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Silicon fertilizer increased potato drought tolerance and reduced soil N_2O emissions in two Danish soils at field scale

Yvonne Musavi Madegwa[1,2,5]✉, Yihuai Hu[1,3,5], Jörg Schaller[4] & Klaus Butterbach-Bahl[1,2]

Silicon (Si) fertilization enhances drought tolerance, but its effectiveness under field conditions and drought intensities remains uncertain. Moreover, the role of Si in regulating greenhouse gas emissions is poorly understood. Therefore, we conducted a field experiment, to assess the effects of Si fertilization on potato yields and on N_2O and CH_4 emissions under drought stress, considering both agronomic and environmental effects. The experiment was conducted on 2 soils (Orthic haplohumod-sand and Typical agrudalf-clay) with drought intensity as main plot (acute drought-AD and severe drought-SD) and Si fertilizers as split plots (amorphous silica-ASi, diatomaceous earth-DE and no-Si addition-control). AD treatments had higher yields than SD, due to higher soil moisture availability. In both soils, Si fertilizers (ASi and DE) produced higher yields associated with enhanced soil moisture and phosphorus content compared to the control. Si fertilizers significantly reduced cumulative N_2O emissions in both soils, with an average reduction of 31% compared to the control, likely due to altered denitrification processes. Our results indicate that, at field scale, Si fertilization has the potential to be a sustainable solution for maintaining potato production while reducing agricultural N_2O emissions under drought stress in Denmark.

Keywords Drought tolerance, Methane, Nitrous oxide, Potatoes, Silicon fertilizers, Soil moisture

Potato (*Solanum tuberosum* L.) is one of the world`s most important staple crops feeding more than one billion people and being cultivated in more than 100 countries[1]. However, recent studies have observed and predicted a significant decline in potato yields due to the increased occurrence of drought induced by climate change[2–4]. This is of particular concern as potato is one of the most drought-sensitive crops due to its small and shallow fibrous root system, which impedes soil water uptake from deeper layers[1,5]. Given the paramount importance of potatoes to global food security, it is imperative to improve their resilience to drought. Silicon (Si) fertilizers have the potential to improve the potato resilience to drought stress by increasing the soil moisture content and nutrient availability[6,7].

Si is the second most abundant element in the Earth's crust, accounting for approximately 28% by weight[8]. Although Si is abundant in soils as different minerals, only monosilic acid [Si $(OH)_4$] is available for plants[9]. Plants that actively accumulate high levels of Si (10–100 g kg^{-1} dry weight) are termed "accumulators" with specialized Si transporter genes, whereas "non-accumulators" accumulate low levels of Si (< 5 g kg^{-1} dry weight) by passive uptake[10,11].

Most studies have focused on the effects of Si fertilizers on accumulator monocot crops such as maize and rice, assuming that the efficacy depends on the active Si uptake capacity of the crop. Numerous studies have reported that under drought stress, Si fertilization improves several plant traits such as leaf area, photosynthetic pigments, growth, biomass, nutrient uptake, root development and soil moisture in various Si-accumulating

[1]Pioneer Center Land-CRAFT, Department of Agroecology, Aarhus University, Ole Worms Allé 3, Building 1171, Aarhus 8000, Denmark. [2]Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Atmospheric Environmental Research (IMK-IFU), Kreuzeckbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany. [3]Key Laboratory of Development and Application of Rural Renewable Energy, Biogas Institute of Ministry of Agriculture and Rural Affairs, Renmin South Road, Chengdu, Chengdu 610041, Sichuan Province, China. [4]Silicon biogeochemistry working group, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany. [5]These authors jointly supervised this work: Yvonne Musavi Madegwa and Yihuai Hu. ✉email: yvonnemadegwa@agro.au.dk

species like maize, rice, wheat, grasses and barley[12–16]. However, other studies showed that non-accumulators also respond positively to Si application during drought, suggesting that the benefits of Si fertilizer extend beyond accumulator plants. Specifically, Si amendments improved yields, vegetative growth, development and nutrient status in non-accumulating crops such as soybean, tomato, common bean and cucumber under drought[17–19] or water availability[20,21]. Despite this evidence, few studies have investigated the effects of Si fertilizers on the performance of potato, a non-accumulating species, especially under drought conditions at the field scale[22,23].

Silicon (Si) fertilizer application also alters soil physical and chemical properties. Si addition has been shown to increase nitrogen (N) and phosphorus (P) availability, and soil aggregate structure in ways that increase water holding capacity[15,24,25]. These changes in soil properties contribute to plant drought resistance but also influence microbial Carbon (C) and N cycling processes and the associated production and emission of the greenhouse gas nitrous oxide (N_2O) and methane (CH_4)[26,27]. In both paddy rice and barley systems, Si fertilizers modulated microbial abundance, C decomposition and denitrification gene expression, suggesting that Si amendments can potentially mitigate N_2O and CH_4 emissions[28–30]. Reducing N_2O and CH_4 emissions is of great importance given its considerable global warming potential of 273 and 36 respectively, which contributes significantly to the climate impact of agriculture[30,31]. Despite this, the potential of Si amendments to mitigate N_2O emissions from agricultural soil has not been well studied[32].

The amount of Si available to plants in soil has decreased significantly over the years. This is due to agricultural extraction of the nutrient by continuous plant uptake, necessitating the application of Si fertilizers[19,33,34]. The most common Si fertilizers used in previous studies have been industrial by product slags (blast furnace slag, steel slag and phosphorus slag), natural Si minerals ($CaSiO_3$) and artificial amorphous silica (ASi)[35–37]. However, it has been observed that slags have a low soluble Si concentration and may contain toxic compounds[36,38,39]. Additionally, $CaSiO_3$ and artificial ASi are very expensive with $CaSiO_3$ having the additional disadvantage of limited mining sources[38]. Given the critical role of Si in mitigating crop stress under drought conditions, there is a need for a source of Si that is both sustainable and cost effective. In this context, the utilization of diatomaceous earth (DE) provides a promising alternative.

Diatomaceous earth (DE) is a sedimentary rock formed from the fossilized remains of single-celled algae[40]. DE consists of approximately 70–90% silicon dioxide (SiO_2) and also contains various minerals such as iron (Fe), aluminum (Al), calcium (Ca), and sodium (Na). DE has remarkable properties, including high permeability (0.1–10 mD), high porosity (35–60%), and high surface area. Several previous studies have highlighted the potential of DE as a Si source for plant production. A study by[41] proposed the use of DE to enhance rice performance in contrasting soils of southern India. Their findings revealed significant increase in soil plant available Si content, nutrient uptake, and rice grain yields in alkaline, acidic and neutral soils. Similarly, research by[42] demonstrated that DE increased soil Si content, N, P, potassium (K) levels and plant biomass in sugarcane and maize crops. Thus, DE appears to be a promising contributor to the Si cycle and warrants consideration as a viable Si source for agricultural purposes.

Potatoes are an important crop in Denmark, grown on about 60,000 ha. Droughts during the growing season are expected to increase in the future with climate change, and irrigation of potato fields is already a widespread practice in Denmark. Understanding the benefits of Si fertilization for increasing the drought tolerance of potato and reducing the demand for irrigation water, while at the same time reducing the emission of the greenhouse gases N_2O and CH_4, can be an important strategy for climate change adaptation and mitigation.

This study therefore focused on (1) determining the influence of Si fertilizer on soil and potato yield parameters (biomass and yield) and chemical (Silicon and Phosphorus) properties under drought stress; (2) evaluating the effect of Si fertilizer on soil N_2O and CH_4 emissions, and (3) comparing the efficacy of DE in comparison to ASi in increasing potato drought tolerance and reducing soil N_2O and CH_4 emissions. Based on the existing literature, we hypothesized that Si-supplementation would increase potato drought tolerance, as measured by positive yield responses, and that ASi and DE as Si-supplements would have comparable effects on crop performance and soil N_2O and CH_4 mitigation potential.

Results

Influence of Si fertilizer and drought intensity treatments on soil moisture content

During the experimental period, acute drought treatments received 553 mm of rainfall and 114 mm of irrigation while severe drought treatments received 280 mm of rainfall and 89 mm of irrigation (Fig. 1, Table S3). Overall acute drought treatments received 298 mm more precipitation than severe drought treatments (Fig. 1, Table S3). The drought intensity treatments significantly ($p < 0.001$) affected the soil moisture content in both soils, with the highest values observed in acute drought (25.5 ± 0.6% - clay, 11.8 ± 0.6% - sand) compared to severe drought (19.7 ± 1.5% - clay, 9.4 ± 0.6% - sand). In addition, in clay acute drought treatments, Si fertilizers significantly ($p < 0.001$) increased the soil moisture content with the highest values observed in ASi (27.9 ± 1.1%) compared to control (23 ± 1.1%) (Fig. 2). A similar trend was observed for the sandy soil with highest values observed in Si fertilizers (ASi-11.4 ± 0.8%, DE-10.7 ± 0.9%) compared to the control (9.8 ± 0.8%), although these values were not significantly different ($p = 0.42$) (Fig. 2).

In sandy soil, the ASi treatment consistently increased water retention at all suction levels compared to the control, indicating improved moisture availability. The DE treatment primarily enhanced water retention under wetter conditions (i.e., lower suction); however, its effect diminished as suction increased (Fig.S1). In clay soil, the ASi treatment also showed a consistent improvement in water retention across the entire suction range, suggesting its effectiveness regardless of moisture level. In contrast, the DE treatment improved water retention mainly under drier conditions (i.e., higher suction). Regarding the plant-available water (PAW) analysis (Fig. S2) in clay soil, DE achieved the highest PAW (23.5 ± 2.6%), followed by ASi (21.8 ± 0.5%), and the control (20.8 ± 2.5%), though these differences were not significant ($p = 0.35$). In sandy soil, PAW was higher with the

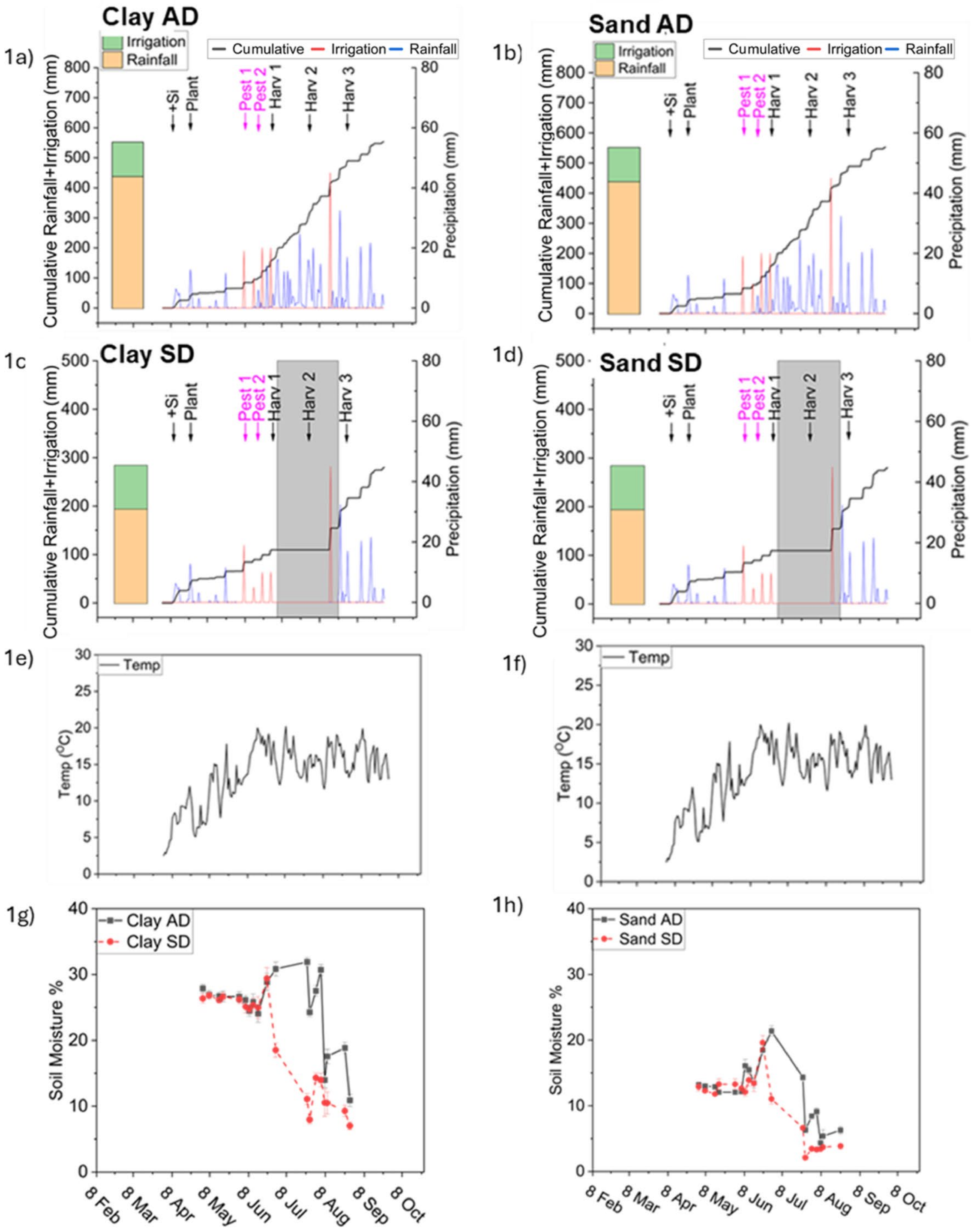

Fig. 1. Management practices and cumulative precipitation (Rainfall + Irrigation) in clay (1a, 1c) and sand (1b, 1 d), temperature (1e, 1f) and soil moisture % (1 g, 1 h) during the potato growing season in clay and sand soil respectively. The grey shaded region in SD treatment indicates the duration of the drought. Legend: SD-Severe drought, AD-Acute drought, Si-Silicon fertilizer (ASi and DE), Plant-planting, Pest-Pesticides (Pest 1 and Pest 2-Fluazinam and Oxathiapiproline), Harv-Harvesting (Harv 1-Tuber initiation, Harv 2-Tube bulking, Harv 3-Tuber maturity).

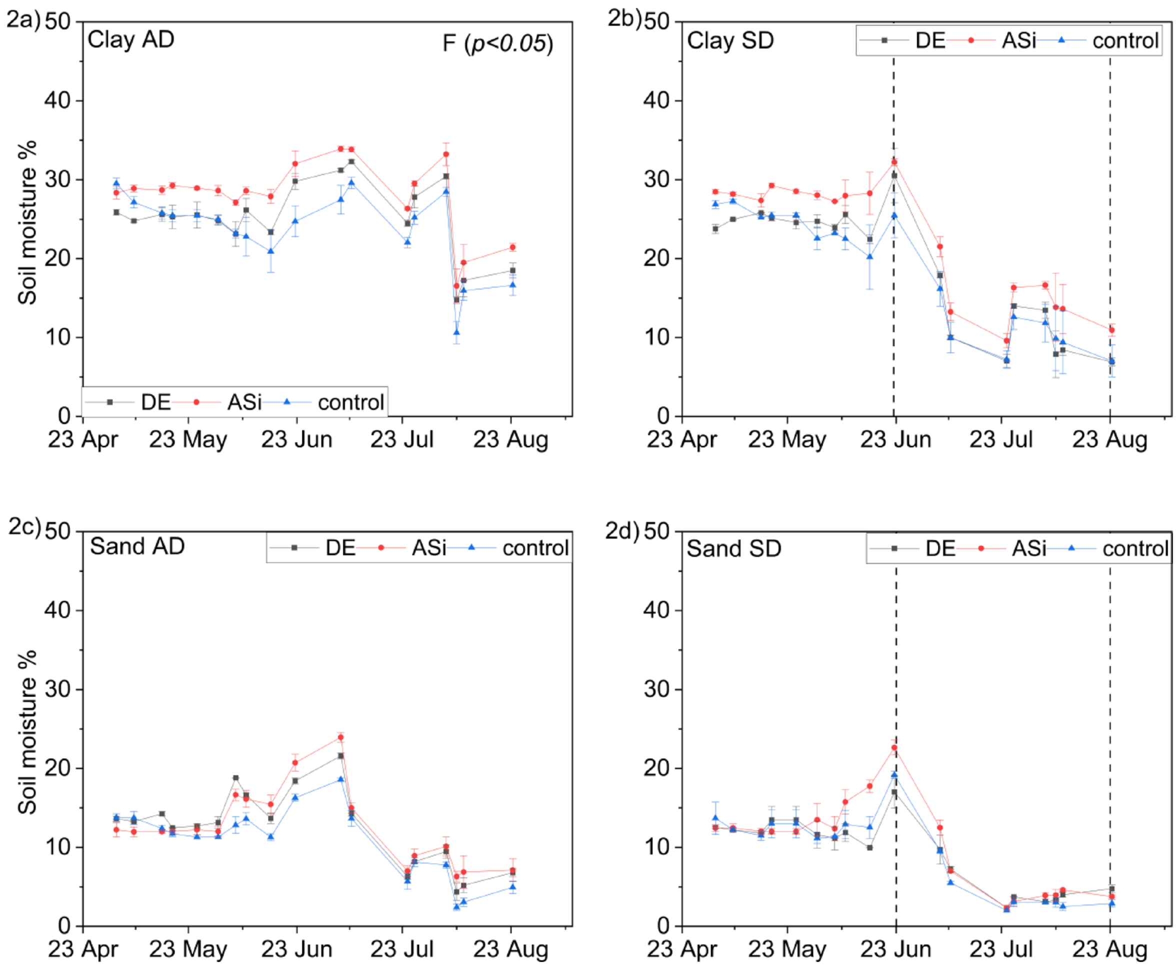

Fig. 2. The effect of Si fertilizers on soil moisture content (Vol %). Vertical dashed line in severe drought treatments (2b, 2 d) indicate the duration of the drought. Error bars show mean standard deviation (mean ± SD) ($n = 3$). Significant levels for the entire time series are displayed as $p < 0.05$. Legend: AD-Acute drought, SD-Severe drought, DE-Diatomaceous earth, ASi-Amorphous silica.

ASi (13.2 ± 0.8%) and DE (12.8 ± 0.6%) treatments than with the control (11.9 ± 0.4%), though these differences were not statistically significant ($p = 0.12$).

Influence of drought intensity and Si fertilizer on potato biomass development

In the sandy soil, the interaction between drought intensity and Si fertilizer significantly ($p < 0.01$) increased tuber fresh weight at bulking with the highest values observed in acute drought with ASi (9.2 ± 1.4 t ha^{-1}) fertilizer (Fig. 3). In addition, under acute drought treatments, Si fertilizers significantly ($p < 0.05$) increased tuber fresh weight (DE-6.9 ± 1.3, ASi-9.2 ± 0.8 t ha^{-1}) compared to control (2.8 ± 0.7 t ha^{-1}). At tuber maturity, drought intensity significantly ($p < 0.001$) affected tuber fresh weight with highest values in acute drought (42.6 ± 3.6 t ha^{-1}) compared to severe drought (23.8 ± 1.9 t ha^{-1}). In addition, Si fertilizers (DE-34.7 ± 4.8, ASi-36.8 ± 4.3 t ha^{-1}) had higher tuber fresh weight compared to the control (28.1 ± 6.1 t ha^{-1}), although these differences were not significant ($p = 0.23$) (Fig. 3). In clay soils at tuber bulking, drought intensity treatments significantly ($p < 0.05$) affected tuber fresh weight with highest values in acute drought (7.0 ± 0.4 t ha^{-1}) compared to severe drought (3.9 ± 0.8 t ha^{-1}). At tuber maturity, drought intensity ($p < 0.001$) and Si fertilizers ($p < 0.05$) significantly increased tuber fresh weight. Specifically in drought intensity treatments, highest values were observed in acute drought (44.5 ± 1.9 t ha^{-1}) compared to severe drought (31 ± 1.7 t ha^{-1}) while in Si fertilizer treatments highest values were observed in ASi (43.2 ± 3.2 t ha^{-1}) compared to DE (36.4 ± 3.9 t ha^{-1}) and control (33.7 ± 2.8 t ha^{-1}) (Fig. 3).

Above-ground biomass and root fresh weight responded similarly to drought intensity and Si fertilizer treatments in sand soil during tuber bulking. The interaction of drought intensity and Si fertilizer significantly ($p < 0.01$) increased the potatoes aboveground biomass and roots fresh weight with highest values observed in acute drought with Si fertilizers (ASi and DE) compared to control (Fig.S3 and Fig.S4). Values were not significantly different for the clay soil (Fig.S3 and Fig.S4).

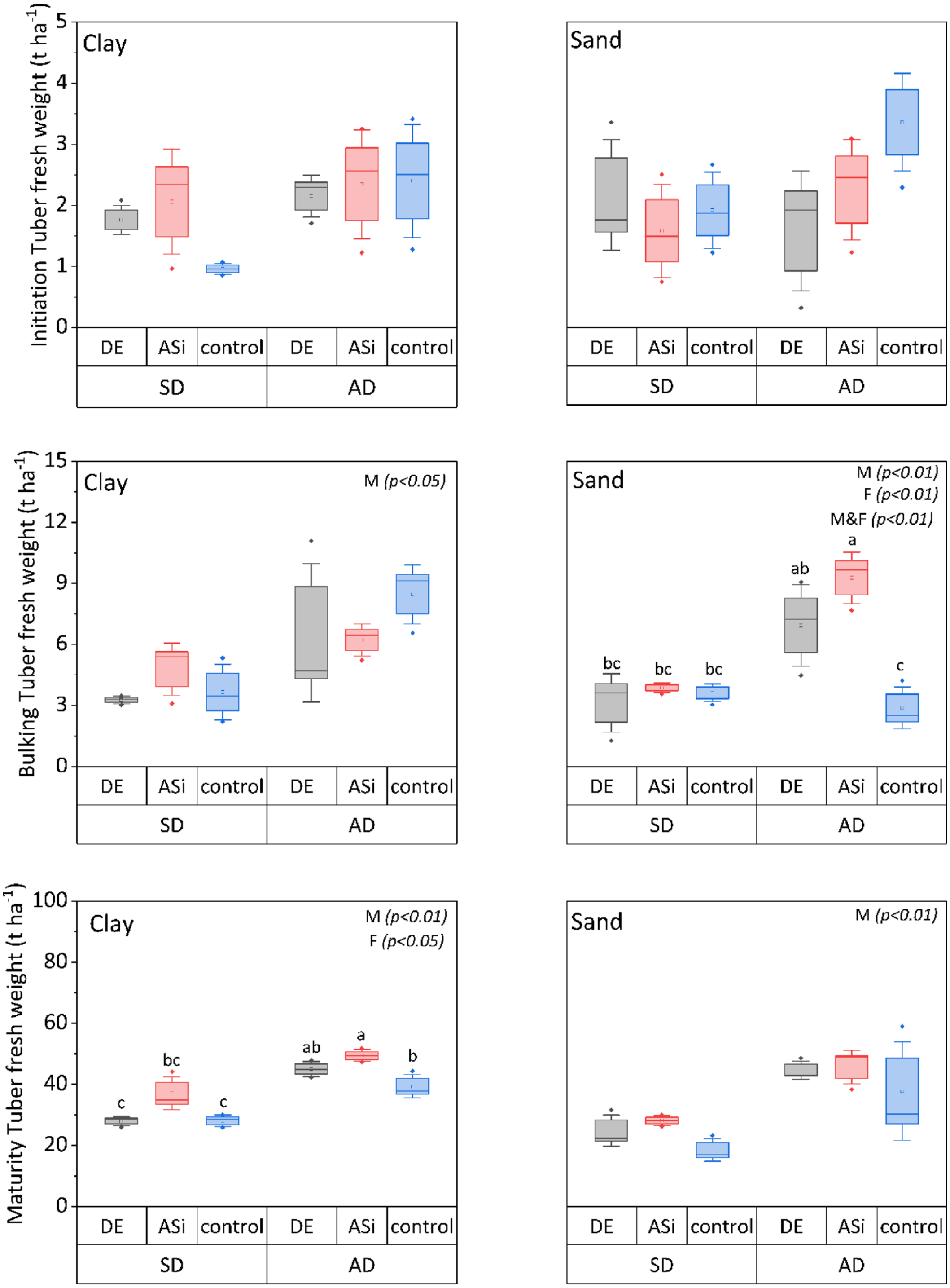

Fig. 3. Box plots showing the effect of drought intensity and Si fertilizers on the tuber fresh weight of potatoes at tuber initiation (30th June 2023), bulking (30th July 2023) and maturity (30th August 2023). Each boxplot represents 3 replicates ($n = 3$). The letters above boxplots indicate significant differences ($p < 0.05$) between treatments. Legend M-Moisture, F-Fertilizer, DE-Diatomaceous earth, ASi-Amorphous silica, AD-Acute drought, SD-Severe drought.

Influence of drought intensity and Si fertilizers on plant phosphorus and silicon content

Effect of drought intensity and Si fertilizer on leaf and root phosphorus content

In sand soil, differences in total precipitation and thus, drought intensity significantly ($p < 0.001$) affected leaf P content at tuber initiation with higher values observed in acute drought (19.8 ± 0.7 mg Kg^{-1}) compared to severe drought (15.4 ± 0.4 mg Kg^{-1}). At tuber bulking, the interaction of drought intensity and Si fertilization significantly ($p < 0.01$) increased the leaf P content with highest values observed in acute drought with ASi (30.9 ± 0.3 mg Kg^{-1}) fertilizer treatments. The effect of Si fertilizer varied based on drought intensity. In acute drought treatments, ASi (30.9 ± 0.3 mg Kg^{-1}) had significantly ($p < 0.05$) higher leaf P values compared to control (27.5 ± 0.9 mg Kg^{-1}), while in severe drought treatment, ASi (28.9 ± 0.7 mg Kg^{-1}) and control (28.6 ± 0.8 mg Kg^{-1}) had significantly ($p < 0.01$) higher values compared to DE (25 ± 0.8 mg Kg^{-1}) (Fig. 4). In clay soil, drought intensity significantly ($p < 0.001$) affected the leaf P content at bulking with highest values observed in acute drought (23.9 ± 0.9 mg Kg^{-1}) compared to severe drought (19.2 ± 1.2 mg Kg^{-1}). Moreover, the effect of Si fertilizers on leaf P content in clay soil followed a similar trend with higher values observed in Si fertilizers (DE-27.01 ± 2.7 mg Kg^{-1}, ASi-28.7 ± 1.9 mg Kg^{-1}) compared to control (26.4 ± 2.1 mg Kg^{-1}) though these values were not significantly different ($p = 0.71$) (Fig. 4).

In sand, drought intensity significantly ($p < 0.001$) affected root P content with highest values observed in acute drought (15.6 ± 1.1 mg Kg^{-1}, 13 ± 1.7 mg Kg^{-1}) compared to severe drought (11.5 ± 0.7 mg Kg^{-1}, 7.8 ± 0.7 mg Kg^{-1}) at tuber bulking and maturity, respectively. In clay soil, the interaction of drought intensity and Si fertilizer significantly ($p < 0.001$) increased the root P content at tuber bulking, with highest value observed in acute drought with ASi (35.1 ± 0.7 mg Kg^{-1}) treatments. Furthermore, in clay soils at tuber maturity, the highest values were recorded in Si fertilizers (DE-16.5 ± 1.4 mg Kg^{-1}, ASi-17.7 ± 2.8 mg Kg^{-1}) compared to the control (16.3 ± 1.8 mg Kg^{-1}) (Fig.S5).

Effect of drought intensity and Si fertilizer on leaf and root Si content

In sand, drought intensity significantly ($p < 0.001$) affected the leaf Si content with highest values observed in severe drought (1745.9 ± 118.3 mg kg^{-1}) compared to acute drought (1181.5 ± 102.9 mg kg^{-1}) at bulking. The influence of Si fertilizer application on the leaf Si content followed a similar trend in both drought intensity treatments with highest values observed in Si fertilizers, i.e. ASi (1578.5 ± 135.4 mg kg^{-1}) and DE (1426.8 ± 210 mg

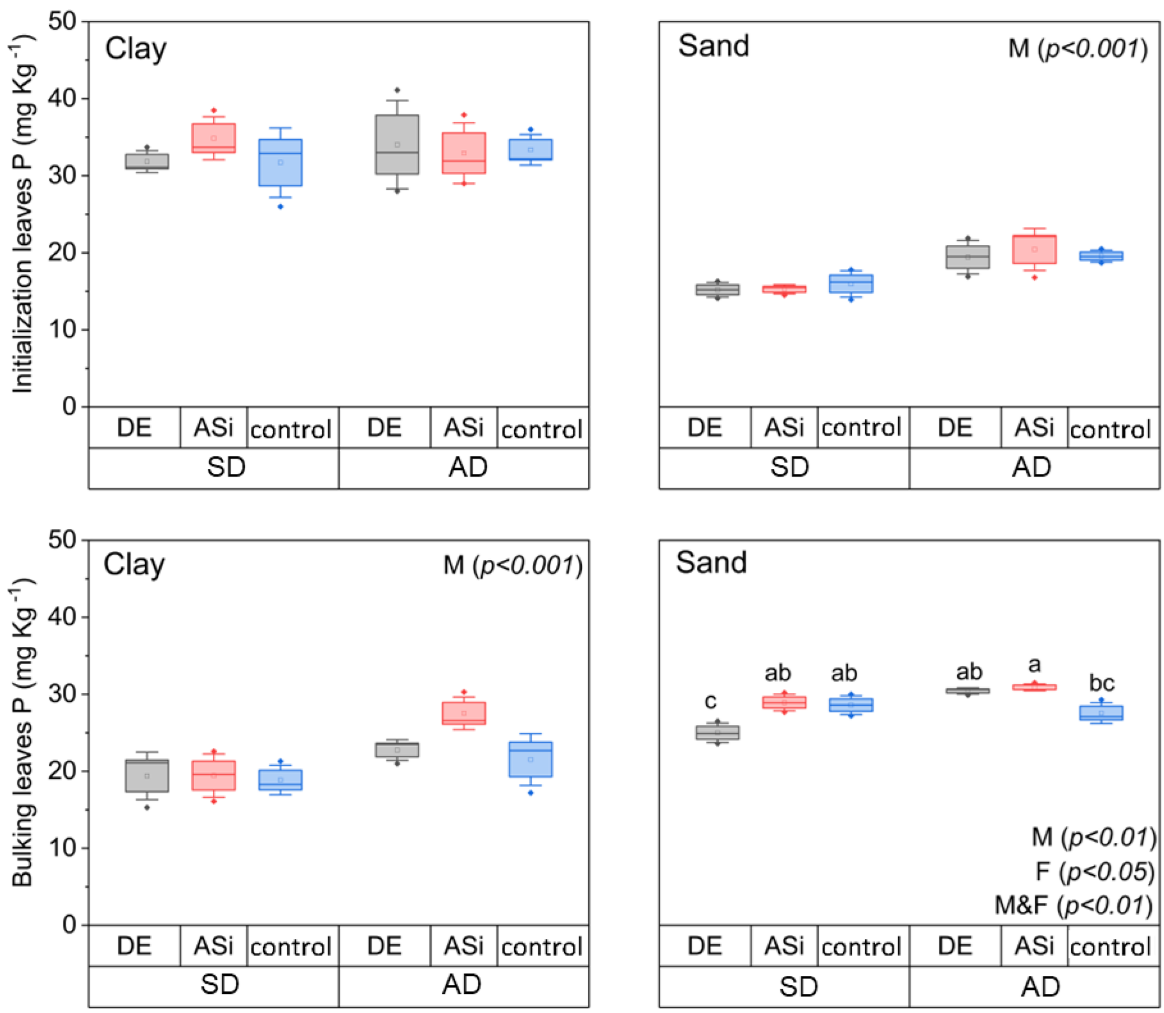

Fig. 4. Box plots showing the effect of drought intensity and Si fertilizers on the leaf P content at tuber initiation (30th June 2023) and bulking (30th July 2023). Each boxplot represents 3 replicates ($n = 3$). The letters above boxplots indicate significant differences ($p < 0.05$) between treatments. Legend M-Moisture, F-Fertilizer, DE-Diatomaceous earth, ASi-Amorphous silica, AD-Acute drought, SD-Severe drought.

kg^{-1}) compared to control (1385.7 ± 302 mg kg^{-1}), although these values were not significantly different ($p = 0.79$) (Fig. 5). In clay, drought intensity ($p < 0.001$) and Si fertilizer ($p < 0.01$) significantly increased leaf Si content at bulking. For drought intensity treatments, highest values were observed in acute drought (1309.4 ± 167.2 mg kg^{-1}) compared to severe drought (735.6 ± 81.5 mg kg^{-1}). Regarding Si fertilizer treatments, significantly ($p < 0.05$) higher values were observed in DE (1257.8 ± 211 mg kg^{-1}) and ASi (1187.4 ± 157.1 mg kg^{-1}) compared to control (622.1 ± 121 mg kg^{-1}) (Fig. 5).

In sand soil, the interaction of drought intensity and Si fertilizer significantly ($p < 0.001$) increased the root Si content with highest values observed in acute drought treatments with ASi (2603.8 ± 368 mg kg^{-1}) at bulking (Fig.S6). The influence of Si fertilizer on root Si content varied based on drought intensity treatments. In acute drought treatments, ASi (2603.8 ± 368 mg kg^{-1}) had significantly ($p < 0.001$) higher Si content compared to control (564.1 ± 239.3 mg kg^{-1}), while in severe drought treatments, DE (1877.3 ± 250 mg kg^{-1}) had significantly ($p < 0.001$) higher Si content compared to control (857.4 ± 323.8 mg kg^{-1}). At maturity, Si fertilizer significantly ($p < 0.05$) increased the root Si content with highest values observed in ASi-1458.1 ± 241.3 mg kg^{-1} and DE-845.9 ± 193 mg kg^{-1} compared to control (624.7 ± 97.5 mg kg^{-1}) (Fig.S6). In clay soils overall analysis showed that Si fertilizer significantly ($p < 0.05$) increased the root Si content with highest values observed in ASi-966 ± 503.5 mg kg^{-1} and DE-731 ± 423 mg kg^{-1} compared to control (437.1 ± 220 mg kg^{-1}) (Fig.S6).

Greenhouse gas emissions during the potato growing season

N_2O emissions during the potato growing season

In both sand and clay soils, the application of Si fertilizer significantly ($p < 0.01$) reduced soil N_2O emissions (Fig. 6). Specifically in clay soil, ASi fertilizer reduced N_2O emissions by 34% compared to control treatments while in sand soil, ASi reduced N_2O emissions by 39% compared to control (Fig. 6). Considering emissions in each soil separately, in both sand and clay soils, Si fertilizers reduced cumulative N_2O emissions compared to control (Fig. 7, Table.S4, Fig.S7). Specifically in sand soils with severe drought treatment, ASi significantly ($p < 0.01$) reduced cumulative N_2O emissions by 40% compared to the control group. A similar trend was observed in sand acute drought treatments where ASi and DE both significantly ($p < 0.01$) reduced N_2O emissions by 35%

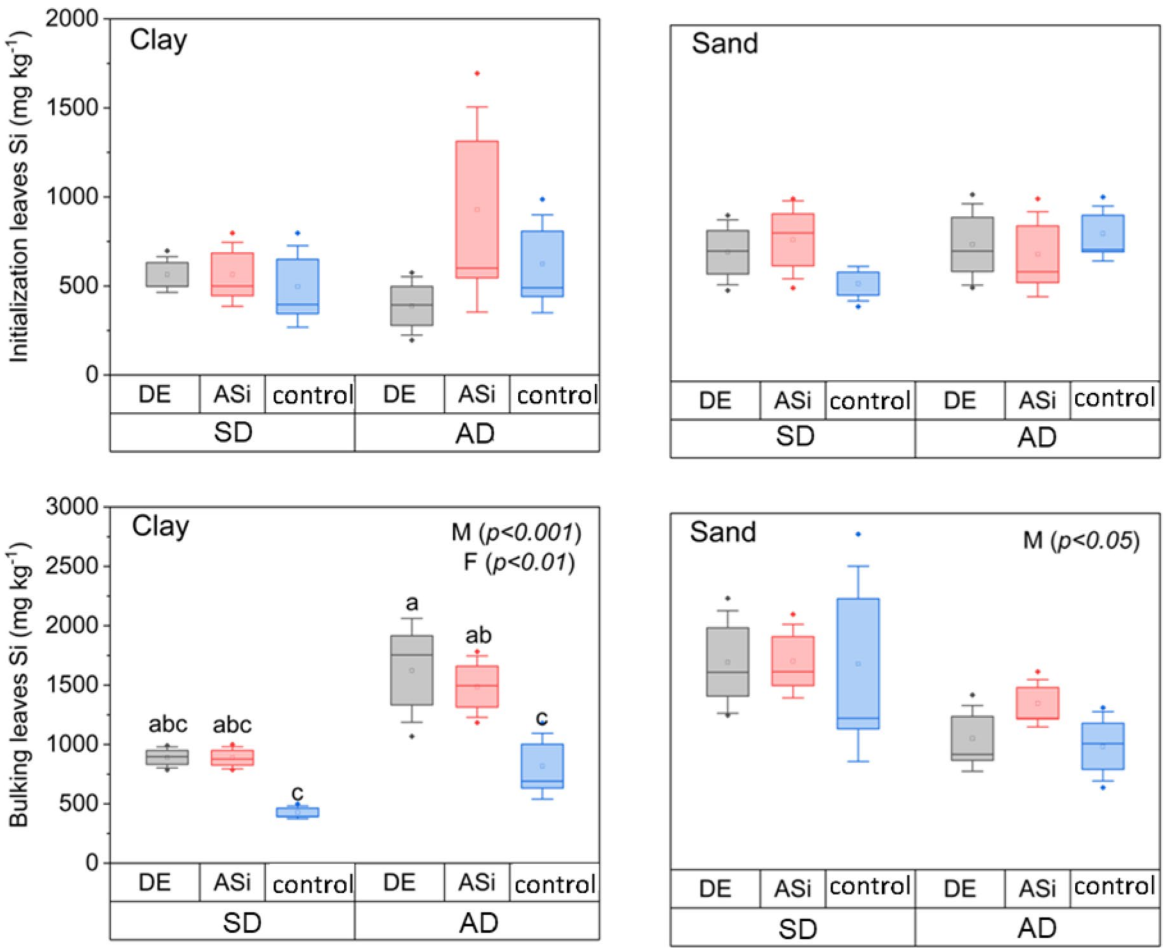

Fig. 5. Box plots showing the effect of drought intensity and Si fertilizers on leaf Si content at tuber initiation (30th June 2023) and tuber bulking (30th July 2023). Each boxplot represents 3 replicates ($n = 3$). The letters above boxplots indicate significant differences ($p < 0.05$) between treatments. Legend M-Moisture, F-Fertilizer, DE-Diatomaceous earth, ASi-Amorphous silica, AD-Acute drought, SD-Severe drought.

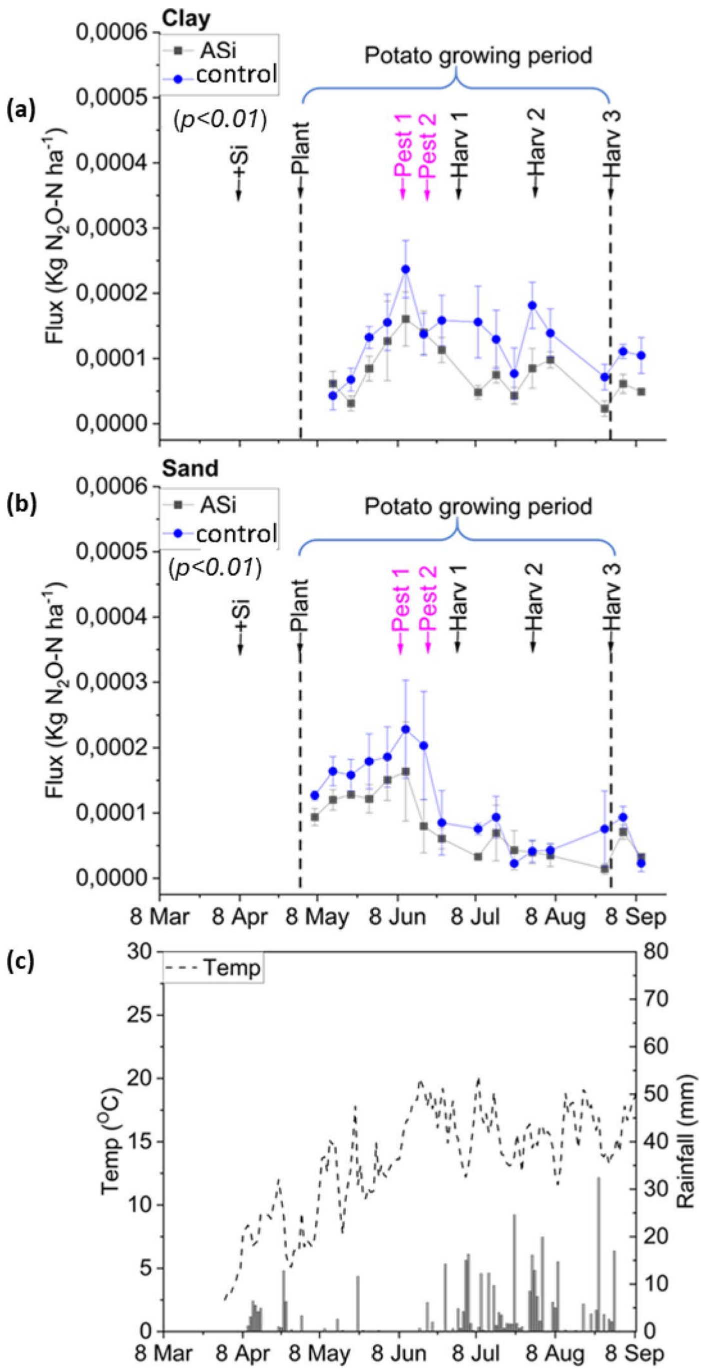

Fig. 6. Line graphs showing the effect of drought intensity and ASi fertilizers on soil N_2O cumulative emissions in clay (a) and sand (b) soils. Significant levels for the whole sampling period are displayed as $p<0.05$. Dotted line graph (c) shows daily temperature during the experimental period and bar graph (c) showing rainfall during the experimental period. Legend: ASi-Amorphous silica, Si-Silicon fertilizer (Both ASi and DE), Plant-planting, Pest-Pesticides (Pest 1 and Pest 2-Fluazinam and Oxathiapiproline), Harv-Harvesting (Harv 1-At tuber initiation, Harv 2-Tube bulking, Harv 3-Tuber maturity).

compared to control (Fig. 7, Table.S4 and Fig.S7). In clay soil under severe drought treatments, ASi significantly ($p<0.01$) reduced emissions by 68%, while DE caused a 50% reduction compared to control (Fig. 7, Table.S4 and Fig.S7). In clay acute drought treatments, both ASi and DE reduced emissions by 14% compared to the control. However, these values were not significantly different ($p=0.79$) (Fig. 7, Table.S4, Fig. S7).

CH_4 fluxes during the potato growing season

In both sand and clay soil, Si-based fertilizers had the highest CH_4 uptake during the potato growing season although these values were not significantly different (Fig.S8, Fig.S9, Table S4). More specifically, in sandy

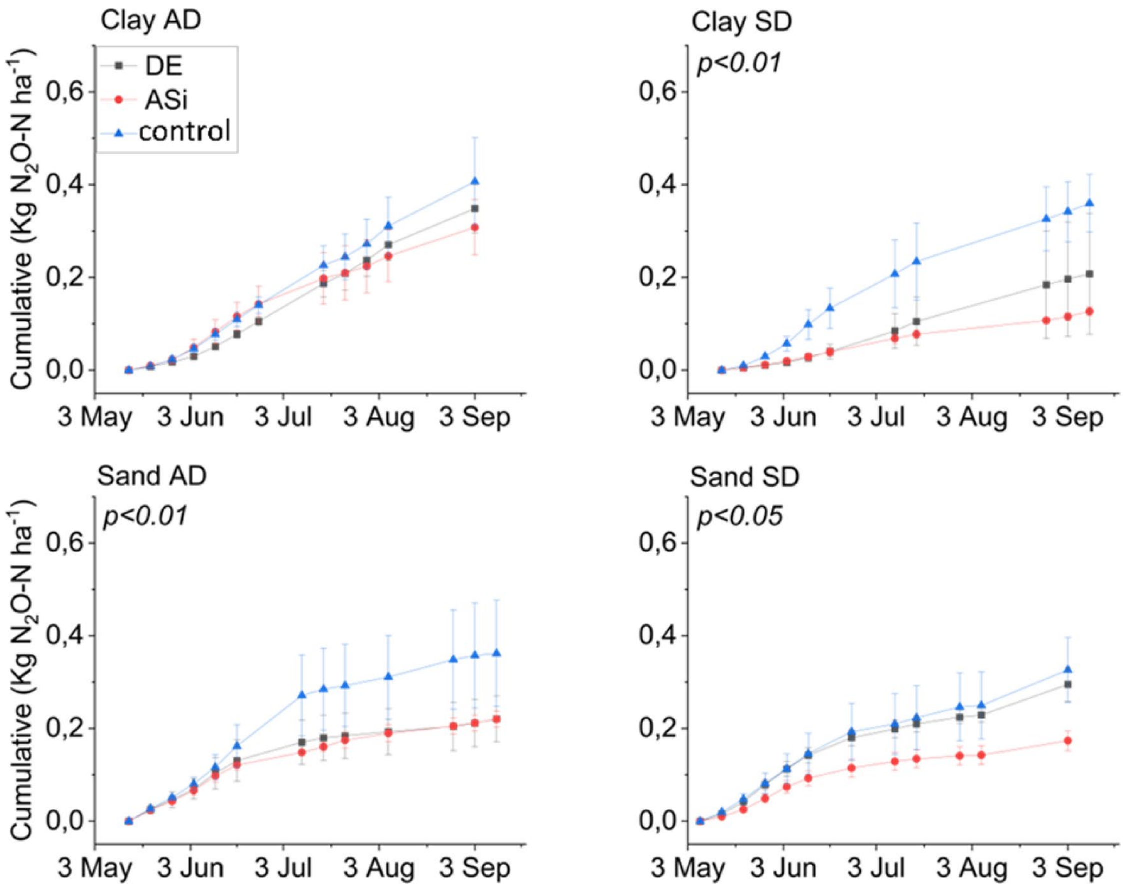

Fig. 7. Line graphs showing the effect of drought intensity and Si fertilizers on soil N_2O cumulative emissions during the potato growing season (24th April to 30th August 2023). Significant levels for the entire time series are displayed as $p < 0.05$. Legend F-Fertilizer, DE-Diatomaceous earth, ASi-Amorphous silica, AD-Acute drought, SD-Severe drought.

soil acute drought treatments ($p = 0.45$), DE had 12% higher CH_4 uptake compared to the control. In clay soil with severe drought treatment ($p = 0.68$), the highest CH_4 uptake was observed in Si fertilizers (ASi and DE) which had CH_4 uptake of 23% and 9% respectively, compared to control. In clay with acute drought moisture treatments ($p = 0.82$), DE increased CH_4 uptake by 8% compared to the control, though these values were not significant (Fig.S8 and Fig.S9, Table S4).

Discussion

Effect of Si fertilizer on soil moisture content

To the best of our knowledge, this is the first study to manipulate soil moisture content at the field scale using automatic rain shelters in the field to clarify the effects of Si fertilization on potato performance and soil N_2O and CH_4 fluxes under two different drought intensity conditions: (acute and severe). This study provides valuable insight into how Si fertilization influences potato performance under water-limited moisture conditions.

Our results show that Si fertilizers increased soil moisture content in both drought treatments (Figs. 1 and 2). This was supported by soil water retention (Fig.S1) and plant-available water (Fig.S2) analysis, which showed higher values in Si-treated soils (ASi and DE) compared to the control. Previous studies have shown that amorphous Si has a water holding capacity between 700 and 800% by forming silica gels[21]. This may explain the greater soil moisture retention observed in our Si treatments compared to control treatments. Our data on water retention and PAW provide direct evidence that Si fertilization improved soil water-holding properties, thereby increasing plant water availability under drought. These findings are consistent with earlier research[21,43,44] that attributed the enhanced water-holding capacity of Si-based fertilizers to their high surface area and porosity.

Although Si fertilizers (ASi-11.4%, DE-10.7%) did not produce a statistically significant increase in soil moisture compared to the control (9.8%) in sandy soil, this trend is still important from an agronomical perspective. Potatoes are extremely drought-sensitive and can suffer substantial yield losses even with modest declines in soil water availability[45]. Thus, even slight improvements in moisture retention under sandy soils may translate into meaningful yield benefits. These findings highlight the potential role of Si fertilization in strengthening potato resilience to drought, especially in water-limited environments.

Effects of Si fertilizers on plant Si and P nutrition

Si fertilization increased the plant P content (Fig. 4 and Fig.S5), with the degree of increase varying with sampling time and drought intensity. Our observations are in agreement with[15] who reported an increase in wheat P content at tillering after ASi fertilization. Further supporting our findings[46] investigated the effect of different rates of Si fertilizer application rates (0, 5.2, 10.4, 15.6, and 20.8 μg kg^{-1}) on the N and P nutrient content and reported that Si fertilization increased P nutrient availability. The observed increase in plant-available P following Si application can be attributed to the observed enhanced root growth stimulated by Si fertilization in our study (Fig. S5). This observation aligns with that of[47] who reported that the application of Si fertilizer stimulates root growth, enabling plants to explore larger soil volumes and acquire more P from deeper layers.

As expected, Si fertilizer application increased the Si content of plants (Fig. 5 and Fig.S6), with the range of increase varying with sampling time and drought intensity, in line with previous studies. Drought affected the Si concentration of potato leaves, with higher values in severe drought compared to acute drought in sandy soil (Fig. 5). Research by[48] also found that water deficit increased leaf Si uptake in grasslands. These results are consistent with those of [49], who showed that drought stress resulted in greater Si accumulation in potato leaves, which is in agreement with our results for sandy soil. Our result is particularly important because potato is considered a non-accumulator of Si and therefore has a low Si uptake into aboveground biomass. However, data from the previous studies and of our own study suggest that the Si uptake mechanism in potato may change under drought stress[49]. Interestingly, in clay soil, Si accumulation in leaves was observed to be higher in acute drought compared to severe drought (Fig. 5), which is in line with findings of[50]. These results suggest that soil characteristics may influence the Si uptake pattern of potatoes at different soil moisture contents.

Effect of Si fertilization on potato yields, above and below ground biomass

The application of Si fertilizer was found to increase potato yield, above and below ground biomass with the degree of increase varying with sampling time and drought intensity (Fig. 3, Fig.S3 and Fig.S4). The observed increase in yield may be attributed to the increased soil moisture content observed after the application of Si fertilizers. According to[15], the increased soil moisture due to ASi fertilization enables plants to maintain their physiological processes during drought conditions, resulting in increased plant biomass and yield production. This view is supported by the findings of[18], who reported that Si fertilization increased plant performance and attributed this to an enhanced ability of plants to absorb water and maintain their physiological processes. Furthermore, a recent study by[51] suggested that increased moisture availability after Si fertilization may explain the beneficial effects of Si on crops during periods of drought, rather than plant Si uptake.

However, some studies argue that the increased yields during drought following Si fertilization may be related to the beneficial influence of Si accumulation on plant growth. One view is that Si enhances crop biomass and yield by increasing plant water use efficiency (WUE) by reducing diffuse plant water losses if stomata are closed[4,52]. Although our study did not directly measure transpiration rates, the observed increase in potato leaf Si content after Si fertilization is consistent with the hypothesis of previous research that leaf Si accumulation may have improved plant WUE, potentially contributing to the increased biomass and yield observed in Si-fertilized plots. Furthermore, the observed increase in both plant P content and soil P availability after Si fertilization in our study could potentially contribute to the increased potato biomass and yield. This is consistent with the findings by[53,54] who reported that P is one of the main nutrients limiting potato production, with increased P availability improving potato growth and maturity.

Although there were no statistically significant increases in potato yields or aboveground biomass with Si fertilizers across all moisture treatments and sampling times, the overall trend indicated higher yields in Si-fertilized plots. While these improvements were not significant, they can be valuable for farmers, particularly in developing countries, where even minor yield increases can lead to higher household incomes and improved food security[55]. In addition to improving yields, Si fertilization also enhanced soil moisture and nutrient availability in our study, providing additional long-term benefits. Recent studies suggest that farmers are increasingly focused on resilience and climate-smart practices, in which the combined benefits of Si fertilization could play an important role extending beyond yield improvement[56,57].

Effect of silicon fertilizer on soil N_2O and CH_4 fluxes

In our experiment there was a spike of N_2O emissions immediately after N fertilizer application (Fig. 7, Fig.S7). This is likely due to increase in N availability from N fertilization. This sudden increase in N availability has been shown to stimulate microbial processes such as nitrification and denitrification which in turn lead to increased N_2O emissions[58,59].

Our research demonstrated that differences in N_2O emissions between Si fertilizer treatments were more pronounced in dryer soil (Fig. 7). Research by[60] found that in dry soil, N_2O emissions occurred mainly from nitrification. Fertilizer additions usually influence the soil nitrification rate, which would explain the pronounced differences in Si fertilizer additions in drier sand soils compared to clay in our experiments. Although we did not directly measure nitrification rates in our study, based on the existing research findings we can assert that Si based fertilizers may influence a specific process in the nitrification process in drier soils although more research needs to be conducted to clarify the exact pathways within the nitrification process that may be influenced by the Si fertilizers.

In our experiment the average total cumulative N_2O emissions were 2.5 Kg N_2O-N ha^{-1} in both soils (Fig. 7, Table S4, Fig.S7). These values are within the accepted range for emissions on potatoes of 1 to 3 Kg N_2O-N ha^{-1} that has been reported in for potato cultivation by other researchers[61,62]. Silicon-based fertilizers reduced average and total cumulative soil N_2O emissions during the potato growing season (Figs. 6 and 7 and S7) in line with research by[32]. Similar results were observed by[63], who found that application of Si fertilizer (Na_2SiO_3) reduced N_2O emissions in Moso bamboo forests. Their two-year experiment showed a 41% reduction in cumulative N_2O

emissions with a low Si application rate (0.225 mg ha^{-1}) and a 48.3% reduction with a higher Si application rate (1.125 mg ha^{-1}) over the entire experimental period. These results were attributed to Si fertilization increasing soil porosity and aeration, increasing the soil oxygen concentration, which likely inhibited the microbial denitrification process, which may have been the case in our experiment[64]. However, as that study used Na_2SiO_3 as Si fertilizer the effect could not clearly be attributed to Si due to the high sodium content of the fertilizer.

Furthermore, the observed decrease in N_2O emissions may be attributed to the fact that Si fertilizers potentially enhance the complete denitrification process in the soil. Researchers[29] conducted a study on the effect of Si application on barley growth and N_2O emissions. Their results showed that the presence of silicic acid from Si fertilizers enhanced the complete denitrification process, resulting in increased N_2 emissions and decreased N_2O emissions, which is consistent with our findings on N_2O. Furthermore, a two-year study by[27] on paddy soils showed that Si fertilization decreased N_2O emission rates and denitrification potential. This occurred by increasing the abundance of complete denitrification genes including cytochrome cd_1 nitrite reductase (nirS), copper-containing nitrite reductase (nirK) and nitrous oxide reductase (nosZ). These findings further support the view that Si fertilization promotes full denitrification.

In our experiment the average total cumulative CH_4 emissions were – 5.52 Kg CH_4-C ha^{-1} in both soils (Figs. S8 and S9, Table S4). These values have significantly higher CH_4 uptake than those recorded in an earlier study by[65] who reported that cumulative CH_4 emissions in potatoes ranged from – 2 to 1.5 Kg CH_4-C ha^{-1}. The increased CH_4 uptake observed in our study can be attributed to frequent rewetting of soils through irrigation. This likely stimulated methanotrophic activity. or the activity of microbes that consume CH_4, and therefore enhanced CH_4 uptake in both sandy and clayey soils[66]. Specifically, the frequent rewetting improves gas diffusion and oxygen availability in soil pore spaces, activating dormant methanotrophs and increasing CH_4 uptake.

Silicon fertilizers increased soil CH_4 uptake (Fig.S8 and Fig.S9, Table S4), although these differences were not statistically significant. Similar findings were reported by[63], who observed that the application of Si fertilizer (Na_2SiO_3) reduced CH_4 emissions in Moso bamboo forests. They attributed this reduction to improved soil aeration and increased CH_4 oxidation, which likely contributed to the observed increase in CH_4 uptake in our study. Additionally[33] noted that Si fertilization increased soil Fe ion concentrations, a factor associated with increased CH_4 uptake in agricultural soils. This mechanism may also have played a role in our experiment.

Although not always statistically significant, Si fertilizers generally reduce N_2O and CH_4 emissions. Nevertheless, reducing these greenhouse gas emissions is environmentally important given that CH_4 and N_2O are extremely potent greenhouse gases with global warming potentials about 36 and 273 times greater than that of CO_2, respectively[67]. As[68] highlighted in the study, even small variations in CH_4 and N_2O fluxes can substantially affect climate change.

Potential of diatomaceous Earth as a source of Si fertilizer

Based on our results, DE has the potential to serve as a Si fertilizer for potato production under drought conditions, when the application rate is adjusted to provide a similar amount of Si per ha. We reached this conclusion by analyzing results where Si fertilizer treatments showed significant differences. We then compared whether these results showed significant differences between ASi and DE treatments. The majority of the results showed that there were no significant differences between ASi and DE values, indicating that DE could be a viable substitute for ASi fertilizers in improving drought tolerance in potato. Our results are consistent with those of[69,70] who conducted experiments to investigate the effect of DE as a Si source for improved potato performance. Their results showed that DE application significantly increased the nutrient content, potato yield, and tuber quality, which is consistent with our results. In addition, a study by[41] found that DE could be considered as a valuable source of Si to enhance rice growth and yield in various soils of South India.

Our findings are significant because of the role that Si fertilizers play in enhancing drought tolerance in potatoes. This is particularly significant given the important role potatoes play in global food security and the crop's high susceptibility to drought[1,47]. In addition, DE as a source of Si represents a sustainable alternative to address the challenges identified with currently used Si fertilizers, i.e., expensive, toxic, and not readily available Si[36,38]. This research is particularly relevant for Denmark, where DE is a by-product of the insulation manufacturing industry and is usually discarded after use. Our results provide an argument for adding value to this "waste product" as a source of Si fertilizer for agricultural production.

While our results show that Si fertilization improves potato drought tolerance and reduces N_2O emissions under Danish field conditions, several limitations restrict the broader application of these findings. First, our study was conducted on two temperate Danish soils (a sand Orthic Haplohumod and a clay Typic Agrudalf). Therefore, the findings can't be extrapolated to all soil types. The effects of Si fertilization may differ in soils with contrasting chemical properties, such as highly acidic, alkaline, or Si-depleted soils, where the solubility and plant availability of Si can vary substantially. Second, our study is considered a short-term experiment, conducted over one cropping season. To understand the residual and long-term effects of Si fertilization on soil health and crop performance, long term experiments are necessary. Finally, our study was focused exclusively on potatoes. Testing Si fertilization across diverse crops, cropping systems, and climatic regions will be essential to determine whether the agronomic and environmental benefits observed here can be extended more broadly.

Materials and methods

Study site

The experiment was conducted from April to September 2023 during the potato growing season at the semi-field facilities at the Research Center in Foulum (56º 30 N, 9º 35E), Department of Agroecology, Aarhus University, Denmark. The climate in the region is characterized by a mean annual precipitation of 800 mm and a mean annual temperature of 7.4 °C[71]. The soils used in the experiment were categorized as Typic Agrudalf - clay (USDA soil classification) (sampled from Rønhave, Denmark, and hereafter referred to as clay) and Orthic

Analysis	Orthic haplohumod -Sand	Typic Agrudalf -Clay
Clay %	5.8	17.6
Silt %	2.1	12.9
Sand %	90.7	67.2
pH	7.2	7.1
Bulk Density (g cm^{-3})	1.6	1.3

Table 1. Initial soil properties at 0–30 cm[72].

haplohumod - sand (USDA soil classification) (sampled from Jyndevad, Denmark, and hereafter referred to as sand). The initial soil characteristics are summarized in Table 1.

Experimental layout and treatments

The trials were set up in 36 plots, each 1.6 m long and 2.7 m wide, allowing the planting of 4 rows of potatoes. The experimental design was a completely randomized design with a split-split plot arrangement. The main plots were soil type: sand and clay; split plots were drought intensity treatments: acute drought (AD) and severe drought (SD); split-split plots were silicon (Si) fertilizer treatments (15 t Si ha^{-1}) applied as: Amorphous silica (ASi) (Aerosil 300, Evonik Industries, Germany), Diatomaceous earth (DE) (SkamoSteel Aggregate, Biosilica, Denmark) and a no-Si control (Table S1). Due to the difference in Si content between ASi (99.8% SiO_2) and DE (77% SiO_2) (Table S2) the amount of each fertilizer applied was based on its Si content. Therefore, a greater amount of DE was applied compared to ASi, to ensure that all Si-fertilized treatments received the same amount of Si input per ha. This adjustment ensures that any observed differences between the DE and ASi treatments are due to the source or form of the fertilizer, rather than to differences in Si dosage.

Soil preparation, potato planting and management

During seedbed preparation on March 28th 2023, the soils were ploughed to a depth of 0.3 m with a ploughing machine. Subsequently, on the 4th of April 2023 the Si fertilizers (i.e., ASi and DE with 15 t Si ha^{-1}) were manually raked into the soil after soil surface application. Prior to planting on April 24th inorganic fertilizers i.e., 110 N Kg ha^{-1}, 24 P Kg ha^{-1}, 118 K Kg ha^{-1}, 17 Mg Kg ha^{-1} and 46 S Kg ha^{-1} were incorporated into the soil by a tractor..

Potatoes were planted on April 24th in ridges at a depth of 0.12 m, with a spacing of 0.25 m between plants and 0.75 m between rows. Fluazinam (0.6 L ha^{-1}, Corteva Agriscience, Denmark) and Oxathiapiproline (0.15 L ha^{-1}, Corteva Agriscience, Denmark) fungicides were applied on the 7th and 18th of July to reduce fungal infestation during the potato growing season for all treatments. Harvesting was conducted three times during the potato growing season at tuber initiation (30th June 2023), tuber bulking (30th July 2023) and tuber maturity (30th August 2023). After the final harvest, the potato crop residues were left on the soil surface.

Drought intensity treatments establishment

During the experimental period Denmark experienced anticipated drought conditions. We therefore made use of the ambient decreased rainfall conditions to establish the acute drought treatments in both soils. The extreme drought treatment was established on June 23rd, 2023, i.e. after the establishment of the potato crop, when the potato plant height was 50 cm. To exclude rainfall, the semi-field facility used for our experiments is equipped with an automatic mobile roof that was activated to cover the drought treatments during rainfall events. However, due to the drought in Denmark during the experimental period, additional irrigation was provided for the acute drought treatments, while the amount of irrigation was reduced during the experimental period for the severe drought treatments (Table S3). At the end of the experiment, the acute drought plots received 298 mm more precipitation (both rainfall and irrigation) than the severe drought plots during the experimental period (Table S3). The drought treatments ended on August 23rd 2023, about 1 week before the final harvest.

Plant, soil sampling and analysis

Plant sampling and analysis

For plant growth analysis, whole plant samples were collected from each soil ($n=2$), fertilizer treatment ($n=3$) and replicate ($n=3$) at three consecutive sampling times, i.e. at tuber initiation, bulking and maturity. At tuber initiation and bulking, one plant from each plot was sampled for analysis. At tuber maturity, all remaining plants in each plot were sampled. After sampling, the fresh weight of leaves (g), shoots (g), roots (g) and tubers (g) were determined. Leaves, shoots and roots were then oven-dried at 40 °C for 2–3 days and the dry weight (g) was determined. The samples were then ground before chemical analysis of Si and P.

Plant chemical analysis was conducted on samples collected from 3 replicates ($n=3$) in each fertilizer treatment ($n=3$). Plant Si concentration was determined by mixing 0.03 g of plant material with a 30 mL aliquot of Na_2CO_3. The solution was then placed in a water bath at 85 °C for 5 h and then filtered at 0.2 mm pore size according to[73]. Si concentrations in the extracts were measured with ICP-OES (Varian, Vista-Pro radial, Palo Alto, California, USA). For P analysis, 0.2 g of plant material was digested in a closed vessel microwave digestion system (CEM-Mars5, CEM Corporation, Matthews, NC, USA) at 180 °C with 3 mL HNO_3 and 2 mL H_2O_2. Total plant P concentration was determined by a spectrophotometer after digestion of 0.2 g samples with $HClO_4$ and HNO_3[74].

Soil sampling and analysis

Soils for chemical analysis were sampled before fertilizer application (1st April 2023) and after final harvest (30th August 2023). For chemical analysis, soil samples collected from 3 replicates (n = 3) in each fertilizer treatment (n = 3) were analyzed for Si and P. Si and P were determined using the Mehlich-III method[75] followed by spectrometer and flame photometry[76].

Soil moisture measurements (0–30 cm) were collected each week at the same time as gas sampling using the Time Domain Reflectometry (Spectrum Technologies, Inc., Illinois, United states of America). Additionally, we assessed the impact of Si fertilization on soil hydraulic properties, using the HYPROP system (Meter Group, Germany). This device continuously recorded soil matric potential, mean volumetric water content, and evaporation rates. We then calculated plant-available water content from these data[20].

Gas flux measurements and analysis

Gas flux measurements of N_2O and CH_4 were determined using an Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS) analyzer (ABB, Inc., Quebec, Canada). During the experimental period, 10 automatic chambers and 26 manual chambers were used to measure gas emissions (Table S1). For continuous automatic measurements during the potato growing season, we established stainless steel chamber bases in 10 plots, each covering a single potato plant. In clay soils, we set up three automatic chambers for each fertilizer treatment: DE (3 chambers), ASi (3 chambers), and control (3 chambers). For sandy soil, we installed one automatic chamber in the ASi treatment plot. More automatic chambers were installed in clay than in sand soil. This was based on initial measurements which indicated that clay had higher emissions compared to sand soil. For the measurements, we used opaque polypropylene chambers, which were mounted on the plastic chamber bases, which were placed in the soil during the measurements and enclosed for 5 min in each plot.

Manual chamber measurements using the closed fast chamber method[77] were conducted at least twice a week during the daytime (between 7.00 am and 5.00 pm, based on the results of automated flux measurements which showed no significant diurnal variation in fluxes during this time period). For the fast closed chamber method, a lid (37 cm length × 26.5 cm width × 12.5 cm height) with a fan was mounted on top of the base plastic frames (37 cm length × 26.5 cm width) and sample air was circulated by a pump between the chamber to the analyzer (Off Axis Integrated Cavity Output Spectrometry analyzer, Los Gatos Research Inc, CA, USA) and back to the headspace of the closed chamber by means of a 1/8 Teflon (air flow 200 mL min^{-1}). To avoid pressure fluctuations in the closed chamber that could affect the fluxes, a 0.5 m long, open Teflon tube was installed in the chamber lid. When the potatoes grew taller, chamber extensions (50 cm in automatic chambers and 22 cm in manual chambers) were installed.

In terms of gas concentration measurement, the system has a precision of 1.0 (N_2O) and 2.0 (CH_4) ppb per second for the respective gases. Mass flux measurements (F mass m^{-2} h^{-1}) were determined from the linear change of measured gas mixing ratios with time in the chamber headspace (Eq. 1)

$$F = \frac{dq}{dt} * \frac{P * V * M}{R * T * A}$$

.

Equation 1.

where dq/dt is the change in gas mixing ratios over time (h^{-1}), P is atmospheric pressure (atm), V is chamber volume (m^3), M is the molar mass of the gas (mass mol^{-1}), R is the universal gas constant (m^3 atm K^{-1} mol^{-1}), T is air temperature (K), and A is the area of the chamber (m^2). This analysis was conducted in python software (Python Software Foundation, Version 3.10).

To enable statistically valid comparisons between automatic and manual chamber flux measurements, we averaged the data from the automatic chambers and aligned it with the specific measurement times and intervals used for manual chamber sampling. This approach minimized bias due to differences in measurement frequency or time of day. Thus, a statistical comparison of the two methods could be made in both sand and clay soils.

Statistical analysis

Statistical analyses for emissions, soil and plant yield parameters and chemical properties were performed using the Origin software (Origin 2023. OriginLab Corp., Northampton, MA) and data means were reported as sample values. Analysis of variance (ANOVA) was used to determine the effect of soil type, drought intensity and Si fertilizers. Tukey's HSD test was performed to identify significant ($p < 0.05$) interactions.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Received: 27 April 2025; Accepted: 10 October 2025
Published online: 15 October 2025

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Acknowledgements
Thanks to Helle Baadsgaard Sørensen, Lars Norge Andreassen, Xiao Bai and Meshach Aderele for their assistance with field work.

Author contributions
YMM and YH contributed equally to study design, experimental setup, analysis, interpretation and original drafting. J S and K BB contributed to experimental setup, data analysis, draft review and editing.

Funding
This work was funded partly through a stipend to Dr. Yvonne musavi madegwa through the Alexander von Humboldt Scholarship and the Pioneer Center for Landscape Research in Sustainable Agricultural Futures (Land-CRAFT), DNRF grant number P2.

Declarations

Competing interests
The authors declare no competing interests.

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Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-24063-y.

Correspondence and requests for materials should be addressed to Y.M.M.