frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 10 August 2022
DOI 10.3389/fenvs.2022.935012

OPEN ACCESS

EDITED BY
Ilan Stavi,
Dead Sea and Arava Science Center,
Israel

REVIEWED BY
Metin Turan,
Yeditepe University, Turkey
Rishikesh Singh,
Panjab University, India

*CORRESPONDENCE
Jörg Schaller,
Joerg.Schaller@zalf.de

SPECIALTY SECTION
This article was submitted to Soil Processes,
a section of the journal
Frontiers in Environmental Science

RECEIVED 03 May 2022
ACCEPTED 18 July 2022
PUBLISHED 10 August 2022

CITATION
Zarebanadkouki M, Hosseini B, Gerke HH and Schaller J (2022), Amorphous silica amendment to improve sandy soils' hydraulic properties for sustained plant root access under drying conditions. *Front. Environ. Sci.* 10:935012.
doi: 10.3389/fenvs.2022.935012

Amorphous silica amendment to improve sandy soils' hydraulic properties for sustained plant root access under drying conditions

Mohsen Zarebanadkouki[1], Bahareh Hosseini[1], Horst H. Gerke[2] and Jörg Schaller[2]*

[1]Chair of Soil Physics, University Bayreuth, Bayreuth, Germany, [2]Research Area 1 "Landscape Functioning", Leibniz Center for Agricultural Landscape Research (ZALF), Müncheberg, Germany

Climate scenarios predict more frequent and longer drought periods, potentially threatening agricultural yield. The water holding capacity of soils is crucial in controlling drought stress intensity for plants. Recently, amorphous silica was suggested to increase soil water holding capacity and availability. The objective of this study was to explore the potential impact of Si application to soils on the retention and flow of water in soils and their consequence on plant access to water under soil drying conditions. Two sandy soils were mixed with varying contents (0, 1 and 5% g/g) of some selected ASi amendments. The soil water retention and soil hydraulic conductivity were determined using evaporation measurement device implemented in a commercial device called HYPROP. For both soils, an application of ASi at rates of 1 or 5% increased the water holding capacity and soils treated with ASi maintained a higher hydraulic conductivity under soil drying conditions than the control soil. Simulation demonstrated that soils treated with ASi could longer sustain the transpirational demand of plants during a soil drying cycle. These first results confirm expected positive crop-growth effect of silica amendments on hydraulic properties of coarse-textured soils mainly by longer keeping up capillary flow during water extraction by plant roots.

KEYWORDS

available plant water, drought stress, HYPROP, field capacity, permanent wilting point, soil hydraulic conductivity, soil water retention, water holding capacity

Introduction

Ecosystem performance of terrestrial systems and crop production can be reduced by drought due to a reduction in plant available soil water (Michaelian et al., 2011; Fahad et al., 2017). On the continental and global scale, drought risks are suggested to threaten agricultural yield and ecosystem performance in the future due to climate change (Lehner et al., 2006; Allen et al., 2010; IPCC 2013). Water storage decreases during longer drought periods to a critical value at which water is no longer available for plants, initiating severe drought stress and wilting (Anjum et al., 2011). The water retention curve (WRC) describes the capacity of soils to hold water at different soil matric potentials (Saxton and Rawls 2006). Hence, the WRC is a key function controlling the plant available water content in soils. Storage of water within soil pores mainly depends on the pore size distribution of soils and the specific surface area of the soil particles.

Several soil amendments have been proposed to improve hydraulic properties of soil and ultimately plant access to water under soil drying conditions. Among different amendments, the amorphous silica (ASi, which is non-crystalline silicon dioxide) was recently shown to play an import role in improving soil water holding capacity (WHC) and plant available water in coarse textured soils treated with different ASi contents (Schaller et al., 2020a; Schaller et al., 2020b). These observations were attributed to high surface area, adsorption potential and internal porosity of the ASi particles (Schaller et al., 2020a). In line with these laboratory observations, an increased soil moisture during the whole growing season of wheat was reported in field trials for a sandy soil treated with ASi as potential soil amendment (Schaller et al., 2021b).

In addition to improve water holding capacity of soils, the application of ASi in soils was shown to impact hydraulic conductivity of coarse textured soils (Schaller et al., 2020a). As soil dries its hydraulic conductivities drops by several orders of magnitudes and may limit plant access to water (Gardner 1960). Application of ASi in soils was shown to maintain a higher hydraulic conductivity in coarse textured soil under drying conditions. The coarse textured soils mixed with different ASi contents shown an decreased hydraulic conductivity at saturation and an increased hydraulic conductivity under drying conditions compared to control soils (Schaller et al., 2020a).

Agricultural practices were shown to decrease the content of ASi in soils (Struyf et al., 2010; Vandevenne et al., 2012; Carey and Fulweiler 2016) due to yearly extractions of ASi by crop harvest (Vandevenne et al., 2012; Puppe et al., 2021), as many crop plants are Si accumulators (Katz et al., 2021). The natural ASi pool in soils includes phytogenic, zoogenic, microbial, and protozoic Si fractions (Sommer et al., 2006; Puppe et al., 2015). The phytogenic ASi pool consists of phytoliths and other amorphous forms of silica (Schaller et al., 2021a). This ASi is cycled in the soil by littler fall and litter decomposition. The ASi concentration in soils is between 0 and 6% in soils, with agricultural soils being limited to ASi concentration of 0–1% (Schaller et al., 2021a). Hence, agricultural soil are depleted in ASi with potential effects for water holding capacity, available water and hydraulic conductivity.

So far, the effects of ASi on water holding capacity, available water and hydraulic conductivity were only shown for one type of ASi-amendments and two soils (pure sand and a sandy clay loam). On the other side, the ultimate effect of ASi on plant access to water under drying conditions is still unclear. The objective of this study was to explore the potential impact of different ASi-fertilizer on the retention and flow of water in soils and their consequence on plant access to water under soil drying conditions. Additionally, we used model simulations to test if soils treated with ASi could longer sustain the transpirational demand of plants during a soil drying cycle. Our hypotheses were that (i) ASi increases the water holding capacity of soils and (ii) soils treated with ASi maintain a higher hydraulic conductivity under soil drying conditions for longer period of time than the control soil.

Materials and methods

Experimental design and analysis

A carbon-free pure quartz sand and sandy soil collected from a depth of 0–25 cm (Ap1 horizon) of ZALF experimental station Müncheberg (Germany) were selected to determine the effect of different ASi amendments on the retention and flow of water within the soil. The quartz sand had a particle size ranging between 100 and 200 μm, a pH of 5.7 (measured in $CaCl_2$ solution), an electric conductivity of 4 $\mu S\ cm^{-1}$, with no other mineral or organic matter. The sandy soil consisted of 74% sand, 21% silt and 5% clay, a pH of 5.3 (measured in $CaCl_2$ solution), an electric conductivity of 20.5 $\mu S\ cm^{-1}$ and 2.4% organic matter.

The air-dried soils were mixed with varying commercial Si amendments at rates of 0, 1, or 5% (weight). Table 1 shows the Si amendments used in this study and their specific surfaces area and their abbreviations throughout the text. The pure quartz sand was treated with ASi amendments of Sip50, Sip310, Zeo600, and CBK and the sandy soils with Sip50, Zeo600, CBK and Aerosil300. The pure quartz sand was not analyzed for the effect of Aerosil300 as this was already published (Schaller et al., 2020a). As Sipernat50 and Sipernat310 had a comparable effect on soil water holding capacity and conductivity, we used only Sipernat50 for analysis using the sandy soil. The soil mixture was prepared by mixing air-dried soils with different amendments.

Quantification of ASi amendments effects on soil hydraulic properties

The effect of additions of some selected Si amendments on water-related properties of soil, such as soil retention and soil hydraulic conductivity curves, was determined using an evaporation measurement device implemented in a

TABLE 1 List of the selected artificial Si amendments used in this study. These amendments were mixed with pure quartz sand and sandy soil.

Fertilizer	Specific surface area [m^2/g]	Abbreviation	Quartz sand	Sandy soil
[a]Sipernat-50	500	Sip	×	×
[a]Sipernat-310	700	Sip310	×	
[a]Zeofree-600	600	Zeo	×	×
[b]CBK	100	CBK	×	×
[a]Aerosil300	300	Aero		×

[a] Amendments were provided from Evonik Industries, Germany.

[b] Amendments were provided from Chemical plant Bad Köstritz Germany.

commercial device called HYPROP (Meter Group, Germany) combined with the measurements of saturated hydraulic conductivity using a commercial device called Ksat (Meter Group, Germany). In brief, a soil cylinder 250 ml was filled uniformly with the prepared soil mixtures and pre-saturated by capillary rise for 48 h. Then, the saturated hydraulic conductivity of the soil was determined by Ksat using the falling head method. Same soil samples were analyzed with the HYPROP device by imposing an evaporation flux at the surface and monitoring the average soil water content and soil matric potentials at two locations (with intervals of 2.5 cm). This information was used to fit the soil water retention and hydraulic conductivity curves (Peters et al., 2015) according to the Peters–Durner–Iden (VG-PDI) model (Iden and Durner 2014) implemented in the program "Hyprop Fit". The effect of Si on soil water availability for plants was quantified first by the conventional plant available water (θ_{AWC}). This is described as the soil water between field capacity (FC) and permanent wilting point (PWP). Water content at a matric potential of h = 15,000 cm is generally accepted as the lower limit of PWP referred to here on as the θ_{PWP}. The soil water content at FC (referred to as the θ_{FC}) was determined according to Assouline and Or (2014), who defined the FC as the soil matric potential in which the hydraulic continuity within the soil is disrupted causing a significant reduction in soil water drainage. In a second approach, the integral energy (E_I) was calculated as proposed by Minasny and McBratney (2003). The E_I indicates the amount of energy plants require to extract water from soil (expressed in joule per kg of water, which will be equal to the unit of pressure head [cm], assuming the density of water to be 1 g cm $^{-3}$). In this case, we examined the ease of extracting a unit volume of water from the soil in the range of FC till PWP as follows

$$E_I(\theta_{FC}, \theta_{PWP}) = \frac{1}{\theta_{FC} - \theta_{PWP}} \int_{\theta_{PWP}}^{\theta_{FC}} h(\theta) d(\theta) \qquad (1)$$

where $\theta_{fc}, \theta_{pwp}$ are the soil water content (cm^3 cm^{-3}) at FC and PWP, respectively, and h is soil water potential (cm). Note the smaller is the integral energy the easier will be for plants to extract a unit volume of water from soil.

Modeling of Si amendments impacts on soil-plant-water relations

The potential impacts of Si amendments on soil-plant water relations were analyzed by solving water flow equation derived from the combination of the Darcy equation with the mass conservation principle (i.e., known as the Richards' equation). Assuming that soil water flow towards a single root is radial symmetric, the Richards' equation in radial coordinate (Van Lier et al., 2006) can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[rk(h) \frac{dh}{dr} \right] \qquad (2)$$

where θ is the volumetric water content (cm^3 cm^{-3}), h is the soil matric potential (cm), k is the soil hydraulic conductivity (cm s^{-1}), r is the radial coordinate (cm), and t is time (s). Here the soil water matric potential is expressed as matric head in cm. Eq. 2 was numerically solved in Python using a finite difference method based on the scheme presented by Van Lier et al. (2006). In brief, the right side of this equation was first linearized into an ordinary differential equation (ODE) form by discretizing the derivatives using a mid-point finite difference method combined with the Picard iterative method (Celia et al., 1990). The resulting linear ODE was then solved in Python using scipy. integrate.solve ivp to achieve the time integration on the left side.

Model parameterization

Root water uptake was modeled assuming that the root and soil are concentric cylinders of radii r_0 and r_b, respectively (Carminati et al., 2011). Here we considered a maize plant grown in a pot with a radius (r_{pot}) of 5 cm, height (h_{pot}) of 30 cm, with an average root radius (r_0) of 0.08 cm, a total root length (L_{tot}) of 1,500 cm and average daily transpiration (E) of 5.5×10^{-4} cm^3 s^{-1}. Assuming that roots are uniformly distributed within the pot, then our radius of soil domain (r_b) was calculated as

TABLE 2 The Peters–Durner–Iden (PDI) model parameters describing retention curve and hydraulic conductivity curve of sandy soil treated with different ASi contents.

Treatments	**Fitting parameters values**								
	α [1/cm]	**N**	**Θ_r**	**Θ_s**	**PF_{dry}**	**k_s [cm/d]**	**T**	**Ω**	**a**
Aero_1%	0.02	3.93	0.18	0.41	5.26	19.00	−0.78	0.02	−2.38
Aero_5%	0.02	3.41	0.38	0.53	5.31	12.02	−1.00	0.10	−2.42
CBK_1%	0.02	3.74	0.13	0.41	6.52	9.00	−1.00	0.01	−2.46
CBK_5%	0.03	3.57	0.29	0.57	6.98	8.00	−1.00	0.01	−1.98
Sip_1%	0.02	3.91	0.16	0.41	5.03	8.00	−1.00	0.10	−2.57
Sip_5%	0.01	3.31	0.27	0.48	6.63	7.99	−1.00	0.05	−2.10
Zeo_1%	0.02	5.33	0.19	0.38	5.00	23.54	−1.00	0.06	−1.76
Zeo_5%	0.01	1.10	0.01	0.51	5.23	12.00	−3.13	0.10	−3.38
Control	0.02	3.71	0.10	0.41	5.00	500.00	0.31	0.00	−2.78

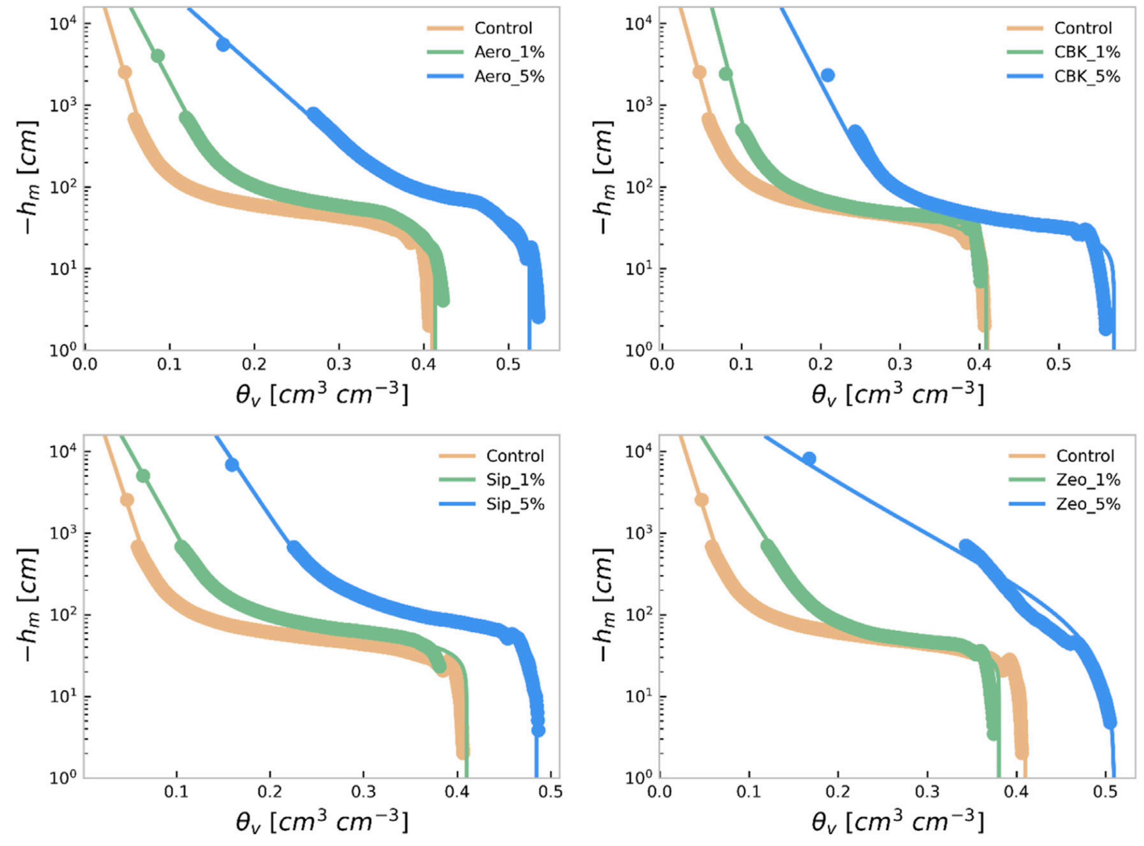

FIGURE 1
Different ASi amendments increase soil water holding capacity of sandy soil. The dots are the measured retention curves, and the lines are the estimated retention curves based on the PDI model. Under soil drying conditions, different ASi amendments increased soil water content (θ_v) at any given soil matric potential (h_m). The results of different ASi amendments on the retention curve of pure quartz sand are given in Supplementary Figure S1 as supplementary information.

$$r_b = \sqrt{\frac{V_{pot}}{\pi L_{tot}}} \tag{3}$$

where V_{pot} is the volume of pot. Similarly, assuming a uniform root water uptake along the root system, the flux of water into the root surface (q_0, cm s^{-1}) was calculated as

$$q_0 = \frac{E}{2\pi r_0 L_{tot} F_{act}} \tag{4}$$

where F_{act} indicates the fraction of roots active in root water uptake. Here we assumed that only 63% of the root system is actively involved in root water uptake (Zarebanadkouki et al., 2012). Eq. (3) was numerically solved by discretizing the soil domain into 100 numerical grids of equal size. The effect of Si on soil-plant water relation was analyzed by predicting the soil matric potential as a function of distance from the root surface, assuming two contrasting scenarios. In scenario I, we parameterized the hydraulic properties of soil (i.e., $\theta(h)$ and $k(h)$) based on the measurements of control soils. In scenario II, we parameterized the hydraulic properties of soils based on the measurements of soils treated with Si (Table 2). In both scenarios, for simplicity, Eq. 2 was subjected to a similar water content as the initial condition, a zero-flux boundary condition at the outer part of the soil (r_b), and a constant flux of q_0 at the inner part of soil (i.e., at rot surface in soil r_0).

Results

Silica amendments strongly increase the soil water holding capacity

The Hyprop-fitted soil water retention curves showed that ASi-amendments increased the water content at soil saturated conditions (Figure 1; Supplementary Figure S1 as supplementary information). The fitted PDI model parameters are given in Table 1. The sandy soil had an initial saturated water holding capacity of 0.41 cm^3/cm^3 (control without adding Si amendments). The water content at saturation increased due to addition of 5% ASi amendments (for 5% Aero-to 0.53 cm^3/cm^3, 5% CBK to 0.56 cm^3/cm^3, 5% Sip to 0.49 cm^3/cm^3, and 5% Zeo to 0.51 cm^3/cm^3). However, the addition of 1% of these amendments did not change saturated water content. At matric potential values lower than -80 cm, every Si-amendments at any concentration increased the water content of soil compared to the control. Similar effects were observed in pure quartz sand for the tested Si-amendments (Supplementary Figure S1 as supplementary information).

The effect of ASi on water availability for plants was evaluated by estimating the plant available water (θ_{AWC}) described as the soil water content between field capacity (FC) and permanent wilting point (PWP). Si increased the θ_{AWC} in both sandy soil and pure quartz sand at any tested concentrations of Si amendments (Figure 2; Supplementary Figure S2, respectively). The increase in plant-available water content for sandy soil by addition of 1 and 5% (g g^{-1}) ASi were 21% by 1% Aero, 99% by 5% Aero, 41% by 5% CBK, 19% by 1% Sip, 61% by 5% Sip, 52% by 1% Zeo, and 240% by 5% Zeo (Figure 2). Note that the soil matric potential at FC was determined according to Assouline and Or (2014) by taking into account the drainable soil pore size distribution to characterize the loss of hydraulic continuity within soil pores during soil drainage. This concept relies on the pore size distribution derived from soil retention curve. The results showed that the soil matric potential at FC was -78 cm for control sandy soil, -91 cm for 1%Aero, -109 cm for 5% Aero, -82 cm for 1% CBK, -66 cm for 5% CBK, -100 cm for 1% Sip, -151 cm for 5% Sip, -69 cm for 1% Zeo, and -1,114 cm for 5% Zeo.

The effect of ASi on water availability for plants was also evaluated by estimating the integral energy (E_I) according to the concept proposed by Minasny and McBratney (2003). The E_I indicates the amount of energy required by plants to extract a unit amount of water (expressed in cm) from the soil at various moisture contents within the available range (from FC to PWP). The energy required for the sandy soil increased by additions of 1 and 5% (g g^{-1}) ASi-fertilization were 42% by 1%Aero, 82% by 5% Aro, 4% by 1% CBK, 29% by 5% CBK, 39% by 1% Sipe, 61% by 5% Sip, 52% by 1% Zeo, and 248% by 5% Zeo (Figure 2). The energy required by plants to extract water from soils increased for the pure quartz sand by 1 and 5% (g g^{-1}) of ASi-amendments were 12% by 1% CBK, 92% by 5% CBK, 37% by 1% Sip, 148% by 5% Sip, 63% by 1% Sip310, 154% by 5% Sip310, 54% by 1% Zeo, and 162% by 5% Zeo (Supplementary Figure S2 as supplementary information). These results indicate that more energy is needed for plants to extract a unit volume of water from both soils treated with any Si amendments and any concentrations.

Silica amendments improve soil water flow

The estimated soil hydraulic conductivity curves of sandy soil and pure quartz sand are shown in Figure 3; Supplementary Figure S3 in the supplementary information, respectively. The application of ASi fertilizers reduced the hydraulic conductivity of soils at near saturation compared to the control soils (without any ASi). In both the quartz and the sandy soils, a lower hydraulic conductivity at the near-saturated zone was observed in treatments of 5% ASi compared to controls. As soil dried, the presence of ASi in both soils prevented a large drop in the hydraulic conductivity of soils and maintained a higher hydraulic conductivity than the control soils.

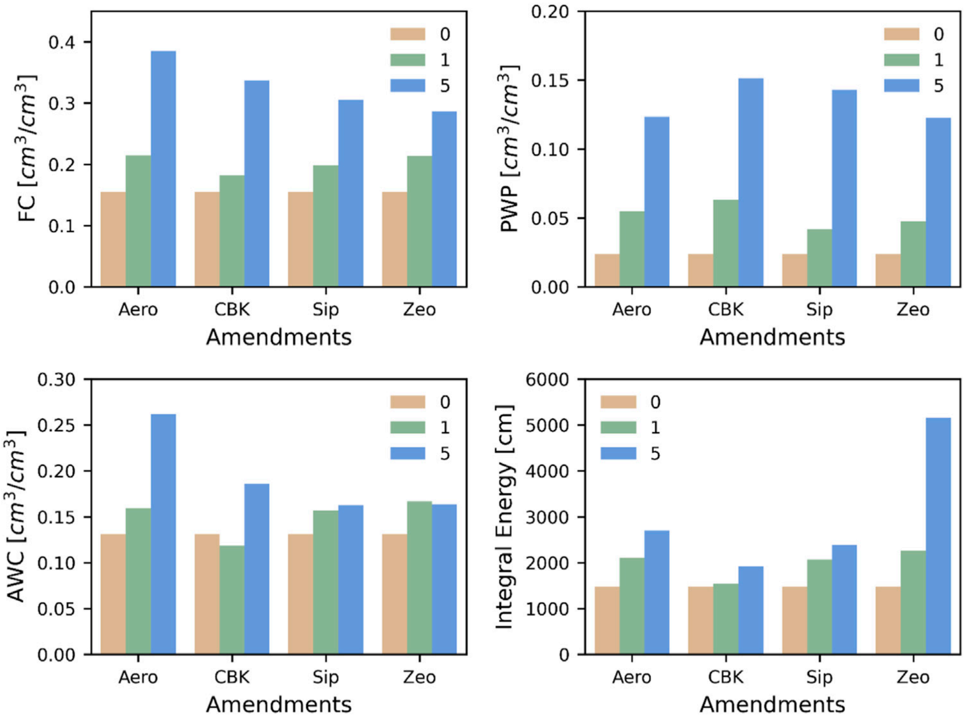

FIGURE 2
Different ASi amendments increase field capacity (FC), permanent wilting point (PWP), available water (AW) and integral energy of sandy soil. This data was extracted from the fitted soil retention curves (Figure 1).

Silica amendments mitigate water stress to plants: Simulation results

To better illustrate the effect of Si on plant access to water under soil drying conditions, we simulated root water uptake by considering a single root extracting water from soils treated with and without Aerosil300 at a concentration of 1 and 5%. In our simulation, the hydraulic properties of soil domain were parameterized based on the measured hydraulic properties of soils (Figure 1). Figure 4 shows an exemplary profile of soil matric potential at different time intervals during soil drying at a constant rate. With no Aerosil300 addition (Figure 4, left), the matric potential remained rather flat with minimal gradients for the first 50 h. Starting from 60 h on, a remarkable matric potential gradient developed close to the root. After 65.2 h, the matric potential dropped at the root surface and reached the predefined PWP. This drop is related to the radial nature of root water uptake requiring a greater flux at the vicinity of roots (radial geometry related) and also nonlinear reduction of hydraulic conductivity (soil hydraulic properties related) as soil dries (Gardner 1965). Adding 1% Aerosil300 in the sandy soil delayed the large drop in matric potential at the root surface and let water extraction from the soil 82.5 h before the soil matric potential reached the predefined PWP (Figure 4 right). The simulated matric potential at the soil-root interface (Figure 5) showed that by the addition of 1 and 5% Aerosil300, the matric potential drop across the soil towards the root surface was attenuated.

Discussion

The objective of this study was to explore the potential impact of Si application to soils on the retention and flow of water in soils and their consequence on plant access to water under soil drying conditions. Our findings showed that i) increasing the ASi content in both soils resulted in a strong increase in the water holding capacity of soils, ii) soils treated with ASi maintained a higher hydraulic conductivity under soil drying conditions than the control soil, and iii) with the help of model simulation we showed soils treated with ASi could longer sustain the transpirational demand of plants during a soil drying cycle.

The improved water retention upon the ASi application was associated with an enhanced plant available water content. This enhancement can be explained by the water adsorption capacity of the added ASi (Schaller et al., 2020a). The ASi may impact soil water retention by increasing the capillary force holding water within soil pores (Tuller et al., 1999), which is directly related to the pore size

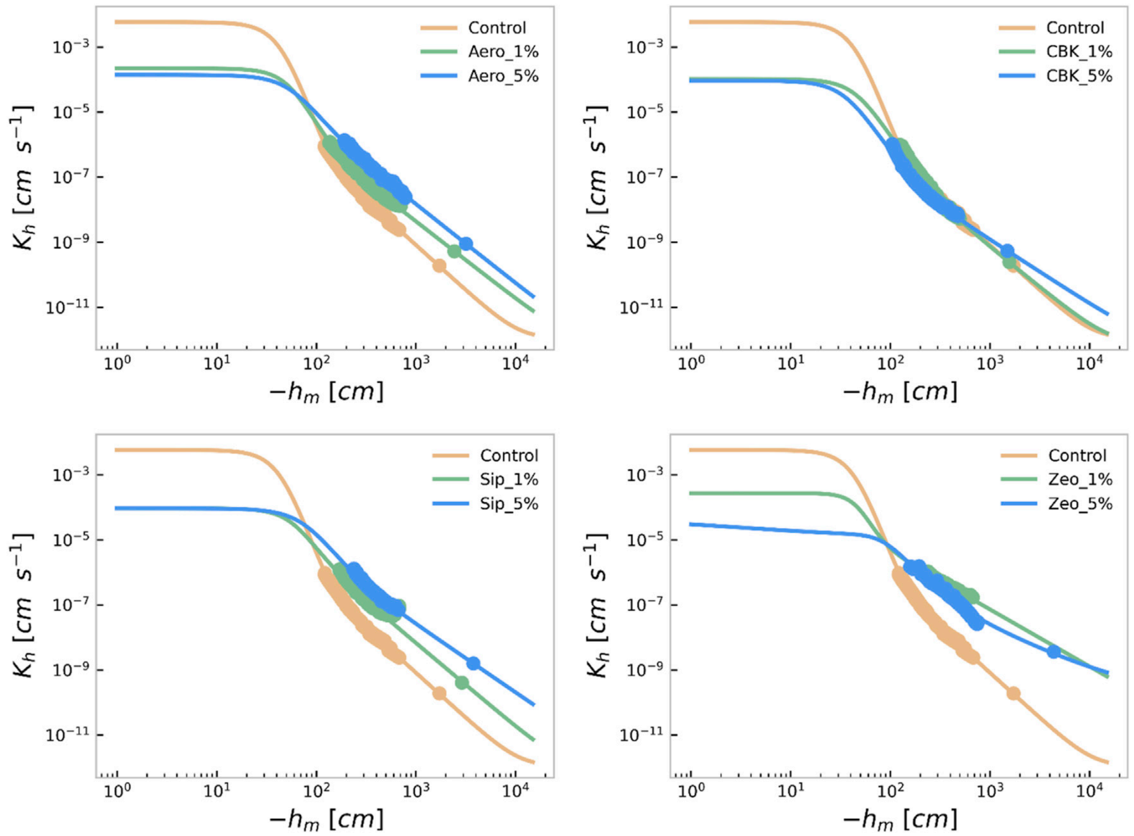

FIGURE 3
Different ASi amendments reduced the hydraulic conductivity of soils at near-saturated conditions, but it maintained a higher hydraulic conductivity as soil dried in sandy soil and pure quartz sand (Supplementary Figure S3 as supplementary information). The dots are the measured hydraulic conductivity curves, and the lines are the estimated curves based on the PDI model.

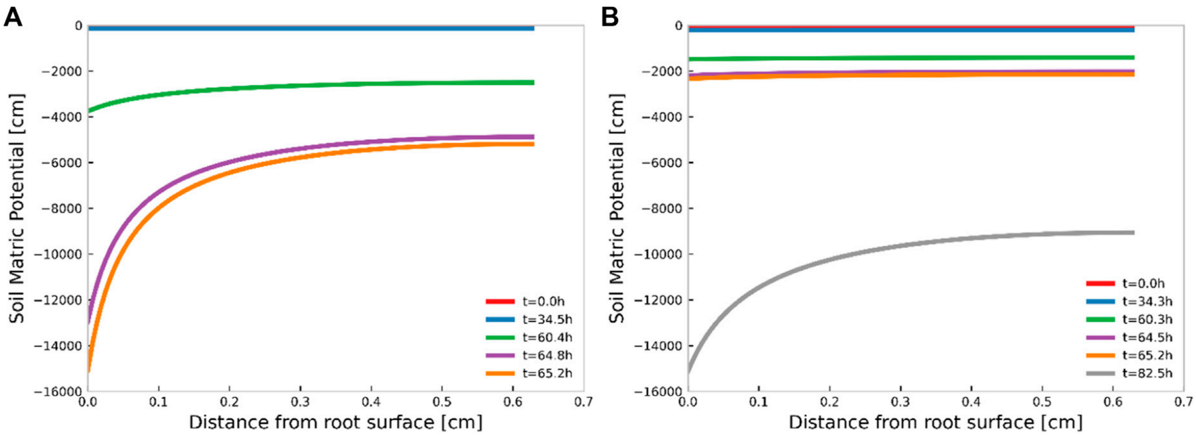

FIGURE 4
Simulated profiles of the matric potential plotted as a function of distance from root surface at different time steps for the case of sandy soil treated with **(B)** and without **(A)** an addition of 1% Aerosil300. A steady rate root water uptake is simulated till soil matric potential reached a critical value corresponding to PWP at the root surface in the soil. With the addition of 1% Aerosil300, root water extraction induced soil drying cycle lasted 17.3 h longer [t = 82.5 h, **(B)**] than for the control.

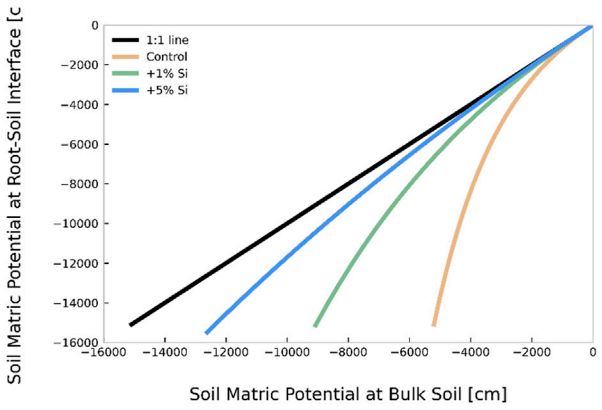

FIGURE 5
Matric potential at the root surface $h(r_0, t)$ as a function of the matric potential at the outer radius of the soil domain $h(r_b, t)$, calculated for sandy soil treated with different contents of Arosil300. The deviation from the 1:1-line shows a drop in soil matric potential across the soil domain due to the nonlinear reduction of soil hydraulic conductivity as the soil dries.

distribution of soils (the smaller the pore size, the greater is the capillary force). In coarse-textured soils, such as those studied here, the application of ASi may shift the soil pore size distribution towards smaller pores due to the smaller size of newly added particles and by filling of larger pores by the amorphous silicate. In addition, the retention of water in the presence of ASi can also be affected by increased adsorptive forces acting on the liquid phase (Tuller et al., 1999) due to the large specific surface area and also internal porosity of ASi particles.

The effect of ASi amendments on water availability to plants was not only evaluated in terms of plant water content but also in terms of energy required for plants to extract a unit volume of water from soil by estimation of integral energy based on retention curve data (Minasny and McBratney 2003; Van Lier et al., 2006). The results showed more energy would be needed by plants to extract water from soils treated after ASi-amendments and this energy increases with ASi content in the soil. This indeed is related to the retention of water within soil with stronger capillary and adsorptive forces.

The measurements of K_h showed that under soil drying conditions, sandy soils treated with different ASi amendments maintain higher hydraulic conductivity than the control. This suggests application of ASi into sandy soil facilitates the flow of water within soil and possibly towards the plant roots under soil drying conditions. The latter effect was clearly illustrated from the simulated profile of matric potentials around a single root extracting water from soil during a drying cycle. Soils treated with 1% Aerosil 300 could sustain water extraction from soil under steady rate conditions for a longer time than the control soil. Indeed, as soil dries, its hydraulic conductivity drops by several orders of magnitude, limiting water flow within the soil. Therefore, a large gradient in water potential develops in the vicinity of roots in soil. The modeling results showed that mixing soils with 1 or 5% Aerosil 300 by resulting in a higher K_h under drying conditions delays the development of large gradients in matric potential in soil and, therefore, may favor root water uptake. This enhanced soil water availability and K_h during drying conditions may explain the better plant performance during drought after ASi-fertilization as found in other studies (Hattori et al., 2005; Chen et al., 2011; Ibrahim et al., 2018; Schaller et al., 2021b).

When the soil water potential approaches the PWP in coarse-textured soils such as those from ZALF (Müncheberg) or the pure sand, the liquid phase may become spatially discontinuous or fragmented (Tecon and Or 2017), reducing microbial activities and nutrient diffusion. The addition of ASi increasing the water content at PWP, may potentially increase microbial activities and diffusion of solutes and nutrients. We expect the largest effects of ASi-amendments on soil water relations for coarse-textured soils as the small particles of ASi may help to decrease the fraction of pore water that is draining freely due to gravity, whereas for fine-textured soil the ASi may rather clog the pores decreasing water availability.

Conclusion

Here we explored the impact of ASi amendments on soil hydraulic properties and effects on water movement in sandy soil under soil drying induced by plant roots. The results confirmed that sandy soils treated with ASi held higher plant available water and maintained a higher hydraulic conductivity under soil drying conditions than the control soil. The simulation results of root water uptake suggest that increased plant available water content and unsaturated hydraulic conductivity explain longer sustainment of plants' transpirational demand during soil drying. Our findings contribute to the overall understanding of how ASi mitigates drought stress for plants by changing soil-plant-water relations via improving flow and retention of water within coarse-textured soils.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

JS had the idea. JS, MZ, and HG designed the experiments. MZ and BH conducted the experiments and did the measurements. BH and MZ did the modelling. MZ, JS, and HG wrote the manuscript. All authors discussed the results and commented on the manuscript.

Acknowledgments

We thank Gisela Ciesielski from the Institute of Soil Science and Site Ecology (Technische Universität Dresden, Germany) for carrying out the HYPROP-measurements of the sandy soil samples.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.935012/full#supplementary-material

References

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., et al. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manage.* 259, 660–684. doi:10.1016/j.foreco.2009.09.001

Anjum, S. A., Xie, X.-y., Wang, L.-c., Saleem, M. F., Man, C., and Lei, W. (2011). Morphological, physiological and biochemical responses of plants to drought stress. *Afr. J. Agric. Res.* 6, 2026–2032. doi:10.5897/AJAR10.027

Assouline, S., and Or, D. (2014). The concept of field capacity revisited: Defining intrinsic static and dynamic criteria for soil internal drainage dynamics. *Water Resour. Res.* 50, 4787–4802. doi:10.1002/2014wr015475

Carey, J. C., and Fulweiler, R. W. (2016). Human appropriation of biogenic silicon–the increasing role of agriculture. *Funct. Ecol.* 30, 1331–1339. doi:10.1111/1365-2435.12544

Carminati, A., Schneider, C. L., Moradi, A. B., Zarebanadkouki, M., Vetterlein, D., Vogel, H. J., et al. (2011). How the rhizosphere may favor water availability to roots. *Vadose Zone J.* 10, 988–998. doi:10.2136/vzj2010.0113

Celia, M. A., Bouloutas, E. T., and Zarba, R. L. (1990). A general mass-conservative numerical solution for the unsaturated flow equation. *Water Resour. Res.* 26, 1483–1496. doi:10.1029/wr026i007p01483

Chen, W., Yao, X., Cai, K., and Chen, J. (2011). Silicon alleviates drought stress of rice plants by improving plant water status, photosynthesis and mineral nutrient absorption. *Biol. Trace Elem. Res.* 142, 67–76. doi:10.1007/s12011-010-8742-x

Fahad, S., Bajwa, A. A., Nazir, U., Anjum, S. A., Farooq, A., Zohaib, A., et al. (2017). Crop production under drought and heat stress: Plant responses and management options. *Front. Plant Sci.* 8, 1147. doi:10.3389/fpls.2017.01147

Gardner, W. (1965). Dynamic aspects of soil-water availability to plants. *Annu. Rev. Plant Physiol.* 16, 323–342. doi:10.1146/annurev.pp.16.060165.001543

Gardner, W. R. (1960). Dynamic aspects of water availability to plants. *Soil Sci.* 89, 63–73. doi:10.1097/00010694-196002000-00001

Hattori, T., Inanaga, S., Araki, H., An, P., Morita, S., Luxova, M., et al. (2005). Application of silicon enhanced drought tolerance in Sorghum bicolor. *Physiol. Plant.* 123, 459–466. doi:10.1111/j.1399-3054.2005.00481.x

Ibrahim, M. A., Merwad, A.-R. M., and Elnaka, E. A. (2018). Rice (Oryza Sativa L.) tolerance to drought can be improved by silicon application. *Commun. Soil Sci. Plant Anal.* 49, 945–957. doi:10.1080/00103624.2018.1448856

Iden, S. C., and Durner, W. (2014). Comment on "Simple consistent models for water retention and hydraulic conductivity in the complete moisture range" by A. Peters. *Water Resour. Res.* 50, 7530–7534. doi:10.1002/2014wr015937

IPCC (2013). *Climate change 2013: The physical science basis. Contribution of working Group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Katz, O., Puppe, D., Kaczorek, D., Prakash, N. B., and Schaller, J. (2021). Silicon in the soil–plant continuum: Intricate feedback mechanisms within ecosystems. *Plants* 10, 652. doi:10.3390/plants10040652

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., and Kaspar, F. (2006). Estimating the impact of global change on flood and drought risks in europe: A continental, integrated analysis. *Clim. Change* 75, 273–299. doi:10.1007/s10584-006-6338-4

Michaelian, M., Hogg, E. H., Hall, R. J., and Arsenault, E. (2011). Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. *Glob. Chang. Biol.* 17, 2084–2094. doi:10.1111/j.1365-2486.2010.02357.x

Minasny, B., and McBratney, A. (2003). Integral energy as a measure of soil-water availability. *Plant Soil* 249, 253–262. doi:10.1023/a:1022825732324

Peters, A., Iden, S. C., and Durner, W. (2015). Revisiting the simplified evaporation method: Identification of hydraulic functions considering vapor, film and corner flow. *J. Hydrol. X.* 527, 531–542. doi:10.1016/j.jhydrol.2015.05.020

Puppe, D., Ehrmann, O., Kaczorek, D., Wanner, M., and Sommer, M. (2015). The protozoic Si pool in temperate forest ecosystems—quantification, abiotic controls and interactions with earthworms. *Geoderma* 243, 196–204. doi:10.1016/j.geoderma.2014.12.018

Puppe, D., Kaczorek, D., Schaller, J., Barkusky, D., and Sommer, M. (2021). Crop straw recycling prevents anthropogenic desilication of agricultural soil-plant systems in the temperate zone – results from a long-term field experiment in NE Germany. *Geoderma* 403, 115187. doi:10.1016/j.geoderma.2021.115187

Saxton, K. E., and Rawls, W. J. (2006). Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Sci. Soc. Am. J.* 70, 1569–1578. doi:10.2136/sssaj2005.0117

Schaller, J., Cramer, A., Carminati, A., and Zarebanadkouki, M. (2020a). Biogenic amorphous silica as main driver for plant available water in soils. *Sci. Rep.* 10, 2424. doi:10.1038/s41598-020-59437-x

Schaller, J., Frei, S., Rohn, L., and Gilfedder, B. S. (2020b). Amorphous silica controls water storage capacity and phosphorus mobility in soils. *Front. Environ. Sci.* 8, 1–12. doi:10.3389/fenvs.2020.00094

Schaller, J., Puppe, D., Kaczorek, D., Ellerbrock, R., and Sommer, M. (2021a). Silicon cycling in soils revisited. *Plants* 10, 295. doi:10.3390/plants10020295

Schaller, J., Scherwietes, E., Gerber, L., Vaidya, S., Kaczorek, D., Pausch, J., et al. (2021b). Silica fertilization improved wheat performance and increased phosphorus concentrations during drought at the field scale. *Sci. Rep.* 11, 20852–20912. doi:10.1038/s41598-021-00464-7

Sommer, M., Kaczorek, D., Kuzyakov, Y., and Breuer, J. (2006). Silicon pools and fluxes in soils and landscapes - a review. *Z. Pflanzenernahr. Bodenk.* 169, 310–329. doi:10.1002/jpln.200521981

Struyf, E., Smis, A., Van Damme, S., Garnier, J., Govers, G., Van Wesemael, B., et al. (2010). Historical land use change has lowered terrestrial silica mobilization. *Nat. Commun.* 1, 129. doi:10.1038/ncomms1128

Tecon, R., and Or., D. (2017). Biophysical processes supporting the diversity of microbial life in soil. *Fems Microbiol. Rev.* 41, 599–623. doi:10.1093/femsre/fux039

Tuller, M., Or, D., and Dudley, L. M. (1999). Adsorption and capillary condensation in porous media: Liquid retention and interfacial configurations in angular pores. *Water Resour. Res.* 35, 1949–1964. doi:10.1029/1999wr900098

Van Lier, Q. d. J., Metselaar, K., and Van Dam, J. C. (2006). Root water extraction and limiting soil hydraulic conditions estimated by numerical simulation. *Vadose Zone J.* 5, 1264–1277. doi:10.2136/vzj2006.0056

Vandevenne, F., Struyf, E., Clymans, W., and Meire, P. (2012). Agricultural silica harvest: Have humans created a new loop in the global silica cycle? *Front. Ecol. Environ.* 10, 243–248. doi:10.1890/110046

Zarebanadkouki, M., Kim, Y. X., Moradi, A. B., Vogel, H. J., Kaestner, A., and Carminati, A. (2012). Quantification and modeling of local root water uptake using neutron radiography and deuterated water. *Vadose Zone J.* 11, vzj2011.0196.0196. doi:10.2136/vzj2011.0196