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Reviews and syntheses: Process coupling between diatom silicon cycling and carbon export under ocean acidification

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Abstract： Ocean acidification alters seawater carbonate chemistry and can affect both silicon production by diatoms and the dissolution and recycling of particulate biogenic silica. This review focuses on marine planktonic diatoms and their siliceous particles, integrating evidence on cellular silicon allocation, community silica production, particle export, and preservation during water-column transport. Silicification responses depend on species and environmental conditions, and cellular silicon quotas, silica deposition rates, and community production need not change in parallel. Lower pH can slow silica dissolution under some conditions, but the resulting preservation also depends on particle properties and transit time. We use a budget decomposition of production, export efficiency, and water-column transfer to examine decoupling across stages and the conditions under which enhanced preservation can offset reduced production. Similar silicon-to-carbon flux ratios at a given depth can arise from different intermediate processes. Compensation depends on the relative changes in the budget components and the depth of assessment, while enhanced short-term preservation and reduced long-term silicon resupply to surface waters may be parts of the same feedback. The implications for carbon export remain contingent on particle sources, community replacement, and differential silicon and carbon losses. Long-term carbon sequestration additionally requires constraints on the location of organic carbon remineralization and the duration of isolation from the atmosphere. Research should prioritize paired production measurements, linked production–dissolution experiments using particles of common origin, and flux observations at multiple depths to test when silicon-cycle responses can explain changes in carbon export.

1 Introduction

Diatoms are major contributors to marine primary production and link the oceanic silicon and carbon cycles(Martin-Jézéquel et al., 2000; Ragueneau et al., 2006; Tréguer et al., 2018). Most diatoms take up dissolved silicic acid from seawater and convert it into biogenic silica (BSi) that forms their cell walls.

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Cell growth and death, followed by particle sinking and dissolution, transform silicon between dissolved and particulate phases and redistribute it among water layers(Hildebrand, 2003; Suman et al., 2024). Diatom production therefore depends on external inputs and physical transport as well as silicon regenerated through BSi dissolution(Brzezinski et al., 2024; Tréguer et al., 2021). Silicon availability relative to other nutrients influences diatom production and community composition, making silicon supply an important consideration in marine primary production and nutrient recycling (Tréguer et al., 2021; Kristiansen and Hoell, 2002; Makareviciute-Fichtner et al., 2024).

Diatoms produce organic carbon through photosynthesis, and their cells and derived particles contribute to the vertical transport of particulate organic carbon (POC) through direct sinking, aggregation, and food-web processing(Iversen, 2023; Wakeham and Lee, 1993). Siliceous frustules can increase particle density and promote sinking, but whether this yields more efficient carbon transfer also depends on cell condition, community composition, particle transformations, and losses during transit(Williams, 2025). Surface diatom carbon production and deep carbon flux consequently have no fixed proportional relationship. Spring observations in the subpolar Southern Ocean showed that BSi flux attenuated more rapidly with depth than POC flux within the mesopelagic waters examined, demonstrating that silicon and carbon transfer efficiencies can differ(Williams, 2025; Williams et al., 2025). Assessing diatom contributions to carbon export thus requires linked production and flux observations; diatom abundance or particle silicon content cannot substitute for direct evidence of carbon transport.

Ocean uptake of atmospheric CO_2 alters seawater carbonate chemistry, increasing both CO_2 availability and H^+ concentration(Doney et al., 2009; Bates et al., 2014). These changes can affect diatoms through different pathways, with net effects governed by species traits and environmental conditions. Experiments with natural communities show variable responses of diatom abundance, taxonomic composition, and size structure to elevated CO_2 (Bach and Taucher, 2019). For silicon cycling, Petrou et al. (Petrou et al., 2019)found that acidification reduced silicon incorporation in some taxa within a natural Southern Ocean community. By combining mesocosm experiments, observations, and models, Taucher et al. (2022) proposed that slower BSi dissolution at lower pH could increase silicon transfer to depth and reduce its long-term resupply to surface waters. The former response concerns the initial production input, whereas the latter concerns subsequent losses and the depth of regeneration; both can occur simultaneously. Their combined consequences depend on response magnitudes, particle transport, and

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physical replenishment. Assessing carbon export further requires testing whether organic carbon responds correspondingly.

This review integrates evidence on silicon production, silica dissolution and recycling, and vertical particle transport in marine planktonic diatoms and their derived siliceous particles within a framework linking production, particle transfer, and regeneration (Fig. 1). Light, temperature, and nutrients are considered as environmental controls on these processes, while growth measurements help interpret the relationship between silica deposition and cell division. Comparisons among species account for differences in representativeness between diatoms with a clear silicon requirement and unusual model species such as Phaeodactylum tricornutum. We address three questions: at which stages do silicon and carbon responses decouple; under what conditions can improved particle preservation offset reduced silicon production; and when can silicon-cycle changes explain carbon export, rather than requiring additional particle and flux evidence?

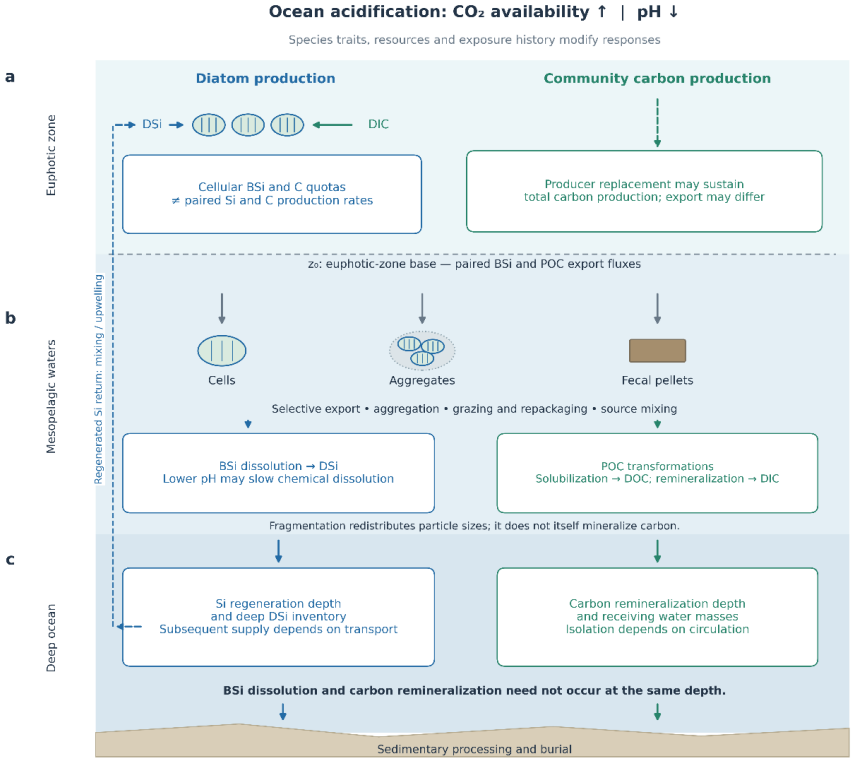


Figure 1. Silicon–carbon coupling and decoupling across the water column under ocean acidification.

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2 Comparing evidence across the diatom silicon cycle

2.1 Defining metrics of silica production and particle transport

Specific growth rate describes cell proliferation, the cellular BSi quota represents silica content per cell, and community silica production measures BSi formation per unit time. BSi standing stock per unit water volume reflects the combined effects of production, loss, and transport(Tréguer et al., 2021). Quotas and production rates may respond differently when cell division and silica deposition are not synchronized(Claquin et al., 2002). Lower cellular quotas may also reflect changes in cell volume or culture stage. Identifying quota dilution associated with faster division requires measurements of cell abundance, size, and silica deposition rates on a consistent normalization basis.

Measurement methods determine the processes and timescales represented by individual metrics and delimit their interpretation (Table 1). Silicon isotope tracers and PDMPO fluorescence labeling provide information on silicon incorporation or silica deposition over a defined incubation window; their integration times and calibration conditions should be reported separately(Brzezinski and Phillips, 1997; Mcnair et al., 2015). Hot alkaline extraction measures extractable BSi(Ragueneau and Tréguer, 1994), but natural particle samples can contain living cells, empty frustules, and siliceous debris, so content alone does not measure production. Carbon assimilation, POC accumulation, and net carbon production likewise require method-specific definitions. In vertical transport studies, sinking velocity describes particle motion, whereas flux also depends on particle abundance and composition. Export flux is defined as the downward particulate flux across the base of the euphotic zone. Fluxes at greater depths describe subsequent transfer. Transfer efficiency is expressed as the flux at a deeper horizon divided by that at a shallower reference horizon, provided that source regions and sampling periods are appropriately matched(Buesseler and Boyd, 2009).Mesocosm trap fluxes are interpreted according to their actual sampling boundaries.

Table 1. Process meanings and interpretive limits of the principal metrics.

Metric category	Principal metrics	Process represented	Interpretive limits
Growth and cellular metrics	Specific growth rate; cell size; cellular BSi and C quotas	Cell proliferation and elemental accumulation	Quotas are not production rates; cell-, volume-, and surface-area-normalized results require separate comparisons

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Metric category	Principal metrics	Process represented	Interpretive limits
Production rates	Silicon uptake, silica deposition, or BSi production; carbon assimilation	Material formation within matched time windows	Integration times and measured processes differ; silicon and carbon require paired measurements at the same scale
Community inventories	BSi, POC, and diatom biomass per unit water volume	Standing stocks resulting from production and losses	Changes also reflect sinking, grazing, dissolution, and community composition
Elemental ratios	Cellular Si:C; suspended-particle or flux BSi:POC	Elemental proportions in a specified pool	Check numerator, denominator, sources, and molar or mass basis; ratios do not determine absolute fluxes
Particle transport	Sinking velocity; BSi and POC fluxes at specified depths	Motion or transport across depth horizons	Velocity is not flux; depth, source region, lag, and trapping bias require matching or assessment
Water-column preservation	Dissolution and remineralization rates; flux retention; depth attenuation	Losses and their relative depth distribution	Relative preservation does not establish higher absolute flux or long-term carbon sequestration

2.2 Scale and source dependence of silicon–carbon ratios

Cellular Si:C describes elemental allocation within cells, suspended-particle BSi:POC describes the composition of a mixed particle pool, and the BSi:POC flux ratio describes elemental transport across a specified depth horizon. The latter two may include organic carbon from non-diatom sources, empty frustules, and siliceous debris, and thus differ in source composition from ratios measured in living diatoms(Tréguer et al., 2021). Comparisons should report silicon and carbon contents or fluxes separately and use a consistent molar or mass basis. Flux ratios at multiple depths can help assess relative losses, but their interpretation still requires matching particle source regions, formation times, and sinking lags(Buesseler and Boyd, 2009; Williams et al., 2025).

We define silicon–carbon decoupling as a change in the relative responses or transfer of silicon and carbon with respect to an explicit control, initial state, or reference depth. Decoupling in allocation, production, and transfer concerns elemental composition, production rates, and flux changes, respectively, and should be evaluated at the relevant scale. A decrease in the Si:C ratio can reflect a reduction in cellular silicon content, an increase in cellular carbon content, or concurrent changes in both.(Mejía et al., 2013; Xu et al., 2023). It does not by itself establish improved carbon fixation efficiency or determine the direction of carbon export.

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2.3 Comparability of carbonate chemistry and exposure history

CO_2 enrichment generally increases dissolved inorganic carbon (DIC) while leaving total alkalinity (TA) approximately unchanged. Direct strong-acid addition primarily lowers TA and does not directly increase DIC in a closed system(Schulz et al., 2009). Treatments with similar pH can therefore differ in carbonate-system composition(Gattuso and Lavigne, 2009). Acid addition and combined chemical manipulations should be evaluated using measured parameters (Gattuso and Lavigne, 2009; Schulz et al., 2009). Comparability also depends on temperature, salinity, pH scale, and chemical changes during cultivation, rather than pH alone.

Biological growth in batch cultures can consume inorganic carbon and alter DIC and pH. Semi-continuous cultures and chemostats help stabilize growth but do not automatically maintain constant carbonate chemistry(Gattuso and Lavigne, 2009). Comparisons between constant and fluctuating exposure should report the mean, amplitude, and period of the fluctuations. Short-term, long-term, and gradual treatments help resolve response speed, persistence, and exposure-history effects, respectively. Phenotypic changes in long-term cultures require additional evidence from recovery cultures or common-garden assays to distinguish physiological acclimation from heritable change(Xu et al., 2023).

This process-based narrative synthesis organizes evidence around silica production, dissolution, particle export, and silicon resupply. Controlled acidification experiments identify treatment responses, studies without acidification manipulations inform the underlying processes, and scenario models assess feedbacks across scales; these evidence types are considered separately. The interpretive value of single-species cultures, natural-community experiments, and field observations depends on the question and measured endpoint, rather than system size. Reviews are used to trace research developments, original studies support specific interpretations, and theses can provide experimental details. A thesis and journal article based on the same dataset are not treated as independent replicates. Representative studies and their interpretive scope are summarized in Table 2.

3 Silicon production in living diatoms: responses and environmental controls

3.1 Silicon uptake, deposition, and net cellular accumulation

Net cellular BSi accumulation depends on silicon uptake and deposition, together with losses through efflux and dissolution(Milligan et al., 2004). Carbonate chemistry may influence these processes through

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carbon acquisition, cellular acid–base homeostasis, and growth state, but changes in seawater pH cannot be equated directly with changes in the intracellular silica deposition environment(Milligan et al., 2004; Hervé et al., 2012). Milligan et al. (2004) associated higher silicon quotas in Thalassiosira weissflogii at low CO_2 with lower silicon efflux and dissolution losses, showing that quota changes need not arise from enhanced uptake. The pH-gradient experiments of Hervé et al. (2012) also showed that cellular acid–base status and silica formation respond to external pH. These results offer mechanistic insights, but the broad treatment range differs from future acidification driven by atmospheric CO_2; interpretation should retain that distinction in experimental purpose and environmental range.

Acidification experiments reveal variable silicification responses across experimental systems and measurement endpoints (Table 2). Petrou et al. (2019) observed reduced silicon incorporation in some taxa in a natural Southern Ocean community, whereas Li, F. et al. (2019)detected no significant change in cellular BSi content in T. weissflogii at pCO_2 levels of 400, 800, and 1600 µatm. The studies measured incorporation and cellular content, respectively, and differed in species and environmental setting. Their response directions therefore do not establish a contradiction. A decrease in cellular quota establishes a change in silica content, but changes in frustule thickness or mechanical properties require corresponding structural and mechanical measurements.

Table 2. Experimental systems, measured endpoints, and interpretive scope of representative studies.

Study and evidence type	System and principal endpoints	Principal findings	Interpretive scope
Milligan et al., 2004 CO_2-manipulated cultures	T. weissflogii; silicon metabolism, quotas, and isotopic fractionation	Higher quotas at low CO_2 associated with lower efflux and dissolution losses	Distinguishes accumulation, uptake, and retention; does not alone predict export
Hervé et al., 2012 pH mechanism experiments	Model diatoms; cellular acid–base status and silica formation	Cellular status and silica formation sensitive to external pH	Broad pH manipulation informs mechanisms; not a standard CO_2 acidification scenario
Mejía et al., 2013 CO_2-manipulated cultures	Two Thalassiosira species; cellular Si:C and carbon acquisition	Si:C varied with carbonate chemistry	Supports allocation responses; carbon export not tested
Qu et al., 2018 Multifactor cultures	Coscinodiscus sp.; CO_2, temperature, nitrate; silica content and Si:C	Environmental factors interacted	Combined effects require separation; no universal direction of acidification response assumed

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Study and evidence type	System and principal endpoints	Principal findings	Interpretive scope
Petrou et al., 2019 Natural-community acidification experiment	Southern Ocean community; single-cell silicon incorporation	Reduced silicification with taxon-specific responses	Direct silicification evidence; needs links to community contributions and export
Li, F. et al., 2019 CO_2-manipulated cultures	T. weissflogii; 400, 800, 1600 µatm; BSi content	No significant change in BSi content	Content endpoint does not establish absence of responses in all silicon metabolic processes
Li, W. et al., 2019 Gradual and abrupt CO_2 treatments	Two Thalassiosira species; 180–1000 µatm; growth, BSi, POC	Changes over low to intermediate CO_2; stabilization at higher levels	Full-gradient trends differ from present-to-future acidification responses
Xu et al., 2023 Short- and long-term multifactor cultures	P. multiseries; 30 and 800 days; BSi, POC, Si:C	BSi decreased with pCO_2; carbon response depended on culture state	Supports persistence; does not alone establish genetic adaptation
FitzGerald-Lowry et al., 2025 Light × CO_2 cultures	T. weissflogii and P. tricornutum; area-normalized BSi and PDMPO	Higher area-normalized BSi at low light and elevated CO_2; deposition inhibited under high light	Content and deposition differ; silicification in the unusual model species near detection limit
Taucher et al., 2022 Mesocosm synthesis and modeling	Sinking/suspended Si:N; Earth system simulations	Sinking Si:N increased by 17 ± 6%; predicted redistribution to depth and supply feedbacks	Preservation interpretations and model projections treated separately; not an absolute POC-export conclusion
Williams et al., 2025 Field observations without acidification manipulation	Subpolar Southern Ocean; mesopelagic BSi and POC fluxes	BSi transfer efficiency could be lower than that of POC	Constrains differential losses; not attributable to acidification
Suessle et al., 2026 Related alkalinity-enhancement mesocosm evidence	North Sea; TA, pH, exported BSi:POC, sinking velocity	Lower exported BSi:POC at higher pH; no systematic corresponding velocity response	Alkalinity enhancement is not a strict reverse CO_2 acidification experiment; does not establish sequestration
Seebah et al., 2014 Warming × CO_2 cultures	T. weissflogii; extracellular polymers, aggregation, sinking	Polymer changes under combined treatment did not coincide with greater aggregation and sinking	Links polymers, aggregation, and transport; combined effects differ from acidification alone
Boxhammer et al., 2018 Natural-community mesocosm and budget	Trophic organic matter transfer and export	Greater transfer to higher trophic levels at elevated CO_2 without corresponding export increase	Trophic transfer and particle export can diverge; interpretation depends on budget boundaries

Note: Stoichiometric ratios are interpreted according to the definitions used in each study. Differences in species, treatment ranges, and methods preclude treating these studies as directly poolable replicates.

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3.2 Temporal coordination of cell division and silica deposition

Elevated CO_2 may reduce the energetic cost of carbon acquisition in some diatoms, but responses of cell division, silica deposition, and cellular quotas still require separate measurements(Wu et al., 2014). Regulation of carbon-concentrating mechanisms (CCMs) offers a possible explanation, although faster growth or a lower Si:C ratio alone does not identify the route of energy reallocation. Different siliceous structures are formed at different points in the cell cycle, making the timing of division relative to deposition relevant to quota changes(Claquin et al., 2002).

Li, W. et al. (2019) gradually increased pCO_2 from 180 to 1000 µatm in cultures of Thalassiosira pseudonana and T. weissflogii. Growth accelerated over the lower to intermediate part of the gradient while cellular BSi and POC both decreased; several metrics stabilized at higher CO_2. This demonstrates that proliferation and cellular content can respond asynchronously. Because the gradient included levels below the modern background, however, its overall trend cannot be interpreted as the response from present-day to future acidification. Gradual and abrupt treatments also differ in exposure history and adjustment time(Li et al., 2019). Continuous-culture experiments by Claquin et al. (2002) showed that light, nutrient limitation, and the cell cycle influence silicon, carbon, and nitrogen allocation, providing background evidence for interpreting the temporal coordination of division and deposition.

3.3 Light, nutrient supply, and species functional traits

Light can modify silicification responses to elevated CO_2, and silica content and deposition do not always change in the same direction. FitzGerald-Lowry et al. (2025) combined pCO_2 levels of 350 and 800 µatm with irradiances of 20 and 200 µmol photons m^{-2} s^{-1}. In T. weissflogii, surface-area-normalized BSi content was higher under low light and elevated CO_2, whereas elevated CO_2 inhibited PDMPO-based silica deposition during the labeling period under high light. Responses across irradiance treatments therefore depend on the endpoint and do not support a general claim that acidification thins diatom frustules under high light. The study indicates a relationship between photochemical status and silicification, but the causal pathway requires targeted testing.

Nutrient supply also influences the relationship between silica deposition and division. In an upwelling environment, McNair et al. (2018) found that some diatoms reduced silicon investment per unit surface area under limited silicon supply while maintaining proliferation, indicating resource-dependent

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plasticity in cellular silicon allocation. Such evidence helps interpret background conditions but is not itself an acidification response. Multifactor experiments on a large centric diatom by Qu et al. (2018) further showed that CO_2, temperature, and nitrate availability jointly affected silica content and Si:C, with interactions modifying response magnitudes. Nutrient and temperature conditions are consequently necessary explanatory variables when comparing acidification studies.

In cross-species syntheses, a broader suite of functional traits—including cellular morphology, carbon acquisition mechanisms, and baseline silicon demand—fundamentally dictates the methodological basis and normalization metrics for comparing acidification responses. Cell size often covaries with surface-area-to-volume ratio, morphology, carbon acquisition, and baseline silicon requirement, so size alone cannot predict the acidification sensitivity of silicon quotas(Wu et al., 2014). Results normalized to cell number, volume, or surface area should be compared separately to distinguish size changes from changes in silicon investment per unit structure. The silicon requirement and silicification traits of P. tricornutum differ from those of most conventionally silicified diatoms(Martino et al., 2007). Under the experimental conditions described above, its silicification signal was near or below the detection limit; the results should initially be confined to the tested species and conditions, with extension to other taxa requiring validation(Fitzgerald-Lowry et al., 2025). Cross-species synthesis should therefore rely on actual silicon requirements and measurable functional traits rather than taxonomy or size as proxies for response direction.

3.4 Silicon–carbon allocation and response persistence

Under ocean acidification, shifts in seawater carbonate chemistry directly modulate the intracellular allocation between biogenic silica and particulate organic carbon in marine diatoms. Mejía et al. (2013) examined relationships among Si:C, seawater pH, and carbon acquisition in two Thalassiosira species, providing evidence for allocation responses. Xu et al. (2023) used elevated CO_2 treatments of 1000 and 2000 μatm in short- and long-term multifactor cultures of Pseudo-nitzschia multiseries. Cellular BSi decreased with increasing pCO_2, whereas carbon-content responses varied with culture conditions. In some short-term treatments, decreased BSi and increased POC jointly lowered Si:C. BSi responses observed in both 30-day and 800-day cultures support some persistence of silicon allocation changes, although interpretation must retain the effects of temperature, acidification magnitude, and culture history(Xu et al., 2023).

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Although phenotypic responses may remain stable over extended culture periods, the observed persistence of altered silicon allocation does not inherently demonstrate evolutionary adaptation or heritable genetic change. Distinguishing reversible acclimation, selection within cultured populations, and heritable change requires common-garden assays, recovery cultures, or evolutionary comparisons, while accounting for changes in cell size and culture conditions over time(Jin et al., 2022). Taken together, existing studies show no uniform direction of acidification effects on cellular silicon allocation or deposition(Bach and Taucher, 2019). Variation partly reflects resources, species traits, exposure history, and measurement endpoints, and quotas need not track production rates. Extending cellular responses to community silica production requires the abundance and production contribution of each taxon(Tréguer et al., 2018; Bach and Taucher, 2019).

4 Ocean acidification effects on silica dissolution and silicon resupply

4.1 pH effects and the kinetics of biogenic silica loss

BSi dissolution converts particulate silicon to dissolved silicon (DSi) and is an important component of silicon recycling(Tréguer et al., 2021). Within pH ranges relevant to natural seawater, lower pH can slow chemical dissolution at silica surfaces, providing a kinetic basis for changes in preservation under acidification(Hervé et al., 2012; Taucher et al., 2022). Comparisons of materials and media by Cappelle et al. (2008) showed effects of both salinity and pH. Van Cappellen et al. (2002) also identified surface properties, material composition, and the degree of undersaturation with respect to silica as important controls. The pH effect should therefore be evaluated within the conditions set by temperature, ionic composition, DSi concentration, and material reactivity(Van Cappellen et al., 2002; Cappelle and Behrends, 2008).

Warming generally accelerates dissolution and may act in the opposite direction to decreasing pH, with the net effect depending on treatment magnitude, material, and environment(Van Cappellen et al., 2002). Lower DSi generally implies greater undersaturation, but initial rates also depend on surface reactivity and organic coatings. Rates should be distinguished from cumulative losses: the amount dissolved over a given period depends on reaction kinetics, removal of dissolution products, and environmental changes. For sinking particles, cumulative loss during a finite transit time is more relevant than dissolution extent after prolonged static incubation alone(Martino et al., 2007; Moriceau et al., 2014).

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4.2 Effects of initial particle state on biogenic silica dissolution

Material origin and pretreatment alter silica exposure and solid–liquid exchange conditions. Purified frustules, dead diatom remains, and natural aggregates represent different particle states(Loucaides et al., 2012). Purified material helps isolate chemical effects, but removal of organic components and cleaning may alter surface properties(Van Cappellen et al., 2002; Hervé et al., 2012; Loucaides et al., 2012). Remains and aggregates more closely resemble natural particles, yet differ in organic coverage, damage, and composition(Bidle and Azam, 1999; Martino et al., 2007). Dissolution comparisons should report these initial properties rather than applying pH relationships from purified materials directly to intact natural particles(Moriceau et al., 2014).

The enzymatic degradation of protective organic coatings directly regulates the physical contact between seawater and the underlying silica frustule, thereby modulating biogenic silica (BSi) exposure and dissolution kinetics. Bidle and Azam (1999) found that marine bacterial degradation of diatom organic components accelerated silicon regeneration. This provides evidence for a biological control but does not directly establish an acidification response or show that coating degradation is the sole rate-limiting step for all particles.

Concentration distributions and exchange within aggregates further influence overall dissolution. Reactive transport modeling by Moriceau et al. (2014) showed that internal DSi accumulation and restricted diffusive exchange can alter the local driving force for dissolution, causing aggregate responses to depart from expectations for a homogeneous water body. This is not equivalent to internal pH buffering. External pH effects still require evaluation in relation to particle size, porosity, and exchange conditions. Particle formation environments may also influence subsequent losses through initial properties; these legacy effects should be distinguished from the direct effects of the dissolution environment.

4.3 Joint effects of dissolution kinetics and sinking time on silica preservation

In the subsurface water column, the cumulative preservation of biogenic silica (BSi) at any specified depth is governed by the dynamic interplay between chemical dissolution kinetics and physical particle transport. Other conditions being similar, slower sinking extends exposure and may increase cumulative loss, whereas slower dissolution increases retention over the same transit time. Inferring flux changes

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from chemical rates therefore requires simultaneous constraints on sinking time and particle reactivity(Van Cappellen et al., 2002; Loucaides et al., 2012).

Across five mesocosm experiments, Taucher et al. (2022) found that Si:N in sinking particles increased by an average of 17 ± 6% under elevated CO_2, without a consistent change in suspended particles, and identified reduced BSi dissolution at lower pH as a plausible explanation. This supports a change in exported particle composition, but Si:N cannot replace Si:C or independently separate silicon and organic carbon losses. Modeling by Moriceau et al. (2007) showed that particle formation and transport affect silicon flux profiles. As related evidence, Suessle et al. (2026) observed lower exported BSi:POC at higher pH in a North Sea alkalinity-enhancement mesocosm experiment, without a systematic correspondence between the ratio and sinking velocity. Alkalinity enhancement changes TA and is not a strict reverse treatment of CO_2-driven acidification. Together, these studies indicate that silica preservation and particle motion require independent measurement to explain their combined effects on flux(Moriceau et al., 2007; Taucher et al., 2022; Suessle et al., 2026).

4.4 Regeneration depth and replenishment of surface silicon inventories

Silicon regenerated within the euphotic zone is available for local reuse, whereas silicon regenerated at depth requires physical transport back to the surface. If slower dissolution allows more particulate silicon to leave the euphotic zone and mixing, upwelling, or external inputs are insufficient, surface resupply may decline(Taucher et al., 2022; Brzezinski et al., 2024). A post-bloom silicon budget in the North Atlantic showed that storm-driven entrainment and silica dissolution jointly supported subsequent production (Brzezinski et al., 2024); the dissolution contribution was inferred from the budget rather than measured directly. Recycling therefore needs to be evaluated together with physical replenishment.

Taucher et al. (2022) incorporated pH-dependent dissolution into an Earth system model and projected silicon redistribution to the deep ocean and a decrease in global diatom biomass by 2200 under the specified scenarios. This result depends on parameters governing production, particle reactivity, and circulation and does not represent an observed global trend. Strong external inputs or physical transport may buffer resupply changes, but whether they offset reduced recycling depends on the balance between supply and production demand. Stronger stratification alone likewise does not imply silicon depletion.

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Overall, the translation of lower-pH dissolution kinetics into particle preservation depends on initial particle state and transit time(Van Cappellen et al., 2002; Moriceau et al., 2007; Taucher et al., 2022). Extending that response to surface resupply additionally requires particle inventories, regeneration depth, and physical replenishment(Moriceau et al., 2014; Tréguer et al., 2021; Brzezinski et al., 2024). With comparable inventories and transport conditions, slower dissolution may reduce silicon regeneration within the euphotic zone, but the actual regeneration flux still depends on particle abundance and residence time(Moriceau et al., 2014; Brzezinski et al., 2024). Short-term preservation and long-term supply should therefore be assessed separately(Moriceau et al., 2014; Bach and Taucher, 2019).

5 Community composition and particle transformations in carbon export

Whether the production and dissolution responses described above translate into carbon export also depends on community production contributions and particle formation, transformation, and transport. The following sections examine these links at community and particle scales.

5.1 Taxon contributions to community silicon and carbon production

Community BSi production depends on the abundance and per-cell production rate of each taxon. Volume-normalized rates should be weighted by the corresponding biovolume so that abundance and rates share a consistent basis. Natural-community experiments by Petrou et al. (2019) and taxon-resolved observations by McNair et al. (2018) indicate that differences in silicification among taxa affect community responses. Changes in community-average Si:C can arise from within-species allocation or taxonomic replacement, with their production consequences depending on the actual contributions involved. Increased relative diatom abundance can also reflect declines in other groups, making absolute abundance and production measurements necessary. Size and chain formation are useful explanatory traits, but the evidence does not justify assuming that acidification necessarily favors either smaller or larger taxa(Wu et al., 2014; Bach and Taucher, 2019).

5.2 Silica allocation and whole-particle sinking

Cellular silicon quotas, the mass fraction of BSi, and frustule structure have different physical meanings(Miklasz and Denny, 2010). Sinking also depends on particle size, shape, density, and porosity(Miklasz and Denny, 2010; Raven and Waite, 2004). Stokes' law provides an approximation for ideal spherical particles at low Reynolds numbers, but its use for chains and irregular aggregates requires

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evaluating geometry and flow conditions and cannot replace sinking measurements(Miklasz and Denny, 2010). Living-cell physiology and compositional losses after death can also change density, so BSi content does not directly determine buoyancy(Raven and Waite, 2004). Bach et al. (2016) found that bloom-aggregate sinking velocity did not increase monotonically with opal ballast and that porosity influenced this relationship. Testing whether acidification changes sinking through silica allocation requires paired measurements of composition, size, density or porosity, and velocity, with living cells distinguished from derived particles(Bach et al., 2016; Raven and Waite, 2004; Miklasz and Denny, 2010).

5.3 Context-dependent effects of aggregation and food-web processing

Aggregation changes size, porosity, and organic composition and can modify how cellular responses propagate to particle transport(Thornton, 2002). Sticky substances such as transparent exopolymer particles (TEP) participate in aggregation, but an increase in their abundance does not determine the direction of the sinking response(Mari et al., 2017). In controlled experiments using the coastal diatom T. weissflogii, Seebah et al. (2014) observed that alterations in extracellular polymer production under combined warming and ocean acidification were decoupled from subsequent increases in particle aggregation and sinking velocities. Polymer production, particle formation, and transport therefore require separate assessment. This multifactor result informs context dependence rather than establishing a general effect of acidification alone.

Food-web processing—encompassing grazing, repackaging, and fecal pellet formation—provides an alternative transport pathway that alters the vertical fate of primary production inputs(Steinberg and Landry, 2017). Whether changes in cell-wall defenses affect carbon export through grazing remains to be tested with linked measurements. Fecal pellets can support rapid transport but may fragment and degrade in the water column. Boxhammer et al. (2018) found that elevated CO_2 enhanced organic matter transfer to higher trophic levels without a corresponding increase in export, demonstrating that trophic transfer and particle export need not respond together. Aggregation and food-web processes are thus conditional controls whose effects depend on particle properties, consumer activity, and losses during transit.

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5.4 Spatial and temporal correspondence between particle sources and export fluxes

Regional fluxes depend on particle abundance, composition, and origin as well as sinking velocity(Buesseler, 1998). Controlled cultures resolve changes in particle properties, mesocosms connect community responses to shallow particle collection, and field observations constrain natural water-column transfer(Bach and Taucher, 2019). Their sampling boundaries and represented processes differ. Comparing production and export therefore requires establishing the spatial and temporal context of each measured flux(Buesseler, 1998; Bach and Taucher, 2019).

Deep particles may be separated from surface production by sinking lags and source-region displacement. Spring observations in the subpolar Southern Ocean showed faster attenuation of BSi than POC flux in mesopelagic waters, providing field evidence of differential silicon and carbon transfer(Williams et al., 2025). Because acidification was not manipulated, this study constrains transport under natural conditions rather than establishing an acidification effect.

The evidence reviewed here shows that community production contributions, particle composition, and export pathways jointly affect the transmission of production signals(Tréguer et al., 2018). Individual cell or particle properties alone do not explain regional fluxes. Linking these processes to acidification requires observations with corresponding sources and matched time windows, while other process studies help formulate and test possible mechanisms of transmission(Tréguer et al., 2018; Williams et al., 2025).

6 Diagnosing silicon–carbon coupling across stages and developing conditional predictions

The preceding sections synthesize evidence on silica production, dissolution, and particle transport. Here we examine how these processes jointly determine silicon and carbon fluxes: first by identifying stages of decoupling, then by evaluating production–preservation compensation through budget decomposition, and finally by considering the conditions under which silicon-resupply feedbacks affect carbon export and long-term sequestration.

6.1 Stage dependence and mechanisms of silicon–carbon decoupling

At the production stage, silicon–carbon relationships involve both cellular element allocation and absolute production rates(Mejía et al., 2013). Asynchronous responses of cellular BSi, POC, and Si:C frequently occur in controlled cultures (Mejía et al., 2013; Xu et al., 2023), yet shifts in cellular quotas alone do not establish changes in community production rates. Diagnosing production-stage decoupling

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thus requires paired measurements of silica deposition and carbon assimilation(Mejía et al., 2013). Furthermore, community-scale interpretations must distinguish within-species physiological adjustments from taxonomic replacement(Mcnair et al., 2018). A lower silicon investment per cell can coexist with stable or even elevated community silica production, while changes in average Si:C may simply reflect shifts in producer composition. Consequently, cross-scale diagnosis requires identifying whether observed responses stem from per-cell rates, taxon abundances, or their combination, rather than comparing the directional shift of a single metric.

As primary production signals transit into sinking particles and move below the euphotic zone, selective export, source mixing, and differential losses further modify elemental ratios(Christina and Passow, 2007). Intact cells, empty frustules, and cellular debris enter the sinking pool in proportions distinct from surface standing stocks, while aggregation, food-web repackaging, and mixing with non-diatom organic carbon systematically shift particle BSi:POC away from cellular Si:C(Bach et al., 2016). A declining cellular ratio paired with a stable export ratio suggests selective export or compensating processes, whereas a stable cellular ratio alongside a shifting export ratio points to altered particle sources, export pathways, or surface losses(Boxhammer et al., 2018). Below the euphotic zone, differential attenuation further decouples these signals: biogenic silica dissolution and organic carbon remineralization operate under distinct kinetic controls governed by transit time and environmental conditions(Van Cappellen et al., 2002). As field observations by Williams et al. (2025) demonstrate, the presence of heavy silica ballasting does not guarantee synchronous vertical transfer of silicon and carbon. Therefore, silica preservation gains under ocean acidification must be evaluated independently of carbon remineralization before inferring enhanced carbon export efficiency(Taucher et al., 2022).

This synthesis yields a fundamental methodological imperative: identical flux ratios at the deep endpoint can conceal major discrepancies in intermediate processes, whereas an altered endpoint ratio alone cannot pinpoint the precise stage of decoupling(Christina and Passow, 2007; Tréguer et al., 2018). To resolve these ambiguities and accurately quantify the net climate feedback of the diatom-mediated biological pump, future research must systematically connect all three stages within unified spatial and temporal frameworks(Bach and Taucher, 2019). Specifically, studies should pair taxon-resolved rate measurements of carbon assimilation and silica deposition at the surface(Mcnair et al., 2018; Petrou et al., 2019), track physical aggregation and trophic repackaging during export(Bach et al., 2016;

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Boxhammer et al., 2018), and independently constrain subsurface organic carbon remineralization against biogenic silica dissolution kinetics(Van Cappellen et al., 2002; Loucaides et al., 2012). Only by integrating absolute fluxes with relative elemental shifts across matched source waters, standardized observation windows, and consistent reference depths can we distinguish short-term particle preservation from long-term oceanic carbon sequestration under ongoing ocean acidification(Taucher et al., 2022; Brzezinski et al., 2024).

6.2 Budget decomposition and conditional attribution of silicon and carbon fluxes

To organize evidence across stages, particulate flux at a specified depth can be decomposed into the product of production, export efficiency, and transfer efficiency(Buesseler, 1998). When source regions correspond, time windows are matched, the budget is approximately steady, and inventory changes and lateral inputs are negligible, the flux of element i at depth z can be written as:

$$F_i(z) = P_i \times \varepsilon_i \times T_i(z) \quad (1)\text{(Christina and Passow, 2007)}$$

Here, P_i is the areal production rate integrated over the euphotic zone in the source region; $\varepsilon_i = F_i(z_0)/P_i$ is the fraction of production exported as particles across reference boundary z_0; and $T_i(z) = F_i(z)/F_i(z_0)$ is the fraction of that flux retained between z_0 and z(Boyd and Trull, 2007). All components should use consistent elemental units and time bases, and the operational definition of carbon production should be specified(Laws et al., 2000). This identity is a diagnostic relationship based on component definitions, not an independent predictive model(Dunne et al., 2005). Attribution requires independent observations rather than reconstruction of all components from the terminal flux.

For silicon and carbon with corresponding sources and a common molar basis, this gives:

$$\frac{F_{Si}(z)}{F_C(z)} = \frac{P_{Si}}{P_C} \times \frac{\varepsilon_{Si}}{\varepsilon_C} \times \frac{T_{Si}}{T_C} \quad (2)\text{(Nelson et al., 1995)}$$

Equation (2) decomposes the terminal flux ratio into the production ratio, relative export efficiency, and relative transfer efficiency(Tréguer et al., 2018). Paired production measurements constrain the first term, particle formation and selective export constrain the second, and paired fluxes at multiple depths constrain the third(Brzezinski et al., 2024; Williams et al., 2025). Cellular quota ratios cannot replace production-rate ratios, and total POC flux cannot be treated as diatom-derived carbon flux without source attribution(Bach et al., 2016; Mcnair et al., 2018). With total production and fluxes from mixed

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communities, the framework describes community-scale elemental budgets(Taucher et al., 2022). Applying it to diatom-mediated carbon transport requires additional constraints on the diatom-derived organic carbon contribution(Smetacek, 1985).

A given flux-ratio change can arise from different combinations. Higher BSi:POC may reflect relatively greater silicon production, selective export, or improved relative silica preservation, but it may also result from increased POC loss(Christina and Passow, 2007). Attribution should therefore begin with absolute silicon and carbon fluxes before evaluating changes in the production, export, and transfer ratios(Buesseler, 1998; Tréguer et al., 2018). For a single element, the flux response in an acidification treatment relative to its control is determined by the product of the relative changes in the three components(Taucher et al., 2022). This treatment-to-control ratio differs from the silicon-to-carbon ratio in Eq. (2). If export efficiency is unchanged, flux at the target depth can be maintained or increased only if the product of the relative production and transfer-efficiency changes is at least 1(Petrou et al., 2019). If export efficiency decreases, a larger preservation gain is required(Williams et al., 2025). Reduced silicon production and slower dissolution loss can thus coexist without necessarily offsetting one another(Taucher et al., 2022; Petrou et al., 2019).

Compensation between production and preservation is fundamentally depth-dependent, as enhanced preservation below z_0 cannot retroactively change the flux already exported across z_0 but can significantly modify the amount reaching greater depths(Taucher et al., 2022; Moriceau et al., 2007). Consequently, reduced export at the base of the euphotic zone may coexist with a smaller reduction, or even an increase, in deeper flux relative to the control, depending on the balance between production and transfer responses (Fig. 2a). Such an increase represents a treatment effect at a specified depth, rather than an increase in flux with depth. Moreover, similar silicon-to-carbon flux-ratio responses can arise from different changes in production or transfer (Fig. 2b). Silicon and carbon therefore require separate evaluation; silica preservation parameters alone cannot predict carbon flux (Williams et al., 2025). Application of this framework requires production, export, and transfer measurements with corresponding sources and time windows (Table 3), rather than combining cellular quotas, dissolution rates, and trap ratios from unrelated systems. Where inventory changes, lateral transport, or source-region displacement are appreciable, the budget must include these contributions (Buesseler, 1998; Christina and Passow, 2007). Where sinking

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lags are important, production and collection windows should be aligned or time delays represented explicitly.

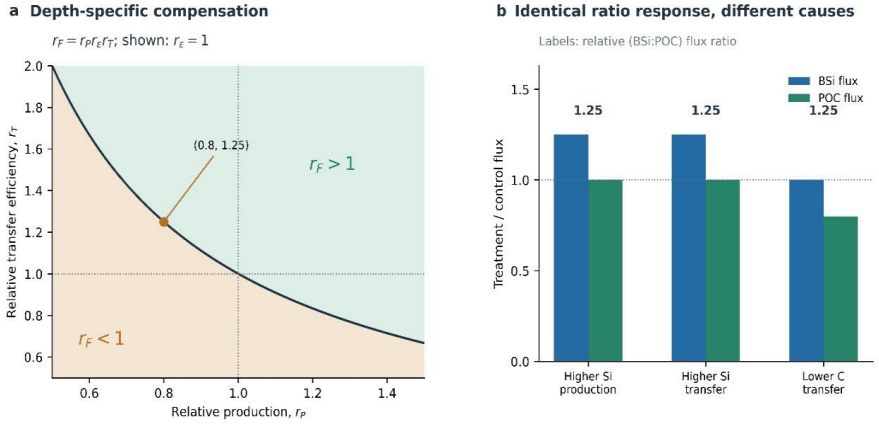


Figure 2. Production–transfer compensation and alternative drivers of silicon-to-carbon flux-ratio responses.(Both panels present analytical illustrations rather than observations. Export efficiency is held constant in (a); only the indicated component varies in each scenario in (b))

Table 3. Conditional interpretation and key evidence for responses across stages.

Response scenario	Key question	Conditional interpretation	Required evidence
Lower cellular Si:C	Does allocation change correspond to production decoupling?	Quota ratios alone do not determine community production or carbon export; independent changes in silicon and carbon production and taxon contributions are needed	Paired production rates; cell abundance and size; taxon contributions
Reduced silicon production and slower dissolution loss	Can preservation gains offset lower production?	Flux at a specified depth depends on the product of relative changes in production, export efficiency, and transfer efficiency	Matched production measurements; reference export flux; BSi fluxes at multiple depths
Changed community-average Si:C	What are the contributions of within-species adjustment and taxonomic replacement?	Community production responses and dominant sinking taxa may differ; export direction requires independent testing	Taxon- or size-resolved production; elemental allocation; sinking-particle sources

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Response scenario	Key question	Conditional interpretation	Required evidence
Enhanced silica preservation and potentially deeper regeneration	Does subsequent silicon resupply decline?	If regeneration deepens and physical replenishment is insufficient, subsequent diatom production may be limited; the carbon response is not uniquely determined	Silica losses and DSi profiles; physical replenishment; long-term production and flux observations

6.3 Long-term silicon-resupply feedbacks and limits on carbon sequestration inference

Short-term changes in silica preservation may affect long-term production through recycling(Tréguer et al., 2021; Taucher et al., 2022). The modeling evidence discussed in the section on silica dissolution indicates that slower dissolution can deepen regeneration and reduce surface silicon supply under specified scenarios (Taucher et al., 2022). The critical issue is not preservation alone, but whether silicon regenerated at depth returns to the euphotic zone rapidly enough to meet production demand(Van Cappellen et al., 2002; Loucaides et al., 2012). External inputs, mixing, and upwelling may buffer this effect, and feedback strength requires joint assessment of silicon budgets and physical replenishment(Brzezinski et al., 2024). The consequences for carbon export involve an additional ecological step: producer replacement(Tréguer et al., 2018; Bach and Taucher, 2019). Other taxa may compensate for total carbon production when diatom contributions decline, but their export and transfer efficiencies need not be equivalent. Maintaining total production therefore does not establish stable carbon export, and declining diatom production does not imply a proportional decline in export(Christina and Passow, 2007; Boxhammer et al., 2018). The carbon production, export, and transfer components in Eq. (1) must be reassessed rather than extrapolating silicon-supply changes directly to carbon flux(Buesseler, 1998).

Beyond the initial export of organic matter from the surface ocean, a fundamental conceptual distinction must be drawn between upper-ocean carbon export and true long-term sequestration.(Christina and Passow, 2007). POC flux at the base of the euphotic zone measures the rate at which particulate carbon leaves surface waters, whereas deeper flux describes subsequent transfer(Buesseler et al., 2007). Long-term sequestration additionally depends on the water masses receiving remineralized carbon, circulation pathways, and the time before renewed atmospheric exchange(Devries et al., 2012). Carbon converted from POC to DIC may remain isolated from the atmosphere for long periods, so deep particulate flux is not equivalent to the amount sequestered. Silicon regeneration and carbon remineralization need not

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occur at corresponding depths, and deep silicon accumulation alone cannot establish carbon isolation time(Williams et al., 2025). Seafloor burial additionally requires accounting for subsequent sedimentary losses(Ragueneau et al., 2000). The constraints that silicon cycling places on carbon export are therefore process- and scale-dependent(Taucher et al., 2022). Short-term assessment requires matched production and flux observations, while long-term feedbacks also depend on resupply, community replacement, and physical transport(Brzezinski et al., 2024). The diagnostic framework specifies these conditions and testable process combinations rather than assigning a carbon-sink response from a single silicon metric(Bach and Taucher, 2019).

7 Research priorities for linking silicon-cycle responses to carbon export

The principal gaps identified above concern links between stages: whether cellular allocation tracks production, whether production conditions alter subsequent particle losses, and whether local responses extend to water-column fluxes and long-term resupply. Future experiments and observations should address these gaps by testing how changes in production and particle losses jointly affect elemental fluxes and silicon resupply.

7.1 Linking production and particle-loss experiments to separate effects

At the upper-ocean production stage, rigorously diagnosing elemental decoupling requires paired and temporally synchronized rate measurements of silica deposition and carbon assimilation rather than relying solely on cellular quotas(Petrou et al., 2019; Xu et al., 2023). Silicon and carbon production should be measured under the same treatments and matched time windows, alongside cell abundance, size, division state, and BSi and POC quotas(Bach and Taucher, 2019; Xu et al., 2023). Silicon isotope tracers, PDMPO, and carbon assimilation methods differ in integration time and measured processes; calibration and normalization should be reported, and supplementary measurements such as cell-cycle observations selected for specific hypotheses(Mcnair et al., 2015). Natural communities additionally require the production contributions of dominant taxa or size fractions(Petrou et al., 2019). Paired rates test whether production responses diverge, whereas quotas and taxon contributions explain the origin of Si:C changes and test whether compositional and production responses correspond(Mejía et al., 2013; Xu et al., 2023).

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To systematically connect surface biomineralization to subsurface silica recycling, utilizing biogenic particles of common origin is essential for distinguishing formation legacy effects from direct environmental controls on dissolution.(Van Cappellen et al., 2002; Loucaides et al., 2012). Crossing growth and subsequent dissolution conditions allows comparison of particles with different growth histories in the same water conditions and particles of common origin under different dissolution conditions(Moriceau et al., 2007; Taucher et al., 2022). This separates formation legacy effects from direct environmental effects and tests their interaction(Bidle et al., 2002). Initial BSi, POC, size, frustule integrity, and pretreatment should be documented, with further characterization selected according to the mechanistic hypothesis(Bidle and Azam, 1999; Moriceau et al., 2014).

Beyond single-element budgets, accurately resolving subsurface attenuation requires the simultaneous, coupled tracking of both biogenic silica dissolution and organic carbon loss pathways(Van Cappellen et al., 2002; Loucaides et al., 2012). DSi release rates and particulate BSi decline can support a silicon budget(Nelson et al., 1995; Ragueneau et al., 2000). POC decline, however, must be partitioned among conversion to dissolved organic carbon (DOC), remineralization, and changes in the sampled particle pool due to settling, size changes, or sampling cutoffs(Steinberg and Landry, 2017). Fragmentation itself does not mineralize carbon but alters transport and subsequent degradation. Quantifying remineralization requires complementary DIC production or respiration measurements rather than POC decline alone(Boyd and Trull, 2007). Controlling or recording exposure duration can test whether initial differences are amplified or reduced during subsequent losses and provide evidence for production–preservation compensation using material of common origin(Moriceau et al., 2007; Taucher et al., 2022).

7.2 Testing water-column fluxes and long-term feedbacks across scales

Field validation should pair absolute BSi and POC fluxes and report sampling depths, time windows, and flux ratios(Buesseler et al., 2007; Christina and Passow, 2007). Multiple depths allow transfer efficiencies to be estimated and initial export differences to be tested against subsequent losses(Boyd and Trull, 2007; Taucher et al., 2022). Attenuation fits should specify the depth range, functional assumptions, and uncertainty rather than assume identical curves for silicon and carbon(Williams et al., 2025). Attribution to acidification additionally requires controlling or constraining covariates such as temperature, nutrients, and physical transport(Bach and Taucher, 2019). Paired elemental fluxes identify responses but do not alone establish acidification causality(Riebesell and Gattuso, 2015).

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Flux measurements should be combined with particle-source and transport-history information(Boyd and Trull, 2007; Buesseler et al., 2007). Distinguishing cells, aggregates, fecal pellets, and debris helps identify dominant export pathways, while trapping biases, sinking lags, and lateral transport require assessment or correction(Steinberg and Landry, 2017; Buesseler et al., 2007). Even profiles at multiple depths cannot readily attribute changes to concurrent production when sources and time windows are mismatched(Boyd and Trull, 2007; Williams et al., 2025). Their purpose is therefore to establish a transport budget with corresponding sources, not simply to increase the number of sampling depths(Buesseler, 1998; Christina and Passow, 2007).

Ecological representativeness determines the range over which these relationships apply(Tréguer et al., 2018).Studies should include diatoms with clear silicon requirements and different sizes and morphologies, together with validation in natural communities. Taxonomy and size are not substitutes for response measurements(Bach and Taucher, 2019).Light, temperature, and nutrient combinations should address specific hypotheses, while complete reporting of carbonate chemistry, nutrient conditions, culture methods, and exposure history helps separate species traits from experimental effects(Wu et al., 2014; Li et al., 2019).

Experimental parameters can support model-based hypothesis tests and sensitivity analyses(Muller and Nisbet, 2014).Regional or global long-term predictions additionally require evaluation of scale applicability and uncertainty constrained by calibration and independent data(Zurell et al., 2020). Silicon-resupply feedbacks should link regeneration depth, mixing, upwelling, and external inputs to determine whether preservation changes are sufficient to alter surface supply(Taucher et al., 2022; Brzezinski et al., 2024). Carbon export and sequestration assessments also need producer replacement, carbon remineralization distributions, and circulation(Tréguer et al., 2018). Testing experiments, field observations, and models against one another can establish which relationships extend across scales and which remain specific to particular species or environments(Bach and Taucher, 2019).

8 Conclusions

Ocean acidification affects diatom silicon cycling through cellular silica formation, particle transport, and recycling. Existing evidence supports species- and environment-dependent production responses, while lower pH can slow silica dissolution under some conditions. Reduced production and improved

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preservation can coexist. Net flux at a specified depth depends jointly on production, export efficiency, and transfer efficiency, and compensation depends on their relative changes and the depth considered.

Silicon–carbon relationships are stage-dependent. Cellular allocation, community production, mixed-particle composition, and depth-specific fluxes describe different processes, with taxon contributions, selective export, and differential losses altering their correspondence. Similar terminal flux ratios can conceal different intermediate processes. Budget decomposition provides a diagnostic means of distinguishing such scenarios, but its use requires independent observations of the components. Enhanced short-term silica preservation may also accompany reduced long-term surface resupply; its consequences for carbon export depend on physical replenishment, producer replacement, and transport pathways.

Silicon-cycle metrics constrain diatom-mediated carbon transport but do not alone determine the direction of carbon export or long-term sequestration. Export assessment requires silicon and carbon fluxes matched in source, depth, and time, together with particle-loss evidence. Long-term sequestration additionally requires the location of carbon remineralization, circulation, and atmospheric isolation times. Linking paired production measurements, particle transformations using material of common origin, and fluxes at multiple depths is a research priority for testing compensation and silicon–carbon decoupling across stages.

Code and data availability

All data sources are cited in the text. No new data is presented.

Author contributions

Luo Qiaoqi and Zhou Qianqian drafted the first version of the text. Zhang Yueping and Wen Shuting revised the first draft. The manuscript was then revised and edited with comments from all authors.

Competing interests

The authors declare that they have no conflict of interest..

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