^a
		p -values				
A		0.778	0.000	0.000	0.000	0.939
B		0.033	0.007	0.000	0.000	0.051
C		0.236	0.005	0.025	0.003	0.909
A × B		0.047	0.078	0.065	0.634	0.000
A × C		0.020	0.000	0.023	0.053	0.003
B × C		0.000	0.076	0.528	0.138	0.173
A × B × C		0.026	0.000	0.102	0.096	0.049

Abbreviations: BD—bulk density, CWC—capillary water capacity, FC—field capacity, PWP—permanent wilting point, AWC—available water capacity; Different letters denote statistically significant differences according to analysis of variance and Tukey's procedure ($p < 0.05$).

3.2. The Share of Sown and Unsown Species

The species composition of the forage grass monoculture sown in 2017 changed over the six-year research period (Figure 2). In the first two years of use (2018, 2019), the sward was dominated by the sown species. In 2018, the highest weed infestation in *F. arundinacea* monocultures occurred at the first regrowth (respectively: No Si and Si—14 and 18%). For the other monocultures, regardless of Si use, the share of weeds (Monocotyledonous and Dicotyledonous together) in the sward did not exceed 6%.

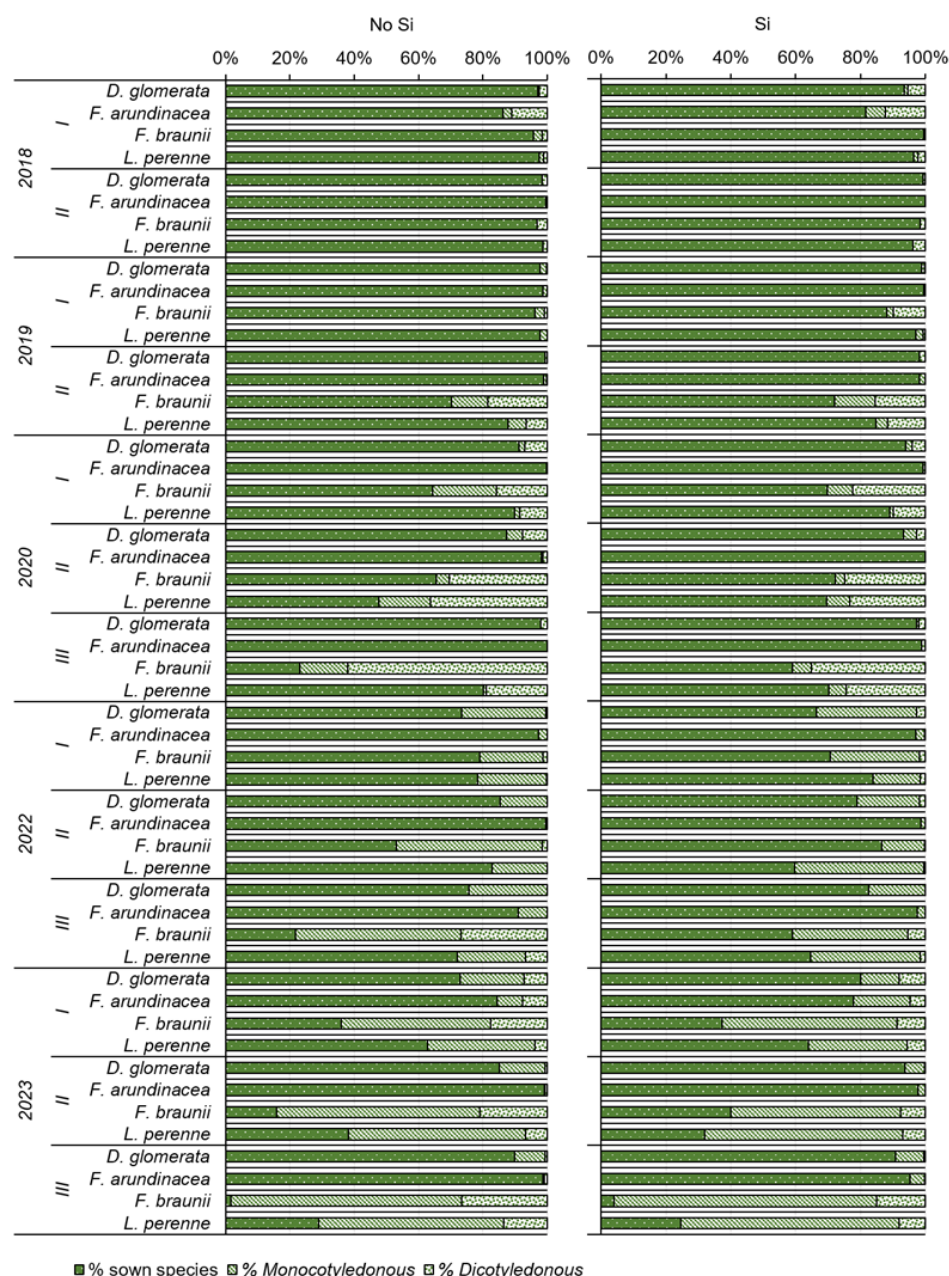


Figure 2. The proportion of sown species (*D. glomerata*, *F. arundinacea*, *F. braunii*, *L. perenne*) and weeds (Monocotyledonous and Dicotyledonous) in each regrowth (I, II, III) throughout the duration of the study period (2018–2023).

In the second year of utilization (2019), the largest share of other species was characterized by sowings of *F. braunii* in the second regrowth (approximately 30%). Monocultures of *D. glomerata* and *F. arundinacea* in both regrowths were distinguished by the presence of sown species at nearly 100%. However, the presence of other species in *L. perenne* sowings was visible only in the second regrowth, at about 12–14%.

In the following year (2020), the smallest proportion of weeds in each regrowth was recorded in *F. arundinacea* monocultures (approximately 1%). Slight weed infestation during this period was also characteristic of *D. glomerata* sowings. In *L. perenne*, the proportion of other species was noticeably lower in the first regrowth (about 11%) and higher in the second, especially under conditions without Si application (52%). Meanwhile, sowings of *F. braunii* in the third year of use (2020) were characterized by similar weed infestation

levels (around 30–35%) in the first and second regrowth and significantly higher in the third regrowth, particularly in the absence of Si (77%).

Monocultures of *F. arundinacea* in each regrowth in the fifth year of utilization (2022) were characterized by a very high proportion of sown species. In the case of *D. glomerata*, greater weed infestation persisted in the first regrowth (respectively: no Si and Si—27 and 33%) and was lower in the following two regrowths. Monocultures of *L. perenne* were characterized by a higher proportion of weeds under conditions of Si application, especially in the second and third regrowth (40% and 35%, respectively). The proportion of weed infestation in *F. braunii* monocultures in the fifth year of use increased significantly with each subsequent regrowth, especially in the absence of Si application (from 21% to 78%).

In the sixth year (2023) of utilization, the sowings of *F. arundinacea* and *D. glomerata* were characterized by a significantly higher proportion of sown species than in *L. perenne* and *F. braunii*. In *L. perenne* monocultures, the weed proportion increased both in the absence of Si (to 71%) and with Si application (to 75%). The monoculture with the smallest proportion of sown species was *F. braunii*. The share of this species decreased without Si to just 2%, whereas with Si application to 4%.

In the first three years of utilization, among the weeds in the sown areas, Monocotyledonous plant species dominated, mainly *Elymus repens*, *Poa annua*, and *Festuca rubra* (Figure 2). In subsequent years (2022–2023), the proportion of Dicotyledonous species also increased (*Erigeron annuus*, *Cirsium arvense*, *Taraxacum officinale*, *Plantago lanceolata*, *Stellaria media*). In monocultures of *F. braunii* and *L. perenne*, in the fifth and sixth years of use, *D. glomerata* appeared, and its share, especially in the third regrowth, ranged from 20% in 2022 to 40% in 2023.

3.3. Sward Parameters

Research has shown variability in the values of the analyzed traits over successive years of use. Regardless of other factors, the highest level of soil cover with plants (PC) was observed in 2020 (Table 2). In the other years, PC values did not differ significantly. The high PC values in 2020 resulted from good plant cover on soils in the sown *D. glomerata* and *F. arundinacea*, particularly on plots fertilised with Si (70.1% and 75.9%, respectively) (Figure 3). Monocultures of *D. glomerata* were characterized by a high degree of PC in the first two years of the study (2018 and 2019), whereas *F. arundinacea* was in subsequent years (2020–2023). It was also shown that the application of Si significantly increased PC values (by 4.9%) (Table 2). At the same time, sowings of *F. braunii*, on which Si was not applied, throughout the entire study period exhibited the lowest PC values compared to the other species (Figure 3).

The average DM values, regardless of other factors, were the highest in the fifth and sixth year of sward utilization (2022, 2023), while the lowest were in 2019 (Table 2). Sowings of *F. arundinacea* stood out with the highest DM, whereas *L. perenne* had the lowest value of this trait. The annual yields of all monocultures in the second year of use (2019) were limited by low rainfall, which totalled only 384 mm (Figures 1 and 4). Conversely, high yields in 2022 and 2023 were mainly observed in monocultures of *F. arundinacea* and *D. glomerata*. A significant increase in annual yields under Si application was also demonstrated, particularly for *D. glomerata*, *F. braunii*, and *L. perenne*. The increase in yields due to Si application was evident in the first and last years of the study across all mentioned monocultures, as well as in the second year for *D. glomerata*, and in the third year for *F. braunii*. In the case of *F. arundinacea*, the difference between variants without Si and with Si was not significant (Figure 4).

The plants of individual grass species distinguished themselves by the highest relative chlorophyll content (SPAD values) in the last (2023) and first (2018) year of use (Table 2). Regardless of other factors, sowings of *D. glomerata* and *F. arundinacea* were characterized

by significantly higher values of this parameter compared to the other species. Moreover, the Si application increased the chlorophyll content (by 4.9%) significantly. It was evident, especially in the last two years (2022 and 2023). A significant increase in SPAD values was noticed under Si application across all evaluated species, with the highest values of this trait recorded in *D. glomerata* and *L. perenne* plants (Figure 3).

Table 2. Mean values of grass features (PC—soil cover with plants (%), dry mass in regrowth—DM Mg/ha), chlorophyll content—SPAD units, light transmittance coefficient—T, leaf area index—LAI) and results of ANOVA (*p*-values) presenting main effects and the interactions for analyzed variables: year (A), species (B), silicon application (C) and regrowth (D).

Factors		PC	DM	SPAD	T	LAI
Year (A)	2018	58.4 ^a	1.75 ^b	34.6 ^c	0.26 ^b	2.00 ^d
	2019	57.7 ^a	1.47 ^a	32.5 ^{ab}	0.42 ^d	1.13 ^a
	2020	62.3 ^b	1.67 ^b	33.1 ^b	0.33 ^c	1.61 ^b
	2022	58.1 ^a	2.12 ^c	32.3 ^a	0.34 ^c	1.86 ^c
	2023	57.0 ^a	2.16 ^c	35.9 ^d	0.21 ^a	2.46 ^e
Species (B)	<i>D. glomerata</i>	64.1 ^d	1.95 ^c	35.1 ^c	0.23 ^a	2.23 ^d
	<i>F. arundinacea</i>	62.2 ^c	2.24 ^d	33.9 ^b	0.26 ^b	2.02 ^c
	<i>F. braunii</i>	50.7 ^a	1.72 ^b	33.0 ^a	0.35 ^c	1.66 ^b
	<i>L. perenne</i>	58.3 ^b	1.56 ^a	32.7 ^a	0.40 ^d	1.49 ^a
Si application (C)	No Si	57.4 ^a	1.69 ^a	32.9 ^a	0.36 ^b	1.53 ^a
	Si	60.2 ^b	2.04 ^b	34.5 ^b	0.25 ^a	2.17 ^b
Regrowth (D)	I	61.0 ^c	2.51 ^c	33.1 ^a	0.28 ^a	2.14 ^c
	II	56.3 ^a	1.82 ^b	34.5 ^a	0.32 ^b	1.75 ^b
	III	58.0 ^b	1.25 ^a	33.8 ^a	0.33 ^b	1.62 ^a
		<i>p</i> -values				
A		0.000	0.000	0.000	0.000	0.000
B		0.000	0.000	0.000	0.000	0.000
C		0.000	0.000	0.004	0.000	0.000
D		0.000	0.000	0.052	0.001	0.000
A × B		0.000	0.096	0.029	0.057	0.033
A × C		0.562	0.613	0.149	0.179	0.149
B × C		0.215	0.739	0.978	0.882	0.492
A × B × C		0.424	0.996	0.933	0.983	0.995

Different letters denote statistically significant differences according to analysis of variance and Tukey's procedure (*p* < 0.05).

The light transmittance coefficient (T) was the highest in the second, third, and final year of the study (Table 2). Regardless of other factors, the highest values of T were observed in monocultures of *L. perenne* and *F. braunii* (respectively, 0.40 and 0.35), while lower values were found in sowings of *F. arundinacea* and *D. glomerata* (respectively, 0.26 and 0.23). It was also shown that, under conditions without Si, the sowings exhibited values higher by 44% than those with Si. This relationship was confirmed for all species in each year of the study (Figure 3).

Monocultures of grasses differed in leaf area index (LAI) across the years of research (Table 2). The highest values of this parameter were demonstrated in 2023 and 2018, while the lowest were in 2019. Additionally, regardless of the year of research and Si application, sowings of *D. glomerata* and *F. arundinacea* exhibited higher LAI values than those of other monocultures. The application of Si increased the LAI by approximately 42%. In each year of research, the Si application in all species' sowings increased LAI. These relationships were significant, except for *L. perenne* and *F. arundinacea* in the first year of use (2018) (Figure 3). The study also showed variability in sward parameters depending on regrowth. In the spring regrowth (first regrowth), the highest values of PC, DM, and LAI were recorded, whereas in autumn (third regrowth), the monocultures were characterized by the highest T.



Figure 3. Mean values of soil cover with plants (PC; %), relative chlorophyll content (SPAD units), light transmittance coefficient (T) and leaf area index (LAI) for grass species (Dg—*D. glomerata*, Fa—*F. arundinacea*, Fb—*F. braunii*, Lp—*L. perenne*) under silicon application (No Si, Si) in the years 2018–2023. Different letters within each year separately denote statistically significant differences according to analysis of variance and Tukey's procedure ($p < 0.05$).

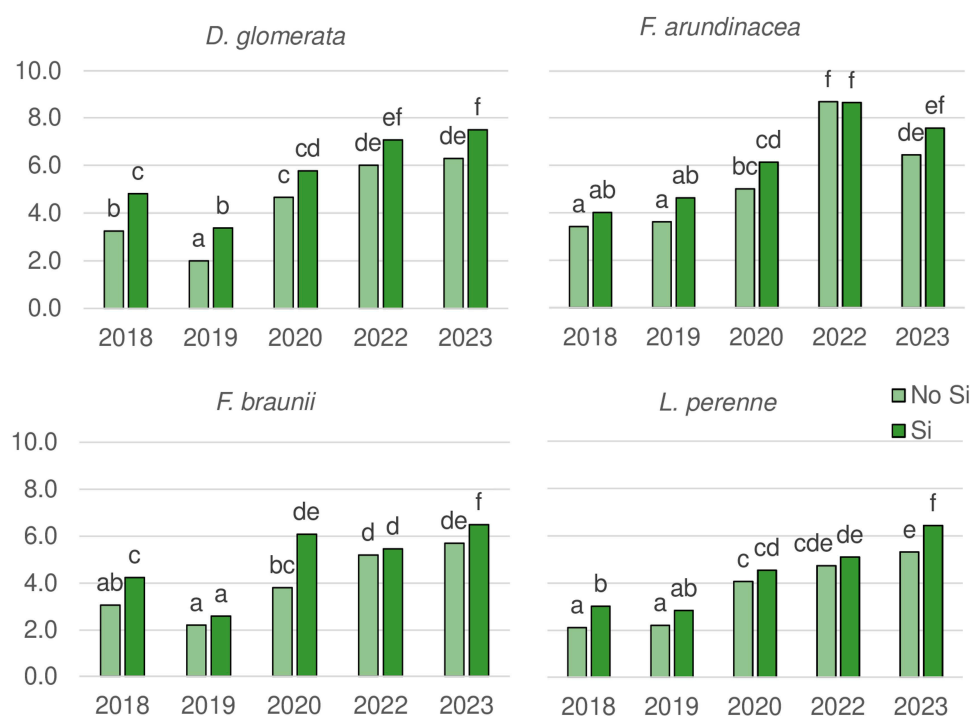


Figure 4. Annual yield (Mg/ha) of grass species (*D. glomerata*, *F. arundinacea*, *F. braunii* and *L. perenne*) depending on the Si application from 2018 to 2023. Different letters denote statistically significant differences according to analysis of variance and Tukey's procedure ($p < 0.05$).

3.4. Relationships Between the Analyzed Parameters

PCA of the first year of utilization (2018) of forage grass sowings showed that the first component explained approximately 45.2% and the second 21.9% of the analyzed variability (Figure 5A,B). Growing conditions had the greatest impact on AWC values, which were highest in *L. perenne* sowings without Si application. A strong positive correlation between CWC and SPAD values was also demonstrated. High values for these traits were observed in *F. arundinacea* sowings without Si application. Conversely, a negative correlation was found between DM and T.

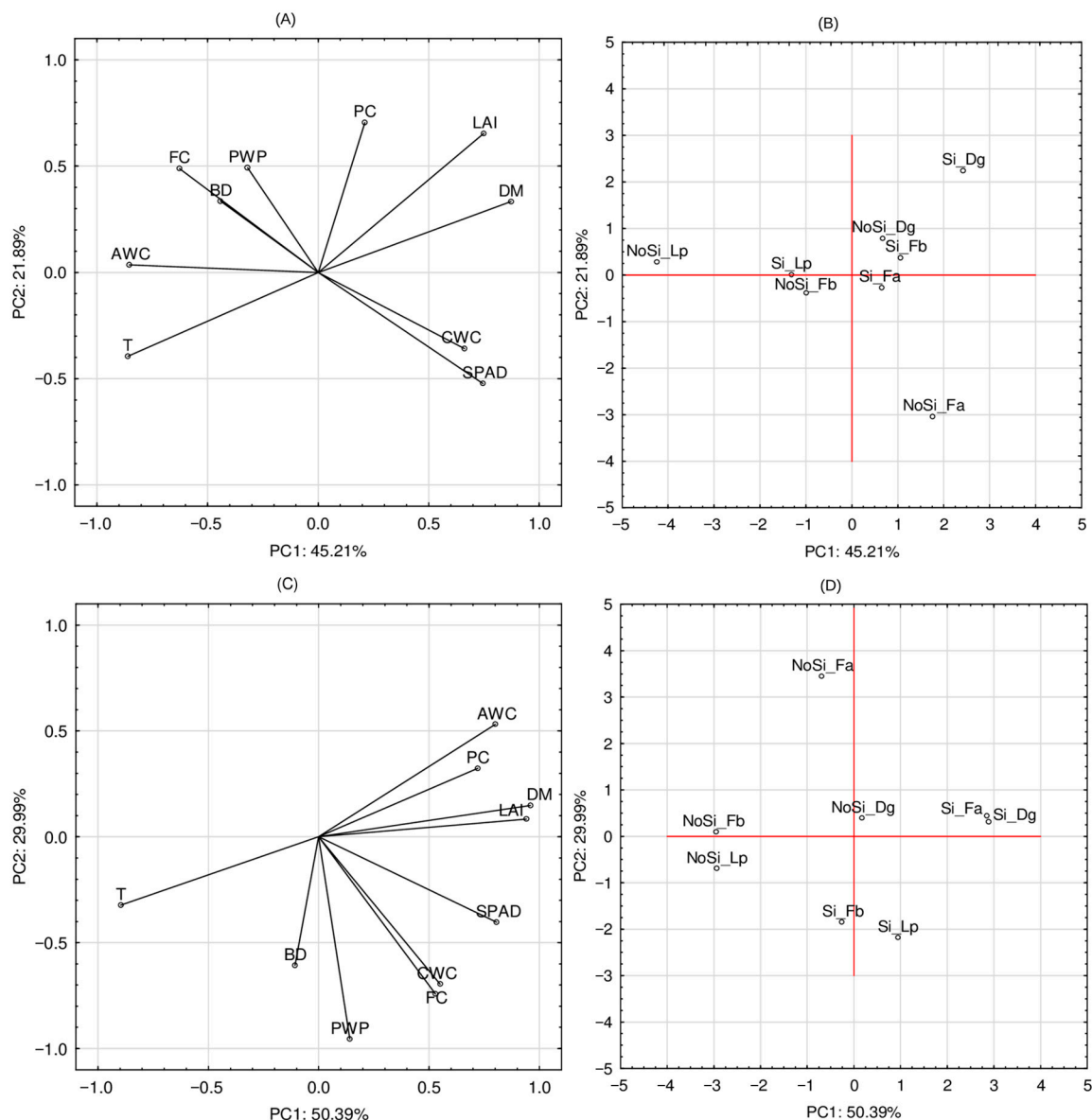


Figure 5. Results of principal component analysis (PCA) showing relationships among all analyzed parameters (A) in 2018, (C) in 2023, and for the species (Dg—*D. glomerata*, Fa—*F. arundinacea*, Fb—*F. braunii*, Lp—*L. perenne*) and Si application conditions (no Si, Si) (B) in 2018, (D) in 2023; PC—soil cover with plants, SPAD—chlorophyll content, T—light transmittance coefficient, LAI—leaf area index, DM—dry mass in regrowth, BD—bulk density, CWC—capillary water capacity, FC—field capacity, PWP—permanent wilting point, AWC—available water capacity.

In the sixth year (2023) of use, the first component PC1 explained approximately 50.4% of the studied variability, and the second PC2 explained 30% (Figure 5C,D). The application of Si in grass swards had the strongest effect on DM and LAI. At the same time, the values

of DM and LAI were the highest when Si was used in monocultures of *F. arundinacea* (increased by 17.5 and 24.4%, respectively) and *D. glomerata* (increased by 19.1 and 19.8%, respectively). A positive correlation was found between CWC and FC, while a negative correlation was noticed between T and AWC, T and DM, and T and LAI. The analysis also showed that high T values were associated with the absence of Si application in swards of *F. braunii* and *L. perenne*. Conversely, the use of Si in monocultures of *L. perenne* resulted in high CWC and FC values.

4. Discussion

In the case of forage grasses, an important aspect of utilization is obtaining an appropriate amount of high-quality plant biomass over many years. Therefore, the durability and viability of species in subsequent years, as well as good soil cover with plants, are significant, especially under conditions where increasingly frequent periods of atmospheric and soil drought are observed. We examined the effect of foliar Si application on the durability of *D. glomerata*, *F. arundinacea*, *F. braunii*, and *L. perenne*, aboveground biomass, weed infestation, and soil water properties over 6 years of utilization. The response of grass species was characterized across variable weather conditions (Figure 1).

Research indicates that the presence of perennial grasses with well-developed root systems increases organic carbon content and improves soil moisture parameters. The roots enhance both the number of macropores responsible for infiltration and the number of micropores responsible for capillary retention, allowing the soil to retain more water available to plants. A durable plant cover increases the water content retained at field capacity, with the effect particularly pronounced in light soils under perennial crops [28–30]. However, over time, root presence can increase the number of macropores and infiltration capacity, thereby reducing soil water retention capacity [31]. The six-year period of utilization of forage grasses in our study resulted in decreases in CWC, FC, and PWP. Regardless of other factors, in the *F. arundinacea* monoculture, the soil was characterized by significantly lower FC and PWP values than in other crops. According to the literature, species with a deep root system, such as *F. arundinacea*, enhance water infiltration by maintaining the continuity of the macropore (biopore) network, allowing water to flow into deeper soil layers and promoting water storage in the soil. Conversely, species with a dense root system concentrated in the surface layer, such as *L. perenne*, effectively limit surface runoff and soil erosion, improving retention in the plough layer [32–34]. A factor conducive to the development of grass roots, especially during periods of water deficit, is the application of Si [35]. In our research, the year 2018 was characterized by lower annual rainfall (409.1 mm) than the year 2023 (573.8 mm). Therefore, the application of Si in the first year of the study may have contributed to more intensive root development, which, in turn, increased the values of water capacity of the soil.

The proportion of grass species sown in monocultures changed over the years of use. Varied weather conditions influenced species durability in the sward. *F. arundinacea* was distinguished by a stable share during the study period. Weed infestation of its sowings did not exceed 20% after six years. In the studies by Georgieva et al. [36], over a nine-year grazing period, this species achieved both high stability parameters and high productivity. Furthermore, the authors emphasised the usefulness of *F. arundinacea* for cultivation across a wide range of environmental conditions. Under water-deficit conditions, the deep, well-developed root system of this species, as well as its root metabolic efficiency, are considered the main elements of a strategy for avoiding, tolerating, and regenerating after stress [37].

In our own research, *D. glomerata* was also a well-maintained species over a 6-year period of utilization. The proportion of weeds in its sowings increased to about 30% only in the fifth year of use, which may be related to low rainfall, particularly during the first

spring regrowth. According to the literature, threats to the durability of *D. glomerata* may include high temperatures and prolonged water deficits combined with improper, overly intensive use [38]. The resilience of this species results from a well-developed root system and the ability to limit growth under drought conditions [39]. Additionally, a relatively stable number of shoots, resulting from the balance between their death and the formation of new ones, facilitates rapid regeneration after the soil is re-moistened [40]. In our studies, *D. glomerata* was also observed in sowings of *F. braunii* and *L. perenne* during the fifth and sixth years of use. Previous studies by Borawska-Jarmułowicz et al. [25] highlighted the high competitiveness of this species and its durability in mixed sowings.

In the studies conducted, the share of *F. braunii* and *L. perenne* in the monocultures systematically decreased. For *F. braunii*, by the third year, the weed infestation reached 77% (without Si). In the final year of the study, the share of *L. perenne* decreased to 25%, whereas *F. braunii* was characterized by the smallest share in the sowings compared to the other species. Our earlier research on temporary grassland under organic and conventional cultivation indicates a decline in the participation of *L. perenne* and *F. braunii* in the sward in subsequent years [24,25]. According to the literature [41,42], both of these species, compared with *F. arundinacea* and *D. glomerata*, are characterized by lower durability and survival, particularly under conditions of soil water deficiency.

In the literature, there is a lack of data clearly defining the impact of Si application on changes in the botanical composition of the sward. In the studies by Radkowski et al. [43], Si fertilisation positively influenced the presence of legume plants in the sward, while simultaneously limiting the share of other plants. Other research [24,25] did not demonstrate an effect of Si application on the composition of the clover-grass sward. In our studies, regardless of other factors, no clear effect of Si application on the percentage share of Monocotyledonous and Dicotyledonous species in monocultures of *D. glomerata*, *F. arundinacea*, and *L. perenne* was observed. Only in *F. braunii* sowings was the proportion of other plants approximately 10% higher under Si application than without Si. The appearance of other Monocotyledonous and Dicotyledonous species was associated with periods of water deficiency and with decreasing durability of the sown species. In field conditions, it is difficult to determine which habitat factors most strongly influence the species' share in the sward.

Assessing the vitality and productivity of plants requires indicators that describe both the canopy structure and its physiological properties [44]. In agricultural practice, including on grasslands, the leaf area index (LAI), which relates to the canopy structure, i.e., the surface area of the plant assimilation organs relative to the ground surface, is measured, as is the SPAD index, which indicates the relative chlorophyll content in the leaves [45,46]. Complementing these is the coefficient (T), which determines the ratio of the amount of photosynthetically active radiation (PAR) below the plants to the amount of PAR above the canopy, providing information on the light transmittance through the canopy. The combined interpretation of these parameters enables a comprehensive assessment of vegetation architecture, the efficiency of photosynthetically active radiation (PAR) capture, sward density, physiological condition, and potential biomass productivity [47]. Plants in the sward exhibited the highest SPAD and LAI values in the final year of use. Sufficient, evenly distributed rainfall supported plant regeneration after mowing. However, drought conditions in the second year significantly limited the values of these parameters. Farooq et al. [48] point out that a rainfall deficit restricts nutrient transport to the roots, decreases cell turgor, and slows the activity of enzymes involved in photosynthesis. As a result, chlorophyll content and SPAD values decline. At the same time, water deficiency limits cell division, accelerates leaf ageing, and causes earlier leaf death, thereby decreasing LAI [46]. The research also confirmed variability in the examined parameters across

grass species [49]. Swards of *D. glomerata* and *F. arundinacea* were characterized by high SPAD and LAI values. In monocultures of *L. perenne* and *F. braunii*, these traits had low values. Simultaneously, it was shown that the T parameter was the highest in the sowing of *L. perenne* and *F. braunii*, indicating lower plant density and poorer light utilisation by the sward. Conversely, monocultures of *F. arundinacea* and *D. glomerata* were characterized by low T values, which suggest better plant density (with higher PC values) and good PAR absorption, leading to higher forage yield [50,51].

The beneficial effect of Si on plants is associated with improved growth conditions [52] and with processes that make them less susceptible to pest attacks and increase tolerance to abiotic stresses [21,53]. According to the literature data positive effects may be associated with more effective nutrient uptake by plants, osmotic adjustment, modifications in gas exchange, enhanced antioxidant defence, and changes in the expression of stress-responsive genes [54]. Moreover, the impact of Si on physiological parameters varies significantly with plant species, genotype, growth stage, and stress severity [55]. There are many studies in the literature confirming the positive effect of applying various forms of Si on the growth of shoots, roots, and their mass under drought conditions [26,54,56,57], although they are not always conclusive [58]. In the research by Santana et al. [59], calcium silicate accelerated leaf growth but shortened their lifespan. Furthermore, under drought conditions, it did not mitigate the negative impact of stress on Zuri grass's morphological, structural, and productive traits. According to Pang et al. [54] and Barão [58], a positive effect of silicon fertilisation was observed mainly when plants were exposed to growth-limiting factors. In favourable conditions for development, the response to Si application is often minimal because the plant does not utilise the defence mechanisms activated by Si. These findings from many years of field research indicate that Si application, regardless of other factors, positively influenced DM, PC, SPAD, and LAI, whereas T values were higher in the absence of Si. Elevated Si levels in plant leaves enhance chlorophyll biosynthesis and reduce its degradation caused by water deficit [60]. According to Rizwan et al. [61], the application of Si under drought stress can enhance gas exchange and nutrient uptake, which may contribute to improved photosynthesis and, consequently, greater biomass accumulation and plant growth. It should be noted that forage grass species cultivated on degraded soil were exposed to multiple factors, which is why their response to Si application in subsequent years was variable.

PCA analysis showed that in the sixth year (2023) of sward utilization, Si application most strongly affected DM and LAI in monocultures of *F. arundinacea* and *D. glomerata*. The large assimilation surface and high biomass production of these species, supported by Si supplementation, indicate their suitability for sowing on degraded soil with a rapidly drying upper layer and a significant proportion (about 50%) of particles smaller than 0.25 mm and larger than 10 mm in the structure. At the same time, high T values were associated with the lack of Si in sowings of *F. braunii* and *L. perenne*. The high proportion of weeds in the monocultures of these species hindered the achievement of good sward density, especially in the absence of Si application. However, the use of Si in *L. perenne* monocultures resulted in improved soil water properties (increased CWC and FC values). Under the influence of Si application, *L. perenne* plants develop numerous fine roots that, in the upper soil layer, can create many pores capable of storing water [35,62].

The studies also found significant negative correlations between T and annual yield ($r = -0.86$) and LAI ($r = -0.89$), as well as between T and AWC ($r = -0.65$). Limited transmittance of PAR through the crop canopy indicates more efficient utilization of PAR by the surface of the assimilation organs of grasses during photosynthesis, and consequently higher biomass and yield production. Furthermore, soils with higher water-holding capacity enable longer maintenance of the plants' photosynthetic activity, promote the develop-

ment of a larger LAI, and increase above-ground biomass. As a result, a more compact canopy with increased shading develops, thereby diminishing light transmittance to the soil surface.

5. Conclusions

The durability and vitality of grass species were influenced by soil conditions, plant biological properties, and weather conditions during the growing season. Low precipitation levels and their unfavourable distribution, along with high summer temperatures, led to reduced biomass production and intensified sward degradation, as evidenced by lower soil cover by plants and weed infestation in crops. Six years after sowing, *F. arundinacea* and *D. glomerata* were better suited to cover degraded soil than the other species. They were distinguished by their largest and most stable share of the sward (92.2% and 85.5%, respectively), low weed infestation (7.8% and 14.5%, respectively), high biomass (7.01 and 6.89 Mg/ha, respectively), and well-covered soil surface (61.4% and 58.9%, respectively). Simultaneously, the usefulness of *F. braunii* and *L. perenne* for soil cover was limited by the declining share of these species in the sward (22.5% and 41.7%, respectively), high weed infestation in subsequent years, lower biomass production (at the level of 6.10 and 5.88 Mg/ha, respectively), and reduced soil cover (50.6% and 57.2%, respectively).

Foliar application of Si increased grass species yield (by 21%), soil cover by plants (by 4.9%), relative chlorophyll content (by 4.9%), and LAI (by 41.8%) and reduced light transmittance (by 44%). The Si application had the strongest effect on the monocultures of *F. arundinacea* and *D. glomerata*, particularly for DM (increased by 17.5% and 19.1%, respectively) and LAI (increased by 24.4% and 19.8%, respectively). Changes in soil water properties in grass monocultures in response to the application of Si nanoparticles were limited. Given the benefits of silicon in plant fertilisation, further research is recommended, particularly on grass species used to revitalise heavily transformed and degraded soils.

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