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OPINION

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Could large-scale silicon supplementation of crop-lands mitigate the impacts of climate change?

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Societal Impact Statement

Intervention strategies that involve supplementing crop-lands with silicon have significant scope for carbon capture and drought mitigation, offering wide-ranging societal impacts. These include contributing to decarbonisation goals, enhancing food security, providing economic benefits and reducing environmental damage associated with intensive agronomic practices. This article highlights emerging evidence that suggests elevated atmospheric CO_2 and water limitation may impair silicon accumulation in plants. While this does not negate the outlined societal benefits, we argue that these limitations must be thoroughly quantified and incorporated into large-scale implementation plans to ensure the reliability and effectiveness of silicon intervention strategies.

Summary

Silicon accumulation in plants is increasingly recognised as playing an important functional role in alleviating environmental stresses. Most research to date has focussed on relieving agronomic stresses in crops, including pest and pathogen damage, soil salinity and drought. Recently, attention has turned to large-scale silicon application to agricultural landscapes as a potential anthropogenic climate change mitigation strategy. This includes silicon fertilisation to enhance soil carbon storage through advanced weathering of silicates, or by incorporating carbon in phytoliths in plant tissues. While these geoengineering approaches have potential, they could also present significant challenges. This article explores the opportunities and limitations for silicon-based interventions in mitigating the impacts of rising atmospheric carbon dioxide levels and increased incidences of drought. We argue that despite the promise of silicon supplementation in reducing plant stress under climate change, research paradoxically shows that these very climate conditions can significantly impede silicon accumulation in plants. We propose a framework to guide the development of silicon intervention strategies to mitigate climate change and the research questions that should be addressed to ensure their effectiveness under future environmental conditions.

KEYWORDS
CO_2, crops, decarbonisation, environment, global change, silica, silicon, water deficits

1 | BACKGROUND AND SCOPE

Anthropogenic climate change and environmental harm more generally present significant challenges for current and future human societies. Since pre-industrial periods, we have witnessed significant increases in atmospheric CO_2 concentrations, accompanied by changes in the frequency of extreme weather, with more unpredictable precipitation often leading to both floods and extended periods of drought (Easterling et al., 2000; IPCC, 2023). Plants and soils not only serve as key indicators of climate change, revealing detrimental impacts such as reduced crop productivity and soil degradation, but they also offer significant opportunities to mitigate environmental stresses. Supplementing plants with silicon via soil application, for example, has long been advocated for agronomic benefits, including improved yield together with enhanced resilience to biotic (e.g., pests and diseases) and abiotic (e.g., drought and salinity) stresses (Debona et al., 2017; Guntzer et al., 2012; Haynes, 2017b).

While there is a broad consensus that silicon accumulation has the capacity to alleviate a diverse range of biotic and abiotic stresses, the precise mechanisms underpinning the functional role of silicon in plants (Coskun et al., 2019) and its consistency for mitigating stress are still debated (Thorne et al., 2020). Despite this, many plant species, such as grasses (Poaceae), accumulate significant amounts of biogenic silicon, which is taken up from the soil as bioavailable orthosilicic acid (H_4SiO_4) via both passive and active mechanisms (Ma & Yamaji, 2015). The Poaceae contain many important agricultural crops (Carey & Fulweiler, 2016), with just three species (rice, wheat and maize) providing around 42% of human calories globally (Deutsch et al., 2018). Silicon is transported via the xylem and deposited as silica (SiO_2) in various plant tissues (Raven, 1983). While silicon is the second most abundant element in the Earth's crust, the bioavailable form, orthosilicic acid, can become deficient in many agricultural soils (Clymans et al., 2011), and there is growing interest in whether this could be remedied with silicon supplementation strategies (Haynes, 2017a). These endeavours were traditionally framed in an agricultural context, but researchers are now considering whether applying silicon at scale could assist in managing anthropogenic climate change at the landscape level (Beerling et al., 2018; Song et al., 2013; Taylor et al., 2017; Thorne et al., 2020).

In this opinion piece, we focus on the predicted rises in atmospheric CO_2 levels and occurrences of drought. We initially consider how silicon supplementation via geoengineering may both mitigate CO_2 rises via increased carbon sequestration and improve drought tolerance in plants. We then consider how these two drivers (i.e., higher CO_2 and water scarcity) affect silicon accumulation in plants. We argue that the physiological constraints in the plants ability to accumulate silicon under these changed environmental conditions should also be considered when we evaluate the potential benefits of silicon supplementation for climate change mitigation.

2 | CARBON SEQUESTRATION USING SILICON SUPPLEMENTATION

The silicon cycle begins with the weathering of silicon, primarily as silicate minerals, from rocks. These minerals are then transported by rivers to oceans, where they are taken up by marine organisms such as diatoms. The death of these organisms, and to a lesser extent their photosynthetic activity while alive, and their deposition on the ocean floor sequesters carbon. In the process, this connects the silicon cycle to the carbon cycle through carbon storage in marine sediments (Cornelis et al., 2011). Additionally, the weathering of rocks, whereby atmospheric CO_2 reacts with rainwater and soil minerals (e.g., calcium and magnesium) to produce carbonates, is an important natural mechanism for carbon capture (Song et al., 2014). There is global interest in how this weathering process, and carbon capture, can be accelerated by supplementing soils with silicon-rich substances (silicates) to increase the availability of calcium and magnesium, which subsequently react with atmospheric CO_2 to form soil carbonates (Beerling et al., 2020; Beerling et al., 2024; Kelland et al., 2020; Taylor et al., 2017). At least 13 recent, or current, enhanced weathering rock trials are underway across the globe (Figure 1) although it is notable that these are absent from the global South.

Beyond enhanced rock weathering, carbon capture can be achieved by increasing plant growth and photosynthesis, which draws down more CO_2 from the atmosphere (Beerling et al., 2024, Kelland et al., 2020). This process increases soil organic matter production and promotes its stabilisation and persistence, reducing carbon loss through decomposition and erosion and ultimately promoting carbon storage (Figure 2). Persistence may be enhanced when organic material in the plant is locked up in silicon-rich phytoliths during phytolith formation, referred to as phytolith-occluded carbon (PhytOC), which are highly resistant to decay and mineralisation, thereby creating a stable carbon sink (Parr & Sullivan, 2005; Song et al., 2017). The PhytOC fraction in soils is small compared with the main pool of carbon, however, with a recent estimate of carbon sequestration as PhytOC each year being 11–190 Tg C $year^{-1}$, representing between <1% and 13% of total carbon sequestration in soils globally (de Tombeur et al., 2024). Calculating percentages of PhytOC in phytoliths and differing assumptions regarding the dissolution of phytoliths in the soil complicate the issue (Hodson, 2019), but silicon fertilisation may at least increase PhytOC sequestration (e.g., Huang et al., 2020).

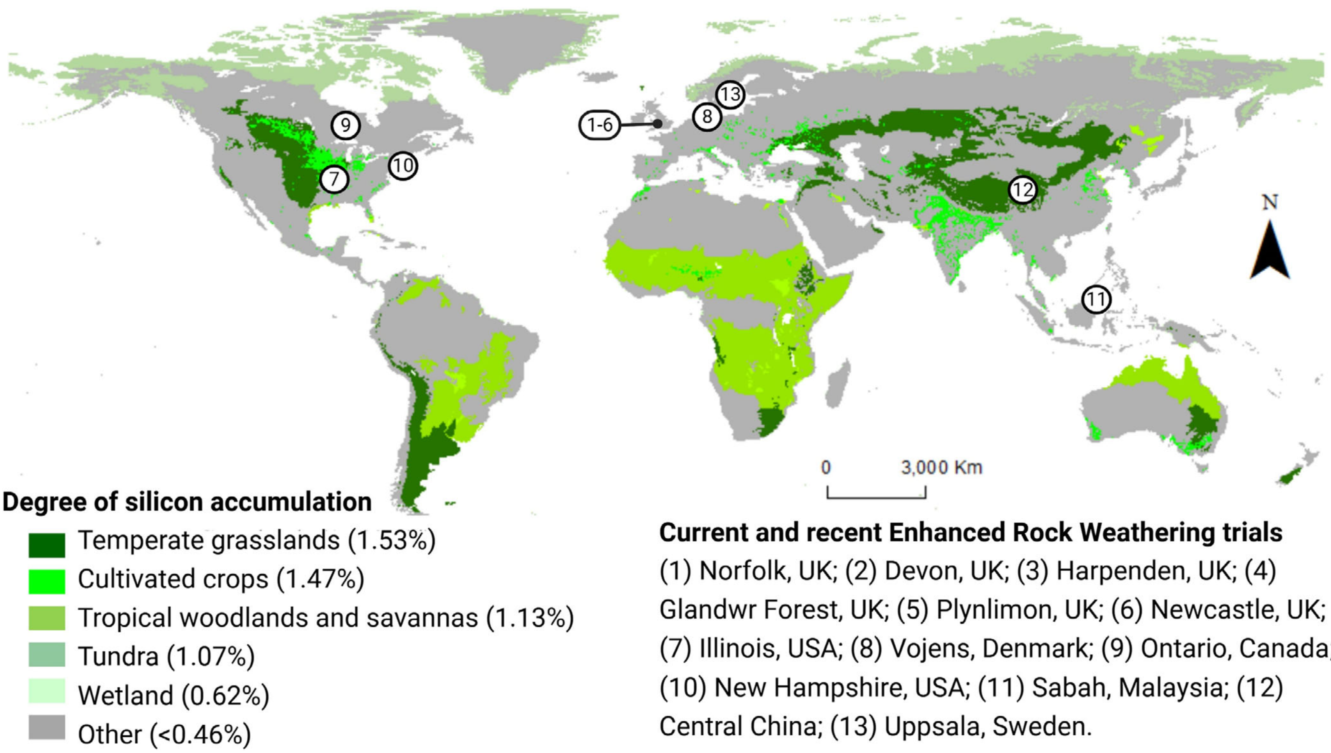

FIGURE 1 The global potential of silicon supplementation as a climate change mitigation strategy. The map shows land cover where the vegetation has a high proportion of silicon accumulating species (taken from Carey and Fulweiler (2012)), where shades of green reflect extent of silicon accumulation; (see Carey and Fulweiler (2012) for full details). Locations of current and recent enhanced rock weathering field trials across the world are also indicated based on information from Forrest and Wentworth (2024).

3 | SILICON ACCUMULATION IN PLANTS UNDER ELEVATED CO_2

Several studies have investigated the impacts of elevated CO_2 on silicon accumulation in plants. Although these findings largely stem from a small number of research teams, most report significant declines in silicon accumulation under elevated CO_2. All but two studies considered the Poaceae, with most focusing on C_3 species, although there were some examples of C_4 species (e.g., Frew et al., 2017; Johnson & Hartley, 2018).

There are several possible mechanisms explaining why plant silicon accumulation is generally lower under elevated CO_2. Firstly, it may relate to rates of gas exchange, with silicon uptake being partly driven by the transpiration stream and stomatal conductance and partly by active uptake (McLarnon et al., 2017). Therefore lower stomatal conductance and transpiration rates under elevated CO_2 are associated with improved water use efficiency (DeLucia et al., 2012) and may contribute to lower silicon uptake. Whenever this has been explored, however, there was no relationship between these physiological parameters and Si accumulation (e.g., Biru et al., 2021). Secondly, and more likely, is that increases in carbon concentrations in plant tissue, which frequently occur under elevated CO_2 (Robinson et al., 2012), have a 'dilution effect' whereby silicon concentrations decrease by necessity (Figure 3). Silicon and carbon concentrations are often negatively correlated in plants due to this 'dilution effect' but potentially also because silicon may act as a metabolically cheaper substitute for carbon-based structural components such as lignin and cellulose (Raven, 1983). Higher carbon accumulation via increased photosynthesis under elevated CO_2 may therefore make silicon accumulation less advantageous, although the 'dilution effect' is likely the primary cause (Johnson & Hartley, 2018). Regardless, silicification is likely to have some disadvantages as a structural resource for the plant compared with carbon (Hodson & Guppy, 2022; Raven, 1983).

4 | DROUGHT ALLEVIATION USING SILICON SUPPLEMENTATION

There are many studies that demonstrate that silicon supplementation alleviates drought stress in many plant species (Cooke & Carey, 2023). These include important cereal crops such as rice (Wang et al., 2019; Yang et al., 2019) and wheat (Johnson, Chen, et al. 2022; Maghsoudi et al., 2016), but other plant taxa including legumes (reviewed by Zhang et al., 2017). However, it should also be noted that several studies do not observe this effect (see review by Thorne et al., 2020). A number of plant-based mechanisms have been suggested to account for drought alleviation, where it occurs, including increased production of antioxidants, binding and co-precipitation with metal ions, modification of element uptake, higher hydraulic conductance and reduced water loss at the leaf surface (e.g., reduced transpiration)

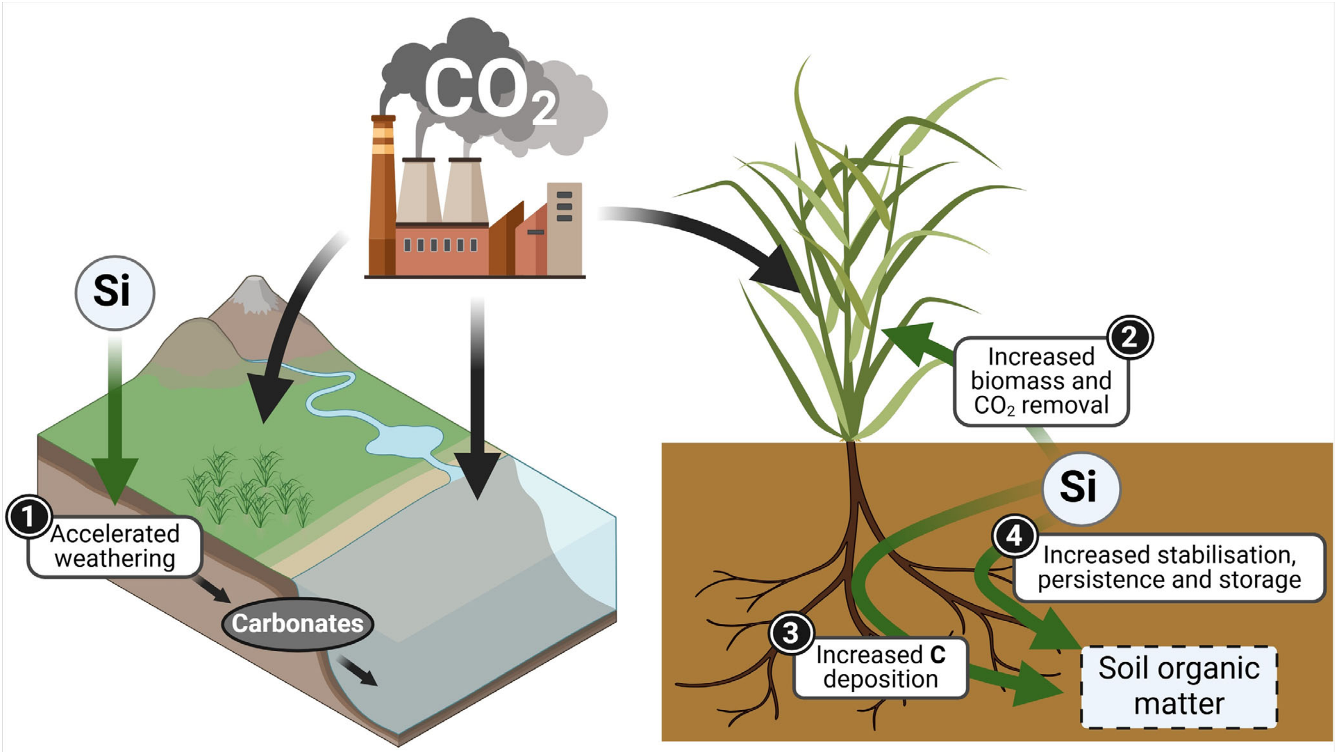

FIGURE 2 Enhancing carbon capture through silicon supplementation. Carbon capture is potentially achievable via (1) accelerated weathering using silicon supplementation, which releases nutrients, improving soil conditions and generating alkaline leachate, which ultimately leads to the export of dissolved inorganic carbon to the oceans (Beerling et al., 2018). In addition, silicon supplementation could further enhance carbon capture through (2) increasing plant growth and photosynthesis, thereby increasing CO_2 uptake; (3) increasing soil organic matter deposition; and (4) promoting the stabilisation and persistence of soil organic matter, by reducing loss via decomposition and erosion. This stabilisation is partly driven by the formation of silicified phytoliths in plant tissues that occlude organic carbon, thereby protecting it from decomposition.

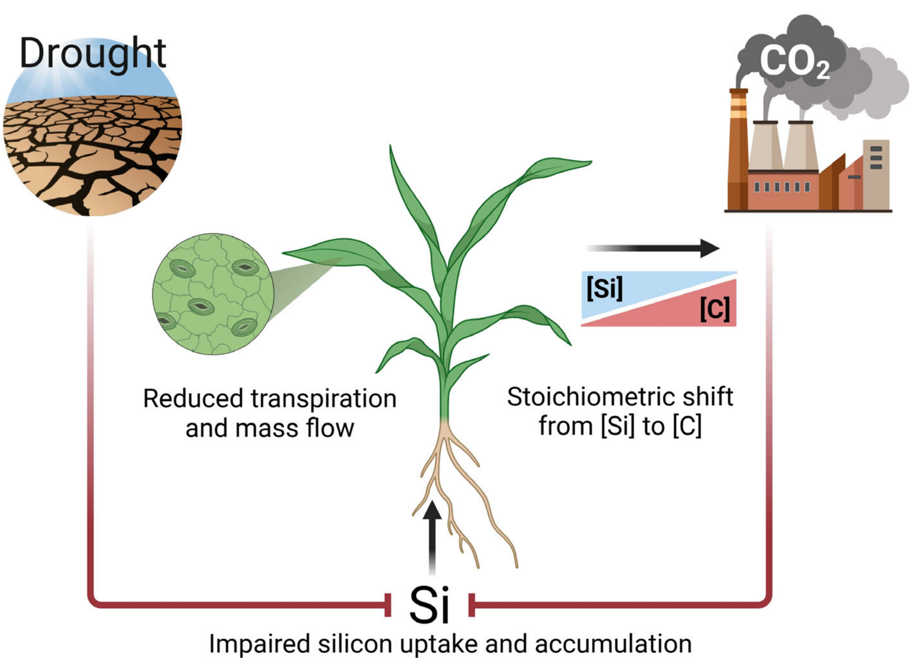

FIGURE 3 The most plausible mechanisms by which drought and elevated atmospheric CO_2 impair silicon uptake and accumulation in plants. The greater availability of carbon and increased rates of photosynthesis under elevated atmospheric CO_2 frequently increase carbon concentrations in leaf tissues, which leads to a 'dilution effect' decreasing the proportion of silicon in tissues. Drought conditions generally reduce transpiration rates and mass flow of water in the plant, likely reducing passive uptake of silicon.

due to silicification (Debona et al., 2017; Liang et al., 2007). Changes in photosynthesis, water balance and oxidative stress appear to be the most significant. These changes may be explained by silicon structures accumulating in the apoplast (see Debona et al., 2017, Thorne et al., 2020 for detailed discussions). The 'apoplastic obstruction hypothesis' proposes that silicon supplementation alleviates drought stress by forming a protective barrier outside of the cells, reducing water loss by limiting evapotranspiration (Coskun et al., 2019). In addition to plant-based mechanisms for silicon supplementation alleviating drought stress, silicon supplementation can also enhance water retention in the soil especially by increasing water holding capacity and plant available water (Kuhla et al., 2021; Schaller et al., 2024). Indeed, it has been argued that this is at least as important as plant-based mechanisms by which silicon supplementation can alleviate drought (Kuhla et al., 2021).

There have been several field evaluations of whether silicon can alleviate water stress (Maghsoudi et al., 2016; Schaller et al., 2021, Johnson, Chen, et al., 2022), generally with good indications that silicon fertilisation could be a useful large-scale intervention strategy. Thorne et al. (2020) conducted a global cost–benefit analysis and concluded that silicon fertilisation may be beneficial in many agronomic situations, but potentially economically infeasible for smallholder farmers in the global south. Viewed in the context of climate change mitigation, however, silicon intervention may offer societal benefits that extend beyond the established agronomic advantages. These broader impacts should be taken into account in future cost–benefit analyses.

5 | IMPACTS OF DROUGHT ON SILICON ACCUMULATION

Silicon accumulation occurs through both energy-demanding active uptake and passive uptake, the latter being strongly influenced by the transpiration stream (Deshmukh & Bélanger, 2016; Ma & Yamaji, 2015). Drought conditions, which reduce transpiration (Farooq et al., 2012), likely also cause declines in passive Si uptake (Figure 3). The relative importance of passive and active uptake will depend partially on plant species, with those accumulating >1% of dry mass in their tissues being reliant on active as well as passive uptake (Deshmukh & Bélanger, 2016). Drought may also limit active uptake, because significant resources may be needed for silicon uptake at a time when reduced transpiration is limiting photosynthesis.

Experimental studies suggest that water limitation generally inhibits silicon accumulation, though some grass species seem able to retain the ability to accumulate silicon under drought conditions (Quigley & Anderson, 2014 Johnson, Vandegeer, et al., 2023). The extent and nature of drought stress, and the level of silicon supplementation, appear to be important in determining whether droughts impact silicon uptake. In wheat, Ma et al. (2016) found that leaf silicon concentrations declined by 22% under moderate drought stress and 15% under severe stress. With silicon supplementation, silicon concentrations were 16% lower in moderately stressed plants, while severely stressed plants maintained levels comparable to well-watered controls. Patterns in drought may influence silicon uptake; barley plants experiencing sustained drought showed considerable declines in silicon accumulation, but this was alleviated to some extent when the drought was followed by a deluge event (Wade et al., 2022). The amount of silicon supplementation may also be important for determining the extent of drought alleviation. In wheat, drought reduced silicon levels by 44% without supplementation. However, the reduction became progressively smaller as silicon supplementation levels increased (Alzahrani et al., 2018).

6 | POTENTIAL SOURCES OF SILICON FOR INTERVENTION STRATEGIES

While not extensively used in agronomic practices, there are several options for silicon supplementation (see Zellner et al., 2021 for details), which could pave the way for scaling up silicon supplementation as a climate change mitigation strategy (Zhang et al., 2018). A comprehensive review of silicon fertilisers, including practicalities, advantages and disadvantages, is provided by Haynes (2017b) along with commercial suppliers listed by Zellner et al. (2021). A number of solid silicon sources have been identified as being suitable for climate mitigation strategies, based on feasibility and availability. In brief, these include wollastonite (a natural calcium silicate), calcium silicate slag (a byproduct of the phosphate and steel production) and diatomaceous earth mined from sedimentary rocks (Haynes, 2017b). The latter contain fossilised diatoms, which can vary significantly in silicon composition depending on diatom species (Zellner et al., 2021). Beerling et al. (2018), advocate the use of basalt, which is an abundant and fast-weathering rock with appropriate mineral chemistry. They highlight its additional benefits for crop production and soil health. Furthermore, the logistics for its use already exist because similar applications (e.g., crushed limestone) are often applied to crop-lands to reverse soil acidification associated with intensive cropping.

7 | FUTURE CHALLENGES

As discussed earlier, increased weathering of silicate rocks may amplify carbon sequestration helping to mitigate rising atmospheric CO_2. However, shifts in the silicon cycle due to climate change could also alter marine ecosystems, impacting their role in carbon absorption and affecting overall climate regulation. Such changes could include altered river exports of silicon due to weathering or plant uptake rates. Additionally, while elevated atmospheric CO_2 may reduce silicon accumulation in terrestrial plants (Table 1), this phenomenon is, to our knowledge, not yet accounted for in the modelling of silicon–carbon cycles (Tréguer et al., 2021). We propose that this is an important factor that should be parameterised in future models. Conducting more empirical studies covering a wider range of plant taxa would help establish robust parametrisation. In particular, grasses

TABLE 1 Studies reporting the impact of elevated CO_2 concentrations on plant silicon accumulation. The elevated treatment of CO_2 indicated, together with plant species (all but Fulweiler et al. (2014) and Johnson et al. (2018) used Poaceae species), whether silicon supply was controlled in potted soil (PS), hydroponic (H) or field (F) conditions, the tissues where silicon concentrations were measured and the overall response under elevated CO_2 concentrations. Downward red arrows reflect significant declines in plant tissue silicon concentration under elevated CO_2 (with approximate % decreases), while horizontal grey arrows reflect no overall effect of elevated CO_2.

CO_2 concentration	Plant species	Was Si manipulated?	Tissues measured	Silicon levels	Reference
640 and 800 ppm	*Phalaris aquatica* (C_3)	Yes (PS)	Foliar Si (%DM)	↓ –18-25%	Ryalls et al. (2017)
640 ppm	*Saccharum* spp. (C_4)	Yes (PS)	Foliar Si (%DM)	→	Frew et al. (2017)
640 ppm	*Saccharum* spp. (C_4)	Yes (PS)	Root Si (%DM)	→	
640 ppm	Pasture grasses (eight species)[a] (C_3/C_4)	No (PS)	Foliar Si (%DM)	↓ –12%	Johnson and Hartley (2018)
640 ppm	*Brachypodium distachyon* (C_3)	Yes (H)	Foliar Si (%DM)	↓ –19%	Biru et al. (2020)
640 ppm	*B. distachyon* (C_3)	Yes (H)	Root Si (%DM)	→	
640 ppm	*B. distachyon* (C_3)	Yes (H)	Foliar Si (%DM)	→	Biru et al. (2021)
640 ppm	*Lolium arundinaceum* (C_3)	Yes (H)	Foliar Si (%DM)	↓ –31%	Biru et al. (2023)
640 ppm	*B. distachyon* (C_3)	Yes (H)	Foliar Si (%DM)	↓ –18%	Hall et al. (2020)
640 ppm	*B. distachyon* (C_3)	Yes (PS)	Foliar Si (%DM)	↓ –32%	Biru et al. (2022)
640 ppm	*Triticum aestivum* (C_3)	Yes (H)	Foliar Si (%DM)	↓ –19%	Johnson, Cibils-Stewart, et al. (2022)
640 ppm	*T. aestivum* (C_3)	Yes (PS)	Foliar Si (%DM)	↓ –45%	Biru et al. (2024)
590 ppm	*L. arundinaceum* (C_3)	Yes (PS)	Foliar Si (%DM)	↓ –17-22%	Johnson et al. (2023)
640 ppm	*Medicago sativa* (C_3)	Yes (PS)	Foliar Si (%DM)	→	Johnson et al. (2018)
500–700 ppm	*Oryza sativa* (C_3)	No (F)	Foliar Si (%DM)	↓ →*	Gória et al. (2013)
600–680 ppm	*O. sativa* (C_3)	No (F)	Foliar Si (%DM)	↓ 13-22%	Kobayashi et al. (2006)
700 ppm	*O. sativa* (C_3)	Partially (F)	Panicle Si (ratio)	↓ –26%	Takahashi et al. (2008)
600 ppm	Six tree species[b] (C_3)	No (F)	Foliar Si (%DM)	→	Fulweiler et al. (2014)

[a]Species tested: *Microlaena stipoides*, *Chloris gayana*, *Lolium rigidum*, *Dactylis glomerata*, *Lolium perenne*, *L. arundinaceum*, *Bothriochloa macra* and *Austrodanthonia bipartita*.
[b]Species tested: *Pinus taeda*, *Cornus florida*, *Cercis canadensis*, *Acer rubrum*, *Liquidambar styraciflua* and *Ulmus alata*.
*Effects reported without displaying data.
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that use the C_3 photosynthetic pathway tend to show larger responses to elevated CO_2 than those using the C_4 cycle (e.g., increased carbon assimilation rates of 33% and 25% for C_3 and C_4 grass species, respectively) (Wand et al., 1999). This suggests that silicon accumulation in C4 plants may be less impacted by elevated CO_2; however, most studies to date have considered C_3 plants, so this is difficult to resolve (Table 1).

While silicon supplementation can alleviate the adverse effects of drought, drought conditions may simultaneously impair silicon accumulation in plants. This aspect tends to be either overlooked or deemphasised, with greater focus placed on findings that support silicon's role in alleviating drought. Nonetheless, plant silicon concentrations are frequently measured under drought conditions and reported in the literature, which is now potentially large enough for quantitative meta-analysis. Such analysis could address whether drought impairs silicon accumulation differently depending on whether plant species rely. on passive uptake versus those that also use active uptake. Another important question is whether drought stress is improved by applying progressively higher levels of silicon or whether there is a threshold to the benefits delivered by silicon supplementation. Moreover, there may be sufficient data to also determine whether there are differences between cultivars or genotypes of the same species. Rice cultivars, for example, showed considerable variation in their recovery responses from salinity stress when supplemented with silicon (Thorne et al., 2022).

Other climatic factors, such as rising air temperatures, undoubtedly play a role in plant silicon uptake with a general trend for higher uptake under warmer conditions (Brightly et al., 2020; Johnson, Vandegeer, et al., 2023). Silicon supplementation may, in turn, alleviate the adverse impacts of heat stress in plants (Liang et al., 2007). There are, however, far fewer studies addressing either of these research questions, and we are unaware of any attempts or proposals to develop silicon intervention strategies to mitigate the effects of rising temperatures. Although this opinion piece does not address rising temperatures for these reasons, we acknowledge this as a significant research gap worthy of further exploration.

8 | CONCLUSIONS

Rice, wheat and maize are major silicon-accumulating grass species, highlighting the potential utility of supplementing crop-lands with silicon at a global scale. However, further cost–benefit analyses are needed. For example, in rice, silicon supplementation proved beneficial for high-yield cultivars under mild salinity stress but was not cost effective for low-yielding cultivars (Thorne et al., 2022). Non-agricultural systems such as grasslands and savannas, which host many high silicon accumulating plant species and account for significant amounts of terrestrial landmass (Figure 1), could also be considered for silicon supplementation strategies (Carey & Fulweiler, 2012).

Silicon intervention strategies offer significant potential for carbon capture and drought mitigation. However, paradoxically, the very drivers that these strategies aim to address—increased atmospheric CO_2 and water scarcity—may also impair silicon accumulation in plants. Gaining a deeper insight into these physiological constraints to plant silicon accumulation is crucial for understanding terrestrial silicon dynamics in the context of global climate change. Research priorities could include (1) more empirical studies addressing the impacts of elevated CO_2 on silicon accumulation, with a focus on incorporating more diverse plant groups (e.g., C_4 species); (2) quantitative meta-analysis of existing works measuring silicon uptake under drought to identify key influencing factors, such as uptake capacity and genotype; and (3) further field testing and cost–benefit analyses that specifically include the benefits of climate change mitigation of silicon supplementation. We are also reliant on data from field trials from the Northern Hemisphere (see Figure 1), but climatic impacts and economic constraints are likely different for the Global South and should be taken into consideration. Addressing these research priorities could help parametrise approaches such as dynamic carbon budget models that predict the potential carbon drawdown and quantitative contribution to atmospheric carbon removal. We conclude that environmental constraints on plant silicon accumulation, specifically elevated CO_2 and drought, must be thoroughly quantified and incorporated into large-scale implementation plans to ensure the reliability and effectiveness of silicon intervention strategies for climate change mitigation.

AUTHOR CONTRIBUTIONS

Scott N. Johnson conceived and proposed the opinion article with contributions from Kimberley J. Simpson and Susan E. Hartley. Susan E. Hartley led the writing of the article with significant contributions from all authors who approved the final submission.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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