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Wpływ zastosowania antytranspirantu na plonowanie i wymianę netto strumieni CO_2 na łące z systemem nawodnienia podsiąkowego

Effect of antitranspirant application on yield and CO_2 fluxes net exchange on the meadow with a subirrigation system

Rozprawa doktorska w dziedzinie nauk inżynieryjno-technicznych
w dyscyplinie inżynieria środowiska, górnictwo i energetyka
Doctoral thesis in engineering and technology sciences
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Wykaz skrótów

AT – *ang. antitranspirant* – antytranspirant

CO_2 – *ang. carbon dioxide* – ditlenek węgla

FA – *ang. fulvic acid* – kwas fulwowy

FAO – *ang. Food and Agriculture Organization of the United Nations* – Organizacja Narodów Zjednoczonych do spraw Wyżywienia i Rolnictwa

FWC – *ang. field water capacity* – polowa pojemność wodna

GHG – *ang.* greenhouse gas – gaz szklarniowy

GPP – *ang. gross primary production* – produkcja pierwotna brutto

GUS – Główny Urząd Statystyczny

HWL – *ang. high groundwater level* – wysoki poziom wody gruntowej

HWL_Si – *ang. high groundwater level with silicon application* – wysoki poziom wody gruntowej z aplikacją antytranspirantu z krzemem

LWL – *ang. lower groundwater level* – niższy poziom wody gruntowej

LWL_Si – *ang. lower groundwater level with silicon application* – niższy poziom wody gruntowej z aplikacją antytranspirantu z krzemem

NDVI – *ang. Normalized Difference Vegetation Index* – znormalizowany różnicowy wskaźnik wegetacji

NEE – *ang. net ecosystem exchange* – wymiana netto ekosystemu

Reco – *ang. ecosystem respiration* – oddychanie ekosystemu

SA – *ang. salicylic acid* – kwas salicylowy

WTD – *ang. water table depth* – poziom wody gruntowej

Streszczenie

Zachodzące zmiany klimatyczne są jednym z większych wyzwań z którymi obecnie musi zmierzyć się rolnictwo. Intensyfikacja emisji gazów cieplarniach i związany z nią wzrost temperatury, a także występowanie ekstremalnych zjawisk atmosferycznych powoduje, że niezwykle ważne jest poszukiwanie sposobów umożliwiających adaptację upraw do zmian klimatycznych. Jednym z takich rozwiązań jest zastosowanie antytranspirantów (AT) czyli środków ograniczających transpirację roślin. AT używane są głównie na uprawach sadowniczych i warzywnych, a ich zastosowaniu na obszarach łąkowych nie poświęcono dotychczas dużej uwagi.

Celem niniejszej pracy było określenie wpływu zastosowania antytranspirantu zawierającego krzem na plonowanie i wymianę netto strumieni ditlenku węgla na trzykośnej łące z systemem nawodnienia podsiąkowego. Badania terenowe przeprowadzono na łące w miejscowości Racot (województwo wielkopolskie) w latach 2021-2022. Na czas trwania doświadczenia, w systemie nawodnienia podsiąkowego, pozostawiono zamkniętą zastawkę na rowie uzyskując tym samym dwa obszary badawcze: jeden z wysokim poziomem wody gruntowej oraz drugi z niższym poziomem wody gruntowej. W obrębie każdego z nich wydzielono po dwa poletka (jedno z zastosowaniem AT oraz jedno bez). Pomiary strumieni CO_2 wykonywano przy zastosowaniu metody dynamicznych komór zamkniętych. Ponadto podczas każdego pokosu oceniono wielkość uzyskanego plonu.

Przeprowadzone badania wykazały, że zastosowanie antytranspirantu z krzemem przyczyniło się do obniżenia plonowania łąki w każdym z pokosów zarówno na obszarze z wysokim jak i z niższym poziomem wody gruntowej. W skali roku redukcja ta wyniosła 11,1–17,8%. Zaobserwowano również, że w pierwszym roku pomiarów (2021) na łące przeważała emisja netto CO_2, podczas gdy w drugim roku (2022) dominowała asymilacja netto CO_2. Odnotowano pozytywny wpływ aplikacji AT na zwiększenie produkcji pierwotnej brutto (GPP) na obszarze z wysokim poziomem wody gruntowej. Uzyskane skumulowane roczne wartości wymiany netto ekosystemu (NEE) wskazały, że aplikacja AT z krzemem pozytywnie wpływa na poprawę bilansu węgla (poprzez zmniejszenie emisji netto lub zwiększenie asymilacji netto w zależności od roku) na obszarze z wysokim poziomem wody gruntowej.

Słowa kluczowe: łąka, antytranspirant, krzem, ditlenek węgla, plon

Abstract

Ongoing climate change is one of the biggest challenges, which agriculture is facing today. The intensification of greenhouse gas emissions, the associated temperature increase, and the occurrence of extreme weather events make it extremely important to find ways of adapting crops to climate change. One possible solution is using antitranspirants (AT) - products that reduce plant transpiration. AT are mainly used on fruit and vegetable crops, whereas their use in grassland areas has not received much attention.

This study aimed to determine the effect of application of silicon-containing antitranspirant on the yield and net exchange of carbon dioxide fluxes in a three-cut meadow with a subirrigation system. Field studies were conducted on a meadow in Racot (Wielkopolskie Voivodeship) in 2021-2022. For the duration of the experiment in the subirrigation system, a closed valve on the ditch was left, thus obtaining two study sites: one with a high groundwater level and the other with a lower groundwater level. Within each, two plots (one with and one without AT application) were separated. CO_2 fluxes were measured using the dynamic closed chamber method. Furthermore, the yield obtained was assessed during each cut.

This study showed that applying an antitranspirant with silicon reduced the yield of the meadow in each cut in both the sites with high and lower groundwater levels. The annual reduction was 11.1-17.8%. It was also observed that in the first year of measurements (2021), net CO_2 emissions predominated in the meadow, while in the second year (2022), net CO_2 assimilation dominated. There was a positive effect of the AT application on increasing gross primary production (GPP), but only in the site with high groundwater levels. The cumulative annual net ecosystem exchange (NEE) values indicate that the AT with silicon application positively improves the meadow carbon balance (by reducing net emissions or increasing net assimilation depending on the year) in the site with a high groundwater level.

Key words: meadow, silicon, antitranspirant, carbon dioxide, yield

1. Wstęp

1.1 Problematyka poruszana w ramach pracy doktorskiej

Zachodzące zmiany klimatyczne powodują, że coraz więcej uwagi poświęca się poszukiwaniu sposobów mogących ograniczyć emisję gazów cieplarnianych (GHG). Działania te skoncentrowane są głównie na zmniejszeniu nadmiernej emisji CO_2 (jednego z najpopularniejszych GHG) z sektorów takich jak energetyka, przemysł czy transport. Jednakże należy pamiętać, że rolnictwo jest również obszarem, który odgrywa rolę w tym zakresie, a ważną jego częścią są łąki (FAO, 2020). Obecnie szacuje się, że trwałe użytki zielone pokrywają około 23% użytków rolnych Unii Europejskiej (Eurostat, 2020). W Polsce trwałe użytki zielone (łąki) zajmują 2 218 431 ha, co stanowi 18,6% wszystkich użytków rolnych kraju, a przy uwzględnieniu pastwisk trwałych 21,4% (GUS, 2022). Niestety, powierzchnia trwałych użytków zielonych w Europie w ostatnich dziesięcioleciach ulega redukcji, ze względu na liczne przekształcenia na inne sposoby użytkowania terenu (Schils i in., 2022).

Łąki pełnią wiele ważnych funkcji, w tym są źródłem paszy dla zwierząt przez co pośrednio oddziałują na światową produkcję żywności. Ponadto obszary łąkowe wspierają bioróżnorodność, zwiększają ochronę gleby przed erozją wodną oraz wietrzną, a także kształtują mikroklimat (Burczyk i in., 2018; Grzegorczyk, 2016). W odniesieniu do CO_2, dotychczasowe badania pokazują, że mogą być one zarówno pochłaniaczem jak i emiterem ditlenku węgla (Schrier-Uijl i in., 2014). Stwierdzono, że na użytkach zielonych elementami, które oddziałują na ilość wyemitowanego bądź też zasymilowanego CO_2 są nawożenie, intensywność użytkowania i sposób zarządzania, występujące gatunki roślin, rodzaj gleby i jej wilgotność, warunki meteorologiczne oraz nawadnianie (Conant, 2010; Liu i in., 2023). Dotychczasowe badania pokazują, że szczególną rolę w tym zakresie odgrywa gospodarowanie wodą, a nadmierne przesuszanie i odwadnianie gleb jest czynnikiem intensyfikującym emisję CO_2 z obszaru łąk (Beetz i in., 2013). Można zatem stwierdzić, że ważnym elementem w walce ze zwiększoną emisją ditlenku węgla z łąk, jest ich nawadnianie i utrzymanie zwierciadła wody gruntowej na odpowiednim poziomie, umożliwiającym rozwój roślin. Niestety z uwagi na ograniczone zasoby wodne, a także występowanie okresów suszy, zadanie to jest coraz trudniejsze do zrealizowania.

Susze są aktualnie dużym wyzwaniem z którym musi zmierzyć się rolnictwo. Ich występowanie ogranicza rozwój upraw i przyczynia się do znaczącej redukcji plonowania (Dietz i in., 2021; Leng & Hall, 2019). W obliczu rosnącego zagrożenia suszami, nieustannie poszukiwane są nowe rozwiązania, które pomogą w adaptacji roślin do okresów deficytu wody. Jednym z nich może być użycie antytranspitantów (AT), czyli środków które ograniczają proces parowania i zabezpieczają rośliny przed nadmierną utratą wody. Do popularnych AT zalicza się produkty takie jak Vapor Gard, kaolin czy też chitosan (Pandey i in. 2017; Mphande i in., 2020). W opublikowanych do tej pory pracach naukowcy wskazują, że AT mają duży potencjał do wspierania wzrostu roślin, poprawy plonowania oraz niwelowania negatywnych skutków czynników stresogennych takich jak susza, zasolenie czy temperatura (Farouk & El-Metwally, 2019; Javan i in., 2013, Kocięcka & Liberacki, 2021; Mphande i in., 2020; Nimir i in., 2015; Yadav i in. 2020). Jednakże, kwestia oddziaływania AT na emisję CO_2 nie została dotychczas dobrze poznana i wciąż wymaga przeprowadzenia badań.

1.2 Innowacyjność pracy

Dotychczasowa uwaga naukowców skupiała się głównie na zastosowaniu AT na uprawach roślin warzywnych oraz sadowniczych. W badaniach rozważano skuteczność tychże preparatów w odniesieniu do poprawy parametrów wzrostu, wielkości owoców, plonowania oraz przeciwdziałania chorobom (Mphande i in., 2023). Uwagę poświęcono również aplikacji AT na zbożach (Guleria & Shweta, 2020; Kettlewell, 2014; Ouerghi i in., 2014). Na podstawie przeprowadzonego przeglądu literatury wykazano, że nie próbowano dotychczas zbadać wpływu zastosowania antytranspirantów na łąkach w kontekście możliwości ograniczenia emisji ditlenku węgla. Niniejsza praca doktorska jest pierwszą, pilotażową próbą użycia antytranspirantu z krzemem w tym celu i krokiem do lepszego poznania działania AT na obszarach łąk. Pomimo, iż eksperyment ma wymiar lokalny (pomiary wykonywane były w ramach jednej łąki), to jego wyniki mogą mieć globalne zastosowanie, w kontekście potencjalnej możliwości ograniczenia nadmiernej emisji CO_2 pochodzącej z łąk i adaptacji tych terenów do zmian klimatu.

1.3 Znaczenie pracy dla rozwoju dyscypliny inżynieria środowiska, górnictwo i energetyka oraz możliwość zastosowania uzyskanych rezultatów w sferze gospodarczej

Realizacja niniejszej pracy doktorskiej oddziałuje na rozwój dyscypliny inżynieria środowiska, górnictwo i energetyka poprzez poszerzenie stanu wiedzy na temat stosowania antytranspirantów na łąkach. W szczególności dotyczy to wpływu tego zabiegu na strumienie netto CO_2, gdzie praca ma charakter pionierski i rzuca światło na obszary nauki, które dotychczas nie były zgłębione. Przeprowadzenie badań in-situ jest krokiem w kierunku znalezienia sposobu umożliwiającego wspomaganie adaptacji roślin do zmian klimatu oraz jednoczesnego zmniejszenia emisji jednego z kluczowych gazów cieplarnianych (CO_2) z obszarów użytków zielonych. Problematyka ograniczenia emisji ditlenku węgla jest aktualnie jednym z ważnych zagadnień nad którym skupiają się naukowcy i znajduje się w zakresie dyscypliny inżynieria środowiska, górnictwo i energetyka.

Ponadto poprzez zastosowanie w eksperymencie systemu nawodnienia podsiąkowego na łące, praca doktorska porusza również zagadnienie gospodarowania wodą w rolnictwie, które jest kluczowe w obliczu zachodzących zmian klimatycznych w szczególności dla obszarów zmagających się z deficytami wody. Właściwa gospodarka wodna opierająca się na optymalizacji wykorzystania i próbie oszczędzania jej zasobów jest aktualnym tematem prac naukowych i wyzwaniem z którym będzie musiała się zmierzyć produkcja rolna. Naukowcy prognozują, że Polska będzie narażona w przyszłości na występowanie coraz częstszych deficytów opadów, długotrwałych susz, a także niedoborów wilgoci w glebie (Piniewski i in., 2020; Pińskwar i in., 2020). Niniejsza praca poza zastosowaniem AT analizuje również wpływ piętrzenia wody w rowie w systemie nawodnienia podsiąkowego na plonowanie, a także emisję CO_2 trzykośnej łąki. Dzięki zastosowaniu dwóch obszarów badawczych jednego bezpośrednio przed i drugiego za piętrzeniem możliwe jest porównanie oddziaływania poziomu wody gruntowej i tym samym nawodnienia na analizowane aspekty.

W odniesieniu do możliwości zastosowania uzyskanych rezultatów z pracy doktorskiej w strefie gospodarczej należy zwrócić uwagę, że niniejsze badania dotyczą nie tylko wpływu AT na emisję CO_2 ale również na plonowanie łąki. Jest to ważny aspekt z uwagi na fakt, że łąki odpowiadają za dostarczenie paszy dla wielu zwierząt gospodarskich i wielkość uzyskanego z nich plonu oddziałuje na dalszą produkcję żywności. Przeprowadzone w pracy doktorskiej analizy w tym zakresie mogą być przydatne dla rolników i stanowić praktyczną wskazówkę dotyczącą stosowania AT i nawodnienia na trzykośnych łąkach.

2. Cel i zakres pracy oraz hipotezy badawcze

Celem pracy doktorskiej było określenie wpływu zastosowania antytranspirantu zawierającego krzem na:

C1) plonowanie trzykośnej łąki;

C2) wymianę netto strumieni ditlenku węgla na trzykośnej łące;

z uwzględnieniem poziomu wody gruntowej w systemie nawodnienia podsiąkowego.

Zakres pracy obejmował:

Z1) Przedstawienie obecnego stanu wiedzy na temat zastosowania antytranspirantów oraz efektów ich działania na roślinach z rodziny wiechlinowatych - traw (*Poaceae*).

Z2) Przegląd dotychczasowych badań dotyczących wpływu wybranych antytranspirantów na łagodzenie skutków suszy u roślin z rodziny *Poaceae* ze szczególnym uwzględnieniem plonowania i parametrów wzrostu roślin.

Z3) Przeprowadzenie dwuletnich pomiarów na trzykośnej łące obejmujących określenie wpływu zastosowania antytranspirantu z krzemem i wysokiego poziomu wody gruntowej w systemie nawodnienia podsiąkowego na:

Z3a) wielkość plonu masy nadziemnej roślin;

Z3b) dzienne oraz skumulowane w pokosach, sezonach wegetacyjnych i poszczególnych latach wartości strumieni produkcji pierwotnej brutto (GPP), oddychania ekosystemu (Reco) oraz wymiany netto CO_2 (NEE).

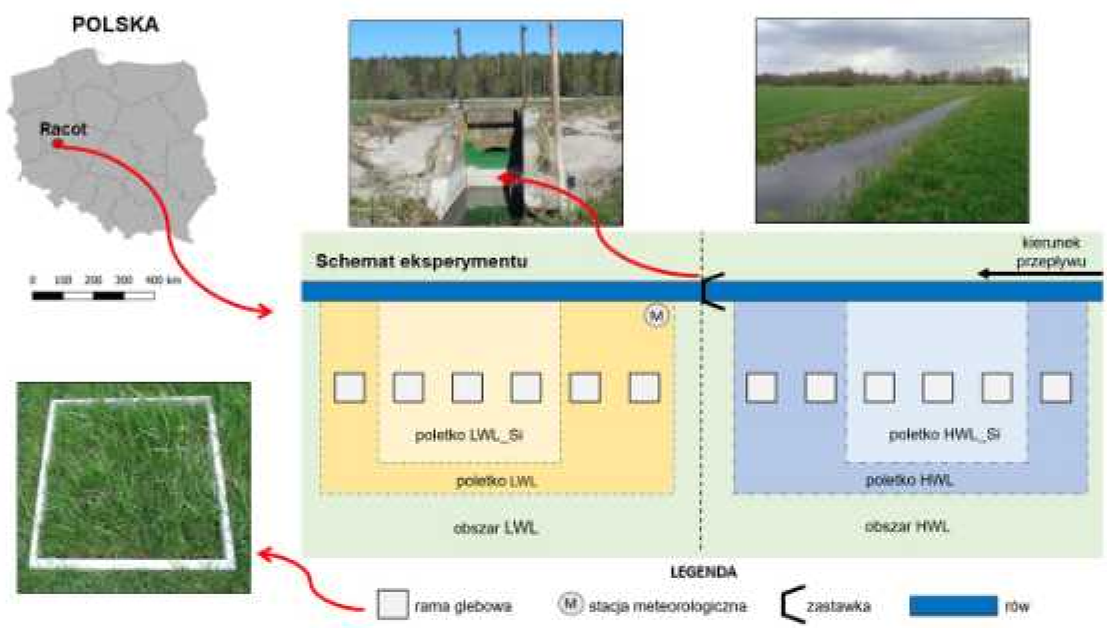
Ponadto w ramach pracy doktorskiej zweryfikowano następujące hipotezy badawcze:

H1) Zastosowanie antytranspirantu z krzemem istotnie wpływa na plon trzykośnej łąki.

H2) Zastosowanie antytranspirantu z krzemem, a także wysoki poziom wody gruntowej w systemie nawodnień podsiąkowych, istotnie wpływa na dzienne strumienie CO_2 na łące.

3. Badania terenowe

Niniejsza dysertacja doktorska stanowi zbiór artykułów spójny nie tylko pod względem poruszanej tematyki dotyczącej zastosowania antytranspirantów, ale również w odniesieniu do miejsca przeprowadzenia badań. Przedstawione w publikacjach P2 oraz P3 wyniki badań terenowych uzyskane zostały z tego samego obiektu badawczego – trzykośnej łąki położonej w miejscowości Racot (województwo wielkopolskie). Na tym obszarze na potrzeby realizacji niniejszej rozprawy doktorskiej w 2021 roku zostało założone doświadczenie terenowe. Wykorzystano w nim istniejący już na łące system nawodnienia podsiąkowego. Na czas trwania doświadczenia zamknięto zastawkę na rowie, co umożliwiło utrzymanie różnicy w poziomie wody i wyznaczenie dwóch obszarów badawczych – z wysokim poziomem wody gruntowej (HWL) oraz z niższym poziomem wody gruntowej (LWL). W ramach każdego z nich wyodrębniono po dwa poletka badawcze – jedno z zastosowaniem antytranspirantu z krzemem (Si), a drugie bez jego użycia. Tym samym finalnie otrzymano cztery poletka badawcze HWL, HWL_Si, LWL, LWL_Si. W obrębie każdego poletka zainstalowano po trzy ramy glebowe na których przeprowadzono pomiary. Ponadto obiekt badawczy wyposażono w niezbędną aparaturę umożliwiającą monitoring warunków meteorologicznych, a także poziomów wody gruntowej i wilgotności gleby. Zainstalowany na potrzeby doktoratu sprzęt pomiarowy szczegółowo opisano w publikacjach P2 oraz P3. Schemat doświadczenia przedstawiono na rycinie 1.



Ryc. 1. Schemat doświadczenia terenowego (źródło: publikacja P3).

Badania terenowe w ramach niniejszej rozprawy doktorskiej odbywały się w latach 2021-2022. Łącznie w tym okresie przeprowadzono 28 kampanii pomiarowych (15 w 2021 roku oraz 13 w 2022 roku). Podczas każdej kampanii wykonywano pomiary strumieni CO_2 w obrębie zainstalowanych ram glebowych na poletkach przy zastosowaniu metody dynamicznych komór zamkniętych (Juszczak i in., 2013; Acosta i in., 2017). Pomiary odbywały się w słoneczne i bezchmurne dni od wczesnego ranka do późnego popołudnia. Miały one na celu określenie wpływu zastosowania AT z krzemem i wysokiego poziomu wody gruntowej w systemie nawodnienia podsiąkowego na strumienie CO_2. Szczegółowy opis metodyki prowadzenia pomiarów została przedstawiony w artykule P3.

Ponadto w ramach niniejszego eksperymentu mierzono również wysokość roślin oraz wartość wskaźnika NDVI w obrębie poszczególnych poletek. Co więcej po każdym z pokosów ścinano ręcznie biomasę, a następnie suszono ją w celu oceny wielkości plonu. Badania te umożliwiły określenie wpływu zastosowania AT z krzemem na plonowanie łąki. Ich szczegółowy opis znajduje się w artykułach P2 oraz P3.

Wszystkie dane uzyskane z pomiarów terenowych zostały poddane dalszym analizom, które szczegółowo opisano w publikacjach P2 oraz P3. Pozwoliło to na weryfikację założonych hipotez badawczych, a także zrealizowanie określonego celu i zakresu pracy doktorskiej.

4. Prezentacja rezultatów

4.1 Rola antytranspirantów w łagodzeniu stresu wywołanego suszą u roślin z rodziny traw (*Poaceae*) – przegląd

Publikacja P1:

Kocięcka, J., Liberacki, D., & Stróżecki, M. (2023). The Role of Antitranspirants in Mitigating Drought Stress in Plants of the Grass Family (Poaceae)—A Review. Sustainability, 15(12), 9165. https://doi.org/10.3390/su15129165

W obliczu zmian klimatycznych susza stanowi coraz większe zagrożenie dla rolnictwa. Poszukiwanie rozwiązań umożliwiających adaptację roślin do długich okresów deficytów wody jest niezbędne dla utrzymania produkcji roślinnej na poziomie pozwalającym zaspokoić obecne zapotrzebowanie na żywność dla ludzi oraz zwierząt. Potencjalnie w tym zakresie korzystne może być zastosowanie antytranspirantów, czyli środków ograniczających transpirację roślin.

Głównym celem artykułu było dokonanie przeglądu i syntetyczne przedstawienie wyników istniejących badań dotyczących wpływu wybranych AT na łagodzenie skutków suszy u roślin z rodziny wiechlinowatych (*Poaceae*). W skład wiechlinowatych inaczej zwanych rodziną traw, wchodzi wiele kluczowych gatunków obejmujących zboża, a także popularnie występujące gatunki na obszarach łąk i pastwisk. W tym artykule przeglądowym zaprezentowano podstawowe informacje dotyczące antytranspirantów oraz ich podział obejmujący trzy grupy: błonotwórcze (ang. film-forming), metaboliczne (ang. metabolic) oraz refleksyjne (ang. reflective). Następnie do dalszych szczegółowych analiz wytypowano antytranspiranty takie jak: Vapor Gard, krzem, chitosan, kwas fulwowy (FA), kwas salicylowy (SA), kaolin, oraz węglan magnezu (M_gCO_3). Ich zastosowanie w odniesieniu do suszy rozpatrywano w kontekście czterech grup parametrów roślin: morfologicznych, fizjologicznych, biochemicznych, a także plonu i jego składników.

Przeprowadzony przegląd artykułów naukowych pokazał duży potencjał użycia antytranspirantów w celu zmniejszenia wpływu suszy na rośliny z rodziny traw. Wiele badań wykazało, że AT mogą łagodzić niekorzystne skutki suszy oraz poprawiać parametry wzrostu i plonowania roślin. Zauważono jednak, że gatunek rośliny, środowisko, rodzaj i zastosowana dawka antytranspirantu są czynnikami, które wpływają na skuteczność i finalny rezultat tego zabiegu, w związku z czym zaleca się dalsze pomiary wpływu AT w warunkach suszy. Ponadto stwierdzono, że naukowcy skupiają dotychczasowe badania głównie na popularnych zbożach, takich jak pszenica czy kukurydza, a mniejsza uwaga poświęcana jest pozostałym roślinom z rodziny *Poaceae*.

Artykuł P1 obejmuje dwa zakresy rozprawy doktorskiej:

Z1) Przedstawienie obecnego stanu wiedzy na temat zastosowania antytranspirantów oraz efektów ich działania na roślinach z rodziny wiechlinowatych - traw (*Poaceae*).

Z2) Przegląd dotychczasowych badań dotyczących wpływu wybranych antytranspirantów na łagodzenie skutków suszy u roślin z rodziny *Poaceae* ze szczególnym uwzględnieniem plonowania i parametrów wzrostu roślin.

sustainability

Review

The Role of Antitranspirants in Mitigating Drought Stress in Plants of the Grass Family (*Poaceae*)—A Review

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Abstract: One of the biggest problems facing agriculture is the occurrence of droughts. Due to ongoing climate change, many regions of the world are exposed to increasingly frequent and prolonged water shortages. The situation may significantly reduce production and the quality of many crops in the *Poaceae* family, including crucial cereals. Therefore, it is important to find solutions that can help adapt plants to the drought phenomenon and reduce its negative effects. One measure that could potentially improve the condition of plants and help them survive under water deficit conditions is the use of antitranspirants (AT), which are products that reduce transpiration. Antitranspirants are divided into three groups: film-forming, metabolic, and reflective types. This review aimed to the current state of knowledge on the effects of selected AT applications on *Poaceae* plants under drought conditions. It demonstrated that AT, in many cases, mitigates the negative effects of drought on crops such as maize, wheat, or rice, which are crucial for global food security. Furthermore, AT often improved growth and yield parameters. These results are particularly relevant for countries that are important cereals producers and are more vulnerable to droughts in the future. However, it should be noted that the results obtained often depend on several factors, such as plant species, environment, type of antitranspirant, and applied dose. Therefore, it is advisable to measure further the effects of AT on plants under drought-stress conditions.

Keywords: antitranspirants; drought stress; cereals; *Poaceae*; grasses; crops adaptation; water deficit; Vapor Gard; chitosan; kaolin

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1. Introduction

The *Poaceae* family, also known as the grass family, includes the world's most important cereal crops. It has several key species that are the primary food source for humans. The *Poaceae* include, among others: maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare*), sorghum (*Sorghum bicolor* L.), proso millet (*Panicum miliaceum* L.), oats (*Avena sativa*), rye (*Secale graine* L.), and triticale (*xTriticosecale*). In addition to cereals, the *Poaceae* family also includes sugarcane (*Saccharum officinarum* L.), bamboo (*Bambusa Shreb.*), and pasture grasses. Moreover, switchgrass (*Panicum virgatum* L.) or giant miscanthus (*Miscanthus giganteus*) are increasingly important, as they can be used as biofuel [1]. According to the latest phylogenetic classification, the *Poaceae* family includes 12 subfamilies comprising a total of 11,783 species [2]. Scientists claim that the grass family is one of the most important groups in the world from an economic point of view [3,4]. Unfortunately, due to climate change, species in the *Poaceae* family, like many other plants, are subject to factors that can significantly reduce the area of land suitable for cultivating these crops.

One of the factors significantly impacting and limiting crop production is the occurrence of different environmental stress factors, which can be divided into two groups: biotic and abiotic stresses. Biotic stress factors include a variety of organisms such as fungi, bacteria, nematodes, insects, herbivores, and viruses. These agents cause diseases, infections, and plant damage [5]. A side effect of the occurrence of biotic stressors is reductions in yield. On the other hand, abiotic stresses are caused by non-living natural elements, such as temperature (both too high and too low), drought, flooding, radiation, salinity, and lack or excess of minerals or heavy metals [6,7]. The severity of abiotic stresses is linked to ongoing climate change. Some regions of the world have recently experienced previously unprecedented temperature extremes. This is causing many crops to be exposed to conditions where the temperature deviates from the optimum for those species.

Moreover, extreme weather events in many regions contribute to increasing droughts and water shortages. Forecasts show that half of the global urban population are projected to live in a water-scarce region by 2050 [8]. Water shortages will also have a strong impact on crops. Therefore, it is crucial to have sustainable irrigation in water-scare regions. The appropriate irrigation scheduling can increase water productivity (i.e., product yield per unit volume of water consumed by the crop) [9]. Climate change strongly influences the irrigation water needs (IWN) through rainfall, temperature, air humidity, and the evapotranspiration of plants. Scientists predict that, up to the 2055 year, reference evapotranspiration (ETo; a sum of evaporation from the soil and transpiration from a reference crop such as, e.g., grass or alfalfa) will increase. This prediction will make the water need for irrigation even higher [10]. Considering, that the world's water resources are limited, an extremely important goal is to find solutions to improve plant productivity in drought conditions. Solutions that extend the geographical boundaries of drought-resistant production and are not solely based on additional irrigation are needed. One of the promising solutions may be the use of antitranspirants [11].

Antitranspirants (AT) are products that reduce transpiration from the above-ground parts of the plants. The basic division of AT comprises three groups: film-forming, metabolic (stomata-closing), and reflective type (Figure 1). The first group includes film-forming antitranspirants. After their application to the plant, a physical barrier (film) is formed over the stomata, thus reducing transpirational water loss. This group mainly includes water-emulsifiable organic polymers, latex, plastics, or wax emulsions [12]. A popular commercial formulation in this group is Vapor Gard® (Bio Agris brand)—a water-emulsifiable organic concentrate composed of di-1-p-menthene ($C_{20}H_{34}$). This terpene polymer also functions under the name of pinolene, which is produced from conifer resins during distillation [13]. The second group is metabolic AT, otherwise known as stomata-closing preparations. Applying this type of AT causes partial stomatal closure, which results in lower transpiration. This group includes substances with hormonal and hormone-like effects [14]. The most common metabolic AT include chitosan, fulvic acid, and abscisic acid (ABA). The last group of antitranspirants is the reflective type, which contributes to increased reflectance and a concomitant reduction in leaf temperature and transpiration rate [14–16]. One of the most popular AT in this group is aluminum phyllosilicate $Al_2Si_2O_5(OH)_4$—also known as kaolin [17]. According to a literature review by Mphande et al. [14], kaolin was the most studied reflective antitranspirant on arable crops from 2009 to 2018. Other preparations included in this group are calcium carbonate ($CaCO_3$) and calcium oxide (CaO), which have similar properties.

The aim of this study was to review and present the effects (mainly on yield and plant growth parameters) of using the popular antitranspirants on *Poaceae* crops under drought stress conditions. The antitranspirants selected for this study included: Vapor Gard, silicon, chitosan, fulvic acid (FA), salicylic acid (SA), kaolin, and magnesium carbonate ($MgCO_3$). The review is based on publications no older than 2000 available in Web of Science and Google Scholar databases. The main objective of this work was to synthesize results obtained to date on the potential effects of antitranspirants in drought mitigation in plants of the *Poaceae* family.

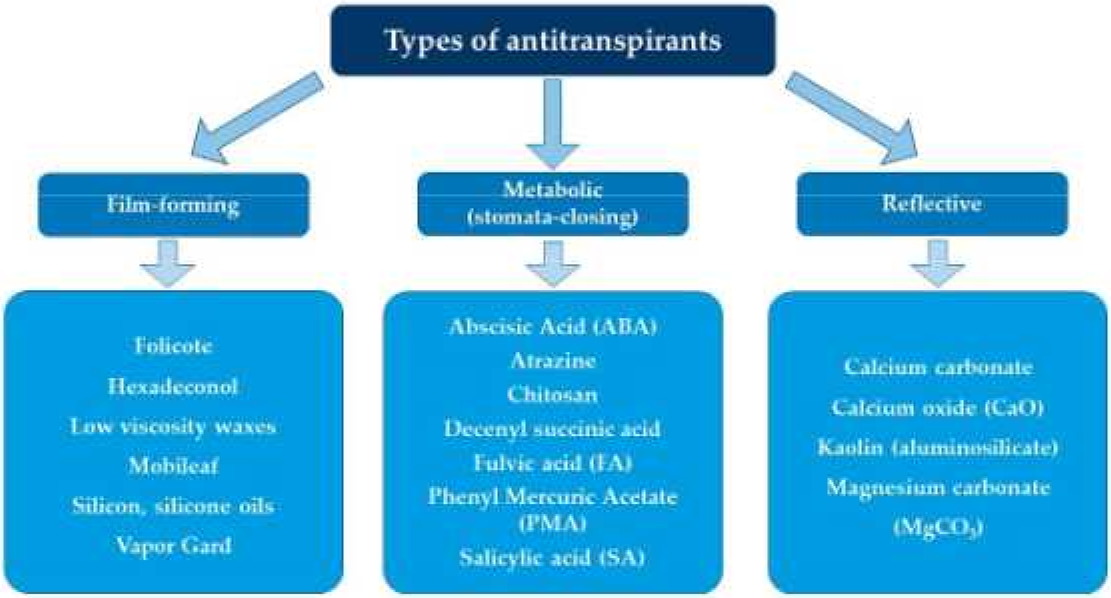

Figure 1. Groups of antitranspirants and their examples based on [14,16,18,19].

2. Drought

One of the most likely climate changes is the occurrence of extreme heat waves and prolonged periods of drought, which significantly impact crop production. The World Health Organization (WHO) defines drought as a prolonged dry period in the natural climate cycle that can occur anywhere in the world. It is a slow-onset disaster characterized by a lack of precipitation, resulting in a water shortage [20]. Long-term water shortages result in reduced plant growth, leaf area, fruit weight, and yield. It is crucial to conduct research to understand better this stress's impact on plants and their adaptation strategies to periods of water deficits [21]. The drought tolerance mechanism is a complex issue that has been the subject of many studies. It involves a lot of physiological and biochemical processes at the cell, tissue, organ, and whole-plant level. Moreover, the duration of the drought, its severity, the term of occurrence, and the rate of development directly impact the plants' response to water deficit [22]. Researchers note that the impact of drought stress can be reduced by applying appropriate agricultural operations. These treatments include seed priming, setting planting and harvesting dates, the application of plant growth regulators, modification of tillage methods such as conservation tillage, and the timely management of weeds. In addition, there is great potential in developing breeding and biotechnology research. This research focuses on producing crop varieties that are tolerant and resistant to drought stress. So far, cultivating resistant varieties has contributed to higher yields under drought conditions and thus can enhance global food security [23]. The researchers emphasize that it is extremely important to include drought-tolerant varieties in national climate change adaptation plans [24]. Among all these ways of alleviating drought stress in plants, using antitranspirants could also be a potential solution. This is due to the fact that the main role of these substances is to reduce transpiration, which should positively affect the ability of the plants to adapt to long periods without water. This fact makes research on applying antitranspirants on plants belonging to the *Poaceae* family increasingly popular.

Both drought and the application of antitranspirants can affect plant parameters such as morphological, physiological, biochemical, yield, and yield components (Figure 2). The morphological ones include elements such as leaf area, number of leaves, plant height, stem width, stem length, as well as other species-specific growth characteristics that can be inhibited under drought. Furthermore, one of the main plant responses to this stress is stomatal closure, which reduces photosynthesis [25]. Changes in photosynthesis are categorized as physiological response. Besides this, it also includes relative water content

(RWC), leaf water potential, stomatal conductance, CO_2 assimilation and transpiration rate, among others. In addition, an important aspect concerning drought is also the plant response, which includes biochemical aspects such as, for example, antioxidant enzyme activity and chlorophyll content. However, from the farmers' point of view, one of the most important groups of parameters affected by drought is the last one comprising yield and its parameters. Elements such as plant dry weight, seed yield, harvest index, number of seeds per spike, and 1000 seed weight, among others, directly affect a crop's productivity and financial return.

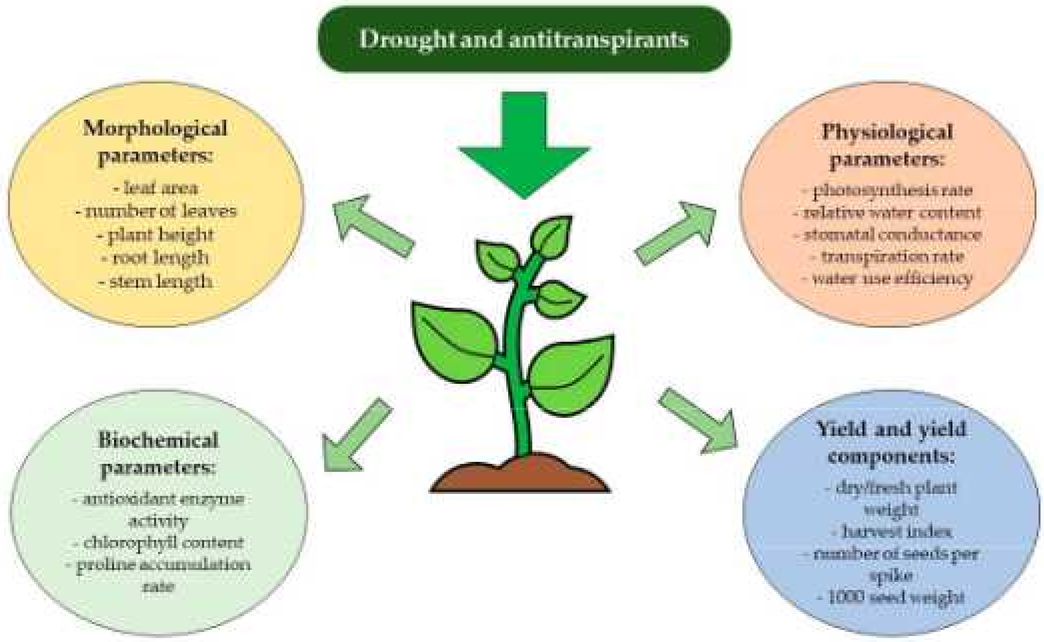

Figure 2. Examples of the effects of drought and antitranspirants on plant parameters.

3. Film-Forming Antitranspirants

3.1. Vapor Gard

One of the most widely used film-forming antitranspirants is Vapor Gard. Its formulation is based on polymer di-1-p-menthene (pinolene). According to Abdullah et al. [26], on wheat under drought, it was seen that plants treated with Vapor Gard used, on average, 45% less water than those untreated. Furthermore, under drought conditions, wheat with antitranspirant received higher grains per spike and more yield than without its use [26]. This is also confirmed by a later study, in which the application of Vapor Gard contributed to a significant increase in spring wheat yield (0.7–1.09 $Mg \cdot ha^{-1}$) under drought conditions. The treatment reduced drought-induced losses in the number of grains per square meter by an average of 13% [27]. Another study using di-1-p-menthene showed that yield decreased, but only when Vapor Gard was applied during the development stage from inflorescence emergence to anthesis. When it was treated before the most drought-sensitive stage (at the flag leaf stage), an improvement in yield was observed [28]. Moreover, research on winter wheat showed that an AT (di-1-p-menthene) applied under water deficit conditions affected yields by reducing grain losses caused by drought [29]. A study by Ouerghi et al. [30] showed that Vapor Gard under water deficit conditions increased leaf water potential in durum wheat and barley. However, at the same time, it was shown that using this antitranspirant at concentrations of 5, 7, and 10% did not reduce the negative effects of water stress on the photosynthetic rate. It was also found that Vapor Gard reduced water deficit, but only for a short time. Other measurements on wheat have demonstrated that, despite a reduction in photosynthesis, higher yields can be obtained when this antitranspirant is applied before the meiosis phase (which is drought-sensitive). This increase has been associated with improved pollen viability [31]. Additionally, an experiment on another plant in this family (maize) showed the positive effect of Vapor Gard on plant height and the number of leaves under water deficit conditions. Furthermore, an improvement in the leaf area index and also in the amount of plant dry matter was observed [32].

Table 1 shows research published since 2000 on the application of Vapor Gard on plants of the *Poaceae* family concerning drought stress. It can be seen that, among all plants, wheat was the dominant one on which experiments were most often conducted. The researchers mainly focused on evaluating aspects related to yield and its parameters. It is noteworthy that there is little research concerning the other plants. This overview shows that the number of experiments concerning the application of Vapor Gard and its effects on drought stress levelling on plants of the *Poaceae* family should be significantly increased. This is particularly relevant for plants that are key for human food security, such as rice and maize.

3.2. Silicon

A few articles also include silicon (Si) or silicone oils as antitranspirants [18,19,33]. However, in their review of antitranspirants, Mphande et al. [14] omitted silicon, arguing that, while it does have a drought-mitigating effect, it is not directly related to transpiration. During experiments conducted on maize, Gao et al. [34] observed that silicon significantly decreased transpiration rate and conductance for both adaxial and abaxial leaf surface [34]. It has also been noted that wheat leaves treated with Si under drought conditions are thicker, which may have the effect of reducing transpirational loss of water [35]. However, there are also studies in which different results were obtained. Measurements on rice showed that applying Si significantly increased the photosynthetic and transpiration rates under drought conditions [36]. Additionally, in wheat, Si under drought conditions contributed to an increase in net photosynthetic rate and transpiration rate, but regarding controls without this stress, no effect of Si on these parameters was observed [37]. Moreover, Gong and Chen [38] showed that silicon can improve photosynthetic ability and increase the leaf net photosynthetic rate in wheat under drought conditions. Rizwan et al. [39] in their review, state that the differential effect of silicon on transpiration is due to the dose applied and the crop type. They also point out that there is still a need for more detailed studies that will provide a better understanding of the effects of Si on gas exchange under drought stress conditions.

Numerous studies highlight that silicon is generally recognized as an element that alleviates plant drought stress [40–42]. However, researchers point out that the effect of its application in many cases is not clear-cut and depends on differences between species, genotypes, and also environmental conditions [43]. It has been observed that Si application increases dry maize matter but only under water deficit conditions. For well-watered plants, no significant differences were observed after the application of Si. Parveen et al. [44] also noted a positive effect on dry matter and showed that seed priming with Si in maize contributes to improving shoot and root lengths as well as their biomass [44]. Moreover, Si priming at a concentration of 0.006 mol·L^{-1} increased the chlorophyll content of the corn crop by 74% under drought stress conditions and by 55% under non-stress conditions [44]. The researchers emphasize that, despite the positive effect of Si on increasing chlorophyll levels under water deficit conditions, a value equal to plants under well-watered conditions was not achieved [45]. In the case of maize, silicon was also found to improve physiological performance, water use efficiency, and productivity under drought stress conditions [46]. Moreover, it has been observed that Si-applied corn shows a higher relative water content (RWC), water potential, and leaf area than untreated corn [35]. On the other hand, Kaya et al. [45] noted that RWC increased with silicon application but only under water deficit conditions. No significant differences were found in well-watered maize.

Improvements in RWC under drought conditions were also observed in wheat [38]. In their study, Gong et al. [47] also observed a correlation that Si use increased the water potential of drought-affected wheat plants at the filling stage but not at the booting stage. The application of silicon in wheat can also influence higher plant growth than those without Si [37]. In the case of sorghum, it was observed that Si application enhanced water uptake ability [48]. In addition, Si was found to reduce the negative effects of drought on dry matter decline in this crop. Interestingly, its beneficial effect was seen only under this stress, while under wet conditions, no effect of Si on this parameter was noticed [48]. Analogous results were obtained for rice, where Si had no effect on dry weight under wet conditions, but during drought stress, a definite improvement in this parameter was observed [36]. Another experiment on rice showed that Si significantly affected plant height growth, rice straw, root yield, and grain yield under reduced soil moisture conditions. It was found that silicon could reduce the water supplied to rice by 30% and maintain straw and grain yield at the same level as under full irrigation [49].

Table 1 shows the studies carried out on the application of silicon concerning drought on plants of the *Poaceae* family. It can be seen that, with the use of this AT, the researchers' interest in each group of parameters was similar, and they investigated morphological, physiological, and biochemical parameters as well as yield and yield components. Furthermore, it can be observed that research with silicon is more popular than with Vapor Gard.

Table 1. Examples of studies on using film-forming antitranspirants (Vapor Gard and silicon) concerning drought stress on *Poaceae* plants.

	Morphological Parameters		Physiological Parameters		Biochemical Parameters		Yield and Yield Components	
	Vapor Gard (di-1-p-Menthene)	Silicon	Vapor Gard (di-1-p-Menthene)	Silicon	Vapor Gard (di-1-p-Menthene)	Silicon	Vapor Gard (di-1-p-Menthene)	Silicon
Barley			[30]					
Forage grasses		[50]		[50]		[50]		[50]
Maize	[32]	[44,46,51]		[34,45,46,51,52]		[44–46,51]	[32]	[45,46,52]
Pearl millet		[53]				[53]		[53]
Rice		[36,49]		[36,49]		[36]		[36,49]
Sorghum		[48]		[48]				[48]
Sugarcane						[54]		
Wheat		[35,37,55]	[26,29,30,56]	[35,37,38,55,57]	[27,56]	[37,38,47,55,57]		[35,37,55]

4. Metabolic (Stomata-Closing) Antitranspirants

4.1. Chitosan

Scientists are increasingly studying the effects of chitosan on plants. In recent years, there has been a rapid growth in the number of published articles on its use on cereals [58]. This is because chitosan is one of the more widespread representatives from the metabolic (stomata-closing) antitranspirants group. Chitosan is a biopolymer derived from chitin. It is non-toxic, biodegradable, and often used as a crop biostimulant [59]. Researchers have noted the potential of chitosan for use on maize to increase water stress tolerance [60]. Measurements carried out under water deficit stress showed that using chitosan on maize increased the content of chlorophyll a, chlorophyll b, and relative water content. Under these conditions, there has also been a significant improvement in shoot length, shoot fresh and dry weights, root length, as well as root dry and fresh weights [52]. Similarly, in the case of wheat, a significant increase in germination rate, wet weight, root length, and root activity was observed after coating with chitosan [61]. Furthermore, it has been demonstrated that chitosan can partially mitigate the effects of drought on wheat, mainly by improving plant growth and development and consequently increasing yield [62]. Moreover, research on wheat under limited irrigation conditions showed an economical yield improvement after using chitosan. The beneficial effect was increased when it was applied together with hydrogel [63]. The exogenous use of chitosan has been demonstrated to improve many diverse parameters such as increases in chlorophyll content, carotenoid, yield parameters, flag leaf area, shoot dry weight, and water use efficiency (WUE) [56]. Moreover, other studies have shown that after the application of chitosan, parameters such as plant height, number of tillers per hill, flag leaf length, and flag leaf width increased compared to the control sample in water deficit. There was also a slight improvement in yield indices such as biological yield, grain yield, and harvest index. However, results exceeding the parameters under normal conditions (without drought) were not achieved [64]. Similar results to those reported by Burondkar et al. [64] were also obtained with chlorophyll and relative water content (RWC) by Singh et al. [65]. Other studies on wheat under drought conditions have shown that applying chitosan nanoparticles also increases grain yield. The highest value was obtained using the highest concentration of this agent tested (90 $\mu mol \cdot mol^{-1}$). It also tested whether the application method influenced AT's effectiveness. However, in this case, no significant differences were found between foliar and the soil-based application of chitosan [66].

Moolphuerk and Pattanagul [67] showed that, under drought conditions, rice treated with chitosan increased chlorophyll a, chlorophyll b, and water content. The improvement in these parameters is promising in the context of climate change. Furthermore, studies on rice have identified that chitosan induces drought resistance [68]. A significant increase in yield and its components was also observed. It is related to the fact that rice produces metabolites that close the stoma and, as a result, transpiration is reduced and plants use less water. This process helps them to survive the drought [69]. Nevertheless, through using chitosan and pusa hydrogel simultaneously under water deficit conditions, higher growth and yield parameters and RWC were achieved compared to the non-use of antitranspirants under normal conditions [64].

In a study of the chitosan application to pearl millet, drought was enforced by stopping irrigation during the flowering period. A reduction in stomatal conductance and limitation in transpiration were observed in the treated samples. Additionally, the use of chitosan caused higher leaf water status under these conditions than in unsprayed plants. Furthermore, 1000 grain weight and grain yield increased [70]. Research has also been conducted on creeping bentgrass (*Agrostis stolonifera* L.). It was recorded that chitosan could significantly improve drought tolerance in these plants. This has been confirmed by study results that show physiological changes, including higher RWC, cell membrane stability, and photosynthesis. Furthermore, under these conditions, chitosan promoted WUE and carbohydrate production [71]. The increases in all relevant parameters compared to the control plants, also under drought conditions, allows concluding that chitosan has the great potential to reduce the negative effects of drought. The tendency of chitosan nanoparticles to reduce the effects of drought stress was also demonstrated in barley. A significant increase in RWC, the 1000-grain weight, and grain protein was observed after its use [72]. Additionally, it has been reported that chitosan improves RWC, chlorophyll a and b, and barley growth parameters under reduced irrigation [73].

Research conducted to date on the *Poaceae* family has included not only the use of chitosan but also its derivatives, such as N-succinyl chitosan and N, O-dicarboxymethylated chitosan. Their application on maize contributes to the plant's tolerance to water stress [74]. Measurements carried out on maize hybrids after the use of chitosan showed that it affected the anatomy of the roots. Moreover, this change directly increases the adaptation of the plant to a period of stress [75]. The timing of AT application was also an interesting issue considered by the researchers. Studies of different dates of chitosan application (before, during, and after a drought) show that the best results were recorded when it was used before the drought. Extensive scientific research and the results discussed above indicate that chitosan can be considered as an effective tool for increasing plant resistance to drought.

The summary of the studies on applying this antitranspirant to drought (Table 2) shows that they were carried out on many aspects of both physiological, biochemical and yield parameters of plants from the *Poaceae* family. Experiments were performed on crops such as wheat, maize, rice, barley, sorghum, pearl millet, bermudagrass, or creeping bentgrass. Previous analyses show that scientific interest in this antitranspirant has increased significantly since 2000 [50]. Therefore, there is a chance that even more knowledge will soon become available for this agent, allowing it to be used more effectively.

4.2. Fulvic Acid (FA)

In studies conducted under drought condition, an increase in the water content of leaves was observed after the application of fulvic acid on winter wheat [76]. This result may lead to the conclusion that this metabolic-type antitranspirant can be an appropriate proxy in minimizing the negative effects of drought. As proof, a study in which soil was mixed with fulvic acid before having wheat grown on it under water stress conditions can be cited. These experiments showed that treatment with AT resulted in greater plant height and root length than plants from untreated soil [77]. Favorable results were also obtained with the maize treatment. CO_2 assimilation, photosynthesis, transpiration rate, and water-use efficiency were increased. Additionally, growth indicators such as the number of leaves, cob length, and fresh and dry weight were improved. Yield, biological yield, grain yield, and harvest index also increased [78]. It was also shown that this AT increased drought tolerance by affecting maize shoot growth and leaf physiology [79]. In a study conducted by Yang et al. [80], a non-significant increase in yield was noted after FA application under drought conditions on maize. Nevertheless, the application of this substrate in combination with a superabsorbent polymer (SAP) significantly increased yield and the number of grains by 19.1% and 23.1%, respectively [81]. A similar result was obtained regarding water use efficiency at the grain yield level of maize under water deficit conditions. FA treatment alone did not cause a significant effect, but together with SAP, contributed to an improvement of 25.3%. Yang et al. [80] suggested that a combination of SAP and FA could be particularly valuable in dry regions of the world.

During the current review, not many articles were found referring to the application of this AT on plants of the *Poaceae* family in the context of drought, as can be seen in Table 2. Therefore, it is important to continue research on the application of this antitranspirant in order to get a complete picture of its impact.

4.3. Salicylic Acid (SA)

Salicylic Acid is classified as a plant growth regulator substance and as an antitranspirant belonging to the metabolic group. Salicylic Acid (SA) is widely used in *Poaceae* crops. Research has been conducted with respect to its use on many crops such as corn, wheat, sorghum, and barley. Under drought conditions, studies of the application of SA on barley have shown that it improves parameters such as relative water content, nutrient contents, and proline accumulation [82]. In addition, an increase in RWC, dry mass improvements, photosynthesis, and net CO_2 assimilation rate was noted with the use of salicylic acid [83]. While conducting other research on the usage of SA, Fayez and Bazaid [84] noted improvements in chlorophyll a and b content, as well as the fresh weight of barley shoots under drought conditions. Additionally, the pre-treatment of barley in the early growth stage with this substance reduces the leaf cell membrane damage caused by water deficit [85]. A positive effect was also noted in the case of rice. As a result, an enhancement in plant height as well as seedling fresh and dry weight was observed [86]. Furthermore, parameters such as fresh and dry weight, RWC, leaf CO_2 net assimilation rate, a-amylase activity, and soluble sugars increased. Moreover, Farooq et al. [86] indicated that the method used to apply SA has an impact on the obtained results, as they showed that foliar application is more effective than seed treatment.

A positive effect was also observed in wheat (cv HD-2329), where plants treated with SA significantly increased dry weight, leaf chlorophyll, and moisture content [87]. Additionally, a subsequent study on two wheat varieties (drought susceptible—Basribey 95 and drought resistant—Ziyabey 98) showed that SA reduces the negative effects of drought. Improvements in parameters such as grains per spike, RWC and chlorophyll content, and antioxidant enzyme activity were observed [88]. In the case of the Zarrin wheat cultivar, improved growth and yield indices were observed when salicylic acid was applied. The plant height, number of tillers per square meter, grains number per spike, 1000 seed weight, and harvest index increased. This shows the drought-alleviating effect of SA [89]. The application of 0.0005 mol·L^{-1} of SA also had a significantly positive effect on wheat height and dry and fresh weight for the 'Yumai 34′ cultivar. Furthermore, a decline in the influence of drought was confirmed by the fact that the absolute water content improved [90]. In Roshan and Mahdavi wheat varieties, using SA mitigated the negative effects of drought stress and improved the vigor index [91]. An enhancement of the stomatal conductance of wheat was also obtained after using salicylic acid. However, a result equivalent to drought-free conditions was not achieved [92]. Nevertheless, the mitigating effect of salicylic acid on drought stress in wheat has been confirmed in several studies [93–96].

Another plant from the *Poaceae* family on which research is being conducted is sorghum. The frequency of this research is related to the fact that the main producers of this cereal are African countries, which, due to their location, often face problems related to water availability. In the case of this species, the application of AT has an alleviating effect against this stress [97]. Under drought conditions, plants treated with SA showed improvements in shoot length, fresh weight, and dry weight values compared to plants that were not treated with SA [98]. Furthermore, an improvement in emergence percentage and rate, chlorophyll b, and protein content was also observed in sorghum [99].

Studies conducted on maize under drought conditions occurring at the 10–12 leaf stage also showed a positive effect of salicylic acid. By applying SA, a significant increase in parameters such as plant height, ears height, length, leaf area, kernel row no per ear as well as per row were observed compared to plants without SA treatment [100]. For maize, foliar application of 100 μmol·mol^{-1} SA was also shown to increase chlorophyll and potassium content, RWC, and leaf membrane stability index under drought conditions. Interestingly, at a higher SA concentration (of 200 μmol·mol^{-1}), a decrease in all of the above parameters, except potassium content, was obtained [101]. The more favorable effect of smaller doses of salicylic acid on growth parameters was also confirmed by Manzoor et al. [102]. Their results show that among the concentrations of 0.005, 0.01, and 0.015 mol·L^{-1} of SA, the lowest dose had the best effect on maize during drought. Moreover, it was shown that SA pre-treatment delayed maize leaf rolling, which is a visual sign of water loss through drought stress to the plant. Hence, it can be concluded that SA reduces water loss and increases the activity of antioxidant enzymes [103].

Another species on which tests have been conducted are lemongrass (*Cymbopogon flexuosus* Steud. Wats.) varieties (Neema and Krishna). Under drought stress conditions, plants with foliar application of SA obtained higher chlorophyll and carotenoid levels. The growth parameters of lemongrass also increased [104]. Furthermore, research has also been conducted on zoysiagrass (*Zoysia japonica*). After exogenous SA pretreatment, they showed an increase in photosynthetic pigments, net photosynthesis rate, and enhancements in the antioxidant system. Thus, salicylic acid was found to reduce the effect of drought on zoysiagrass. Among the tested concentrations of 0.0001, 0.0005, and 0.001 mol·L^{-1} salicylic acid, 0.0005 mol·L^{-1} SA had the most beneficial effect [105]. Similar results were obtained on lolium grass (*Lolium perenne* cv. "Numan"), where an increase in the content of chlorophyll a and b was recorded after the foliar application of SA. These results demonstrate the potential of SA in combating the effects of drought on grasses [106].

As with the other antitranspirants in this group, examples of studies are shown in Table 2. Studies relating to this AT are on a broad spectrum, covering the physiological, biochemical, and yield parameters of plants in the *Poaceae* family. Measurements were carried out on plants such as barley, lemongrass, lolium grass, maize, pearl millet, rice, sorghum and wheat.

Table 2. Examples of studies on using metabolic antitranspirants (chitosan, fulvic acid, salicylic acid) concerning drought stress on *Poaceae* plants.

	Morphological Parameters			Physiological Parameters			Biochemical Parameters			Yield and Yield Components		
	Chitosan	**FA**	**SA**	**Chitosan**	**FA**	**SA**	**Chitosan**	**FA**	**SA**	**Chitosan**	**FA**	**SA**
Barley	[72,73]		[84]	[72,73]		[82,83,85]	[72,73]		[82–85]	[72,73]		
Bermudagrass				[107]			[107]					
Creeping bentgrass				[71]			[71]					
Lemongrass			[104]						[104]			[104]
Lolium grass									[106]			
Maize	[51,60,75,108,109]	[78,79]	[32,100,102, 110,111]	[51,60,74,75,109]	[76,78–81]	[101–103,110,112]	[51,60,74]	[76,78–81]	[101–103,110]	[60,109]	[76,78,80,81]	[32,100,110, 111]
Pearl millet	[70]		[113]	[70]		[113]	[70]		[113]	[70]		[113]
Rice	[67,69]		[86,114–118]	[67,119]		[86,114,115, 118,120,121]	[67,119]		[86,114–118,121–123]	[67,119]		[116–118,121,123]
Sorghum	[124]		[98,99]	[124]		[97]	[124]		[98,99]	[124]		[98,99]
Wheat	[55,61,62,64,77]	[125]	[88–93,95,96, 113,126–129]	[55,63,65,66]		[87,88,92,113, 126–129]	[55,61,63,65, 66,77]	[125]	[87,88,90,92–96,113,126, 128–131]	[55,61–64,66]	[125]	[87–92,113,126, 128,130,131]
Zoysiagrass						[105]			[105]			[105]

FA—fulvic acid, SA—salicylic acid.

5. Reflective Antitranspirants

5.1. Kaolin

Kaolin is popular antitranspirant and a naturally occurring aluminosilicate mineral that is often found on the agricultural formulation market under the commercial name Surround®. It is a powder that is mixed with water and then sprayed on crops, on which it forms a white coating to protect the plants [132]. Youssef et al. [133] conducted studies under different levels of drought stress (100, 80, and 60% ETc evapotranspiration) on Giza 10 maize. When 5% kaolin was applied at both 60 and 80% ETc, higher plant height, leaf flag fresh, and dry weight results were achieved compared to maize samples with 100% ETc and without kaolin. Similar effects were obtained for yield indices such as cob length, number of grains per cob, and 100-grain weight. These results show that using kaolin makes plants use up to 40% less water and can save irrigation water for maize. Moreover, with the application of this AT, the same or even higher yields can be obtained [133]. In studies conducted on rice and different rates of kaolin (4%, 6%, and 8%), an increase in dry matter was noted on treated plants under water deficit conditions. The best results were obtained with 6% kaolin, at which an increase in straw yield, grain yield, and biological yield was recorded, while a dose of 8% kaolin was not as effective [134]. The positive effect of this antitranspirant has also been confirmed by studies conducted on wheat (cv. Gimeza 7). The use of kaolin under drought conditions contributed to improved growth parameters, yield components, photosynthetic pigments, and carbohydrate constituents [135]. Another study on wheat (cv. Sakha 93) revealed that the application of kaolin at both 4% and 6% resulted in increases in the plant height, leaf area, and dry weight of plant roots compared untreated plants under water stress conditions. Moreover, it also positively affected yield components such as 1000-grain weight, number of grains per plant, and dry weight of grains per plant [125].

Table 3 presents a set of studies relating to the application of kaolin on *Poaceae* plants in the context of drought. It can be observed that research on its effect on physiological parameters is not popular. Therefore, the proportion of experiments covering this issue should be increased. Furthermore, it is noticeable that measurements were mainly conducted on the most popular cereals, such as barley, maize, rice, and wheat.

5.2. Magnesium Carbonate $MgCO_3$

Studies regarding the use of magnesium carbonate (6 and 10%) on wheat have shown the beneficial effect of this antitranspirant on plant height, chlorophyll a and b, leaf area, and 1000-grain weight under water stress conditions [125]. Other studies under drought conditions have confirmed that this AT allows less reduction in wheat yields. Measurements proved that drought reduced grain yields by 24.25%. However, after the application of this antitranspirant, the negative effect of drought was mitigated to 9.98% [136]. A reduction in yield losses during drought was also observed in barley [137]. The useful influence of $MgCO_3$ in offsetting the negative effects of drought in barley has also been confirmed by subsequent research. These studies showed that the substance increases water use efficiency [138]. Another study on the same plant showed that using $MgCO_3$ under drought conditions also positively affects chlorophyll and RWC, indicating that $MgCO_3$ has a high potential for use on crops in arid and semi-arid areas [82].

Through analyzing previous studies, it can be seen that a similar trend is apparent for $MgCO_3$ as for kaolin. Studies covering physiological parameters are scarce and therefore should be continued. A detailed overview covering the different groups of plant parameters studied in relation to drought and the application of this AT is summarized in Table 3.

Table 3. Examples of studies on the use of reflective antitranspirants (kaolin, magnesium carbonate) concerning drought stress on *Poaceae* plants.

	Morphological Parameters		Physiological Parameters		Biochemical Parameters		Yield and Yield Components	
	Kaolin	$MgCO_3$	Kaolin	$MgCO_3$	Kaolin	$MgCO_3$	Kaolin	$MgCO_3$
Barley		[137,138]		[82,138]		[82,137]		[137,138]
Maize	[32,133]				[133,139]	[139]	[32,133,139]	[139]
Rice	[140]	[141]				[141]	[134,140]	[141]
Wheat	[125,135]	[125,136]			[125,135]	[125]	[125,135]	[125,136]

6. Risks, Uncertainties, and Future Perspectives for the Use of Antitranspirants

Despite a large number of studies reporting beneficial effects of antitranspirants, some also indicate their absence or negative effects in terms of drought stress mitigation. For example, Ouerghi et al. [30], in their study on durum wheat and barley, did not observe a significant effect of using Vapor Gard on the photosynthetic rate. Thus, this AT did not reduce the negative effect of water stress on this parameter. In measurements using magnesium carbonate, this AT had no clear effect on wheat parameters such as the number of spikes per plant, the number of grains per spike, and the number of grains per plant [125]. Furthermore, the results of experiment on maize and winter wheat indicated an increase in drought sensitivity after treatment with salicylic acid [112]. Moreover, pre-treatment with SA reduced drought tolerance in the wheat cultivar Chinese Spring, but there was no effect on another cultivar tested called Cheyenne [129]. This demonstrates that SA can have different effects on various cereal varieties. Other studies on wheat have shown even more divergent results. Two wheat cultivars on which an exogenous SA was applied under normal conditions demonstrated increased fresh and dry mass of shoots and roots. However, under water stress and with the same SA dose, one cultivar showed a reduction in shoot fresh and dry weights, while the other presented an improvement [127].

The above results indicate that sometimes inconclusive effects regarding the use of antitranspirants have been obtained on *Poaceae* plants. At the same time, it should be noted that scientists are reluctant to publish inconclusive results, and it is also unclear how many parameters and results have been omitted in articles. Furthermore, it is also problematic that the results obtained regarding the use of antitranspirants may depend on the type of plant, the antitranspirant, its dose, the time of application, as well as the characteristics of the environment, and it is often difficult to compare previous studies with each other. This review shows that, despite years of research on various species, further studies are needed to identify factors that directly influence the achieved effects. Once more research has been carried out, thorough analyses need to be conducted to determine which antitranspirant and at what dose will be the most effective solution to offset the effects of drought stress for a given species.

Concerning plants belonging to the *Poaceae* family, particularly the key food-safety crop, it is extremely important to carry out financial analyses. Therefore, estimating exactly how much financial input will be needed to apply antitranspirants in the field is necessary. This is crucial from the farmer's point of view, as the use of AT will not make sense if the total cost of treatment is greater than the damage caused by the drought. Therefore, before the use of AT becomes widespread, there is a need for more research combined with crop-specific cost–benefit analyses.

Furthermore, it should be noted that many uncertainties are still associated with the widespread application of antitranspirants in agriculture. Mphande et al. [14] in their review article, highlight the risks of AT application in terms of potential negative environmental effects. The researchers suggest that, while the effects on AT on individual species are being studied, a broader approach concerning the environment is lacking. In addition, scientific reports shows that these products may also reduce the occurrence of plant pests and, even worse, their natural enemies. Mphande et al. [14] emphasize the need for research in this area to obtain a comprehensive picture of the impact of antitranspirants.

7. Conclusions

The present review demonstrates that further measurements are still needed despite the many studies in the field of antitranspirants. The summaries of AT applications for individual *Poaceae* plants and for parameter groups presented in this article have identified less common research areas relating to drought. It was concluded that it is desirable to increase the number of experiments involving the application of Vapor Gard to plants other than wheat. Looking at the AT analyzed, relatively few articles examine the impact of fulvic acid application in the context of drought. Concerning the reflective AT group, emphasis should be placed on the study of physiological parameters, as most of the articles published to date practically disregard this aspect. Furthermore, when analyzing the studies previously carried out, it is noticeable that scientists mainly focus their research on the more common cereals, such as wheat or maize, and less emphasis is placed on the other plants of the *Poaceae* family. On the positive side, the scientific community's interest in antitranspirants has been growing in recent years, and more and more work is focusing on identifying their effects on plants [58]. This gives hope that soon all of the gaps mentioned above will be filled, and as a result, there will be a significant increase in the knowledge of AT applications.

This review shows the great potential of using antitranspirants to reduce the impact of drought stress of plants in the *Poaceae* family. It demonstrates that antitranspirants can mitigate the adverse effects caused by this stress and improve many plant growth and yield parameters. However, it must be taken into account that the plant species, genotype, environment, type of antitranspirant, and rate of application are key factors that influence the final result and effectiveness. The differential response of plants to AT application depending on several factors has already been signalled in previous work [27,142]. Furthermore, it is important to note that, often in field crops, there is not only just one stress factor but several occurring simultaneously. It is also not uncommon to see a combination involving not only two abiotic factors (e.g., drought and high temperature) but also stresses categorized as abiotic and biotic occurring simultaneously. A prime example is the occurrence of drought together with pathogen infection [143,144]. Scientists emphasize that it is crucial for agricultural production to find ways to allow plants to comprehensively cope with simultaneous stresses of both biotic and abiotic origin [145]. Therefore, future research should continue to analyze the interaction and joint effects of a wide range of stresses on crops and look for solutions that can offset their negative effects on plants. It was also noted that it would be interesting to perform measurements on the joint effects of agronomic treatments and antitranspirant applications [27,142]. It should also be noted that this review and previous studies practically do not consider financial factors. Before the use of AT as a solution to offset the effects of drought stress becomes widespread, detailed analyses should be carried out regarding what costs the farmer will have to bear for applying this treatment. This review shows that antitranspirants have great potential for drought mitigation in *Poaceae*, but further research is still required to obtain a full view of the impact of their widespread use.

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4.2 Wpływ aplikacji krzemu i poziomu wód gruntowych w systemie nawodnienia podsiąkowego na plonowanie trzykośnej łąki

Publikacja P2:

Kocięcka, J., Liberacki, D., Kupiec, J. M., Stróżecki, M., & Dłużewski, P. (2023). Effects of Silicon Application and Groundwater Level in a Subirrigation System on Yield of a Three-Cut Meadow. *Water*, *15*(11), 2103. https://doi.org/10.3390/w15112103

Stosunkowo niewiele uwagi w dotychczasowych pracach naukowych poświęcono zastosowaniu antytranspirantów na roślinach z rodziny traw, które nie są popularnymi zbożami. Niniejsza publikacja miała za zadanie wypełnienie tej luki i zbadanie wpływu aplikacji antytranspirantu z krzemem na trzykośnej łące. W doświadczeniu wykorzystano istniejący system nawodnienia podsiąkowego, aby zidentyfikować oddziaływanie AT w różnych warunkach pod względem poziomu wody gruntowej. Pomiary przeprowadzono na czterech poletkach na obiekcie badawczym z rozdziału 3 niniejszej rozprawy doktorskiej. Głównym celem pracy P2 było określenie wpływu zastosowania antytranspirantu z krzemem na plonowanie trzykośnej łąki z systemem nawodnienia podsiąkowego.

Przeprowadzenie eksperymentu poprzedzono badaniami terenowymi mającymi na celu określenie podstawowych parametrów gleby. Podczas trwania doświadczenia monitorowano warunki meteorologiczne, a także wilgotność gleby i poziomy wody gruntowej. Zidentyfikowano również występujące gatunki roślin oraz oceniono bioróżnorodność poletek badawczych przy wykorzystaniu indeksów Shannona–Wienera, Simpsona, a także Sørensena (Shannon, 1948; Simpson, 1949; Looman i in., 1960). Ponadto w ramach doświadczenia wykonywano pomiary wysokości roślin oraz wskaźnika NDVI. Po każdym z pokosów pobierano biomasę z poletek badawczych, a następnie suszono ją aby ocenić wielkość plonu. Uzyskane rezultaty poddano analizom statystycznym umożliwiającym zweryfikowanie hipotezy badawczej mówiącej, że aplikacja antytranspirantu z krzemem istotnie wpływa na plonowanie łąki.

Przeprowadzone badania wykazały, że roczny plon w 2021 roku dla poletka HWL wyniósł 12,69 $Mg \cdot ha^{-1}$, a dla LWL 12,05 $Mg \cdot ha^{-1}$. Widoczny jest zatem wyraźny pozytywny wpływ wysokiego poziomu wody na roczny plon łąki. Na poletkach z zaaplikowanym antytranspirantem z krzemem odnotowano niższe wartości wynoszące odpowiednio 10,43 $Mg \cdot ha^{-1}$ dla HWL_Si oraz 10,36 $Mg \cdot ha^{-1}$ dla LWL_Si. W oparciu o te rezultaty stwierdzono, że AT z krzemem powoduje redukcję plonu o 17,8% w skali roku dla obszaru z wyższym poziomem wody oraz o 14% dla obszaru z niższym poziomem wody. Rozpatrując wyniki dla poszczególnych pokosów zauważalna jest ta sama tendencja. Potwierdza ją przeprowadzona analiza statystyczna, która wykazała, że antytranspirant z krzemem istotnie wpłynął na obniżenie plonów w każdym z trzech pokosów łąki w 2021 roku.

W artykule P2 zrealizowano cel rozprawy doktorskiej:

C1) Określenie wpływu zastosowania antytranspirantu zawierającego krzem na plonowanie trzykośnej łąki z uwzględnieniem poziomu wody gruntowej w systemie nawodnienia podsiąkowego.

Niniejsza praca obejmuje zakres rozprawy doktorskiej:

Z3a) Przeprowadzenie dwuletnich pomiarów na trzykośnej łące obejmujących określenie wpływu zastosowania antytranspirantu z krzemem i wysokiego poziomu wody gruntowej w systemie nawodnienia podsiąkowego na wielkość plonu masy nadziemnej roślin.

Ponadto w publikacji P2 zweryfikowano hipotezę badawczą:

H1) Zastosowanie antytranspirantu z krzemem istotnie wpływa na plon trzykośnej łąki.

water

Article

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 $Mg \cdot ha^{-1}$, whereas when silicon was applied to this area, it was 10.43 $Mg \cdot ha^{-1}$ (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·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 (μmol·m^{-2}·s^{-1}), wind speed (m·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):

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

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)):

$$H' = -\Sigma\,(pi * \log2\ pi) \tag{2}$$

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_j—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.

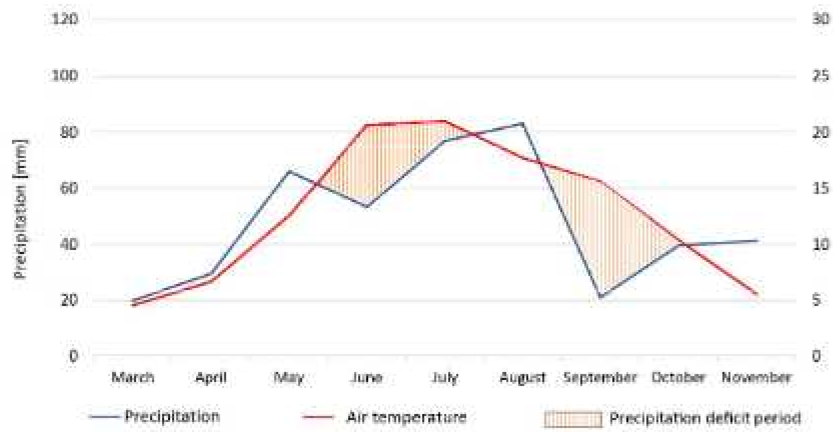

Figure 1. Gaussen–Walter climate diagram with Łukasiewicz modification for the 2021 growing season in Racot.

The characterization of pluvio-thermal conditions carried out using the Sielianinov 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 Sielianinov hydrothermal coefficient *k*.

Month	March	April	May	June	July	August	September	October	November
Sielianinov 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.

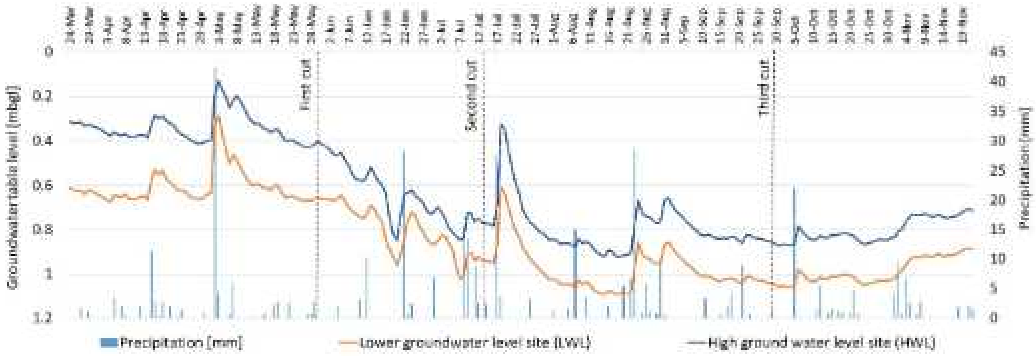

Figure 2. Groundwater levels in 2021 with daily precipitation totals for the measurement sites.

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 $g{\cdot}cm^{-3}$ in the humus horizon (Ap) to 1.66 $g{\cdot}cm^{-3}$ 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.

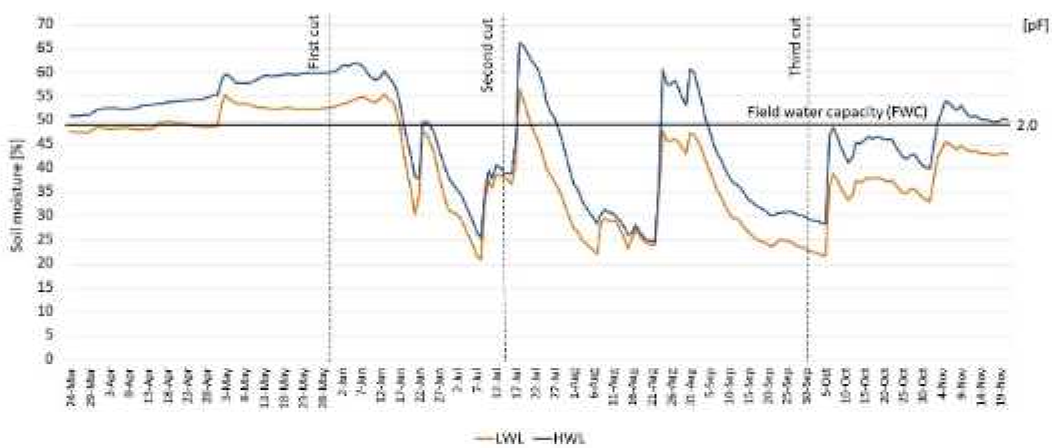

Figure 3. The soil moisture course at the 0–20 cm level in the HWL and LWL sites during the growing season.

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).

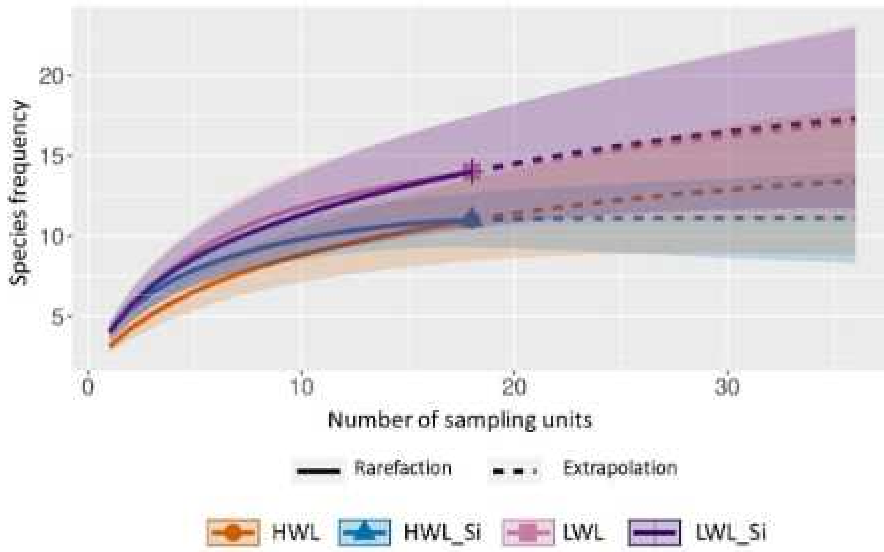

Figure 4. Chao's frequency of identified species occurrence curves for each of the four measurement combinations. Solid lines are rarefaction curves based on sample size, and dashed lines are extrapolation sampling curve. The solid symbols (dots/triangles/squares/dashes) mark the reference samples. The 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.

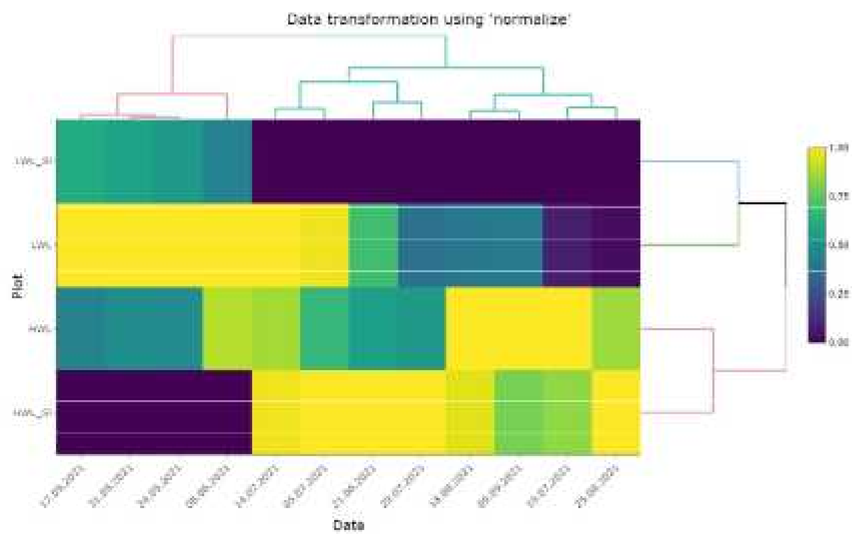

Figure 5. Heat map of the obtained normalized plant heights from individual plots.

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 $\alpha = 0.05$.

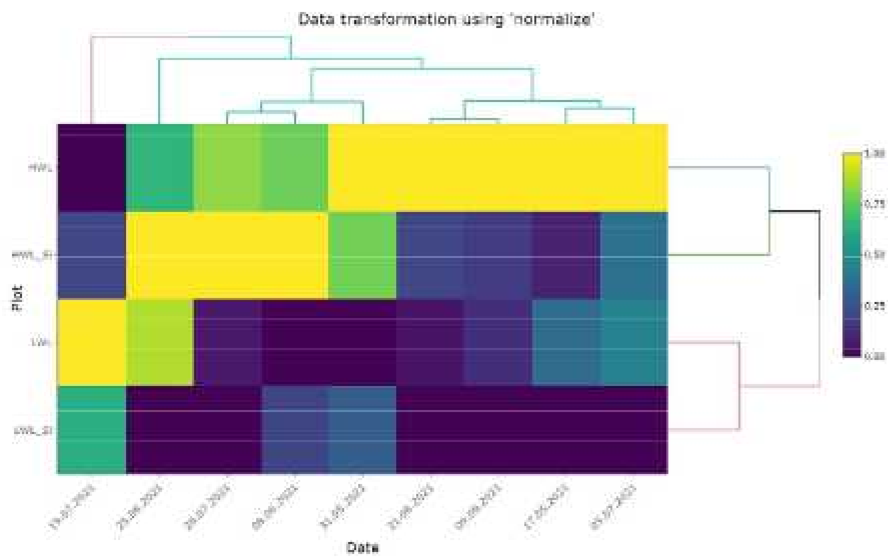

Figure 6. Heat map of the obtained normalized NDVI values from individual plots.

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.

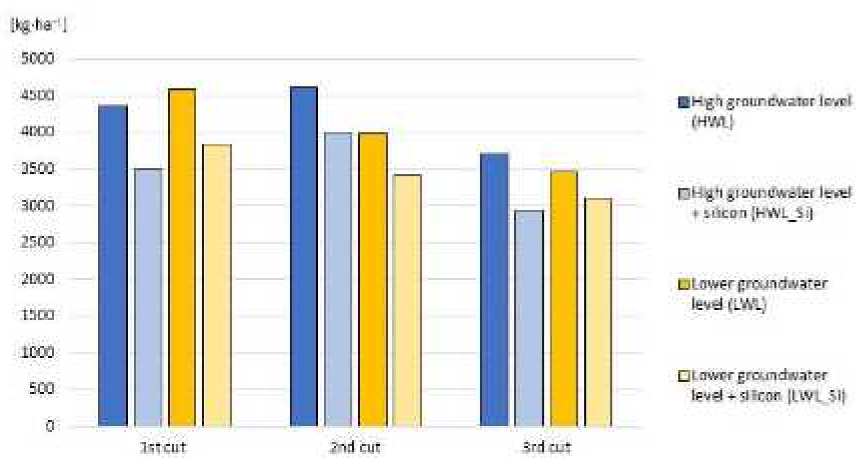

Figure 7. The amount of dry matter obtained in each cut of the meadow [kg·ha^{-1}].

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 $Mg \cdot ha^{-1}$. (Figure 8). From the high groundwater level + silicon (HWL_Si) plot, the annual dry matter volume was 10.43 $Mg \cdot ha^{-1}$. 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 $Mg \cdot ha^{-1}$). 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 $Mg \cdot ha^{-1}$ 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.

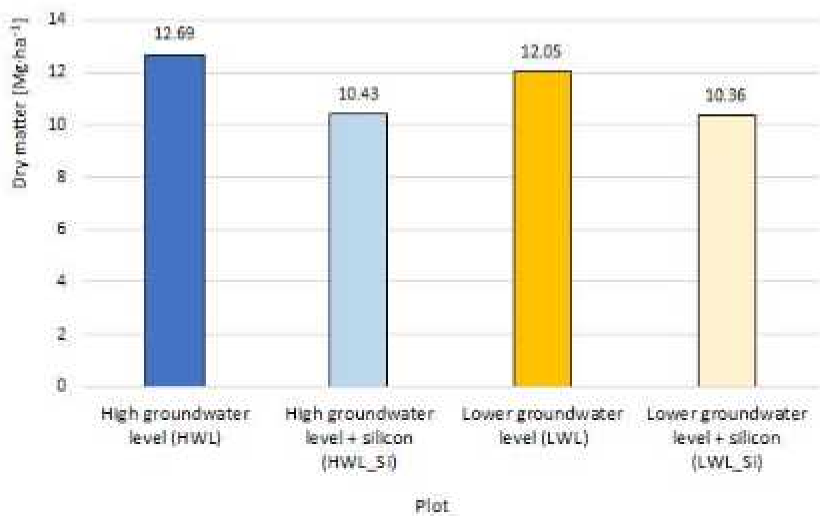

Figure 8. Total dry matter yield over the entire growing season for individual plots [$Mg \cdot ha^{-1}$].

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 $Mg \cdot ha^{-1}$) 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 $Mg\cdot ha^{-1}$, whereas when silicon fertilizer Optysil was applied at a rate of 0.5 $dm^3\cdot ha^{-1}$, the dry matter yield was 5.26 $Mg\cdot ha^{-1}$, and at a rate of 0.8 $dm^3\cdot ha^{-1}$, it was 5.66 $Mg\cdot ha^{-1}$. 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 $kg\cdot ha^{-1}$ for Herbagreen fertilizer and 1 $l\cdot ha^{-1}$ 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 $l\cdot ha^{-1}$ 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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4.3 Wpływ nawodnienia podsiąkowego i stosowania antytranspirantu z krzemem na plon i bilans ditlenku węgla na trzykośnej łące

Publikacja P3:

Kocięcka, J., Stróżecki, M., Juszczak, R., Liberacki, D. (2023). Effect of Subirrigation and Silicon Antitranspirant Application on Biomass Yield and Carbon Dioxide Balance of a Three-Cut Meadow. *Water, 15*(17), 3057. https://doi.org/10.3390/w15173057

Zastosowanie antytranspirantów może bezpośrednio oddziaływać na parametry wzrostu roślin oraz ich plonowanie co dowodzą wcześniejsze badania. Jednakże, kwestii czy użycie tych środków może wpłynąć na emisję CO_2 nie poświęcono dotychczas zbytniej uwagi. Według posiadanej przeze mnie wiedzy publikacja P3 jest pierwszą poruszającą to zagadnienie w odniesieniu do aplikacji AT z krzemem na łące. Głównym celem tej pracy była ocena wpływu zastosowania AT z krzemem oraz poziomu wody gruntowej w systemie nawodniania podsiąkowego na trzykośnej łące na strumienie netto CO_2 oraz wielkość plonu.

Pomiary w niniejszej pracy były prowadzone na tym samym obiekcie badawczym co w artykule P2 – trzykośnej łące w Racocie z zachowaniem układu czterech poletek: HWL, HWL_Si, LWL oraz LWL_Si. Eksperyment obejmował lata: 2021 oraz 2022. W czasie trwania doświadczenia prowadzono systematyczne kampanie pomiarowe strumieni CO_2 przy zastosowaniu metody dynamicznych komór zamkniętych (Juszczak i in., 2013; Acosta i in., 2017). Uzyskane z nich wyniki posłużyły do wymodelowania dla poszczególnych poletek dziennych wartości następujących strumieni CO_2: produkcji pierwotnej brutto (GPP), oddychania ekosystemu (Reco) oraz wymiany netto ekosystemu (NEE). Następnie przy zastosowaniu testów statystycznych zweryfikowano hipotezę mówiącą, że zastosowanie antytranspirantu z krzemem, a także wysoki poziom wody gruntowej w systemie nawodnień podsiąkowych, znacząco wpływa na dzienne strumienie CO_2 na łące. Finalnym etapem pracy było obliczenie skumulowanych w pokosach, sezonach wegetacyjnych oraz rocznych wartości GPP, Reco oraz NEE. Ponadto w ramach doświadczenia po każdym z pokosów pobierano biomasę do oceny wielkości plonu.

Przeprowadzone badania wykazały, że w roku 2021 (który był chłodniejszy i bardziej suchy, niż 2022) na wszystkich poletkach badawczych dominowała emisja CO_2 (dodatnie wartości NEE), natomiast w drugim roku eksperymentu (2022) przeważała asymilacja CO_2 (ujemne wartości NEE). Uśredniona dla wszystkich poletek wartość NEE wyniosła w 2021 roku +247.4 $gCO_2\text{-}C{\cdot}m^{-2}y^{-1}$, a w 2022 roku −187.4 $gCO_2\text{-}C{\cdot}m^{-2}y^{-1}$. Ponadto można zaobserwować, że w obu latach na obszarze z wyższym poziomem wody gruntowej zastosowanie antytranspirantu z krzemem pozytywnie wpłynęło na strumienie netto CO_2 zwiększając pochłanianie lub zmniejszając emisje w zależności od analizowanego roku. Odziaływanie antytranspirantu z krzemem na obszarze z wysokim poziomem wody gruntowej potwierdzono również w analizach statystycznych, które wykazały, że dzienne strumienie GPP, Reco oraz NEE znacząco różnią się między poletkami HWL, a HWL_Si w każdym z pokosów. Pozytywny wpływ AT na tym obszarze odnotowano także w odniesieniu do skumulowanych w sezonach wegetacyjnych wartości GPP.

Ponadto stwierdzono, że aplikacja antytranspirantu z krzemem negatywnie wpływa na uzyskaną wielkość plonu w skali roku oraz w poszczególnych pokosach. Redukcja plonu widoczna była zarówno na obszarze z wysokim jak i z niższym poziomem wody gruntowej. Analizując wpływ zastosowania piętrzenia wody w nawodnieniu podsiąkowym można zauważyć, że obszar z wysokim poziomem wody gruntowej charakteryzował się wyższymi rocznymi plonami, niż ten z niższym poziomem wody gruntowej. W 2021 uzyskano o 5,4% wyższe plony na poletku HWL niż na LWL, a w 2022 o 11,7 %.

W artykule P3 zrealizowano cele rozprawy doktorskiej obejmujących określenie wpływu zastosowania antytranspirantu zawierającego krzem na:

C1) plonowanie trzykośnej łąki;

C2) wymianę netto strumieni ditlenku węgla na trzykośnej łące;

z uwzględnieniem poziomu wody gruntowej w systemie nawodnienia podsiąkowego.

Niniejsza praca obejmuje zakres rozprawy doktorskiej:

Z3) Przeprowadzenie dwuletnich pomiarów na trzykośnej łące obejmujących określenie wpływu zastosowania antytranspirantu z krzemem i wysokiego poziomu wody gruntowej w systemie nawodnienia podsiąkowego na:

Z3a) wielkość plonu masy nadziemnej roślin;

Z3b) dzienne oraz skumulowane w pokosach, sezonach wegetacyjnych i poszczególnych latach wartości strumieni produkcji pierwotnej brutto (GPP), oddychania ekosystemu (Reco) oraz wymiany netto CO_2 (NEE).

Ponadto w publikacji P3 zweryfikowano hipotezę badawczą:

H2) Zastosowanie antytranspirantu z krzemem, a także wysoki poziom wody gruntowej w systemie nawodnień podsiąkowych, istotnie wpływa na dzienne strumienie CO_2 na łące.

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Effect of Subirrigation and Silicon Antitranspirant Application on Biomass Yield and Carbon Dioxide Balance of a Three-Cut Meadow

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Abstract: Meadows are valuable areas that play an important role in the carbon cycle. Depending on several factors, these areas can be carbon sinks or net emitters of carbon dioxide (CO_2) into the atmosphere. In the present study, the use of an antitranspirant (AT) with silicon and the groundwater level in a subirrigation system in a three-cut meadow were evaluated on the carbon dioxide exchange balance and the yield of aboveground biomass. The study was carried out in four experimental plots: with high groundwater level (HWL), with a high water level with AT application (HWL_Si), with a lower groundwater level (LWL), and with a lower groundwater level and AT application (LWL_Si). Flux measurements were made using the closed dynamic chamber method. In the drier and colder 2021, the meadow was a net CO_2 emitter (mean annual net ecosystem exchange (NEE) of all plots: +247.4 $gCO_2\text{-}C{\cdot}m^{-2}y^{-1}$), whereas in the more wet and warmer 2022, assimilation outweighed emissions (mean annual NEE of all plots: -187.4 $gCO_2\text{-}C{\cdot}m^{-2}y^{-1}$). A positive effect of the silicon antitranspirant application was observed on the reduction of carbon dioxide emissions and the increase of gross primary production (GPP) from the plots with higher groundwater levels. For the area with lower water levels, the positive impact of AT occurred only in the second year of the experiment. The yield of aboveground biomass was higher by 5.4% (in 2021) up to 11.7% (in 2022) at the plot with the higher groundwater level. However, the application of AT with silicon contributed to yield reduction in each cut, regardless of the groundwater level. On an annual basis, AT application with silicon reduced the yield by 11.1–17.8%.

Keywords: grassland; net ecosystem exchange; CO_2 emission; subirrigation; groundwater level; yields; silicon; antitranspirant

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1. Introduction

In the face of ongoing climate change, with an increasing greenhouse gas concentration in the atmosphere, it is crucial to take rational measures to limit emissions of these gases from terrestrial ecosystems. Farming is recognized as a sector that significantly contributes to greenhouse gas (GHG) emissions and temperature rise in the atmosphere, both through agricultural production and soil processes [1,2]. Essential components of agriculture production are grasslands, which can act either as a carbon dioxide sink or source [3]. The amount of carbon assimilated or emitted by a meadow ecosystem is determined by its intended use, soil type and its moisture, and type of plant communities and their biomass, as well as meteorological and climate conditions [4]. Grasslands, especially the ones on organic soils, are very sensitive to changes in groundwater levels [5]. It is worth noting that many meadows have been formed due to the drainage of former peatbogs [6,7]. A decrease in the water table depth (WTD) and moisture content of these areas has initiated the decay and mineralization processes of peat, resulting in increased carbon dioxide emissions to the atmosphere [8]. Therefore, it is essential to introduce appropriate water management practices to grasslands to limit soil degradation processes and reduce GHG emissions from organic soils.

Many researchers emphasize that the proper use of drainage infrastructure in grassland areas is extremely important and can improve water management efficiency and reduce the outflow of nitrates from agricultural areas [9,10]. Furthermore, solutions based on managed drainage and irrigation could help mitigate climate change and its effects on agriculture by reducing drought and flood risks [11,12]. Also, it has been shown that a traditional meadow irrigation technique with an open ditch system, previously used in various parts of Europe, is an appropriate management practice that meets ecological and economic objectives [13]. Regulated water management in grassland areas significantly affects the GHG emissions from these ecosystems [14,15]. Properly used and irrigated grasslands can contribute even to CO_2 sequestration [14,16–18]. Therefore, it is rational to raise groundwater levels by subsoil irrigation to a level where the balance of carbon dioxide exchange between the soil and the atmosphere would be sustainable [19]. However, it should also be noted that re-moistening of soils causes direct changes in the composition of vegetation, reflecting new, more humid conditions, increasing biodiversity, restoring carbon cycle processes, and resuming carbon accumulation [20–23].

The proper irrigation of grasslands thus appears to be a valid measure with the biggest potential to reduce CO_2 emissions from soils. Unfortunately, this is an increasingly difficult task to achieve due to limited water resources in many regions of the world, the current climate change, and the increasing frequency of drought periods [24]. Therefore, looking for other alternative methods independent of longitude and latitude, and thus climatic conditions, is crucial. A potential solution for reducing water losses from meadows, which may potentially regulate processes controlling carbon turnover and emissions, could be the application of antitranspirants, i.e., products that reduce transpiration. Among the most popular antitranspirants applied in agronomic practices are Vapor Gard, kaolin, chitosan, and abscisic acid. Previous research showed the great potential of antitranspirants in adapting plants to drought periods [25–28]. It was also proved that the application of Vapor Gard on commercial grass (*Festuca arundinacea* and *Poa pratense*) significantly reduces transpiration but has a negative impact on CO_2 uptake [29]. However, the question of whether these measures can affect carbon dioxide emissions and balance has received no attention and has not been thoroughly investigated and explained.

Therefore, the aim of this study is to evaluate the effects of the application of an antitranspirant (AT) containing silicon and the groundwater level in a subirrigation system in a three-cut meadow on the carbon dioxide fluxes and seasonal balance. The effects of these treatments on the meadow productivity expressed in terms of carbon dioxide assimilated and aboveground plant biomass produced were also analyzed. In addition, the research hypothesis that the foliar application of antitranspirant with silicon, as well as higher groundwater levels, significantly affect daily CO_2 fluxes was verified.

2. Materials and Methods

2.1. Site Description

The study was conducted in 2021–2022 on a meadow (52°03′47′′ N, 16°41′46′′ E) located in Racot, 50 km south of Poznań, the Wielkopolska region, Poland (Figure 1). This meadow is occupied by species such as *Capsella bursa*, *Carex* sp., *Chenopodium album*, *Cirsium rivulare*, *Elymus repens*, *Galium mollugo*, *Glechoma hederacea*, *Lamium album*, *Lamium purpureum*, *Phalaris arundinacea*, *Poa pratensis*. *Polygonum bistorta*, *Ranunculus auricomus*, *Rumex obtusifolius*, *Stellaria media*, *Taraxacum officinale*, *Veronica chamaedrys*, *Veronica persica*. The meadow is cut three times a year for animal feed. In 2021, the cutting took place on 31 May, 14 July, and 30 September, and in 2022 on 6 June, 15 August, and 17 November. The soil consists mainly of fine-grained loose sands, which form Mollic Gleysols. The field water capacity (FWC) for the 0–20 cm soil layer equals 49%. A more detailed soil characterization for the study area is described by Kocięcka et al. [30].

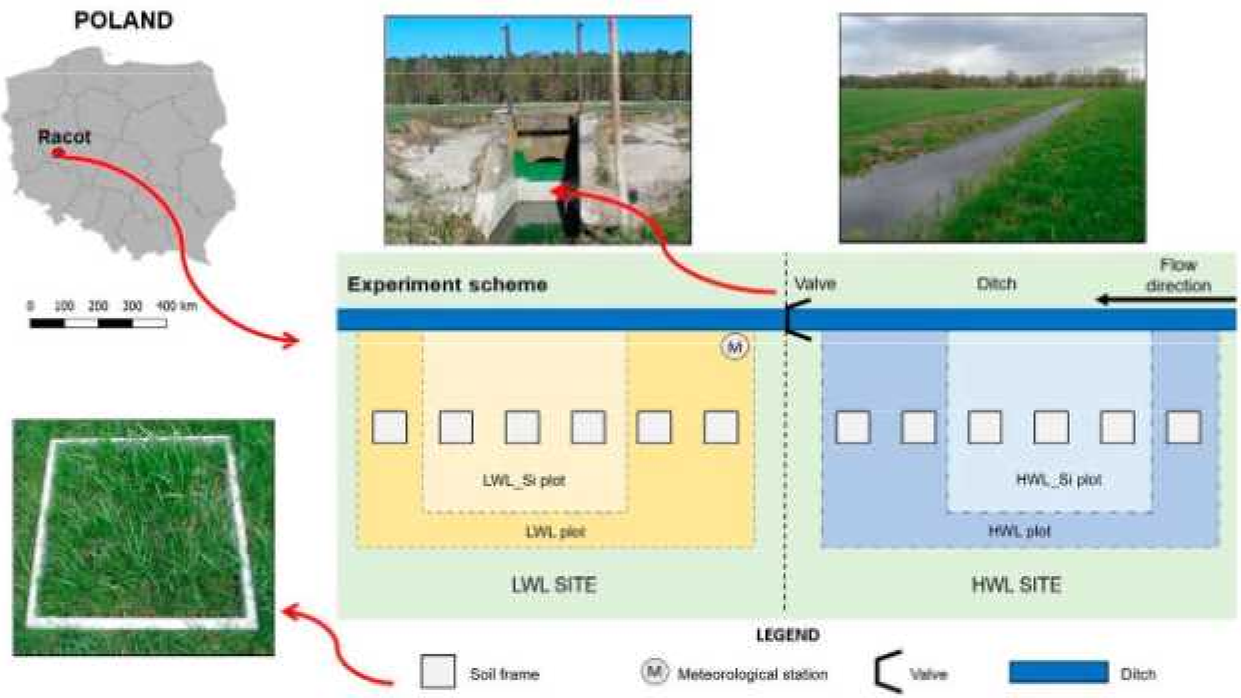


Figure 1. Location of the Racot meadow and scheme of the experiment.

2.2. Experimental Design

A subirrigation system in this area is used to dam the water and regulate the groundwater level. The experiment was carried out on a part of a meadow located directly next to a ditch where a valve damming the water is located (Figure 1). The valve was closed throughout the experiment, which allowed a difference in groundwater levels to be maintained in the area upstream and downstream of the damming. Thus, two distinct sites differing in groundwater level were obtained: high groundwater level (HWL) and lower groundwater level (LWL).

As part of the experiment, an antitranspirant (AT) called *Krzemian* from Chemirol (Poland) was applied to parts of the meadow at both the HWL and LWL sites. The control plots, without chemical treatment, are called HWL and LWL, while the ones with *Krzemian* application are called HWL_Si and LWL_Si for sites with higher and lower WTD, respectively. The applied *Krzemian* consists of orthosilicic acid and micronutrients such as boron, copper, molybdenum, and zinc [31]. It was sprayed foliarly at the beginning of the growing season and after each meadow cutting at a rate of 0.8 L·ha^{-1} with a hand sprayer.

At each of the four experimental plots (HWL, HWL_Si and LWL, LWL_Si), three soil frames (75 × 75 × 20 cm made of PVC) were installed to facilitate chamber measurements. Due to the permanent installation of the soil frames, the agrotechnical measures taken on the meadow could not be carried out. Therefore, the meadow sward was manually cut three times a year and sampled for laboratory analyses. All biomass samples were weighed and dried at 105 °C to obtain the dry matter volume. Then, the results were converted into kg·ha^{-1} to assess yield [30].

2.3. Auxiliary Data

Meteorological and hydrological conditions were monitored in the meadow. Air temperature and relative humidity at 2 m height were measured by a HygroVUE5 thermohygrometer (Campbell Sci., Logan, UT, USA). An SKP215 sensor (Skye Instruments

Ltd, Llandrindod Wells, UK) was used to measure incoming photosynthetically active radiation (PAR). Soil temperature and soil moisture at 5 cm depth at the HWL and LWL sites were monitored by T-107 thermistors (Campbell Sci., Logan, UT, USA) and CS-616 probes (Campbell Sci., Logan, UT, USA), respectively. All data were recorded with 30 min time steps on a CR1000 datalogger (Campbell Sci., Logan, UT, USA). In addition, HOBO U20L-01 dataloggers (Onset, Bourne, MA, USA) were installed at the HWL and LWL sites to monitor groundwater levels. Precipitation was measured on site by a heated rain gauge (Lambrecht meteo GmbH, Göttingen, Germany). To fill the gaps in the meteorological data series, the data from the nearest weather station in Kościan (distance 5 km NW) owned by the Polish Institute of Meteorology and Water Management—National Research Institute was used.

Furthermore, the duration of the growing season in both investigated years was determined by the Huculak and Makowiec method [32] based on the cumulative series of deviations of the mean daily temperature from the threshold value of 5 °C. The beginning of the growing season is defined as the day after which the cumulative values of successive deviations from 5 °C are exclusively positive, and the end of the season when the values are exclusively negative [33].

2.4. Chamber Measurements of CO_2 Fluxes

Carbon dioxide fluxes were measured with the closed dynamic (non-steady-state flow-through) portable chamber system as described in Juszczak et al. [34–36] and Acosta et al. [37]. Two types of chambers were applied—a transparent chamber made from 3 mm thick Plexiglas (Evonik Industries, Darmstadt, Germany) and a non-transparent chamber made from white 3 mm thick PVC, in order to facilitate measurements of net ecosystem exchange (NEE) and ecosystem respiration (Reco), respectively. The chamber dimensions were $0.78 \times 0.78 \times 0.50$ m, and their volume was 0.296 m^3. The gas concentration changes in the chamber headspace were measured by an LI-840 gas analyzer (LI-COR Biosciences, Lincoln, Nebraska, USA) installed in the portable box (equipped with a pump, air-flow controller, filter, batteries, and CR-1000 datalogger (Campbell Sci., Logan, UT, USA). The air was circulated in the closed system between chambers and the gas analyzer through 3 m long Teflon tubes with the constant rate of 0.7 $L \cdot m^{-1}$. Each chamber was equipped with a shielded HygroVUE™5 temperature and relative humidity sensor (Campbell Sci., Logan, UT, USA), 2 computer fans (1.4 W each) to mix the air in the chamber headspace, and a vent to equilibrate air pressure during measurements [34,35]. The transparent chamber was also equipped with an SKP215 sensor to monitor PAR radiation during measurements. Chambers were placed on preinstalled 20 cm high PVC soil frames (0.75×0.75 m) and inserted 15 cm deep into the soil to ensure an adequate seal between the soil and the atmosphere and reduce horizontal gas flow. The tightness of the chamber system and sealing were assured through the rubber installed at the bottom edge of each chamber's walls. Three soil frames were installed per each plot as replicates, resulting in 12 frames installed for the purpose of the experiment.

Chamber measurements were taken every 3 to 5 weeks, only during sunny and cloudless conditions, resulting in 15 and 13 campaigns in 2021 and 2022, respectively. Measurements started early in the morning and were taken until the late afternoon. At each of the plots, NEE measurements preceded the Reco measurements. The chamber closure time was 90 and 150 s for NEE and Reco measurements, respectively.

2.5. CO_2 Flux Calculation and Gap Filling

CO_2 fluxes were calculated in $\mu mol \cdot m^{-2} \cdot s^{-1}$ based on the gas concentration changes in the chamber headspace over the closure time using linear regression, as described in Juszczak et al. [35,36]. Before the flux calculation, the measured CO_2 concentrations were corrected for water dilution by applying water vapor correction in accordance with Webb et al. [38]. Fluxes were calculated based on a minimum of 40 s of data after the exclusion of the first 10–15 s of data to eliminate data noise originating from disturbances occurring after deployment of the chamber. In order to avoid underestimation of the fluxes caused by possible gas saturation or changes in the chamber headspace microclimate (as described in Kutzbach et al. [39]), the steepest part of the regression was used to calculate fluxes after excluding the end part of the data series, wherein possible disturbances occur and disturb the linear slope of the regression.

Gap filling of the CO_2 data series in the periods between campaigns was carried out by applying the empirical model described by Drösler [40] and further elaborated by Hoffmann et al. [41]. Due to a limited amount of flux data, the gap-filling procedure was applied for each of the four plots (HWL, HWL_Si, LWL, and LWL_Si), where all data from replicates were integrated into one data pool. At the first step, for each of the campaigns, the temperature-dependent respiration model of Lloyd and Taylor [42] was fitted to the measured Reco fluxes and air temperatures to estimate the Reco modeling parameters (R_{ref} and E_0):

$$\mathrm{Reco} = R_{ref} \cdot e^{E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)} \tag{1}$$

where Reco is the measured ecosystem respiration ($\mu mol \cdot m^{-2} \cdot s^{-1}$), R_{ref} is the respiration at the reference temperature of 283.15 K (T_{ref}), E_o is activation energy (K), T_0 is the constant starting temperature (227.13 K), and T is the mean air temperature for the time of chamber closure. The Reco modeling parameters were then used to calculate Reco fluxes for the time and temperatures of the NEE measurements in order to calculate gross primary production (GPP) by subtracting the modeled Reco from the measured NEE fluxes.

In the second step, the PAR-dependent campaign-specific GPP model was applied by fitting the rectangular, hyperbolic light response function of Michaelis–Menten (1913) to the calculated GPP ($\mu mol \cdot m^{-2} \cdot s^{-1}$) and measured PAR ($\mu mol \cdot m^{-2} \cdot s^{-1}$) to estimate the GPP modeling parameters (GPmax and α):

$$\mathrm{GPP} = \frac{GP_{max} \times \alpha \times PAR}{\alpha \times PAR + GP_{max}} \tag{2}$$

where GPmax is the maximum rate of CO_2 fixation at infinite PAR ($\mu mol^{-1} \cdot m^2 \cdot s^{-1}$), while α is the light use efficiency (mol CO_2 mol^{-1} photons).

In the next step, the calculated Reco and GPP model parameters were interpolated linearly in the periods between campaigns (as described in Juszczak et al. [36]) in order to calculate Reco and GPP based on the measured air temperatures and PAR, respectively. Finally, NEE was calculated from the formula NEE = GPP + Reco. All fluxes were calculated with 30 min time steps and were recalculated into mass units in order to calculate daily and seasonal sums of Reco, GPP, and NEE.

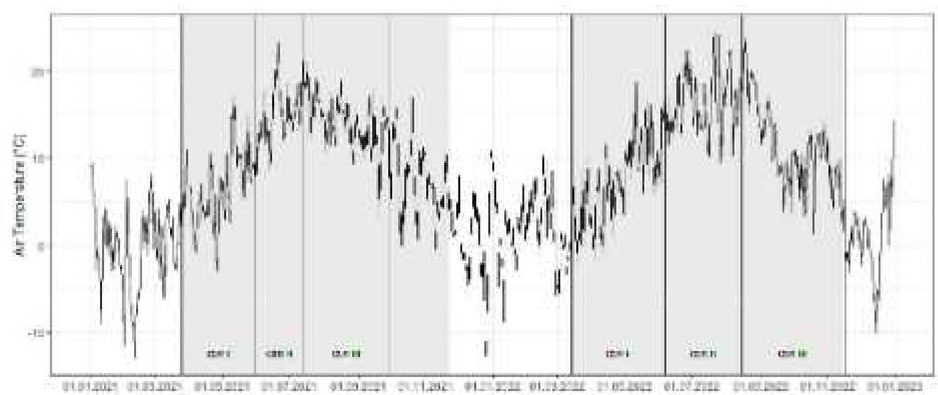
2.6. Statistical Analyses

Statistical analyses were carried out for daily values of Reco, GPP, and NEE fluxes in individual plots. The normal distribution of the values was checked using Shapiro–Wilk's tests. In most cases, the distribution differed from normal, and hence, non-parametric tests were performed. Therefore, the Wilcoxon Matched Pairs Test in Statistica software (version 13) was used to check whether the daily flux rates in individual plots differed significantly in each cut. The level of significance α = 0.05 was accepted in all cases. Furthermore, the Spearman correlation matrix (R-Studio) was performed to analyze the relationship between daily rates of GPP, Reco, NEE, soil moisture (SM), air temperature (TA), and water table depth (WTD) for the individual measurement plots. As a final analysis, a Spearman correlation was carried out between the cumulative GPP, Reco, and NEE values in the cuts and the above-ground biomass yield obtained for each plot.

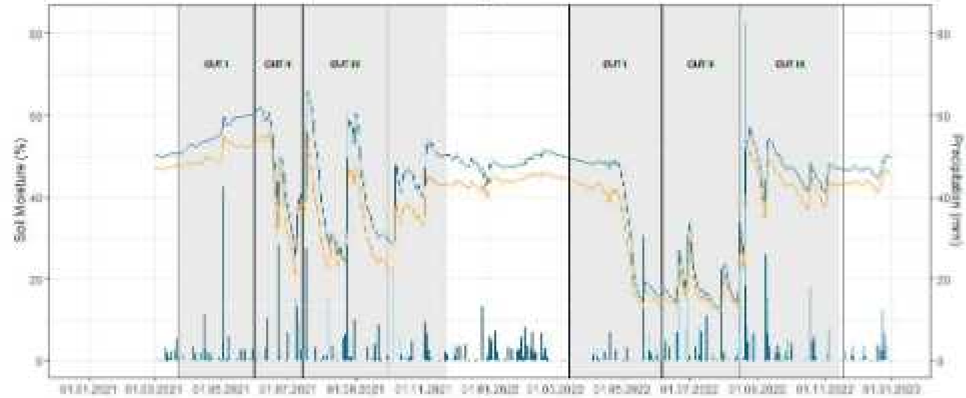
3. Results

3.1. Environmental Conditions

The two-year data series of air temperature, rainfall, soil moisture, and groundwater level are presented in Figure 2. The growing season is marked in grey. The growing season in 2021 lasted 244 days and began on 24 March and ended on 22 November. In 2022, the growing season was three days longer (247 days) and lasted from 14 March until 15 November. The average daily temperature in 2021 was 9.1 °C, whereas 2022 was 1.0 °C warmer. The minimum mean daily temperatures were −10.8 °C and −7.4 °C in 2021 and 2022, respectively. By contrast, the maximum mean daily temperature in 2021 was 26.6 °C, whereas in 2022, it was 1° C higher. The years under study also differed in the amount of precipitation. The yearly sums of precipitation were equal to 539.5 mm and 604.7 mm in 2021 and 2022, respectively. The highest monthly rainfall was recorded in August in both years. In 2021 it reached 84 mm, and in 2022, 135 mm. The driest month in both years was March, with 20 mm of rain in 2021 and no rainfall in 2022. During the entire study period, the WTD levels directly correlated with precipitation episodes. This is most evident in August 2022, when just after an extreme rain event of 83 mm recorded on 20 August, a sharp rise in WTD levels was noted at both HWL and LWL sites (Figure 2b). Within the analyzed years, WTD varied between 0.29 and 1.09 m below ground level (mbgl) as well as between 0.09 and 0.92 mbgl, at LWL and HWL sites, respectively. The highest WTD levels at both sites occurred during winter, whereas the lowest levels were recorded during the summer months (June–August). The same pattern is reflected in soil moisture. The maximum soil moisture value at the HWL site was 66% and occurred on 18 July 2021, immediately after the rainfall. At the LWL site, the highest value of up to 57% was also recorded on the same day. The lowest values of 13% for HWL and 12% for LWL were observed in July 2022. When comparing both years, it can be observed that during the spring-summer period of 2022, soil moisture values were lower than in 2021. The values of the measured parameters during the individual cut periods and collectively during the 2021–2022 growing season are summarized in Table 1.

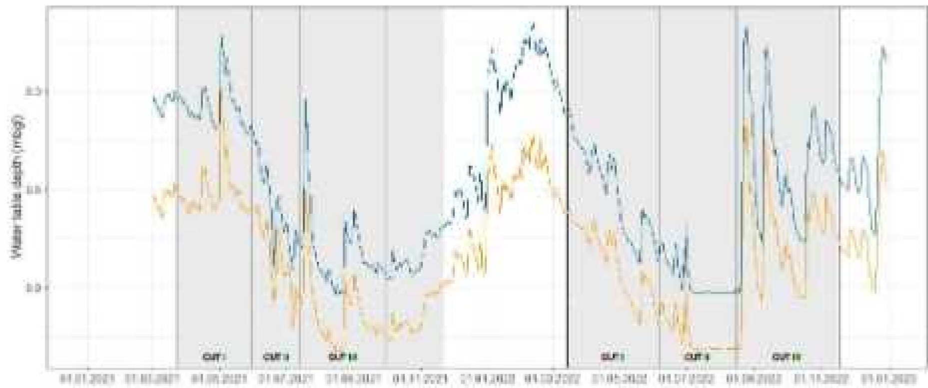


(**a**)



(**b**)

Figure 2. *Cont.*



(c)

Figure 2. Environmental conditions at the study area in 2021–2022; (**a**) air temperature; (**b**) precipitation and soil moisture; (**c**) groundwater table depth at the HWL (blue lines) and LWL (orange lines) sites.

Table 1. Characteristics of individual cuts, including their duration, average daily air temperature, rainfall, average soil moisture, and water table depth (WTD) at the HWL and LWL sites.

Period	Dates	Duration (Days)	Average Daily Temperature (°C)	Precipitation (mm)	Average Soil Moisture HWL (%)	Average Soil Moisture LWL (%)	Average WTD at HWL (mbgl)	Average WTD at LWL (mbgl)
I cut 2021	24.03.21–31.05.21	69	9.0	98.2	56	50	0.34	0.61
II cut 2021	1.06.21–14.07.21	44	19.4	95.7	47	42	0.66	0.81
III cut 2021	15.07.21–30.09.21	78	16.8	138.5	41	33	0.79	0.98
Growing season 2021	24.03.21–22.11.21	244	13.3	404.4	47	41	0.64	0.85
I cut 2022	14.03.22–6.06.22	85	10.2	91.3	37	32	0.61	0.82
II cut 2022	7.06.22–15.08.22	70	19.6	129.7	18	16	0.88	1.05
III cut 2022	16.08.22–17.11.22	94	12.9	237.4	47	42	0.52	0.75
Growing season 2022	14.03.22–15.11.22	247	13.9	458.4	35	31	0.65	0.86

3.2. GPP, Reco, and NEE Fluxes

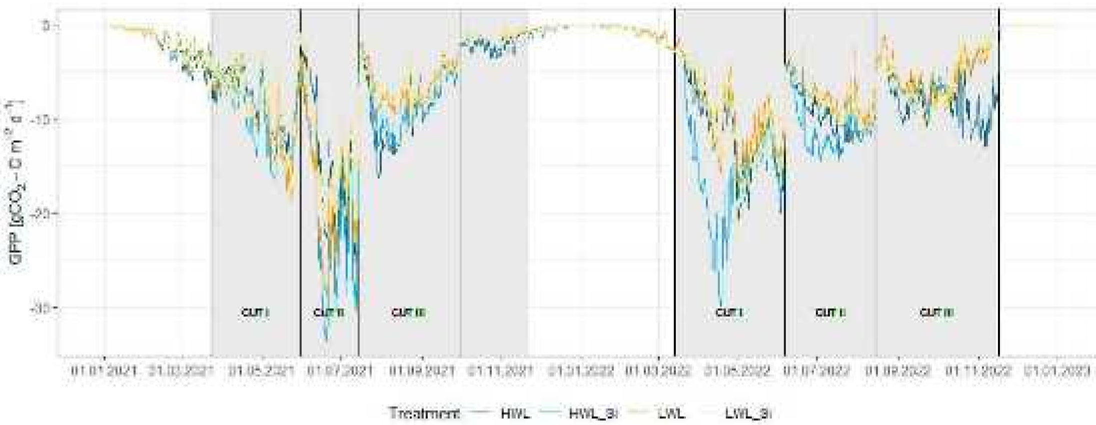
The fluxes of GPP, Reco, and NEE modeled for the individual plots (HWL, HWL_Si, LWL, LWL_Si) for the years 2021–2022 are shown in Figure 3. When analyzing the GPP values, a clear seasonal variation is noticeable. In the winter months, values close to zero occurred, whereas the GPP of the summer months reached up to -33 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$. When interpreting these data, it should be noted that negative GPP values indicate the loss of CO_2 from the atmosphere and its simultaneous assimilation by plants. The highest assimilation rates were recorded in July 2021 when the GPP was -25.53 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$ at the HWL, -33.53 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$ at the HWL_Si, -28.67 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$ at the LWL, and -22.48 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$ at the LWL_Si plot. In addition, during the winter season, the lower activity of microorganisms and plants caused by low temperatures resulted in Reco values close to zero. The increase in air temperature in the spring periods resulted in a gradual increase in Reco (Figure 3b). Regardless of the analyzed plots, the highest CO_2 emission rates occurred in June and July 2021. Reco fluxes reached up to 22.00 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$ at the HWL, 20.63 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$ at the HWL_Si, 17.90 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$ at the LWL, and 26.46 $gCO_2\text{-}C{\cdot}m^{-2}{\cdot}day^{-1}$ at the LWL_Si. Furthermore, daily rates of Reco fluxes were higher in 2021 than in 2022. The modeled daily NEE fluxes expressed very high seasonal variability, especially during the growing period. It has to be noted here that whenever NEE fluxes are positive, emissions prevail over assimilation, whereas when they are negative, the situation is reversed. In the winter season, NEE fluxes were positive, equal to Reco, and close to zero. The highest daily NEE rates occurred in summer months after cutting, and they were close to 11 gCO_2-C·m^{-2}·day^{-1} (11.92 gCO_2-C·m^{-2}·day^{-1} at the HWL, 11.63 gCO_2-C·m^{-2}·day^{-1} at the HWL_Si, 11.75 gCO_2-C·m^{-2}·day^{-1} at the LWL), except for the LWL_Si plot, where the highest NEE fluxes reached up to 18.96 gCO_2-C·m^{-2}·day^{-1}. What is, however, more important, is that the daily rates of NEE fluxes by most of the years were negative, which signifies the predominance of CO_2 assimilation processes over emissions and indicates periods when the meadow was a net sink for CO_2 from the atmosphere. The most negative NEE flux rates were observed in spring 2022 (Figure 3c), particularly for HWL_Si, where they reached −24.28 gCO_2-C·m^{-2}·day^{-1}.

The results of the Spearman correlation matrix carried out for the daily rates of CO_2 fluxes (GPP, Reco, NEE) and environmental variables (SM, TA, WTD) for all experimental plots and for both years (2021, 2022) are presented in the supplementary materials (Figures S1 and S2). Reco correlated most strongly with TA for all treatments in both years. The correlation coefficient for these regressions is between 0.89 and 0.91 for 2021 and between 0.77 and 0.84 for 2022. Correlation between Reco and WTD is negative, with correlation coefficients ranging from −0.50 to −0.59 and from −0.56 to −0.67 in 2021 and 2022, respectively. Correlations between Reco and SM were negative and rather weak, with R from −0.34 to −0.37 in 2021 and from −0.51 to −0.66 in 2022. GPP was negatively correlated with TA and positively with WTD and SM. Although correlation coefficients for GPP vs. TA regressions ranged from −0.59 to −0.63 in 2021, in 2022 they were negligible. In contrast, for GPP vs. WTD, the correlation coefficient ranged from 0.28 to 0.38 in 2021 and from 0.29 to 0.46 in 2022. For GPP vs. SM regressions, R values were at a similar rate. The differences in correlations between 2021 and 2022 are most likely due to different meteorological conditions in both years.

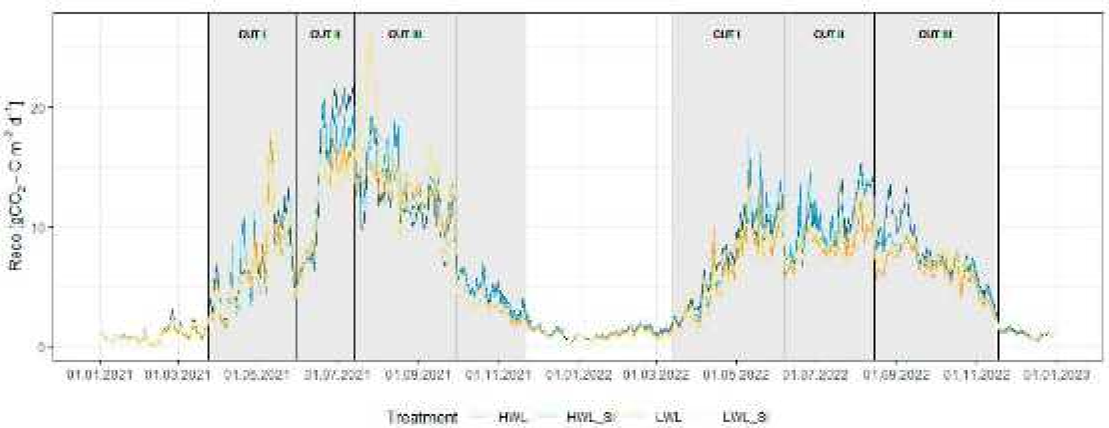
3.2.1. Gross Primary Production (GPP)

Analyzing the daily flux rates in the individual meadow cut, a direct influence of meteorological conditions on their magnitude can be observed (Figure 4). Concerning GPP, it is noticeable that in 2021 the highest fluxes were reached during the second cut (1.06–14.07.21), with the average daily fluxes up to −14.75 gCO_2-C·m^{-2}·day^{-1} for HWL, −20.37 gCO_2-C·m^{-2}·day^{-1} for HWL_Si, −17.36 gCO_2-C·m^{-2}·day^{-1} for LWL and −14.07 gCO_2-C·m^{-2}·day^{-1} for LWL_Si. Values in the I and III cuts were similar to each other, and their average daily values ranged from −6.24 to −9.24 gCO_2-C·m^{-2}·day$^{-1,}$ depending on the plot. The average daily GPP fluxes for the entire growing season in 2021 were −7.99 gCO_2-C·m^{-2}·day^{-1} for HWL, −9.20 gCO_2-C·m^{-2}·day^{-1} for HWL_Si, −7.97 gCO_2-C·m^{-2}·day^{-1} for LWL and −7.15 gCO_2-C·m^{-2}·day^{-1} for LWL_Si. In the 2022 growing season, daily GPP rates were higher for plots with higher WTD and ranged from −9.40 gCO_2-C·m^{-2}·day^{-1} at the HWL to −10.16 gCO_2-C·m^{-2}·day^{-1} at the HWL_Si, whereas at plots with lower WTD, GPP fluxes were at the rates similar to those in 2021 and ranged from −7.41 gCO_2-C·m^{-2}·day^{-1} at the LWL to −8.00 gCO_2-C·m^{-2}·day^{-1} at the LWL_Si plots. Looking at the distribution of daily GPP rates in the individual cuts in the second year of the study, it can be seen that the highest fluxes were reached in the first cut and not in the second cut like in the previous year. Therefore, the seasonal distribution of fluxes is different from the first year of the study, which was influenced by different meteorological conditions.

Statistical analyses were carried out to check whether the differences in daily GPP rates between treatments in each cut were significant. Due to the lack of a normal distribution of daily GPP values, a non-parametric Wilcoxon matched-pairs test was performed. Figure 5 shows the results obtained from the analysis. For all $p < 0.05$, the null hypothesis of no significant difference between the values was rejected. Therefore, it can be concluded that in the I, II, and III cuts in 2022, and also in the I cut in 2021, the daily GPP rates for individual plots differ significantly. In the case of the II cut in 2021, no significant differences were observed between the LWL_Si and HWL plots, and in the III cut in 2021, between LWL and LWL_Si. The results show that WTD significantly impacted the daily GPP fluxes. Furthermore, the application of silicon antitranspirant also significantly affected the daily GPP rates. This was evident for plots with higher and lower WTD in all cuts except for the third cut in 2021, wherein no significant differences were observed between the LWL and LWL_Si plots.



(**a**)



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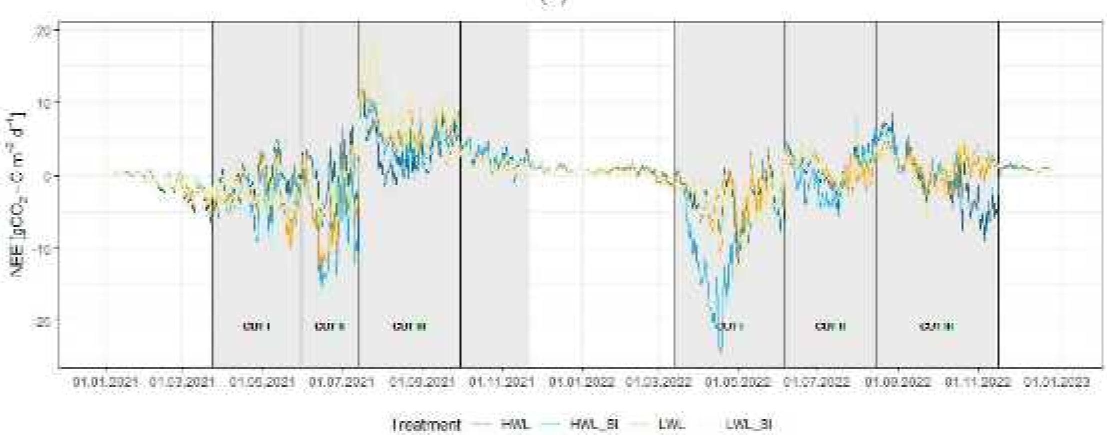
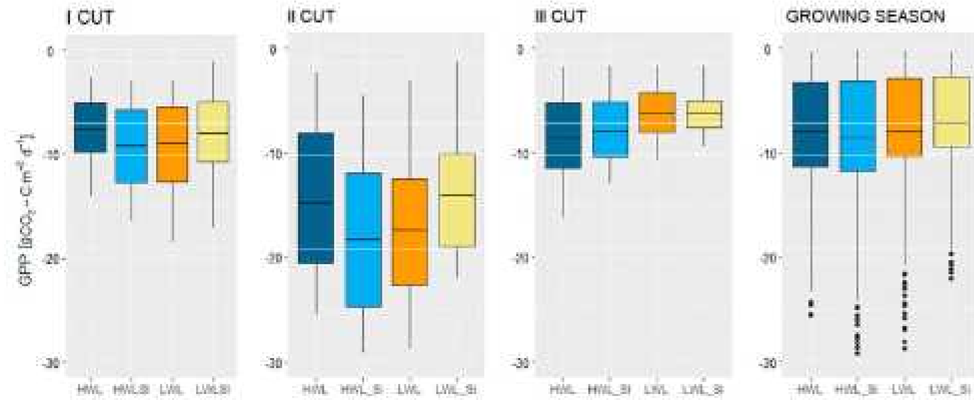


(**c**)

Figure 3. The seasonal dynamics of modeled daily rates of (**a**) GPP; (**b**) Reco; and (**c**) NEE fluxes for control (HWL, LWL) and treated plots (HWL_Si, LWL_Si); grey background marks the growing season.



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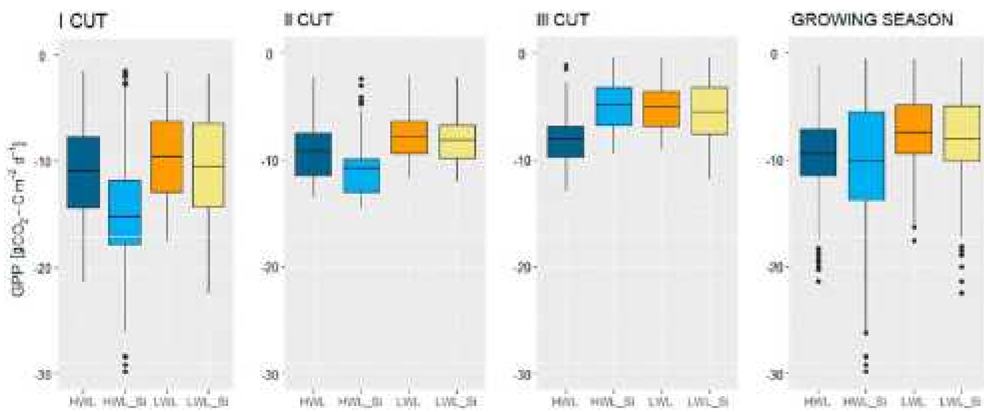


(**b**)

Figure 4. Daily GPP fluxes for each plot per cut and growing season (**a**) in 2021; (**b**) in 2022.

		HWL	HWL_Si	LWL	LWL_Si
I cut 2021	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	<0.05	
II cut 2021	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	0.1048	<0.05	<0.05	
III cut 2021	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	0.7937	

		HWL	HWL_Si	LWL	LWL_Si
I cut 2022	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	<0.05	
II cut 2022	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	<0.05	
III cut 2022	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	<0.05	

Figure 5. Comparison of daily GPP fluxes for individual plots (HWL, HWL_Si, LWL, LWL_Si) using Wilcoxon matched-pairs test in each cut in 2021 and 2022. $p < 0.05$ means that the pairs are significantly different from each other.

Figure 6 shows the cumulative GPP values in each cut. During the two-year study period, the highest uptake for each plot was recorded in the first cut of 2022. This is particularly evident for the HWL_Si plot, wherein GPP fluxes reached −1292.32 gCO_2-C·m^{-2}·cut^{-1} and were two times higher than for the same plot in 2021. When comparing plots with different WTD levels, it can be seen that in the third cut in 2021 and in all cuts in 2022, the HWL plots assimilated more CO_2 than the LWL plots. Therefore, it can be concluded that higher WTD positively affected GPP. In the case of the silicon application, it is apparent that in the area with a higher WTD, the application of the antitranspirant contributed to higher assimilation rates and ecosystem productivity in all cuts except for the third cuts in 2021 and 2022. In the site with a lower WTD, no clear pattern was observed. In 2021, GPP at the plot with lower WTD and silicon application (LWL_Si) was lower by 10% in the first cut and by 19% in the second cut in comparison to the plot without silicon (LWL). In the third cut of 2021, the GPP rates of both LWL plots were similar (−486.47 gCO_2-C·m^{-2}·cut^{-1} for LWL and −488.48 gCO_2-C·m^{-2}·cut^{-1} for LWL_Si). However, in 2022, a pattern opposite to that of 2021 was observed, wherein the plot with the antitranspirant application (LWL_Si) expressed higher assimilation rates than the LWL one.

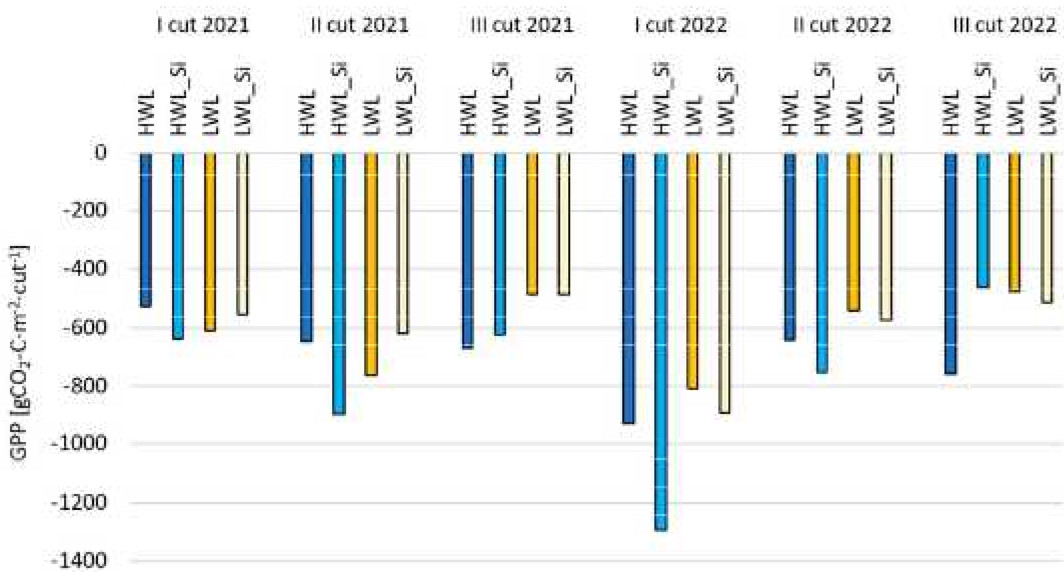
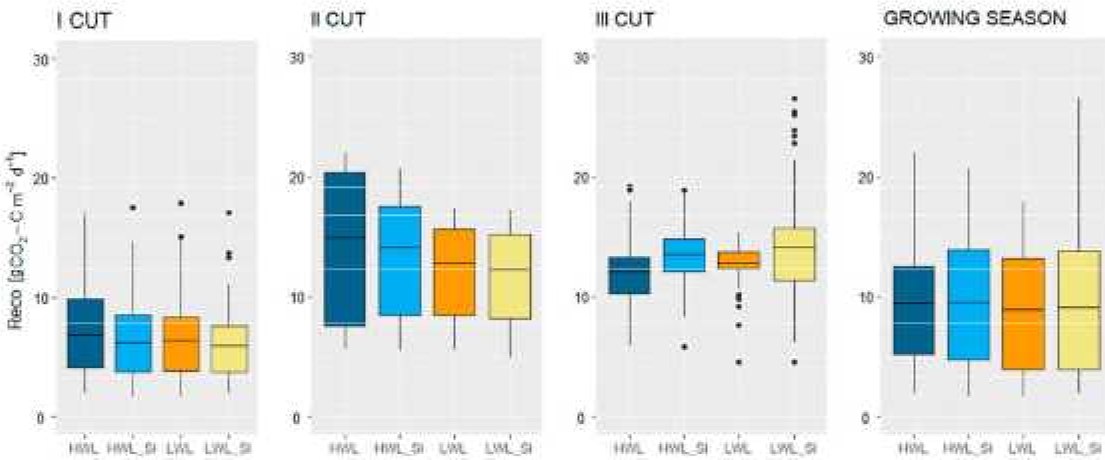


Figure 6. Cumulative GPP values for individual plots in each cut in 2021–2022.

3.2.2. Ecosystem Respiration (Reco)

As ecosystem respiration is one of the most important sources of carbon flux between terrestrial ecosystems and the atmosphere, it is crucial to determine its seasonal variation and the effect of applying a silicon-based antitranspirant. Figure 7 shows the daily Reco fluxes for individual plots in each cut. During the 2021 growing season, the lowest average daily Reco flux was observed in the first cut and equaled to 6.88 gCO_2-C·m^{-2}·day^{-1} for the HWL plot, 6.26 gCO_2-C·m^{-2}·day^{-1} for HWL_Si, 6.41 gCO_2-C·m^{-2}·day^{-1} for LWL, and 5.94 gCO_2-C·m^{-2}·day^{-1} for LWL_Si. The highest daily Reco fluxes were recorded in the second cut for the plots with higher WTD and reached up to 22 gCO_2-C·m^{-2}·day^{-1} for HWL and 20.63 gCO_2-C·m^{-2}·day^{-1} for HWL_Si. For the plots with lower WTD, the maximum daily Reco fluxes occurred in the first cut for LWL (17.90 gCO_2-C·m^{-2}·day^{-1}) and in the third cut for LWL_Si (26.46 gCO_2-C·m^{-2}·day^{-1}). The increase in Reco and higher average fluxes in the second cut were caused mainly by the higher mean daily air temperatures of this period. The TA of the first cut was 9.0 °C, whereas in the second cut it was much higher, reaching 19.4 °C (Table 1).



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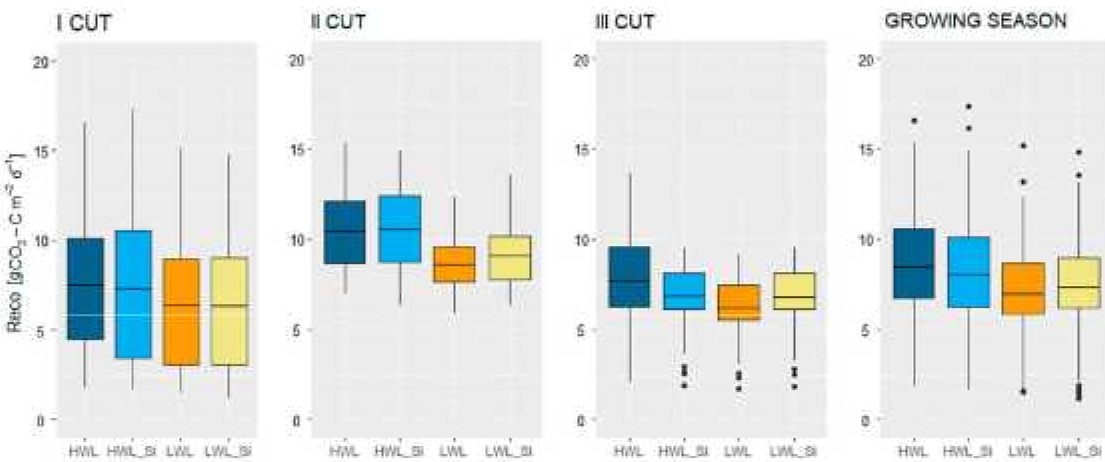


(**b**)

Figure 7. Daily Reco fluxes for individual plots in each cut and growing season (**a**) in 2021; (**b**) in 2022.

The largest range of respiration rates can be observed in the first cut of 2022. Both the lowest (1.81 gCO_2-C·m^{-2}·day^{-1} for HWL, 1.64 gCO_2-C·m^{-2}·day^{-1} on HWL_Si, 1.51 gCO_2-C·m^{-2}·day^{-1} on LWL, and 1.17 gCO_2-C·m^{-2}·day^{-1} on LWL_Si) and the highest daily CO_2 fluxes (16.56 gCO_2-C·m^{-2}·day^{-1} for HWL, 17.34 gCO_2-C·m^{-2}·day^{-1} for HWL_Si, 15.15 gCO_2-C·m^{-2}·day^{-1} for LWL, and 14.79 gCO_2-C·m^{-2}·day^{-1} for LWL_Si) were recorded in this cut for the entire growing season in 2022. The average daily Reco fluxes for the 2022 growing season were 8.47 gCO_2-C·m^{-2}·day^{-1} for HWL, 8.08 gCO_2-C·m^{-2}·day^{-1} for HWL_Si, 6.98 gCO_2-C·m^{-2}·day^{-1} for LWL and 7.33 gCO_2-C·m^{-2}·day^{-1} for LWL_Si, respectively. In the previous year, the daily mean values of Reco fluxes were higher for all plots and reached 9.47 gCO_2-C·m^{-2}·day^{-1} at HWL, 9.54 gCO_2-C·m^{-2}·day^{-1} at HWL_Si, 8.92 gCO_2-C·m^{-2}·day^{-1} at LWL, and 9.12 gCO_2-C·m^{-2}·day^{-1} at LWL_Si.

A Wilcoxon matched-pairs test for daily Reco fluxes in individual plots in each cut showed that in most cases, daily plot emissions differed significantly; $p < 0.05$ (all pairs of plots in the first and second cut in 2021). For the third cut in 2021, the only pair that did not differ significantly was LWL_Si and HWL_Si (Figure 8). The same pair also showed no significant differences in the third cut in 2022. Furthermore, in the 2022 growing season in the first cut, the silicon antitranspirant application had no significant effect on daily Reco fluxes in the site with lower WTD. Moreover, there were significant differences in the daily

CO_2 fluxes in each cut between the plots with higher (HWL) and lower (LWL) groundwater levels. A significant effect of the silicon antitranspirant application on ecosystem respiration was seen in both sites, with higher and lower groundwater levels. The exception is the first cut in 2022, when the AT did not significantly differentiate the daily Reco fluxes in the site with a lower WTD. Therefore, it can be concluded that AT application has a stronger effect in the sites with a higher WTD than for those with a lower WTD.

Cut		HWL	HWL_Si	LWL	LWL_Si
I cut 2021	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	<0.05	
II cut 2021	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	<0.05	
III cut 2021	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	0.7822	<0.05	
I cut 2022	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	0.6097	
II cut 2022	HWL				
	HWL_Si	0.951			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	<0.05	<0.05	
III cut 2022	HWL				
	HWL_Si	<0.05			
	LWL	<0.05	<0.05		
	LWL_Si	<0.05	0.7615	<0.05	

Figure 8. Comparison of daily Reco fluxes for individual plots (HWL, HWL_Si, LWL, LWL_Si) using Wilcoxon matched-pairs test in each cut in 2021 and 2022. $p < 0.05$ means that the pairs are significantly different from each other.

The highest cumulative Reco fluxes were recorded in the third cut of 2021 (Figure 9). This is most likely because the WTD was low during this period. The average WTD at the HWL site was 0.79 mbgl and as deep as 0.98 mbgl at the LWL site. Previous studies show that lowering WTD increases soil respiration [43]. Therefore, meadow treatments that contribute to this process should be avoided [44]. Analyzing the individual plots, it can be seen that in the third cut of 2021, the maximum emission was recorded in the LWL_Si plot and amounted to 1096.78 gCO_2-C·m^{-2}·cut^{-1}, while in the plot without silicon application, it was the lowest (996.11 gCO_2-C·m^{-2}·cut^{-1}). Also, for the site with a higher WTD in the third cut of 2021, a similar pattern was observed. The silicon application resulted in increased emissions (1056.87 gCO_2-C·m^{-2}·cut^{-1}) compared to the plot without silicon treatment (942.24 gCO_2-C·m^{-2}·cut^{-1}). However, it should be noted that this was the only period when this pattern was observed. In the remaining periods, the application of antitranspirant at the site with a higher WTD reduced Reco fluxes, apart from the second cut in 2022, when the fluxes were similar to each other (HWL 734.49 gCO_2-C·m^{-2}·cut^{-1}, HWL_Si: 738.22 gCO_2-C·m^{-2}·cut^{-1}). AT application in site with higher WTD contributed to the reduction of Reco fluxes by 9% and 2.7% in the first cut of 2021 and 2022, respectively. In the second cut, the reduction of Reco fluxes was even higher, and reached 6% and as much as 11.4% in 2021 and 2022, respectively. At the site with a lower WTD, the antitranspirant application reduced Reco fluxes in the first and second cuts of 2021 by 7.4% and 4.1%, respectively, as well as in the first cut of 2022 by only 0.8%. In other periods, the Reco flux rates from plots with antitranspirant application were higher than those without silicon application (in the third cut in 2021 by 10.1%, in the second cut in 2022 by 6%, and in the third cut in 2022 by 9.6%). Therefore, it can be concluded that silicon is more effective in reducing CO_2 emissions in areas with a higher WTD.

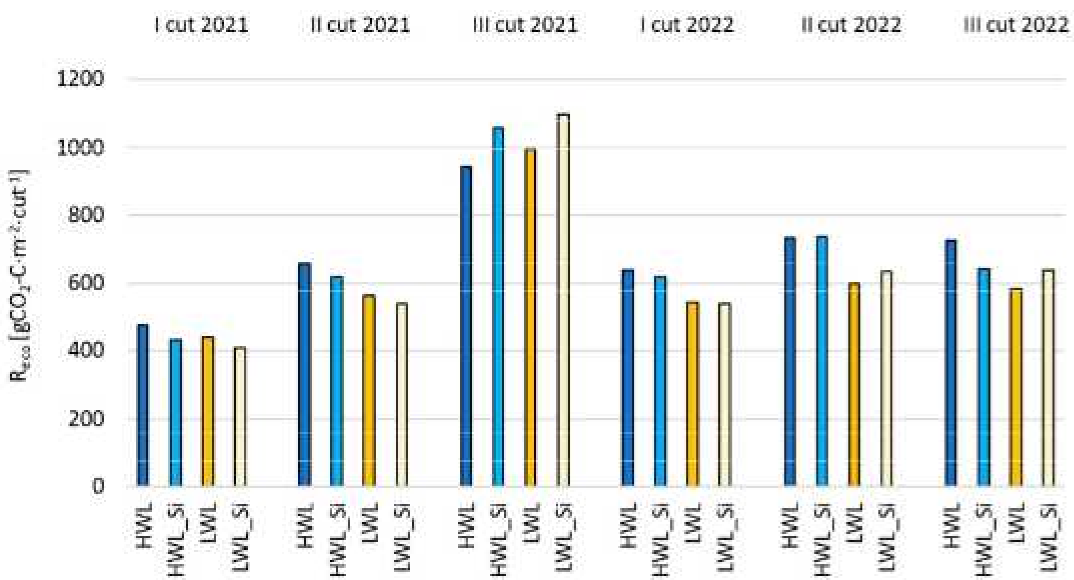


Figure 9. Cumulative Reco fluxes for individual plots in each cut in 2021–2022.

When comparing plots with different WTD, it can be seen that in all cuts of 2022 and in the first and second cuts of 2021, the HWL plot emitted more CO_2 than the LWL plot. The exception is the third cut in 2021, when the Reco flux from the HWL (942.24 gCO$_2$-C·m^{-2}·cut^{-1}) plot was 53.87 gCO$_2$-C·m^{-2}·cut^{-1} smaller than that from the LWL plot. Looking at the individual cuts, it can be observed that the lowest cumulative Reco values occurred in the first cut of 2021. This was also the period when the soil moisture at both HWL and LWL sites was the highest, and reached up to 56% and 50%, respectively. Analyzing the annual patterns of ecosystem respiration, a clear peak in CO_2 flux is observed during periods with high precipitation (Figure 3b).

3.2.3. Net Ecosystem Exchange (NEE)

The daily NEE fluxes for individual plots in each year are shown in Figure 10a,b. There were both positive (indicating ecosystem respiration outweighs assimilation rates) and negative daily NEE fluxes in each of the cuts. The exception is the third cut of 2021, when the daily NEE of the HWL_Si, LWL, and LWL_Si plots had only positive values. The highest (most negative) daily NEE fluxes were recorded in the first cut of 2022 and were equal to −12.01 gCO$_2$-C·m^{-2}·day^{-1} for HWL, −24.28 gCO$_2$-C·m^{-2}·day^{-1} for HWL_Si, −10.56 gCO$_2$-C·m^{-2}·day^{-1} for LWL, and −13.64 gCO$_2$-C·m^{-2}·day^{-1} for LWL_Si. The average daily NEE fluxes for the 2022 growing season amounted to −0.93 gCO$_2$-C·m^{-2}·day^{-1} (HWL), −2.07 gCO$_2$-C·m^{-2}·day^{-1} (HWL_Si), −0.43 gCO$_2$-C·m^{-2}·day^{-1} (LWL), and −0.67 gCO$_2$-C·m^{-2}·day^{-1} (LWL_Si). The 2021 growing season was characterized by higher (positive) average values of NEE, indicating that CO_2 emissions prevailed. The daily average NEE fluxes reached 1.48 gCO$_2$-C·m^{-2}·day^{-1} (HWL), 0.34 gCO$_2$-C·m^{-2}·day^{-1} (HWL_Si), 0.95 gCO$_2$-C·m^{-2}·day^{-1} (LWL), and 1.97 gCO$_2$-C·m^{-2}·day^{-1} (LWL_Si).

Similarly to the analyses above, the Wilcoxon matched-pairs test showed that WTD was a factor differentiating the daily NEE fluxes between plots (Figure 11). In most cuts, daily NEE values differed significantly ($p < 0.05$) between the plots with higher (HWL) and lower (LWL) water table depth. Only in the second cut of 2022, no significant differences were found between these plots. This is most likely due to the WTD of this period being very low, and hence differences in soil moisture between the two sites were minor and did not exceed 2% (18% at HWL vs. 16% at LWL). Application of the antitranspirant at the site with the higher WTD significantly affected the daily NEE fluxes in each of the analyzed cuts. For the area with the lower WTD, statistically significant differences were observed between LWL and LWL_Si only in the second and third cut in 2021 and the first cut in 2022.

In the other periods, the daily NEE values of these plots were not significantly different. To conclude, WTD significantly differentiates the daily NEE fluxes, while the application of antitranspirant significantly affects the NEE values only in the site with a higher WTD.

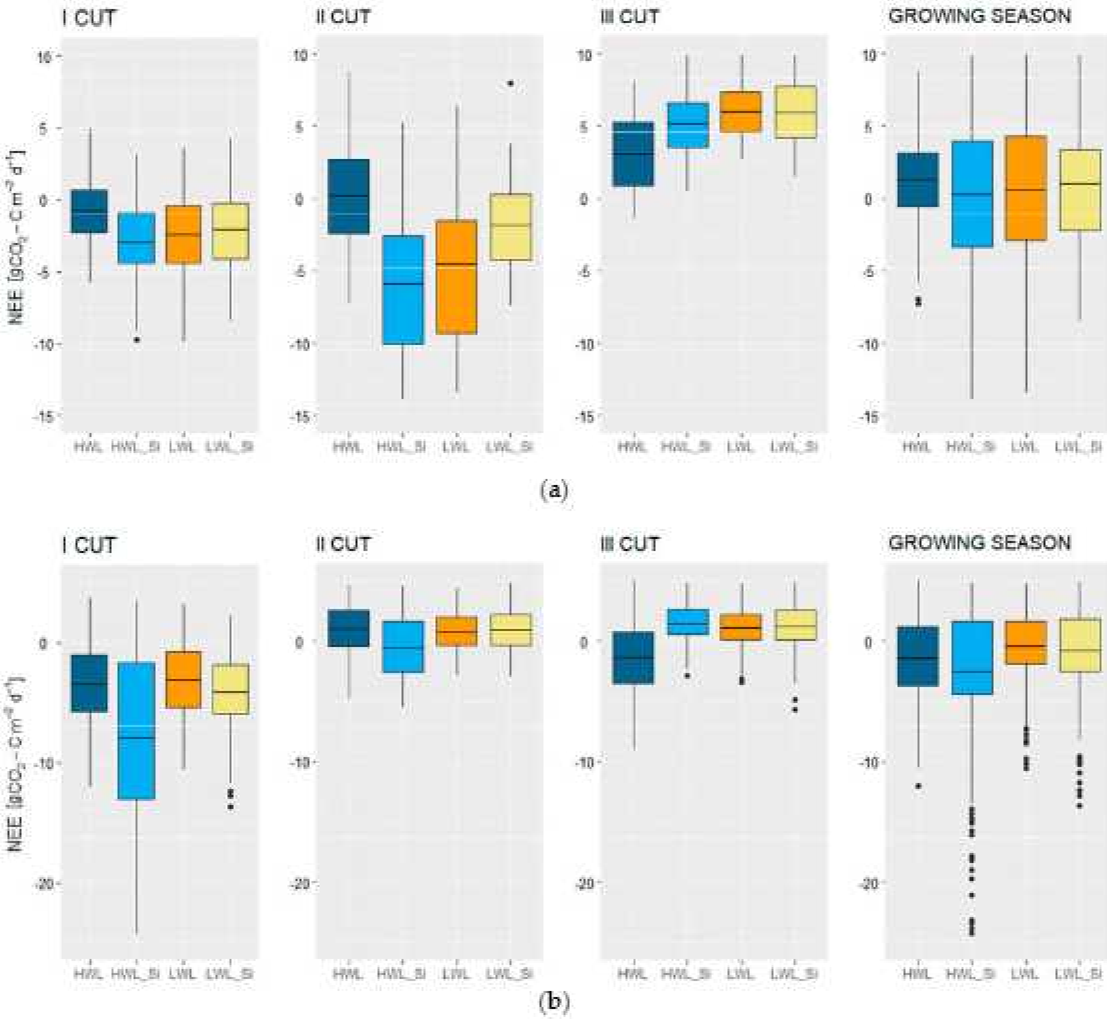


Figure 10. Daily NEE fluxes for individual plots in each cut and growing season (**a**) in 2021; (**b**) in 2022.

The cumulative NEE fluxes in the period of the first cut in both years are negative for all the treatments, indicating that the meadow assimilated more CO_2 than it emitted to the atmosphere, and was a net sink of CO_2 (Figure 12). In both periods, the largest net assimilation was observed at the HWL_Si, where the cumulative NEE reached up to -205.16 gCO_2-C·m^{-2}·cut^{-1} in 2021 and -672.37 gCO_2-C·m^{-2}·cut^{-1} in 2022. For the second cut of 2021, the HWL_Si plot still acted as the largest sink, with a cumulative NEE reaching -278.85 gCO_2-C·m^{-2}·cut^{-1}. However, in this case, positive NEE values were obtained in the plot with a higher WTD without AT application (8.20 gCO_2-C·m^{-2}·cut^{-1}) indicating that emissions outweighed CO_2 assimilation. Interestingly, the LWL and LWL_Si plots also acted as net sinks of CO_2 during the second cut of 2021, with cumulative NEE values of -201.99 gCO_2-C·m^{-2}·cut^{-1} and -79.88 gCO_2-C·m^{-2}·cut^{-1} for LWL and LWL_Si, respectively. The positive effect of AT in the site with a higher WTD was also observed in the second cut of 2022, when the HWL_Si plot was the only one to have a negative cumulative NEE. Therefore, it can be concluded that in the first and second cuts in both 2021 and 2022, a positive effect of silicon antitranspirant application was observed in the site with a higher WTD. However, the pattern varies much more when the period of the third cut is considered. In both years, the HWL_Si and LWL_Si plots treated with silicon antitranspirant had higher (more positive) cumulative NEE than the plots without AT application. For the LWL site, silicon application had a positive effect only in the first cut of 2022, increasing net assimilation rates compared to the plot without application. In other periods, it resulted either in higher net emissions (second cut 2022 as well as third cut 2021 and 2022) or lower net assimilation rates (first and second cut 2021) when compared to the LWL plot without AT application. The application of silicon antitranspirant had a varying effect on NEE fluxes depending on the groundwater level and the cutting period, but for the first two cutting periods, it was more beneficial for the sites with higher WTD where the cumulative NEE was most negative.

I cut 2021	HWL					**I cut 2022**	HWL			
	HWL_Si	<0.05					HWL_Si	<0.05		
	LWL	<0.05	0.0753				LWL	<0.05	<0.05	
	LWL_Si	<0.05	<0.05	0.0625			LWL_Si	<0.05	<0.05	<0.05
		HWL	HWL_Si	LWL	LWL_Si			HWL	HWL_Si	LWL	LWL_Si
II cut 2021	HWL					**II cut 2022**	HWL			
	HWL_Si	<0.05					HWL_Si	<0.05		
	LWL	<0.05	<0.05				LWL	0.1542	<0.05	
	LWL_Si	<0.05	<0.05	<0.05			LWL_Si	<0.05	<0.05	0.3978
		HWL	HWL_Si	LWL	LWL_Si			HWL	HWL_Si	LWL	LWL_Si
III cut 2021	HWL					**III cut 2022**	HWL			
	HWL_Si	<0.05					HWL_Si	<0.05		
	LWL	<0.05	<0.05				LWL	<0.05	<0.05	
	LWL_Si	<0.05	<0.05	<0.05			LWL_Si	<0.05	<0.05	0.0501
		HWL	HWL_Si	LWL	LWL_Si			HWL	HWL_Si	LWL	LWL_Si

Figure 11. Comparison of daily NEE fluxes for individual plots (HWL, HWL_Si, LWL, LWL_Si) using Wilcoxon matched-pairs test in each cut in 2021 and 2022. $p < 0.05$ means that the pairs are significantly different from each other.

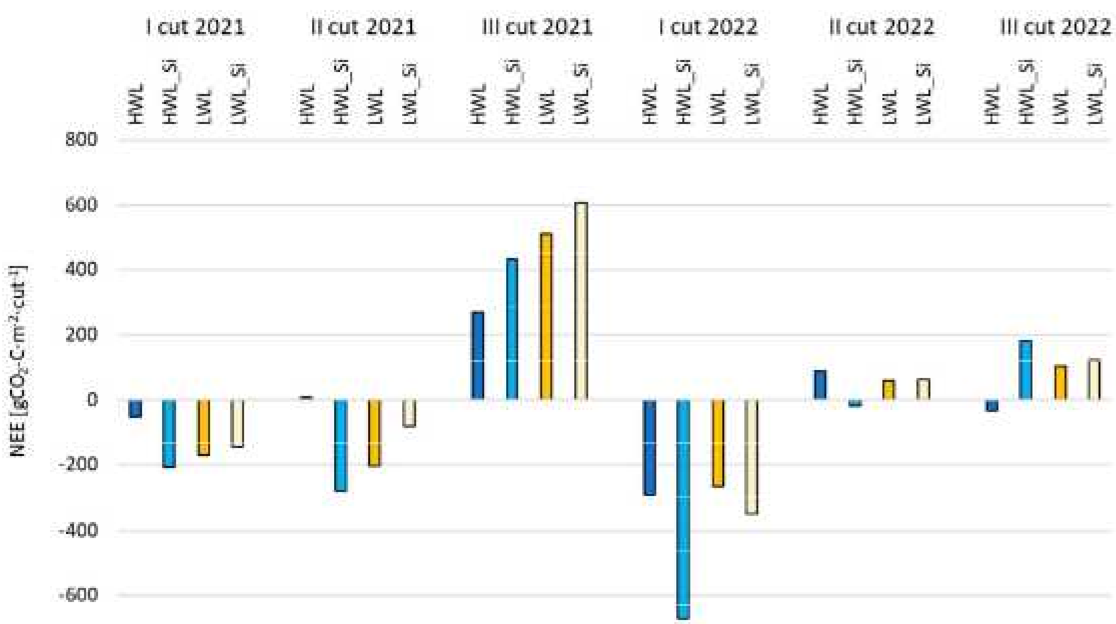


Figure 12. Cumulative NEE fluxes for individual plots in each cut in 2021–2022.

3.3. Growing Season and Annual Carbon Dioxide Balances

The cumulative NEE fluxes for the respective growing seasons of 2021 and 2022 are shown in Figure 13. These two periods differ from each other. In 2021, cumulative seasonal NEE was positive in all treatments, indicating that the meadow was a net CO_2 emitter. However, in 2022, the opposite pattern was observed—the negative NEE indicates that the meadow was a net sink of CO_2 for all treatments. These differences might be related to warmer and wetter conditions in 2022, when the annual and growing season average air temperatures were higher than in 2021 by 1.0 °C and 0.6 °C, respectively, while the annual sum of precipitation was higher by 65.2 mm (Table 1). On the other hand, 2021 had higher average soil moisture than 2022 in both sites with higher (HWL) and lower (LWL) WTD (by 12% and 10%, respectively).

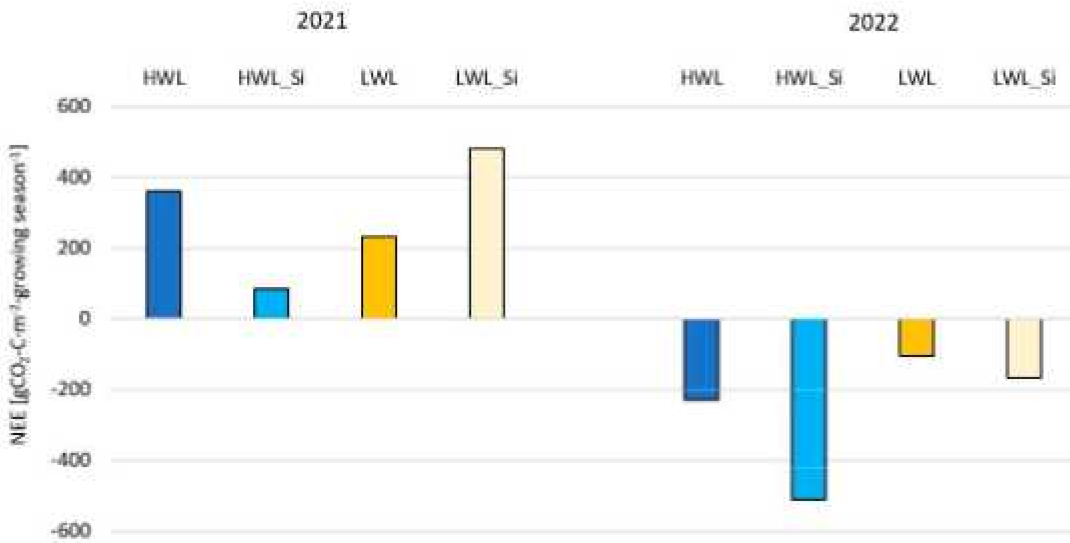


Figure 13. Cumulative NEE values for the 2021 and 2022 growing seasons.

The highest (most positive) cumulative seasonal NEE in 2021 was reached for LWL_Si (481.77 gCO_2-C·m^{-2}·growing season^{-1}, Table 2). In the case of this plot, the CO_2 emission was higher than for LWL by250.19 gCO_2-C·m^{-2}·growing season^{-1} (Reco of LWL plot: 231.57 gCO_2-C·m^{-2}·growing season^{-1}). An inverse relationship was noted for the site with the higher WTD, where the plot with applied AT (HWL_Si) showed a significantly lower cumulative NEE (82.24 gCO_2-C·m^{-2}·growing season^{-1}) than that for the HWL plot without this treatment (360.31 gCO_2-C·m^{-2}·growing season^{-1}). Therefore, in the first year of the experiment, the positive effect of the silicon antitranspirant application on the CO_2 balance was confirmed for the site with the higher WTD. Although the HWL_Si plot was also a net source of CO_2 emitted to the atmosphere, the net emission was smaller than for HWL. The same effect was found in the more wet and warmer growing season of 2022, with the difference that cumulative NEE fluxes were negative for all the plots, as indicated above. Nonetheless, the application of an antitranspirant positively affected the CO_2 balance of the meadow, especially at HWL_Si (−512.18 gCO_2-C·m^{-2}·growing season^{-1}), where the cumulative seasonal NEE was more than twice as much as for HWL (−229.55 gCO_2-C·m^{-2}·growing season^{-1}). The application of antitranspirant also had a positive effect on the CO_2 balance of the site with the lower WTD. Although the differences were much smaller than for the HWL site, the cumulative seasonal NEE was higher (more negative) for LWL_Si (−166.46 gCO_2-C·m^{-2}·growing season^{-1}) than for LWL (−105.69 gCO_2-C·m^{-2}·growing season^{-1}). To conclude, in the growing season of 2022, the application of the silicon antitranspirant increased net CO_2 assimilation by 123% for the site with a higher WTD and by 58% for the site with a lower WTD.

Table 2. Annual and growing season cumulative Reco, GPP, and NEE fluxes for individual plots for 2021–2022.

		Growing Season (gCO_2-$C{\cdot}m^{-2}{\cdot}$Growing Season^{-1})				Annual (gCO_2-$C{\cdot}m^{-2}{\cdot}$Year^{-1})			
Year	**Plot**	**HWL**	**HWL_Si**	**LWL**	**LWL_Si**	**HWL**	**HWL_Si**	**LWL**	**LWL_Si**
2021	Reco	2310.57	2327.85	2175.86	2225.61	2445.37	2446.85	2291.03	2353.52
	GPP	−1950.27	−2245.61	−1944.28	−1743.83	−2131.12	−2397.30	−2106.13	−1912.36
	NEE	360.31	82.24	231.58	481.77	314.25	49.55	184.89	441.17
2022	Reco	2092.23	1996.66	1723.40	1810.22	2234.95	2129.56	1847.76	1924.61
	GPP	−2321.79	−2508.84	−1829.08	−1976.68	−2389.14	−2565.75	−1888.21	−2043.31
	NEE	−229.55	−512.18	−105.69	−166.46	−154.19	−436.19	−40.45	−118.70

The annual cumulative Reco fluxes were higher in 2021 and ranged from 2291.03 to 2446.85 gCO_2-$C{\cdot}m^{-2}{\cdot}year^{-1}$, whereas in 2022 they ranged from 1847.76 to 2234.95 gCO_2-$C{\cdot}m^{-2}{\cdot}year^{-1}$ (Table 2). The cumulative annual GPP fluxes ranged from −1912.36 to 2397.30 gCO_2-$C{\cdot}m^{-2}{\cdot}year^{-1}$ in 2021 and from −1888.21 to −2565.75 gCO_2-$C{\cdot}m^{-2}{\cdot}year^{-1}$ in 2022. Excluding the LWL_Si plot in 2021, in all other treatments in both years, the positive effect of silicon antitranspirant application on CO_2 net balance was confirmed, similarly to the seasonal balances, as indicated above (Table 2).

3.4. Meadow Yield

Table 3 summarizes the meadow sward dry matter values obtained in the individual cuts and the annual total. Regardless of the cut and the area (with high/low groundwater levels), it can be observed that the application of the silicon antitranspirant contributed to a reduction in yield of aboveground biomass. Looking at individual cuts, the biggest reduction occurred in the third cut of 2022. This amounted to −42% in the site with high groundwater levels and −25% in the site with low groundwater levels. The smallest negative impact of the antitranspirant was observed in 2022 during the second cut. The yield reduction was 7% and 4% for LWL and HWL, respectively. Analyzing the yields obtained from the whole year, it can be observed that silicon had a stronger negative effect on yield in the area with a higher groundwater level—it caused a reduction of yield biomass by 17–18%, depending on the year. In the case of lower groundwater levels, the yield reduction was smaller, and reached 14% in 2021 and 11% in 2022. The two-year results clearly suggest that applying the silicon antitranspirant negatively affected yield by reducing the dry matter of the aboveground biomass.

Table 3. Meadow yield of aboveground biomass in individual plots during the study period ($kg{\cdot}ha^{-1}$) [30] and percentage reduction in dry matter after application of the silicon antitranspirant (%).

	1st Cut	**2nd Cut**	**3rd Cut**	**Year**
2021				
HWL	4365.39	4621.57	3706.08	12,693.04
HWL_Si	3489.42 (−20.1%)	3999.88 (−13.5%)	2939.83 (−20.7%)	10,429.13 (−17.8%)
LWL	4587.14	3993.01	3467.47	12,047.61
LWL_Si	3842.25 (−16.2%)	3410.8 (−14.6%)	3111.19 (−10.3%)	10,364.24 (−14.0%)
2022				
HWL	4598.28	3253.43	2179.26	10,030.97
HWL_Si	3897.24 (−15.2%)	3135.94 (−3.6%)	1260.74 (−42.1%)	8293.92 (−17.3%)
LWL	4283.50	2710.34	1984.71	8978.55
LWL_Si	3966.99 (−7.4%)	2513.96 (−7.2%)	1497.3 (−24.6%)	7978.25 (−11.1%)

Concerning the impact of the groundwater level, it can be observed that a higher water level positively affected the biomass yield. In 2021, the yield from the HWL plot equaled 12,693.04 $kg{\cdot}ha^{-1}$ and was 5.4% higher than that from LWL plot (12,047.61 $kg{\cdot}ha^{-1}$). The same situation occurred in 2022, when higher groundwater levels contributed to the annual biomass yield being higher by 11.7%, with 10,030.97 kg·ha^{-1} and 8978.55 kg·ha^{-1} from the HWL and LWL plots, respectively. Analyzing the individual cuts in both years, a continuing trend can be seen—the dry matter yield from the HWL plot was higher than that from LWL for almost all the cuts. The exception is the first cut in 2021, when a higher yield was obtained from the LWL plot. This is most likely due to too-high soil moisture at HWL, which was a limiting factor for plant development. High soil moisture (close to the maximum field water capacity) results in water saturation of the soil pores, causing a concomitant oxygen deficiency in the soil, which can inhibit plant growth and development [30].

Furthermore, when analyzing both years, it is noticeable that considerably higher yields were obtained in 2021 than in 2022. For the HWL plot, these amounted to 12,693.04 kg·ha^{-1}, whereas in the following year, it was 10,030.97 kg·ha^{-1}, i.e., a decrease of 21.0%. A similar trend was observed in the other plots. On HWL_Si, yields in 2022 decreased from 10,429.13 kg·ha^{-1} (2021) to 8293.92 kg·ha^{-1} (20.5% reduction). The largest difference between the years occurred in the LWL plot, where yields in 2022 were 25.5% lower than in 2021 (reduction from 12,047.61 to 8978.55 kg·ha^{-1}). In the case of LWL_Si, the yield reduction was at the level of 23.0%; from 10,364.24 kg·ha^{-1} to 7978.25 kg·ha^{-1}. The obtained differences in yields directly reflect the values of GPP, which depended, among other things, on the different meteorological conditions in both years. Although the year 2022 was warmer and had higher precipitation, the average values of soil moisture in the growing season were lower, which could be indirectly reflected in the obtained yields, which were lower than in the previous year. When the individual cuts are examined, it can be observed that similar amounts of dry matter were harvested from the first cut in 2021 and 2022. Furthermore, all plots apart from LWL had even higher yields in 2022 than in 2021, so the trend in this cut was the opposite of that for the rest of the year. A definite yield reduction between years was already visible during the second cut. This ranged from 21.6% (863.94 kg·ha^{-1}) for the HWL_Si plot to as much as 32.1% (1282.67 kg·ha^{-1}) for the LWL plot. This yield reduction corresponds to one of the driest periods with the lowest soil moisture, which decreased by up to 18% and 16% at the HWL_Si and LWL_Si plots, respectively (Table 1). In comparison, the soil moisture of the same plots in the second cut of 2021 reached 47% and 42% for the HWL_Si and LWL_Si plots, respectively. Therefore, the topsoil in the second cut of 2022 was over-dried, resulting in suboptimal plant development conditions. Furthermore, the second cut in 2022 lasted longer (70 days) than in 2021 (44 days), and thus covered the period with the lowest groundwater levels. Moreover, the unfavorable rainfall distribution during the growing season also affected the results. For example, in August 2022, the total rainfall was 135 mm, of which as much as 83 mm fell on a single day—20 August. The third cut of 2021 was shorter by 16 days and, above all, covered an earlier period—the final cut took place more than a month earlier (30.09.2021) than in 2022 (17.11.2022). This directly resulted in a higher average daily temperature of 16.8 °C in 2021 in the third cut, and one of only 12.9 °C in 2022. Concerning the entire growing season, the average soil moisture was 12% lower in 2022 for the plots with high groundwater levels (47% in 2021 vs. 35% in 2022) and 10% lower for the plots with lower groundwater levels (41% in 2021 vs. only 31% in 2022). This condition could have a direct impact on yield reduction, as was already proved in other studies [45,46].

4. Discussion

4.1. Subirrigation and WTD Impacts on Yield and GPP

The results obtained in this study show significant differences between the daily GPP fluxes on the HWL and LWL plots (Figure 5). Furthermore, in all cuts in the second year of the study and in the third cut in the first year, the cumulative GPP fluxes were higher at the HWL plot than at the LWL plot, which is equivalent to a higher CO_2 assimilation. Therefore, it can be concluded that higher WTD levels positively affect meadow productivity (GPP). A similar trend is observed when aboveground biomass yields are considered. In all cuts except the first cut in 2021, the yield was higher from the HWL plot than from the LWL plot. On an annual basis, maintaining a higher groundwater level contributed to a 5.4–11.7% higher biomass yield.

As the GPP indicates the amount of CO_2 assimilated by plants in photosynthesis, the clear relationship between the GPP and plant biomass exists. These relationships, for the LWL and HWL plots, are shown in Figure 14. When all data are considered (HWL and LWL combined), it is evident that the more carbon dioxide the meadow assimilates (higher GPP), the higher is the harvested aboveground biomass yield, although this correlation is not significant (at the $\alpha = 0.05$). However, when analyzing this correlation, one should consider that only the aboveground yield of plants is taken into account in our study. This study did not estimate the root biomass; hence, it is hard to assess how much carbon sequestered by plants was accumulated in belowground biomass. However, it is well known that the root system of plants might be stronger and its biomass might be higher at sites with a lower WTD and lower soil moisture [47]. Furthermore, other agronomic practices like meadow management, fertilization, and cutting frequency may also impact root biomass. For example, Wang et al. [48] and De Vries et al. [49] indicated a higher belowground carbon allocation and higher root biomass in extensively managed grasslands, when compared to intensively managed meadows. Also, Poyda et al. [50] pointed out that highly fertilized grasslands may lose carbon sequestration capacity due to low underground C allocation. Their study shows that only a low fraction (17%) of net primary production is allocated to the roots. Considering the above, it can be speculated that the correlation between GPP and biomass yield would be stronger when both the above- and below- ground biomass of plants is considered.

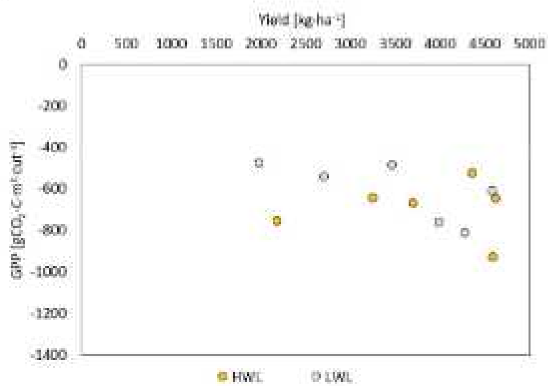


Figure 14. Relationship between cumulative GPP fluxes in each cut and yield of aboveground biomass from HWL and LWL plots.

4.2. Subirrigation and WTD Impacts on CO_2 Emissions

One of the most complex issues in relation to grasslands is the area's water management and its direct impact on CO_2 emissions. Clear differences in daily, seasonal, and annual Reco rates between LWL and HWL plots have been demonstrated in this study. As indicated in Table 2, the annual cumulative Reco rates were higher at the HWL plot (depending on the year, they amounted to from 2092.23 to 2310.57 $gCO_2\text{-}C\cdot m^{-2}\cdot year^{-1}$) than at the LWL plot (from 1723.40 to 2175.86 $gCO_2\text{-}C\cdot m^{-2}\cdot year^{-1}$). These rates of Reco fluxes are similar to those estimated by Poyda et al. [51] for intensive grasslands in Germany (2490–2960 $gCO_2\text{-}C\cdot m^{-2}\cdot year^{-1}$), but they are half of those estimated by Eickenscheidt et al. [52] for a three-cut intensive meadow fertilized with biogas digestate on Mollic Gleysoil (4265 $\pm$ 379 $gC\cdot m^{-2}\cdot year^{-1}$). The broad range of Reco fluxes from grasslands reported in the literature indicates differences in these ecosystems and makes any results comparison complicated, as complex factors, such as soil type and its moisture, plant species composition, fertilization, the intensity of meadow use, grazing, and meteorological conditions may impact the CO_2 emissions from grasslands [14,51,53–55].

Anyway, in the case of this study, the higher Reco rates at HWL than at LWL plots may lead to the conclusion that higher WTD and higher soil moisture are increasing CO_2 emissions from grasslands on organic soils. This finding might be in contradiction to other studies in which it is generally indicated that raising the WTD can have a beneficial effect on reducing CO_2 emissions from degraded peatlands and grasslands [7,14,56]. Abdalla et al. [57] also indicated that too-high groundwater levels can reduce soil respiration (Rs) in grassland due to anaerobic conditions, which are unfavorable for the oxidation of soil organic matter, plant residue, and aerobic respiration. This condition may lead to a reduction of heterotrophic respiration (Rh) of soil microorganisms. On the other hand, Rs accounts for about 45–59% of ecosystem respiration in grasslands, and its contribution to Reco flux may vary from 46% in summer to 59% in winter [57,58]. In the present study, Rs was not measured; hence, it is hard to estimate the amount of CO_2 emitted from soils and its contribution to Reco. But, due to the fact that a higher WTD leads to a higher yield of aboveground biomass and causes higher Reco, it can be speculated that higher CO_2 emissions from HWL plots are a result of higher autotrophic respiration (Ra) of aboveground biomass and may indicate that the Ra/Rh ratio might also be higher at plots with higher WTD. As indicated in Figure 3, cutting the grass reduces Reco fluxes due to the reduction of Ra [51], although this reduction seems to be smaller at LWL plots, where Rs might be higher due to less moisture and smaller plant biomass.

Similarly to this study, Weideveld et al. [59] did not show a positive effect of increasing WTD on the reduction of CO_2 emissions from peat meadow with a subsoil irrigation system (perforated pipes −70 cm from surface level with a spacing of 5–6 m) in the Netherlands, due to the fact that changes in the WTD occurred in the deeper soil layers (60–120 cm depth), which have little impact on organic matter oxidation in the upper layers contributing most to the overall CO_2 emissions. Boonman et al. [60] found that temporal variation in meteorological conditions, spatial variation in landscape seepage, and variation in ditchwater level management decisions can explain the wide range in subsoil irrigation and drainage (SSI) effectivity that other researchers had previously reported. They proved that SSI reduces yearly peat respiration rates in a dry year. On the other hand, in a wet year or when upward groundwater seepage is present, SSI increases peat respiration rates. According to Weideveld et al. [59], future studies on GHG emissions should pay more attention to the manipulation of groundwater levels in the uppermost soil layers (0–30 cm) in grasslands, as it has an essential role in this regard. However, it should be borne in mind that, in the case of grasslands, a rise in the WTD in the higher soil layers also affects the occurrence of plant species that are more tolerant of higher soil moisture levels. The entry of new and different species at higher WTD may be a factor that may also affect CO_2 emissions. Considering the above, the impact of irrigation and the maintenance of the WTD on an appropriate level of CO_2 emissions from grasslands requires a lot of new research to cover a broad range of grasslands and different management strategies.

4.3. Silicon Antitranspirant Impact on Yield and GPP

The results of this study demonstrated that daily, seasonal, and annual GPP fluxes differed between plots with and without antitranspirant application in the site with higher WTD in each cut. For the site with a lower WTD, significant differences in daily GPP fluxes between LWL and LWL_Si were recorded in all cuts except the second cut in 2021 (Figure 5). The cumulative GPP fluxes in each cut show that AT application positively affected I and II cuts in both years by increasing CO_2 uptake at the HWL site (Figure 6). However, for the LWL site, the results varied between years and cuts (Table 2). In the case of yield, unambiguous results were obtained for both sites, demonstrating that the antitranspirant contributed to the reduction of aboveground plant biomass in the meadow (Table 3). These findings are consistent with Radkowski et al. [61], who obtained lower biomass after silicon application in a meadow in Poland.

The relationship between GPP fluxes in individual cuts and aboveground biomass yields for the LWL_Si and HWL_Si plots (Figure 15) clearly demonstrated that with increasing CO_2 assimilation rates, the plant biomass also increases, although this correlation is significant ($\alpha = 0.05$) only for the HWL_Si plot. Still, for the same rates of GPP, the yield was generally higher for the HWL_Si plot than for LWL_Si, indicating the effect of WTD on this relationship, as mentioned above, which may also override the effect of AT application on GPP. Therefore, it is necessary to continue research in grasslands in this scope to understand better silicon's role in CO_2 assimilation and its dependence on groundwater level.

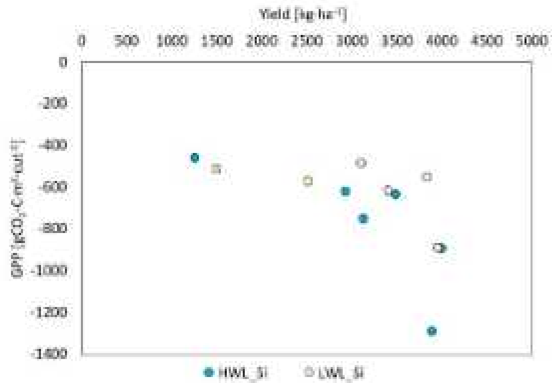


Figure 15. Relationship between cumulative GPP fluxes in each cut and yield obtained from HWL_Si and LWL_Si plots.

4.4. Silicon Antitranspirant Impact on CO_2 Emissions

The results of this experiment show that AT application may have some positive impact on the reduction of Reco fluxes at the site with the higher WTD. Four of the six analyzed cuts proved a positive effect of AT on Reco flux reduction. When considering the site with the lower WTD, this treatment reduced Reco fluxes in three cuts, and this reduction was less than for the site with the higher WTD. Similarly, annual Reco fluxes were smaller at AT-treated plots with higher WTD, but a reversed effect was found at the site with a lower WTD, although all these differences are negligibly small. It can only be speculated that these small differences might be caused by higher yield reduction at site with higher WTD (Table 3).

To the best of our knowledge, there have been no studies to date on the application of silicon antitranspirant in grasslands and its effect on Reco fluxes. Therefore, this is the first time such a field experiment has been conducted; and hence, future studies will need to investigate this effect more in depth.

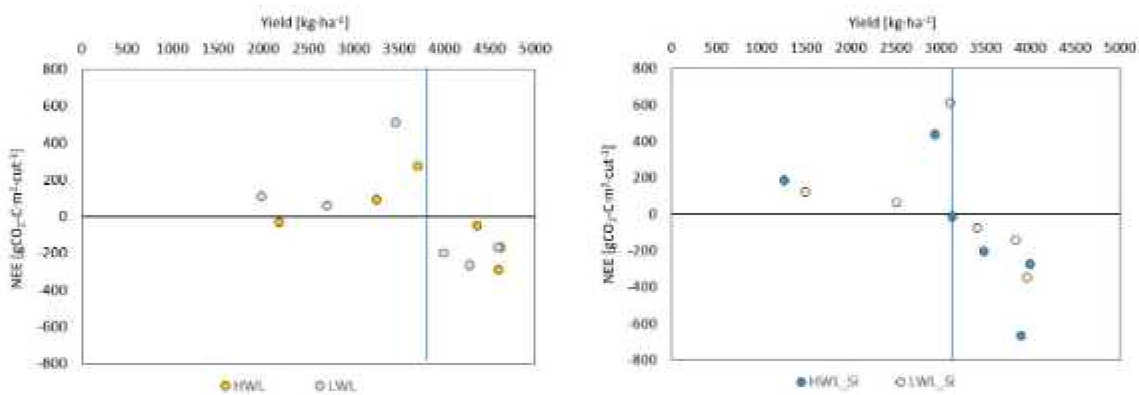
4.5. Silicon Antitranspirant and Subirrigation's Impact on Net Carbon Balances

Researchers are still looking for unambiguous relationships to understand the influences of individual factors on NEE fluxes from grasslands. Previous studies have shown that the intensity of grassland use and cutting events are important aspects impacting NEE variability. Measurements indicated that NEE increases (is less negative, or positive) with the number of cuts. This is mainly because GPP is reduced to almost zero for a few days after harvesting the meadow sward [51,54]. Depending on the year and the prevailing meteorological conditions, meadows can either act as a net sink or a source of carbon dioxide. In a study by Aires et al. [62] on Mediterranean grassland, precipitation was the main determinant of interannual variation in NEE. During a dry year, the grassland was a net source of CO_2 to the atmosphere, whereas during a normal year, CO_2 uptake prevailed. Furthermore, it has been shown that climate change, warmer conditions, and intensive grassland management can negatively affect grassland carbon balances and result in a less-negative annual NEE [48]. However, Zhang et al. [63] found that water availability is more important than temperature for shaping carbon fluxes from alpine meadows. Their results demonstrated that soil water content directly influenced NEE, GPP, and Reco fluxes.

This study shows that the HWL plot in the first year of the study had higher (positive) NEE cumulative fluxes when compared to the LWL plot, representing a greater excess of CO_2 emission over uptake at HWL. In contrast, in the following year, the HWL plot had more negative NEE values than LWL, representing greater uptake (Table 3). A study of Poyda et al. [51] conducted in a three-cut meadow showed a significant correlation between net annual CO_2 balance and mean annual groundwater level. It showed that a meadow system combined with a higher WTD (about 20 cm below the surface) achieved the lowest yield-related greenhouse gas emissions.

In this study, a positive effect on cumulative annual NEE fluxes was only observed in combination with high groundwater levels for the silicon application. The AT treatment in the HWL_Si plot resulted in lower positive NEE fluxes in 2021 than at the HWL plot and more negative NEE fluxes than at the HWL plot in 2022. These results clearly show the positive effect of this treatment on the net carbon dioxide balance. However, a different result was obtained for the lower WTD, where the Si application either increased CO_2 emissions or reduced CO_2 uptake, depending on the year. Therefore, it can be concluded that this AT effect is beneficial when combined with a higher WTD.

There is an interesting aspect, which has been found while comparing relationships between NEE fluxes and the biomass yield cumulated in each cut for the plots with and without AT treatments (Figure 16). Although the yield of biomass on AT-treated plots was smaller, the yield at which the meadow turns from being a net source to a net sink of CO_2 in single cuts shifts from around 3800 $kg \cdot ha^{-1}$ at plots without Si application to 3200 $kg \cdot ha^{-1}$ at the AT-treated plots. Also, in more cases, the cumulated NEE was more negative at the same biomass yield for the plot with silicon application.



(**a**) (**b**)

Figure 16. Relationship between cumulative NEE fluxes in each cut and aboveground biomass yield for (**a**) HWL and LWL and (**b**) HWL_Si and LWL_Si plots. Vertical lines indicate the turning points when the meadow switched from being a net source to a net sink of CO_2 for different yield levels.

4.6. Importance of Results and Future Research Directions

To the best of our knowledge, this study is the first wherein the effect of silicon anti-transpirant application on CO_2 fluxes exchanged between the meadow and the atmosphere was evaluated. It proved that AT treatment has a positive effect on the growing season and annual cumulative NEE fluxes at the site with a higher WTD (Figure 13, Table 2), resulting in reduced net emissions (like in 2021) or increased net CO_2 sequestration (like in 2022). Therefore, it can be concluded that the application of AT under suitable groundwater level conditions has the potential to be a tool to improve the carbon balance of grasslands and reduce the negative climatic impact of grasslands located on degraded peatlands, which are net emitters of CO_2 [5]. On the other hand, the response of plants to the same treatment at the site with a lower WTD is not unequivocal, and this may lead to contradictory conclusions. Hence, it is necessary to continue this research on other grasslands under different climatic conditions and management strategies to have a clearer picture of the impact of antitranspirants on CO_2 budgets.

However, from the farmer's point of view, using AT with silicon in the meadow is disadvantageous, since this treatment contributed to a significant yield reduction. Therefore, it will not be easy to convince farmers that the application of silicon AT is beneficial for the climate, and that this outweighs the profits obtained from animal feed production. The results of this study show the potential for using antitranspirants; however, they are not fully beneficial. Therefore, it is desirable to also carry out further measurements in this respect on other ATs to determine their impacts on both CO_2 emissions and grassland yields. If positive results are obtained in both aspects, detailed economic analyses should be carried out in future studies to determine the costs incurred for applying AT to meadows and the profitability of this treatment.

5. Conclusions

The impacts of subirrigation and silicon antitranspirant application, as well as meteorological conditions, on the net carbon balance of the three-cut meadow was different for individual seasons and years, although some significant and conclusive statements can be formulated.

1. In the drier and colder year (2021), net CO_2 emissions predominated, whereas net CO_2 assimilation predominated in the warmer and wetter year (2022) for all the plots, which highlights the impact of meteorological conditions on the annual NEE of grasslands.
2. Higher WTD and higher soil moisture promote CO_2 emissions from the meadow (Reco is higher), most probably due to an increase in the autotrophic respiration of plants due to higher aboveground biomass.
3. Higher WTD and higher soil moisture promote higher yields of aboveground biomass. The yields were higher by 5.4% (in 2021) up to 11.7% (in 2022) at plot with a higher WTD, which highlights the role of the WTD in maintaining high production in meadows.
4. Silicon antitranspirant application has a positive impact on meadow productivity (GPP), but only on plots with higher WTD.
5. Silicon antitranspirant application has a negative impact on the yield of aboveground biomass (reduction of annual yield from 11.1% to 17.8%). The reduction of yield is higher at the plot with a higher WTD.
6. The yield at which the meadow turns from being a net source to a net sink of CO_2 in single cuts shifts from around 3800 $kg \cdot ha^{-1}$ at plots without silicon antitranspirant application to 3200 $kg \cdot ha^{-1}$ at treated plots, while cumulated NEE is more negative at the same biomass yield for plots with silicon application. It indicates that silicon antitranspirant application may have a positive effect on improving the carbon balance of meadows (either by reducing net emissions or increasing net assimilations).

Although some findings presented in this study are not unequivocal, the obtained results increase our understanding and the current state-of-the-art knowledge about the use of antitranspirants and subirrigation management systems in meadows, and we believe it will stimulate new studies in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15173057/s1, Figure S1: Spearman correlation matrix for daily values of GPP, RECO, NEE, soil moisture (SM), air temperature (TA), and water table depth (WTD) in 2021 for individual measurement plots: (a) HWL; (b) HWL_Si; (c) LWL; (d) LWL_Si.; Figure S2: Spearman correlation matrix for daily values for daily values of GPP, Reco, NEE, soil moisture (SM), air temperature (TA), and water table depth (WTD) in 2022 for individual measurement plots: (a) HWL; (b) HWL_Si; (c) LWL; (d) LWL_Si.

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5. Podsumowanie i wnioski

W oparciu o przeprowadzone w pracy doktorskiej badania i analizy sformułowano następujące główne wnioski:

1) Dotychczas opublikowane badania pokazały, że zastosowanie antytranspirantów na roślinach z rodziny *Poaceae* w wielu przypadkach ma korzystny wpływ na parametry roślin, plonowanie czy też łagodzenie wpływu suszy.
2) Aplikacja AT z krzemem na trzykośnej łące istotnie zmniejszyła wielkość plonu zarówno na obszarze z wysokim jak i z niższym poziomem wody gruntowej.
3) Wyższe roczne plony z łąki uzyskano z obszaru z wysokim poziomem wody gruntowej, niż z obszaru o niższym poziomie wody gruntowej.
4) Zastosowanie AT z krzemem pozytywnie oddziałuje na roczne strumienie netto CO_2 na obszarze z wysokim poziomem wody gruntowej. W zależności od analizowanego roku aplikacja AT z krzemem przyczyniła się do zmniejszenia emisji netto lub zwiększenia asymilacji netto na tym obszarze.

Pozostałe wnioski zostały przedstawione w publikacjach naukowych stanowiących część niniejszej rozprawy doktorskiej. Uzyskane w tej pracy wyniki pokazują, że aplikacja AT z krzemem na obszarze z wysokim poziomem wody gruntowej ma duży potencjał i pozytywny wpływ na wielkość strumieni netto CO_2. Rezultaty te są szczególnie istotne w obliczu zachodzących zmian klimatu i potrzeby redukcji emisji CO_2. Niestety z punktu widzenia rolników użycie AT z krzemem ma negatywny efekt z uwagi na fakt, że powoduje obniżenie plonu łąk. Ważne jest zatem dalsze kontynuowanie pomiarów w tym zakresie na łąkach, poszerzając je o inne rodzaje antytranspirantów oraz różne dawki tychże preparatów. Uzyskane w pracy rezultaty mają pionierski charakter oraz stanowią punkt wyjścia do kolejnych badań dotyczących możliwości zastosowania AT na łąkach. W niniejszej rozprawie po raz pierwszy określono wpływ AT z krzemem na strumienie netto CO_2 na łące z systemem nawodnienia podsiąkowego.

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Liberacki, D., & Stróżecki, M. (2023). The Role of Antitranspirants in Mitigating Drought Stress in Plants of the Grass Family (*Poaceae*)—A Review. Sustainability, 15(12), 9165, https://doi.org/10.3390/su15129165 mój indywidualny udział w jej powstaniu polegał na opracowaniu celu, zakresu oraz koncepcji i metodyki artykułu, zebraniu literatury i dokonaniu jej przeglądu, analizie i interpretacji uzyskanych danych, redakcji oraz napisaniu oryginalnego tekstu artykułu, wykonaniu wizualizacji, a także końcowej edycji tekstu, co stanowi 80% całej pracy.

Podpis

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Oświadczenie o współautorstwie

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Podpis

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Liberacki, D., Kupiec, J. M., Stróżecki, M., & Dłużewski, P. (2023). Effects of Silicon Application and Groundwater Level in a Subirrigation System on Yield of a Three-Cut Meadow. Water, 15(11), 2103, https://doi.org/10.3390/w15112103 mój indywidualny udział w jej powstaniu polegał na współtworzeniu koncepcji, celu oraz zakresu artykułu, przeprowadzeniu badań terenowych oraz analiz laboratoryjnych, analizie i interpretacji uzyskanych wyników, wykonaniu wizualizacji danych, redakcji oraz napisaniu oryginalnego tekstu artykułu, pozyskaniu środków finansowych, a także wykonaniu końcowej edycji tekstu, co stanowi 60% całej pracy.

Podpis

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Liberacki, D., Kupiec, J. M., Stróżecki, M., & Dłużewski, P. (2023). Effects of Silicon Application and Groundwater Level in a Subirrigation System on Yield of a Three-Cut Meadow. Water, 15(11), 2103, https://doi.org/10.3390/w15112103 mój indywidualny udział w jej powstaniu polegał na współtworzeniu koncepcji artykułu, nadzorze nad doświadczeniem, pomocy z zakresu metodyki oraz w przeprowadzeniu pomiarów terenowych, a także wykonaniu końcowej edycji artykułu, co stanowi 10% całej pracy.

Podpis
Daniel Liberacki

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Oświadczenie o współautorstwie

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Podpis współautora

Poznań, 18.09.2023 r.

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Liberacki, D., Kupiec, J. M., Stróżecki, M., & Dłużewski, P. (2023). Effects of Silicon Application and Groundwater Level in a Subirrigation System on Yield of a Three-Cut Meadow. Water, 15(11), 2103, https://doi.org/10.3390/w15112103 mój indywidualny udział w jej powstaniu polegał na współudziale w tworzeniu koncepcji artykułu, zapewnieniu sprzętu do pomiarów terenowych, nadzorze nad doświadczeniem, wsparciu z zakresu metodyki badań i interpretacji uzyskanych wyników, a także wykonaniu końcowej edycji artykułu, co stanowi 10% całej pracy.

Podpis

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Liberacki, D., Kupiec, J. M., Stróżecki, M., & Dłużewski, P. (2023). Effects of Silicon Application and Groundwater Level in a Subirrigation System on Yield of a Three-Cut Meadow. Water, 15(11), 2103, https://doi.org/10.3390/w15112103 mój indywidualny udział w jej powstaniu polegał na przeprowadzeniu terenowych badań gleboznawczych, analiz laboratoryjnych pobranych prób glebowych oraz ich interpretacji, co stanowi 5 % całej pracy.

Dłużewski

Podpis

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Stróżecki, M., Juszczak, R., Liberacki, D. (2023). Effect of Subirrigation and Silicon Antitranspirant Application on Biomass Yield and Carbon Dioxide Balance of a Three-Cut Meadow. Water, 15(17), 3057, https://doi.org/10.3390/w15173057 mój indywidualny udział w jej powstaniu polegał na współtworzeniu koncepcji, celu oraz zakresu artykułu, przeprowadzeniu badań terenowych oraz analiz laboratoryjnych, analizie i interpretacji uzyskanych wyników, wykonaniu wizualizacji danych, redakcji oraz napisaniu oryginalnego tekstu artykułu, pozyskaniu niezbędnych środków finansowych, a także końcowej edycji tekstu, co stanowi 64% całej pracy.

Podpis

J. Kocięcka

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Stróżecki, M., Juszczak, R., Liberacki, D. (2023). Effect of Subirrigation and Silicon Antitranspirant Application on Biomass Yield and Carbon Dioxide Balance of a Three-Cut Meadow. Water, 15(17), 3057, https://doi.org/10.3390/w15173057 mój indywidualny udział w jej powstaniu polegał na współudziale w tworzeniu koncepcji artykułu, zapewnieniu sprzętu do pomiarów terenowych, nadzorze nad doświadczeniem, wsparciu w przeprowadzeniu badań terenowych, analiz i modelowania strumieni CO_2 oraz interpretacji uzyskanych wyników, pomocy w wykonaniu wizualizacji danych, a także wykonaniu końcowej edycji tekstu, co stanowi 12% całej pracy.

Podpis

Poznań, 11.09.2023 r.

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Stróżecki, M., Juszczak, R., Liberacki, D. (2023). Effect of Subirrigation and Silicon Antitranspirant Application on Biomass Yield and Carbon Dioxide Balance of a Three-Cut Meadow. Water, 15(17), 3057, https://doi.org/10.3390/w15173057 mój indywidualny udział w jej powstaniu polegał na współudziale w tworzeniu koncepcji artykułu, zapewnieniu sprzętu do pomiarów terenowych, nadzorze nad doświadczeniem, wsparciu w przeprowadzeniu analiz i modelowania strumieni CO_2 oraz interpretacji uzyskanych wyników, a także wykonaniu końcowej edycji tekstu, co stanowi 12% całej pracy.

Podpis

KIEROWNIK
Pracowni Bioklimatologii

Prof. dr hab. Radosław Juszczak

Poznań, 13.09.2023 r.

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Kocięcka, J., Stróżecki, M., Juszczak, R., Liberacki, D. (2023). Effect of Subirrigation and Silicon Antitranspirant Application on Biomass Yield and Carbon Dioxide Balance of a Three-Cut Meadow. Water, 15(17), 3057, https://doi.org/10.3390/w15173057 mój indywidualny udział w jej powstaniu polegał na pomocy w przeprowadzeniu badań terenowych oraz współtworzeniu koncepcji artykułu, nadzorze nad doświadczeniem, a także wykonaniu końcowej edycji tekstu, co stanowi 12% całej pracy.

Daniel Liberacki
Podpis

Oświadczenie autora pracy doktorskiej o jej oryginalności, samodzielności jej przygotowania i o nienaruszeniu praw autorskich

Joanna Natalia Kocięcka
imię i nazwisko doktoranta

Niniejszym oświadczam, że przedłożoną pracę doktorską pt.: *„Wpływ zastosowania antytranspirantu na plonowanie i wymianę netto strumieni CO_2 na łące z systemem nawodnienia podsiąkowego"*
napisałem samodzielnie, tj.

- nie zleciłem opracowania pracy lub jej części innym osobom,
- nie przepisałem pracy lub jej części z innych opracowań i prac związanych tematycznie z moją pracą,
- korzystałem jedynie z niezbędnych konsultacji,
- wszystkie elementy pracy, które zostały wykorzystane do jej realizacji (cytaty, ryciny, tabele, programy itp.), a nie będące mojego autorstwa, zostały odpowiednio zaznaczone oraz zostało podane źródło ich pochodzenia,
- praca nie była wcześniej podstawą nadania stopnia doktora innej osobie.

Mam świadomość, że złożenie nieprawdziwego oświadczenia skutkować będzie niedopuszczeniem do dalszych czynności przewodu doktorskiego lub cofnięciem decyzji o nadaniu mi stopnia doktora oraz wszczęciem postępowania dyscyplinarnego.

21.08.2023r. J. Kocięcka
data i czytelny podpis autora

Oświadczenie promotorów rozprawy doktorskiej

Oświadczam, że niniejsza rozprawa została przygotowana pod moim/naszym kierunkiem i stwierdzam, że spełnia ona warunki do przedstawienia jej w postępowaniu o nadanie stopnia naukowego.

Data

21.09.2023

Podpis promotora rozprawy

Podpis promotora pomocniczego rozprawy

Oświadczenie autora o zgodności elektronicznej wersji pracy z jej formą wydrukowaną

Joanna Natalia Kocięcka
imię i nazwisko doktoranta

Niniejszym oświadczam, że załączona, wydrukowana wersja mojej pracy doktorskiej pt. *„Wpływ zastosowania antytranspirantu na plonowanie i wymianę netto strumieni CO_2 na łące z systemem nawodnienia podsiąkowego"*

jest zgodna z plikiem w wersji elektronicznej, znajdującym się na załączonym nośniku, przeznaczonym do sprawdzenia w systemie antyplagiatowym.

21.09.2023 r. J. Kocięcka
data i czytelny podpis autora