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Submarine groundwater discharge impacts on coastal nutrient biogeochemistry

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Abstract | Submarine groundwater discharge (SGD) links terrestrial and marine systems, but has often been overlooked in coastal nutrient budgets because it is difficult to quantify. In this Review, we examine SGD nutrient fluxes in over 200 locations globally, explain their impact on biogeochemistry and discuss broader management implications. SGD nutrient fluxes exceed river inputs in ~60% of study sites, with median total SGD fluxes of 6.0 mmol m^{-2} per day for dissolved inorganic nitrogen, 0.1 mmol m^{-2} per day for dissolved inorganic phosphorus and 6.5 mmol m^{-2} per day for dissolved silicate. SGD nitrogen input (mostly in the form of ammonium and dissolved organic nitrogen) often mitigates nitrogen limitation in coastal waters, since SGD tends to have high nitrogen concentrations relative to phosphorus (76% of studies showed N:P values above the Redfield ratio). It is notable that most investigations do not distinguish saline and fresh SGD, although they have different properties. Saline SGD is a ubiquitous, diffuse pathway releasing mostly recycled nutrients to global coastal waters, whereas fresh SGD is occasionally a local, point source of new nutrients. SGD-derived nutrient fluxes must be considered in water quality management plans, as these inputs can promote eutrophication if not properly managed.

Submarine groundwater discharge
The flow of water through continental margins from the seabed to the coastal ocean, with length scales of metres to kilometres, regardless of fluid composition or driving force.

Excessive anthropogenic nutrient inputs drive widespread eutrophication in global coastal waters[1,2]. Despite large investments to reduce nutrient inputs from wastewater and urban and agricultural runoff[3,4], coastal eutrophication and hypoxia continue intensifying worldwide, even where these conventional nutrient sources have decreased[5–7]. Alternative nutrient sources and pathways such as submarine groundwater discharge (SGD) also contribute to persistent water quality issues in the coastal ocean[2]. Pioneering local-scale research in the 1980s revealed extremely high nitrate concentrations in fresh coastal groundwater in Western Australia[8], where fresh SGD fluxes exceeded river nitrate loads and explained ~50% of local primary productivity[9].

Quantitative investigations have since revealed that SGD delivers nutrients and affects water quality in diverse coastal ecosystems, such as estuaries[10,11], coral reefs[12–14], coastal embayments and lagoons[15–17], intertidal wetlands such as mangroves[18,19] and saltmarshes[20–22], the continental shelf[23–25] and even the global ocean[26]. Nevertheless, nutrient fluxes via SGD remain overlooked in most coastal nutrient budgets and water quality models[27].

SGD occurs on timescales of hours to millennia, spatial scales of metres to kilometres and as a low flux over large areas, making it challenging to quantify[28] and, thus, sometimes misinterpreted. As a result, SGD has often been considered a nutrient source to coastal waters only after the 'standard' pathways, such as atmospheric deposition, rivers and sewage, are ruled out.

SGD is ubiquitous in sandy, muddy and rocky shorelines and represents a combination of fresh and saline groundwater interacting with coastal surface waters[29,30] (FIG. 1). Fresh SGD is driven by a positive terrestrial hydraulic gradient and emerges from shallow or deep aquifers intersecting the shoreline[31,32] carrying natural and anthropogenic nutrients from land. Saline SGD (sometimes also referred to as seawater circulation in sediments) is defined as the advection of saline groundwater through intertidal zone sediments and/or across the coastal seafloor, and/or advective porewater exchange on scales larger than one metre[28,30,33]. Saline groundwater also mixes with fresh SGD owing to the interactions of tides and waves, density-driven flow and dispersion processes[34], with the resulting brackish SGD transporting both land-derived

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Key points

- Submarine groundwater discharge (SGD) is an essential component of biogeochemical budgets. Fresh SGD is a source of new nutrients, whereas saline SGD often releases recycled nutrients from sediments.
- SGD-derived nitrogen fluxes exceeded river inputs in ~60% of the reviewed cases and usually counteracted nitrogen limitation in coastal waters due to high N:P exceeding the Redfield ratio.
- Positive impacts of SGD on coastal ecosystems include enhanced coral calcification, primary productivity, fisheries, denitrification and pollutant attenuation.
- Negative impacts of SGD include eutrophication, algal blooms, deoxygenation and localized ocean acidification, depending on site-specific conditions.
- Considering SGD is crucial to reach the United Nations Sustainable Development Goals pollution targets. The US Supreme Court decision to consider SGD under the Clean Water Act represents a positive policy change, signalling broader appreciation of SGD impacts.

Permeability
A measure of the ability of unconsolidated rocks and sediments to allow groundwater flow.

Hydraulic heads
Vertical and horizontal pressure gradients driving groundwater flow.

Biogenic silica
Mineral containing silicon often produced by plankton (such as diatoms and radiolarians) and often well preserved during sedimentation and burial.

and marine-derived nutrients[30,35]. Brackish SGD occurs further offshore, where confined aquifers intersect embayments and on the continental shelf[31,36]. These deeper aquifers are less vulnerable to nutrient contamination from onshore activities because of geological isolation. Where land-derived nutrients are present in confined aquifers, travel times offshore can reach centuries or longer[37].

In this Review, we discuss how fresh and saline SGD drive coastal nutrient dynamics. We summarize SGD fluxes, speciation and distribution of nitrogen, phosphorus and silicon in coastal regions globally. This discussion draws on the considerable growth in the SGD literature in the last ~25 years following the development of geochemical tracer approaches, such as radon and radium isotope mass balance models[38–40], seepage meters[41], hydrogeological models[42–44], resistivity[45,46] and infrared imaging techniques[47,48]. We also put SGD into an ecosystem perspective with thorough comparisons with river-derived nutrient fluxes. Finally, we review the biological implications of SGD and how SGD can be incorporated into water quality management plans and the United Nations Sustainable Development Goals.

Fresh versus saline groundwater

The distinction between fresh and saline SGD is important to consider when interpreting nutrient fluxes to the coastal ocean[49–51] (FIG. 1). Fresh SGD is a source of new water and dissolved species from the marine perspective. In contrast, saline SGD often flushes out recycled nutrients generated during the degradation of sediment organic matter, as well as external nutrient sources entrained from the mixing of fresh and saline waters[35,52]. Saline SGD has a net zero water volume exchange over timescales longer than the cyclic pressure oscillations driving it. Seawater that infiltrates coastal sediments eventually returns to the ocean with a different chemical composition[53] on timescales ranging from days to weeks when driven by tides or storms[35,54,55], and from seasons to years when driven by convection or sea-level oscillations[56–59]. Much emphasis has been given to ubiquitous nearshore tidally driven saline SGD with semi-diurnal, diurnal or fortnightly variations[34,60]. Fewer studies have addressed irregular forcing, such as varying wave conditions[61], storms[62], estuarine density inversions[63] or sea-level anomalies[64], that can flush the upper few metres of coastal permeable sediments and produce large episodic pulses or seasonal offshore saline SGD[65] and deliver both new and recycled nutrients.

The volume of fresh SGD entering the global ocean is relatively small compared with rivers[66,67], accounting for ~1% of total freshwater inputs to the ocean and <1% of total SGD[68]. Fresh SGD is substantial, although, in certain regions such as mountainous, active coastlines in South America and in the tropics, where precipitation, permeability and hydraulic heads are high and surface runoff is low[67,69,70]. Fresh groundwater can locally represent the dominant SGD component in karstic carbonate or volcanic systems, where SGD is often transferred to the ocean through fractures or preferential flow paths that result in submarine springs or point-sourced seeps[71–73]. Fertilizer, animal manure, cesspools and septic systems can leach nutrients into fresh groundwater (FIG. 1), such that nutrient fluxes from fresh groundwater increase the risk of eutrophication in 14–26% of the global coastline associated with estuaries, saltmarshes and coral reefs[66]. However, regional-scale and global-scale estimates of fresh SGD have greater uncertainties than any other water flux, including permafrost melting and ice discharge to the ocean[74], although the uncertainties of SGD are often poorly quantified[75,76].

The global distribution of saline SGD is less understood than that of fresh SGD and scales with the permeability of coastal sediments and tidal and wave energy. Saline SGD is well known to exceed fresh SGD at most sites where it has been quantified[33,35,49,50,56,77–81], and also substantially exceeds river discharge at a global scale[68]. Recycled and new nitrogen and phosphorus are slowly released to surface waters by saline SGD, minimizing extremes and/or buffering the natural seasonal variability of seawater nutrient concentrations[82–85]. This slow and continuous release of nutrients can sustain primary production, especially in the absence of other external nutrient sources[86]. For example, phosphorus is sorbed onto sediments and can be released to groundwater decades later when the chemical conditions become favourable to desorption[87–89]. In the case of dissolved silicate (DSi), saline SGD releases both recycled biogenic silica and some new DSi via dissolution of minerals[79]. If surface water nutrient concentrations exceed coastal

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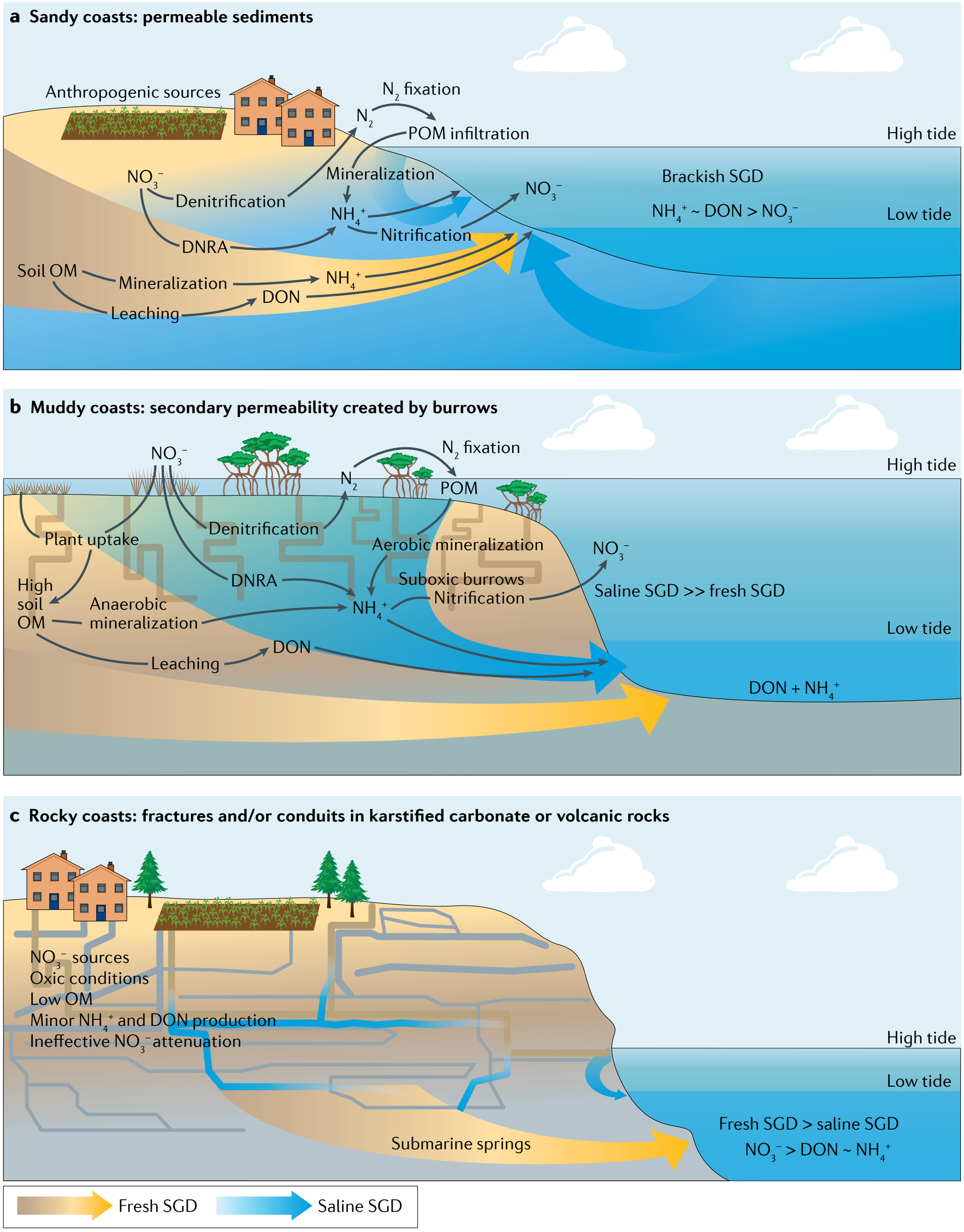


Fig. 1 | **The nitrogen cycle in sandy, muddy and rocky coastal aquifers.** The sizes of the background arrows qualitatively indicate the relative magnitude of fresh and saline submarine groundwater discharge (SGD). **a** | Sandy coasts are often characterized as having brackish SGD with higher concentrations of ammonium (NH_4^+) and dissolved organic nitrogen (DON) than nitrate (NO_3^-). **b** | Muddy coasts often host burrowing fauna, which create secondary sediment permeability and promote aerobic mineralization, nitrate reduction and saline SGD. **c** | Rocky coast SGD tends to be dominated by freshwater, with relatively high concentrations of NO_3^- relative to DON and NH_4^+. DNRA, dissimilatory nitrate reduction to ammonium; OM, organic matter; POM, particulate organic matter.

Denitrification
Microbial process in the nitrogen cycle that converts nitrate to nitrogen gas that flows to the atmosphere.

saline groundwater concentrations, then saline SGD can enhance microbial denitrification by consuming nitrate and, thus, attenuate nitrogen pollution[90]. For example, saline groundwater flow through intertidal sediments removes nitrogen from surface waters in coastal wetlands receiving high nitrogen loads[91]. Most of the global SGD inputs of dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and DSi seem to be derived from saline SGD[26], with fresh SGD representing a minor contribution[66]. However, at sites where fresh SGD is volumetrically important (usually karst or volcanic landscapes with high permeability) (FIG. 1), nutrient

Karst
Landscape formed by carbonate rocks often weathered by dissolution and with abundant conduits for fast groundwater flow.

Unconfined aquifers
Surficial aquifers situated above a low-permeability layer of sediment or rock, and with the upper water layer at atmospheric pressure.

Oxidation-reduction potential
Measure of the tendency of a chemical species to acquire electrons, to be reduced or to lose electrons, or to be oxidized.

fluxes supplied by fresh SGD dominate the local nutrient sources to coastal waters[49,92,93].

Fresh and saline SGD pathways vary between sandy, muddy and rocky coastlines, owing to the unique hydrogeological characteristics of coastal aquifers. Sandy coasts generally consist of highly permeable sediments that effectively connect aquifers to the coastal ocean (FIG. 1a). A typical unconfined surficial sandy aquifer stores fresh groundwater from upland regions, discharging to the sea within or below the intertidal zone. Tidal or wave dynamics can create seawater circulation cells nearshore within beach sediments[94,95], while various forcing mechanisms can drive saline SGD farther offshore[52,65,96–98]. In contrast, muddy coasts dominated by mangroves and saltmarshes (FIG. 1b) are characterized by lower permeability sediments that facilitate saline SGD once the secondary permeability has been enhanced by burrows, root structures or buried vegetation[99–102]. Rocky coasts (FIG. 1c) contain fractures and/or conduits that allow direct fresh SGD flows to the sea with no or minor biogeochemical transformations[14,69,103,104]. The fresh SGD component is usually expected to exceed saline SGD in karst and volcanic coastal aquifers, with fresh groundwater flows susceptible to regulation by tidal forcing mechanisms[46,104].

Topography and geomorphology can also influence SGD, but the effects remain largely unquantified. For example, the regional topography of the coastal zone dictates the slope of the water table and the inland hydraulic gradient in coastal unconfined aquifers, which, in turn, influences fresh SGD[105,106]. Nearshore morphological features, such as beach slope breaks, tidal creeks and heterogeneous stratigraphy, affect seawater circulation in beaches and saline SGD, as observed and modelled in a coarse carbonate sand aquifer on the Cook Islands[107,108] and in saltmarshes in China[100,109].

Fresh SGD carries land-derived nutrients that are an external nutrient source to coastal waters, with considerable variability between sandy, muddy and rocky coastlines. For example, seagrass, mangrove and saltmarsh vegetation assimilate nutrients directly from groundwater (FIG. 1b). Sediment properties like organic matter content control oxidation-reduction potential and the energetic favourability of denitrification. Phosphorus or silicate-bearing minerals in rocks can act as a natural source of DIP and DSi, whereas iron oxides immobilize DIP through sorption[87]. Phosphorus can be released back to porewater when iron oxides are reduced, as observed in saltmarshes[110,111] and sandy aquifers[87] exposed to both fresh and saline SGD. SGD nutrient inputs are also conditioned by the discharge type. Slow, diffusive fresh and saline SGD through sandy permeable sediments allow for greater nutrient transformations in subterranean estuaries[82,112,113], but rapid fresh groundwater discharges through conduits (for example, karstic or volcanic aquifers) prevent substantial nutrient attenuation[114,115]. Fresh and saline SGD ultimately deliver regenerated nutrients associated with the decomposition of organic matter in soils and sediments, and these natural and internal nutrient sources are also a component of nutrient budgets in coastal marine waters[116,117].

Global distribution of SGD studies

Here, we compiled fresh and/or saline SGD-derived fluxes of at N, P and/or Si reported by 239 study cases from 31 countries (FIG. 2, Supplementary Table 1). Most of the flux data relied on radon (27%) and radium (45%) isotope measurement of SGD rates. These methods result in SGD rates that are, on average, a factor of two greater than estimates based on modelling approaches (Supplementary Table 2), likely reflecting the large number of marine processes driving (mostly saline) SGD that are captured by radon and radium isotopes[34,118], whereas hydrological models quantify specific driving forces and components of fresh and saline SGD[33,119,120].

From a climatic zone perspective, SGD nutrient investigations are similarly split between the tropics (27%), subtropics (30%) and temperate (32%) regions (FIG. 2). Polar regions remain severely understudied, with only two studies quantifying SGD-derived nitrogen fluxes in Alaska[121]. Of all studies in the tropics, 50% are located in Asia and 25% are from the Hawaiian Islands. In the subtropics, 37% of the studies are from the USA alone, and only 19% of the study sites are located in the Southern Hemisphere (primarily Australia). Temperate regions between 35° and 60° are mainly represented by Europe (38%) and the east coast of the USA (26%), and are highly skewed to the Northern Hemisphere (93%). In total, 38% ($n = 79$) of the compiled studies were from Asia, followed by North America (33%), Europe (16%) and Australia/Oceania (11%). Only two investigations quantified SGD-derived nitrogen inputs in South America (bay and lagoon ecosystems in Brazil[25,122]) and three in Africa (estuary and lagoon ecosystems in Egypt[123] and South Africa[124]). Thus, there is a clear need to conduct SGD investigations in poorly represented areas in Africa, South America and high latitudes across all ecosystem types. The limited existing datasets and large uncertainties in individual estimates prevent inferring any specific pattern across different climates (Supplementary Table 3).

Several interesting inferences emerge comparing measurements between ocean basins. Median (and interquartile range) SGD rates and inorganic nutrient fluxes are greatest for the Indian Ocean (SGD = 17, 5–48 cm per day; DIN = 11, 3–29 mmol m^{-2} per day), where there was the smallest number of study cases (Supplementary Table 4). For the Pacific Ocean, median SGD rates (9, 2–22 cm per day) and DIN (8, 2–27 mmol m^{-2} per day) and DSi (9, 2–60 mmol m^{-2} per day) fluxes exceed those of the Atlantic Ocean (SGD = 4, 1–10 cm per day; DIN = 2, 2–60 mmol m^{-2} per day; DSi = 2, 0–12 mmol m^{-2} per day), in spite of a large natural variability. The differences in DSi fluxes are likely driven by differences in continental lithology and the presence of active (Pacific) and passive (Atlantic) margins[125]. The median DIP flux for the Mediterranean Sea (0.03, 0.01–0.10 mmol m^{-2} per day; $n = 24$) is approximately three times lower than that of the Atlantic and Pacific oceans (0.10, 0.02–0.48 mmol m^{-2} per day), because the Mediterranean coastline hosts many karstified aquifers that retain phosphate[126].

From the synthesis here, sites with high SGD-derived DIN fluxes are often located in regions with

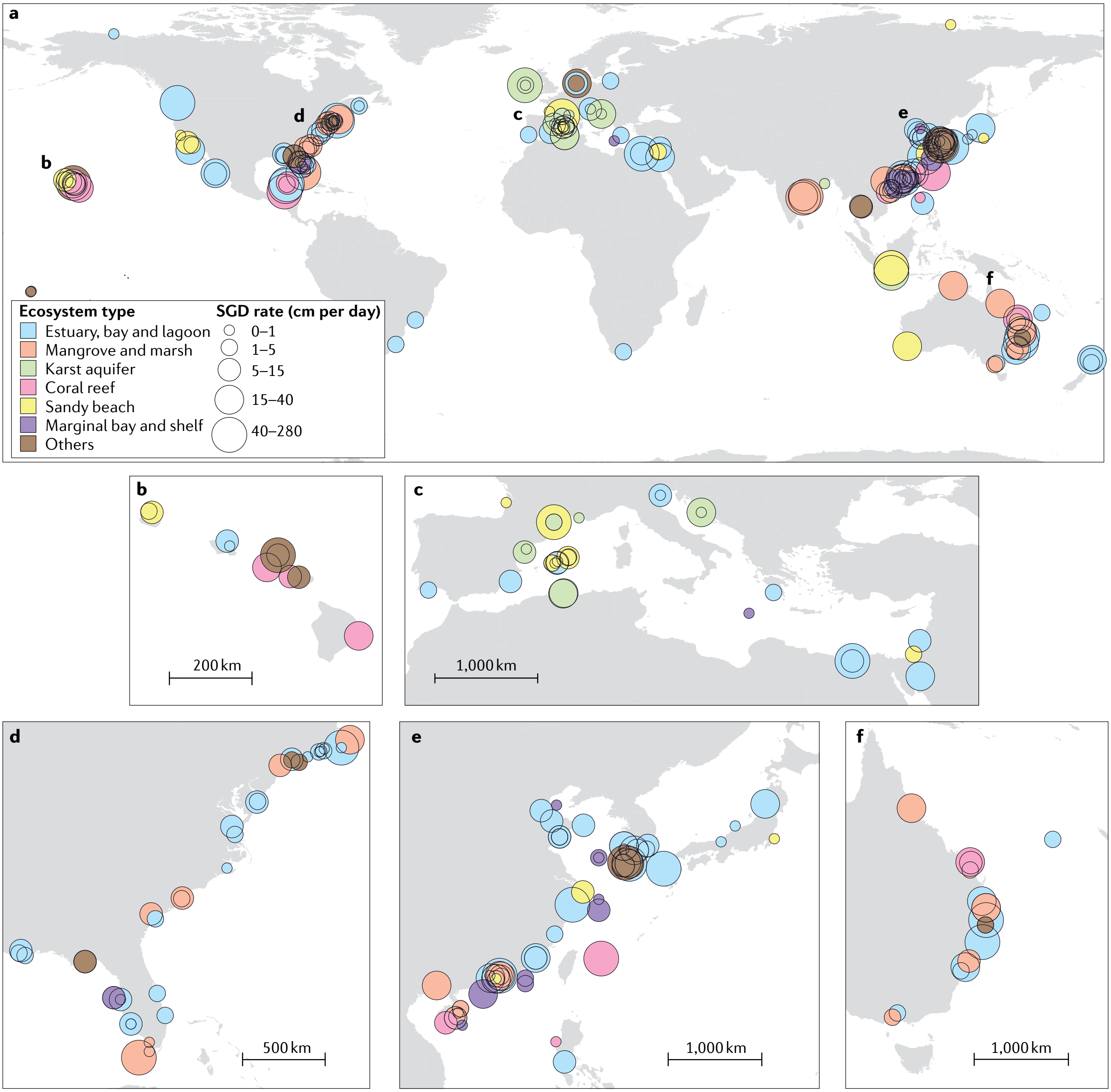


Fig. 2 | **SGD rates from study cases reviewed here. a** | Submarine groundwater discharge (SGD) fluxes globally, colour-coded by ecosystem type, where the size of the circle represents the reported SGD rate. Similar maps for each nutrient are shown in the supplementary material. Investigations where SGD rates are reported without any nutrient fluxes were not included in the compilation. **b** | SGD in Hawaii, USA, with ecosystems coloured and rates scaled as above. **c** | SGD in the Mediterranean. **d** | SGD on the east coast of the USA. **e** | SGD in East Asia. **f** | SGD on the eastern coast of Australia.

contaminated coastal aquifers. These sites include groundwater flowing across septic systems in Hawaii[127], heavily fertilized catchments in the northeast USA[128], urban embayments in China[129] and coastal aquifers with naturally high nitrate due to large bird populations[13]. High DIN fluxes in coral reefs and estuaries (FIG. 3) might be due to measurement bias towards ecosystems that are already known to be impacted by nutrient enrichment. For example, in Waquoit Bay (MA, USA), excessive macroalgal growth and eutrophication have been linked to SGD from multiple perspectives and methods[41,130,131]. However, fresh and saline SGD can sustain relatively high nitrogen fluxes, even at sites with no apparent anthropogenic contamination sources, such as protected saltmarshes on the USA east coast[22,110,132].

The study sites considered ranged from small near-shore sites that spanned ~100 m^2 along beaches[133,134] to large regions that spanned marginal seas such as the

Subterranean estuaries
The locations in coastal aquifers where there is mixing between fresh groundwater and seawater, and chemical reactions modify the composition of submarine groundwater discharge.

Mediterranean Sea[126] and the Yellow Sea[135], or the global ocean[26]. Although there was no direct correlation between the area covered by individual study cases and SGD rates or related nutrient fluxes, grouping the available data into three major classes revealed greater nutrient fluxes on the small (<1 km^2) scale than larger scales (FIG. 3, Supplementary Table 5). This difference could be related to the tendency for small-scale studies to focus on areas where fresh SGD fluxes or nutrient concentrations are likely to be large[32]. These locations include known coastal springs, heads of embayments where fresh groundwater converges or polluted aquifers of particular concern. Additionally, the ratio of surface water area to the shoreline length is much smaller in small-scale studies than in large-scale investigations, which can also explain the scale dependence of SGD fluxes. Median SGD-derived DIN and DIP fluxes in nearshore systems such as estuaries, mangroves, saltmarshes, coral reefs and bays were greater than those in offshore systems such as marginal seas and continental shelves (FIG. 3, Supplementary Table 6). Larger ecosystems often have lower reported SGD rates and related nutrient fluxes. For example, the median DSi fluxes via SGD are largest in estuaries and wetlands and smallest in marginal seas and continental shelves.

Nutrient ratios and speciation

Biogeochemical transformations within coastal aquifers and subterranean estuaries (where fresh and saline groundwater mix[136–138]) dramatically modify nutrient concentrations and chemical speciation along SGD flow paths[112,117,125,131,139]. Indeed, there are salinity gradients and differences between the pH, oxidation-reduction potential and organic matter content of groundwater flow paths and mixing zones that lead to changes in nutrient chemistry before SGD reaches the ocean. Quantifying these transformations is challenging yet essential for estimating total SGD (fresh + saline) nutrient fluxes[138,140]. Some recent investigations bypass this challenge by collecting samples directly from the discharging groundwater, presumably after all biogeochemical transformations within the subterranean estuary have taken place[141–144]. Others rely on onshore fresh groundwater samples to estimate the groundwater end-member under the assumption of minor transformations within the subterranean estuary[145–147].

Sandy, muddy and rocky aquifers have different hydrological and biogeochemical regimes, and nitrogen dynamics in these locations are differently affected by SGD. Nitrogen has a complex behaviour depending on redox conditions, the abundance of oxygen and organic carbon, and microbial communities[21,90,148].

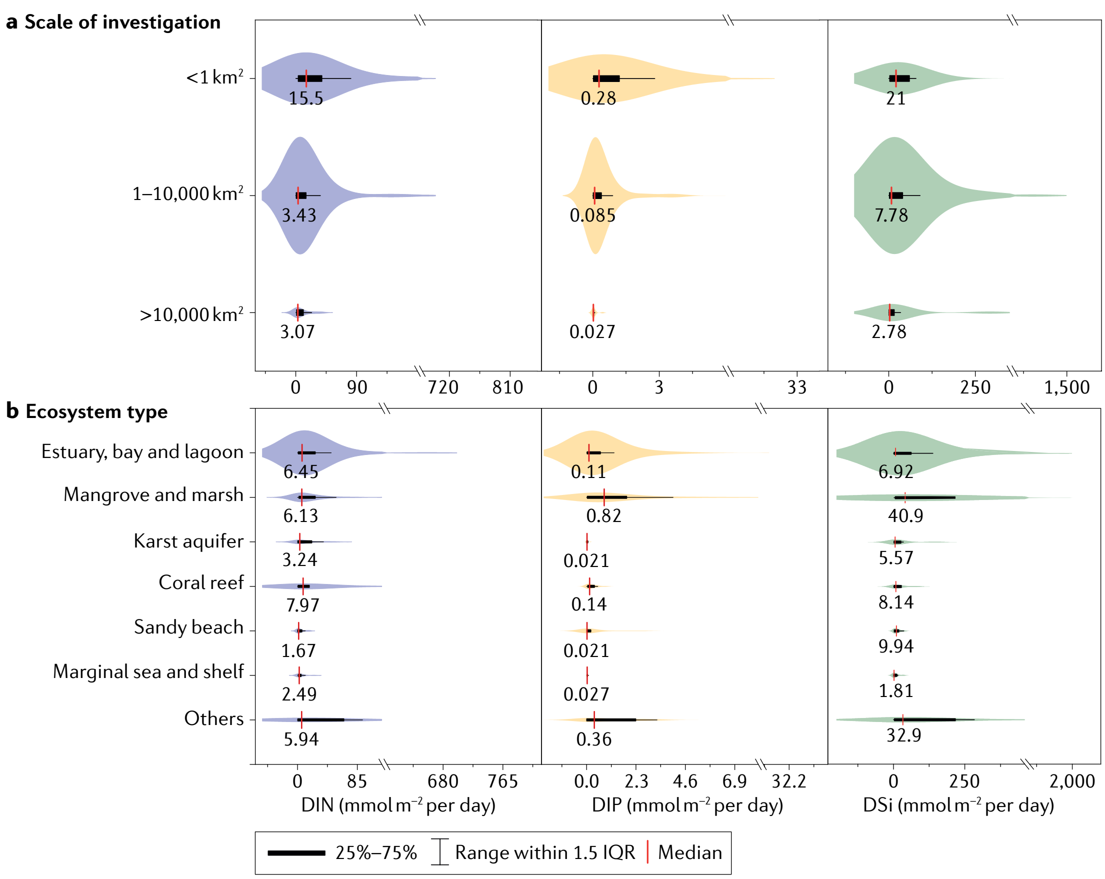


Fig. 3 | **SGD-derived DIN, DIP and DSi fluxes based on different spatial scales and ecosystem types. a** | Average submarine groundwater discharge (SGD)-derived dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and dissolved silicate (DSi) fluxes, separated by scale of the investigation. **b** | SGD-derived nutrient fluxes based on ecosystem type. Medians are noted by the red lines. Data and references are shown in the supplementary online material. IQR, interquartile range.

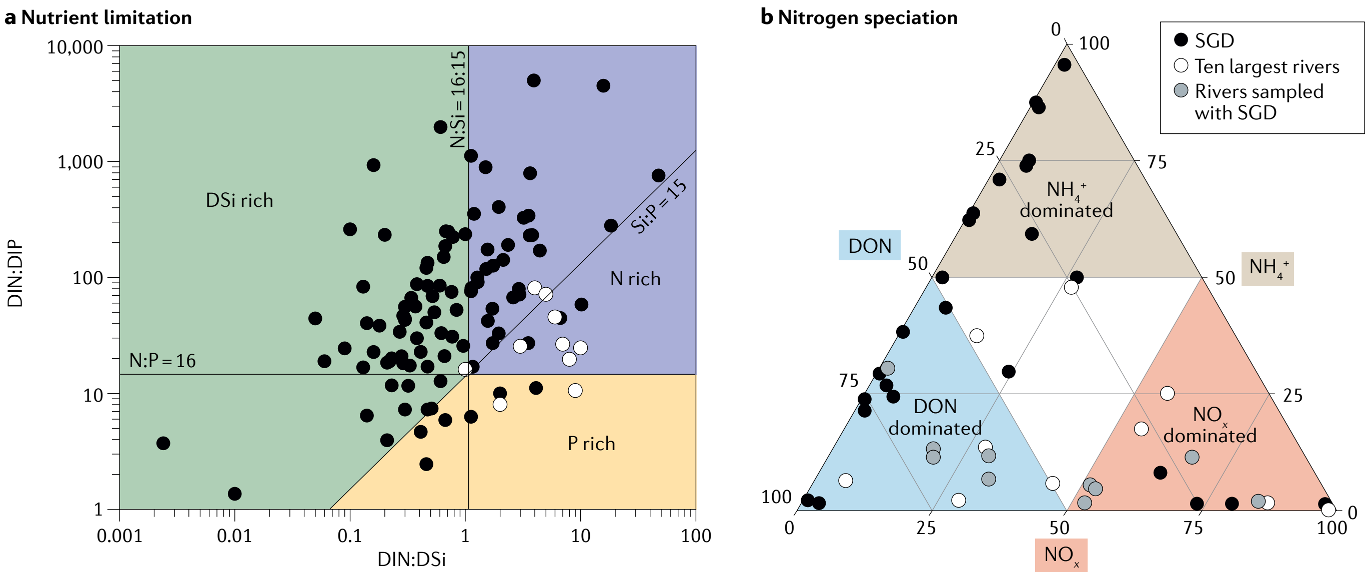


Fig. 4 | **Nutrient limitation and speciation in SGD versus rivers. a** | Dissolved inorganic nitrogen (DIN):dissolved inorganic phosphorus (DIP) versus DIN:dissolved silicate (DSi) ratios in submarine groundwater discharge (SGD) from our global compilation, with the same ratios in the ten largest rivers globally included for comparison. **b** | The relative contribution of the three main nitrogen species in SGD and rivers, showing that SGD is often dominated by ammonium (NH_4^+) and dissolved organic nitrogen (DON), whereas rivers are often dominated by nitrate (represented as NO_x) and DON.

Soil organic matter is remineralized by microorganisms in oxic or anoxic conditions[149], resulting in ammonium release. Ammonium is readily oxidized to nitrate through nitrification in the presence of oxygen (FIG. 1a). Because of oxygen paucity in many organic-rich coastal aquifers, nitrification is generally constrained to the sediment surface, but can become very important in the presence of burrowing animals in muddy sediments[150] (FIG. 1b). In sandy and muddy coastal areas, nitrogen fixation related to abundant sulfate-reducing bacteria in intertidal sediments can eventually turn atmospheric N_2 into ammonium[151,152], which can be easily incorporated into organic matter and infiltrate subterranean estuaries, owing to waves and tides (FIG. 1a,b).

Nitrate is removed by the microbial conversion to N_2 through denitrification in the absence of oxygen and the presence of organic carbon in muds and sand aquifers[90,140,153]. Nitrate can be converted back to ammonium by the dissimilatory nitrate reduction to ammonium (DNRA)[154], both of which can be enhanced by tidally driven SGD in muddy intertidal marshes[155] or permeable sands[156–158]. Moreover, both ammonium and nitrate are also temporarily removed by microbial and plant uptake (FIG. 1b). In contrast to muddy and sandy coasts, however, high nitrate loading and oxygen presence in volcanic and karst coasts (as in Hawaii, Yucatan and in the Mediterranean) lead to a simplified nitrogen cycle, with little nitrate attenuation and high export to the sea[72,115,159,160] (FIG. 1c).

The ratio of nutrients supplied to coastal waters (FIG. 4a) can limit primary production and influence biological communities if the source differs substantially from the Redfield ratio[161]. In the absence of anthropogenic sources, the coastal ocean is often nitrogen-limited, owing to efficient coupling between primary producer uptake, microbial mineralization and sediment denitrification[162,163]. As a result, groundwater inputs with a high N:P or N:Si ratio can encourage the growth of certain phytoplankton groups[163]. For example, diatom blooms often occur at N:Si ratios lower than 1, whereas harmful species (usually dinoflagellates) usually bloom at higher ratios[164]. The DIN:DIP ratios in SGD were above the Redfield ratio of 16:1 in 75% of the study sites, demonstrating that SGD often attenuates nitrogen limitation and stimulates primary productivity in coastal waters (FIG. 4a). The DIN:DIP ratios in SGD study cases ranged from 1 to 12,100 (average ± standard deviation = 259 ± 1,090; n = 169) and the DIN:DSi ratios ranged from 0.1 to 47.5 (2.0 ± 5.4; n = 96). Based on those ratios, SGD in 58% of the compiled study sites had Si-enriched conditions, 36% were N-enriched and 6% were P-enriched relative to the Redfield ratio (FIG. 4a). DIN:DIP ratios were usually >16, even at sites classified as Si-enriched, demonstrating that SGD counters N-limited conditions in most coastal waters.

High DIN:DIP ratios in SGD are expected, as phosphorus is often immobilized through adsorption to mineral surface sites of Fe/Mn oxides[87,89,165] or scavenged by co-precipitation with calcium carbonate[166]. Hence, in hypoxic and anoxic aquifers, including saltmarshes and mangroves, DIN:DIP ratios in SGD can be controlled by the seasonal reduction and oxidation cycling of Fe oxides driving DIP[88,167,168]. Particularly high DIN:DIP ratios are observed in coastal aquifers contaminated by sewage and fertilizers because the phosphorus source is often attenuated faster than nitrogen along groundwater flow paths[145]. Moreover, groundwater nitrogen from fertilizers applied in the last century can still be found in coastal aquifers[37,169]. Despite substantial improvements

Nitrogen fixation
Microbial process that leads to the conversion of nitrogen gas into ammonia/ammonium.

Dissimilatory nitrate reduction to ammonium
Microbial process in the nitrogen cycle that converts fixed nitrogen from nitrate to ammonium.

Diatom
Microscopic algae (unicellular and non-flagellate) with a characteristic wall made up of silica and are one of the most important groups of planktonic marine microalgae.

Dinoflagellates
Group of microscopic algae (mostly unicellular and flagellate) representing one of the most important groups of both marine and freshwater phytoplankton.

in fertilizer management in some European countries, nitrate concentrations in groundwater have not shown any immediate decreasing trend following reductions in fertilizer application[170,171].

Our data compilation supports earlier model predictions[145] that the discharge of legacy N-contaminated groundwater will eventually change the coastal ocean from the current N-limited to a P-limited state. Such a pattern has been observed in a SGD-dominated urban embayment in China, where surface water DIN:DIP ratios have increased from 25 to 96 between the 1980s and the mid-2010s, owing to seepage of contaminated SGD[172]. In the Po river estuary in Italy, a notable increase of DIN:DIP ratios from 47 to 100 between 1970 and 2016 was linked to the discharge of nitrogen-polluted groundwater[173]. Increasing anthropogenic nitrogen inputs in coastal regions could lead to an increasing N:Si ratio, which provides an unfavourable environment for diatoms, while enhancing the likelihood of dinoflagellates and cyanobacteria blooms[174,175].

Although nitrogen is often the nutrient of greatest concern in SGD, few studies have reported detailed nitrogen speciation data. Only 31 studies reported the three major nitrogen species, and 13 studies also reported N speciation in nearby rivers (FIG. 4b). Previous studies often focused on DIN[145] (such as nitrate and ammonium, which are more readily available to primary producers) and overlooked SGD-derived DON (which is assimilated at slower rates[176]) because the contribution of DON to primary production is unknown. Additionally, many SGD studies emphasize nitrate because anthropogenic activities often contribute large nitrate loads[115,177,178], yet, only six of the 31 SGD studies reporting ammonium, nitrate and DON found nitrate to be the dominant form of nitrogen. All of those sites were heavily influenced by local contamination sources.

Groundwater and seawater DON is often derived from soil leachates, zooplankton excretion and leaching from microbial and algal biomass that infiltrate subterranean estuaries[112,176,179,180]. DON increases along the coastal ocean and in surface estuaries, where it often constitutes the largest fraction (73 ± 23%) of the total dissolved nitrogen pool[180]. Only 40 out of the 239 study sites included here reported DON data, and no study revealed the composition and bioavailability of DON in SGD. On average, DIN accounted for 57 ± 28% (median 61%) and DON accounted for 43 ± 27% (median 39%) of total dissolved nitrogen fluxes via SGD. DON and ammonium are relatively more abundant in non-contaminated groundwater[181], but DON may also originate from anthropogenic sources[176]. Refractory DON uptake is often attributed to heterotrophic bacteria over timescales of millennia, but the less abundant labile DON compounds such as amino acids and urea are used up by autotrophic microbes and phytoplankton on timescales of hours to days[180]. Because of high DON contributions via SGD (FIG. 4b), even a small labile portion could make a difference to the amount of N ultimately available to primary producers. Overall, our compilation supports earlier suggestions that DON represents a significant portion of nitrogen in SGD[141,176,179,182,183].

Comparing SGD and river fluxes

Rivers are often assumed to be the primary nutrient source to coastal waters, so riverine nutrient fluxes provide a valuable reference frame for contextualizing SGD (FIG. 5). Global estimates of nutrient fluxes supplied by riverine discharge to the coastal ocean[184–186] are on the order of ~40 Tg N per year, ~9 Tg P per year and ~140 Tg Si per year, although these estimates vary widely depending on the model used[187,188]. River nutrient fluxes vary greatly among the continents, reflecting the regional differences in population, the associated anthropogenic nutrient inputs and the hydrological cycle[189,190]. For instance, natural sources are the main contributor to N fluxes supplied by rivers in Africa, Oceania and South America, whereas most of the N is supplied by anthropogenic sources in Asia, North America and Europe[188].

Basin-wide or global-scale assessments of SGD have suggested that total SGD-derived nutrient inputs are comparable to or higher than river-derived nutrient fluxes in the Mediterranean Sea[126], the coast of China[172] and in the global ocean[26]. For example, total SGD-derived (19×10^{10} mol per year) nitrogen fluxes into the Mediterranean Sea exceed river fluxes (5×10^{10} mol per year)[126] by a factor of ~4. Fresh SGD from karstic springs in the Mediterranean, a dominant regional feature, account for 8–31% of these river-derived nitrogen fluxes[72]. In China, an upscaling of local case studies to the entire coastal zone revealed that total SGD-derived fluxes of nitrogen, phosphorus and silicate account for >50% of all known sources, including rivers, atmospheric deposition and diffusion from sediments[172].

At a local scale, SGD-derived nutrient fluxes exceeded river fluxes in >48% of the compiled study cases, and SGD-derived nutrient fluxes were at least 10% of the river fluxes in >90% of the study sites (FIG. 5). Note that several SGD studies did not report riverine fluxes of nutrients, perhaps because they were conducted in areas with no or minor surface runoff[114,191]. Furthermore, we highlight that any comparison between rivers and SGD at a local scale can be biased, owing to a potential selection of sites where fresh SGD is expected to be high and groundwater pollution is known or expected. Direct comparisons of SGD fluxes across hydrological or land-use gradients using the same method are uncommon, despite observations in Hawaii[160] and northeast USA[176,192] showing a clear impact of land use on SGD-derived nitrogen fluxes.

Global patterns of SGD and river distributions show a similar dependency on land use, with higher nutrient concentrations and N:P ratios in densely populated and agricultural areas[145,172,193,194]. However, nutrient fluxes supplied by SGD and rivers might be considerably different, depending on the magnitude of discharge. For instance, about 70% of global SGD occurs in the Indo-Pacific Oceans, while less than half of the river waters are discharged in the Indo-Pacific[30]. River and SGD fluxes are also considerably different at a local or regional scale. In contrast to river discharge that is restricted to specific point sources along the coast such as river mouths, SGD (particularly the saline component) is ubiquitous along permeable sediment and muddy shorelines, and is relatively diffuse. Therefore,

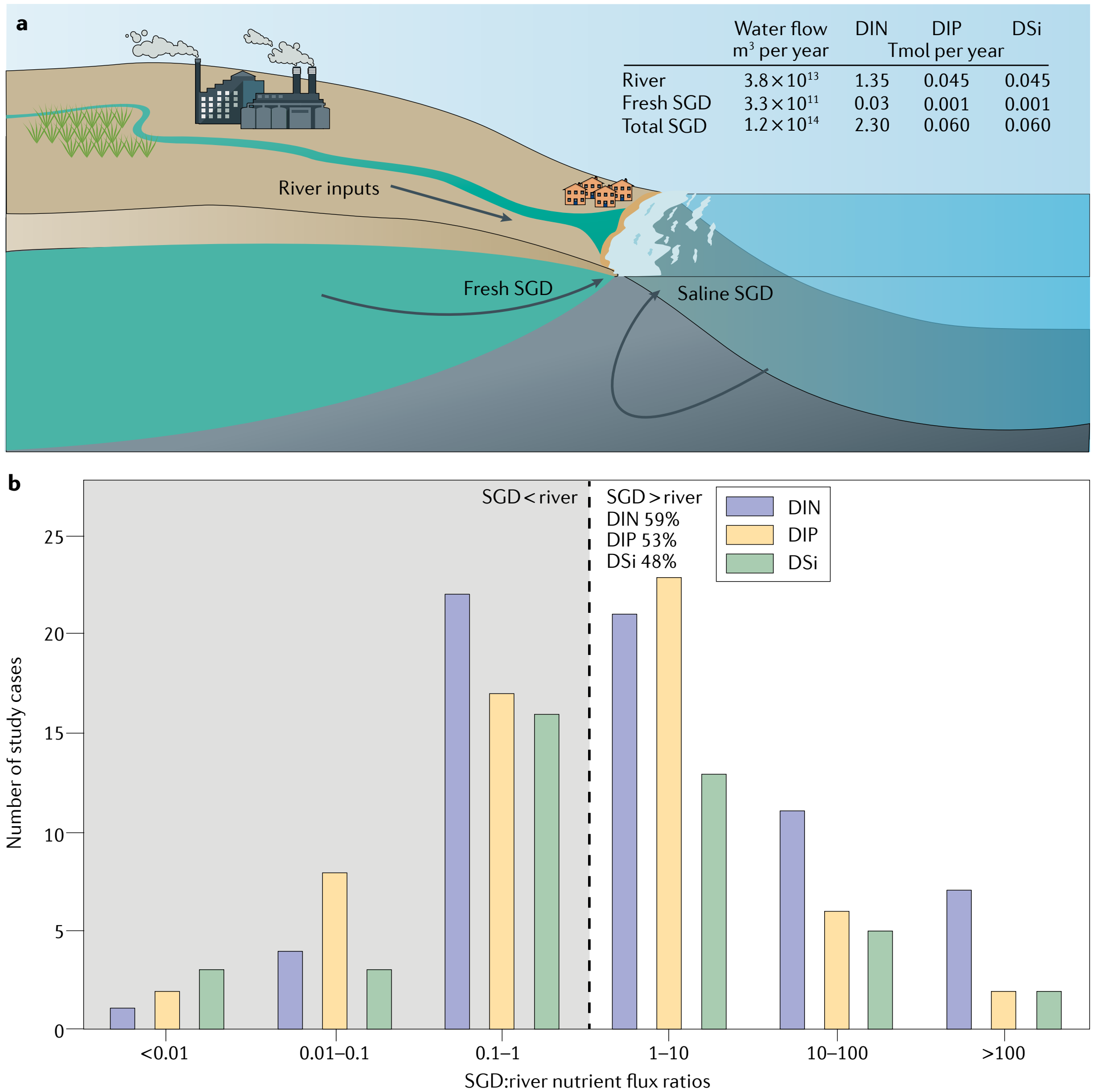


Fig. 5 | **River and SGD-derived nutrient inputs to the ocean. a** | A summary of global-scale fluxes compiled from river[163,187,188], fresh submarine groundwater discharge (SGD)[63] and total (mostly saline) SGD[27,65] estimates. **b** | Histogram of ratios between SGD and river-derived dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and dissolved silicate (DSi) fluxes summarized from the global study cases reviewed here. In >48% of the global study cases, SGD-derived nutrient fluxes exceeded river fluxes. In ~90% of the study cases, SGD nutrient fluxes were >10% of river fluxes, making SGD a non-negligible nutrient pathway in nearly all study sites.

SGD is likely to affect larger coastal areas than river discharges[195].

Both SGD-derived and river-derived fluxes of water and dissolved nutrients to the coastal ocean are affected by seasonal patterns in the hydrological cycle. Seasonal changes in recharge, evapotranspiration and groundwater extraction drive water-level changes onshore that propagate offshore by pressure diffusion. As a result, SGD typically experiences a delayed response to seasonal fluctuations relative to river fluxes[66]. Fresh and saline SGD rates and associated nutrient fluxes can lag peak recharge periods by several months, depending on flow path lengths, aquifer transmissivity, storage properties and recharge volume[59,196,197].

Rivers and SGD are characterized by unique stoichiometric ratios and nutrient speciation (FIG. 4). Nitrate accounts for much of the global increase in anthropogenic nitrogen loads in rivers in recent decades[198,199]. Although rivers are usually dominated by a mixture of nitrate and DON, nitrogen in SGD (particularly saline and brackish) is mostly composed of DON and ammonium, owing to reducing conditions in organic-rich shallow coastal sediments and mineralization of organic matter (FIG. 1). The contrasting nitrogen speciation in SGD and rivers highlights the need for including the three major dissolved nitrogen species in future investigations.

The river nutrient transport to the ocean has more than doubled during the twentieth century[184,186,187,200], as a result of increases in population and fertilizer use[201]. Although no similar datasets exist for long-term changes in total SGD, modelled fresh SGD-derived nitrate fluxes increased by about 40% over the second half of the twentieth century[193]. Given the slower response of

Evapotranspiration
The quantity of water that moves to the atmosphere from the plants and soil; describes the joint effect of transpiration, through the plants, and evaporation, directly from the soil.

Microphytobenthos
Living organisms, such as unicellular eukaryotic algae (mainly diatoms) and cyanobacteria, growing in the upper layers of illuminated aquatic sediments.

Cyanobacteria
Ubiquitous phylum of single-celled bacteria that carry out photosynthesis.

Macrophytes
Large aquatic plants and multicellular algae widespread in marine, brackish and freshwater environments, which are referred to as macrophytes to distinguish from unicellular algae (phytoplankton).

groundwater to anthropogenic nutrient inputs, groundwater polluted several decades ago can continue to discharge, releasing legacy nutrients that impact water quality in rivers and the coast even after pollution sources cease to exist[2,202]. For instance, recent investigations at the mouth of the Mississippi River revealed that most of the N in surface water had been in the watershed for >30 years, as a consequence of the time spent both in the soils and travelling along slow groundwater transport pathways[2,145,193]. Therefore, despite the potential mitigation measures aimed at decreasing terrestrial nutrient loads in polluted areas, it can take decades to achieve the desired reduction of SGD-derived nutrient loads[2,145,193].

The contribution of groundwater-borne nutrients to coastal ocean budgets will likely increase as human activity in coastal watersheds increases[181]. Climate-change-derived alterations of precipitation and evapotranspiration regimes, as well as land-use change, are known to modify the quantity, the quality and the availability of groundwater resources[203]. Climate-driven sea-level rise is also known to modify SGD and biogeochemical cycling within coastal aquifers, and will likely affect the magnitude of SGD-driven nutrient inputs[56,64] and its impact on coastal biological communities. However, long-term quantitative predictions about the effects of climate change on SGD are unavailable.

Biological impacts of SGD nutrients

Research on how SGD nutrients impact marine biota has increased in recent years[204], with nearly 90% of all articles on this topic having been published in the last decade (see the supplementary material). The documented response of marine organisms to SGD is quite variable and site-specific, and can be positive or negative from species, community or ecosystem perspectives (FIG. 6). The response to SGD is sometimes unclear and could change, depending on the specific location or time of the year.

The most documented response to SGD-derived nutrient loading is related to increasing primary productivity of phytoplankton or microphytobenthos[205]. Chlorophyll is often measured as a proxy for primary productivity derived from SGD[206] and most attempts to link SGD and chlorophyll have revealed a positive response[207] (FIG. 6). The increase in primary productivity by SGD inputs from uncontaminated aquifers has been linked to diatom abundance that effectively use up the nitrogen, particularly in areas where SGD can alleviate co-limitation of N and Si (REF.[208]). A trend towards larger phytoplankton cell sizes, such as diatoms, in response to SGD was noted in Hawaiian coastal waters receiving fresh SGD[209]. However, it is clear that increased primary production resulting from SGD nutrient supply does not always exert a positive response in the ecosystem (FIG. 6). Dinoflagellate and cyanobacteria blooms can occur when ammonium is present in SGD or when inorganic nitrogen is transformed by diatoms into organic nitrogen[210]. As observed in Korea[211,212] and Florida (USA)[213], SGD can trigger, fuel and sustain harmful algal blooms, with devastating consequences to coastal ecosystems. In some cases, however, no response was found near sites receiving fresh groundwater springs, indicating that SGD loading does not always induce an increase in primary productivity[214].

Macrophyte cover can increase or decrease in response to SGD. The most studied macrophyte in a SGD context are *Ulva* spp., a leafy alga commonly known as sea lettuce, which grows faster and increases in abundance in response to SGD-derived nitrogen inputs[191,215]. Moreover, nitrogen-rich SGD can also increase the N:P ratio in macrophyte tissues, which can reduce herbivory because fish prefer macrophytes with lower N:P ratios[216]. However, macrophytes can also reduce reproduction to

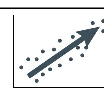
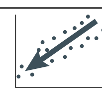
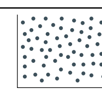
	Biological response	Response to SGD nutrients: Increase	Decrease	Unclear/mixed
				
Species scale	Organism abundance	17	2	9
	Growth and biomass	9	1	2
	Tissue N:P ratio	5	1	2
	Disease	1	–	–
Community scale	Richness	1	1	1
	Chlorophyll a	20	–	6
	Diversity	3	5	2
	N sourcing	21	–	1
	Benthic density	–	1	3
Ecosystem scale	Productivity/photosynthesis	11	–	2
	Respiration	2	1	1
	Anoxia/deoxygenation	1	–	–
	Calcification	3	1	–

Fig. 6 | **The biological impacts of SGD.** The table counts the number of studies demonstrating responses at the species, community and ecosystem scales to submarine groundwater discharge (SGD). SGD can drive multiple biological responses, depending on local conditions. The original references are summarized in the supplementary online material.

Acid sulfate soils
Naturally occurring soils usually found in coastal wetlands with a high content of iron sulfide minerals, such as pyrite; when disturbed by dredging or drainage, the soils come into contact with oxygen, oxidizing pyrite and releasing sulfuric acid (H_2SO_4).

prioritize growth and take advantage of a nitrogen-rich environment created by SGD[217]. In Hawaii, for instance, oligotrophic waters receiving N-enriched SGD had increased macroalgae coverage from <15% at low-SGD sites to ~70% at high-SGD sites[215]. In contrast, eelgrass coverage in eutrophic northeast USA waters reduced from ~50% to <10% in response to SGD N loading, owing to competition with epiphytes growing on their blades[218].

In coral reef ecosystems, increases in macrophyte cover in response to increased nutrient supply by SGD corresponded with a decrease in coral cover (FIG. 6), since macrophytes smother and outcompete corals in high-nitrogen conditions[219,220]. For example, in Hawaii, sites experiencing low SGD had a coral cover of 18%, whereas high-SGD sites had no coral cover[215]. SGD can lead to a net increase in calcification of corals and other calcifying organisms, owing to increased nutrient supply, as observed in three[13,221,222] of the four studies on the topic (FIG. 6). However, this increased calcification is often mitigated by other SGD characteristics, such as low salinity and pH, that can stress corals more than the corals benefit from the nutrients[223]. Additionally, the coral black band disease can be more prevalent in SGD-impacted areas, where nutrient fluxes either stressed the corals or fuelled the microbes that make up the disease[224]. Increased respiration related to increased food and organic matter supply caused by SGD nutrients inducing more primary productivity can also stress corals[225].

Sites influenced by fresh SGD have been shown to provide favourable conditions to enhance growth rates of mussels[226] and oysters[227,228]. Similarly, increased growth rate and abundance of fish in association with fresh SGD sites have been recently documented[229,230], with implications for small-scale fisheries[231]. In general, fresh SGD positively impacts fisheries, which is also known from experiences from fishermen[232]. However, fish abundance and diversity showed mixed results in response to SGD nutrients in some cases[215,233]. Either the SGD-enhanced primary productivity provides enough increase in food at the lower trophic levels that a more diverse community of animals emerges[234], or an opportunistic species outcompetes the other organisms, reducing diversity[235]. Resultant algal blooms[236] or the direct input of anoxic groundwaters[237] can also lead to low-oxygen events and influence fish behaviour and community composition. Whether the nutrients supplied by SGD benefit or harm a marine ecosystem depends on site-specific conditions (community composition, residence times, original trophic state) and just how much nutrient loading and composition results from SGD. Beyond nutrients, the effects of SGD on salinity or temperature can improve fish growth in coastal waters[238].

SGD can also have an indirect biological impact by releasing dissolved inorganic carbon to the coastal ocean as CO_2 or alkalinity[239,240]. SGD can locally enhance seawater pH and partially buffer the coastal ocean against ocean acidification, as observed off mangroves in Australia[241,242] and coral reefs around the Cook Islands[243], which receive large, SGD-derived alkalinity inputs. By consuming CO_2, primary productivity stimulated by SGD-derived nutrient inputs increased seawater pH, which was observed off a Korean volcanic island with large, fresh SGD inputs[244]. Alternatively, high CO_2 from sediment organic matter decomposition[54,245,246] or H_2SO_4 flushed from disturbed acid sulfate soils[247,248] can acidify coastal surface waters and modify carbonate chemistry. Whether SGD is a localized driver or buffer of ocean acidification remains to be investigated and is likely to be site-specific.

Societal and management implications

Groundwater is essentially invisible, and its rate of discharge and nutrient chemistry considerably varies along coastlines. The pollution of coastal groundwater is usually investigated in a compartmentalized context, with limited attention to connected surface waters because it can take decades for coastal groundwater to deliver contaminants to surface waters[2,202,249]. However, there is strong and widespread evidence of the important role of SGD as a coastal nutrient source (FIGS 2,5,6), making it essential to determine how and when SGD-derived nutrients enter the ocean. Thus, decision-makers face two opposing risks: ignoring a potentially important nutrient pollution source or wasting monetary resources quantifying a potentially small source. Without a clear understanding of the role of SGD in ecological, economic and social contexts, management policies and water quality legislation cannot become effective[250].

SGD has not been considered in legislation and major initiatives such as the EU Water Framework Directive and the European Marine Strategy Framework Directive[251]. The EU Water Framework Directive aims to achieve "concentrations in the marine environment near background values for naturally occurring substances"[252]. The European Marine Strategy Framework Directive focuses strongly on terrestrial river inputs to the ocean[253] but missed the opportunity to address hidden fresh and saline SGD inputs. Indeed, groundwater governance decisions are often based on its role in terrestrial groundwater-dependent ecosystems, such as lakes and rivers[252]. Good chemical status for groundwater is defined from a terrestrial ecosystem perspective, overlooking coastal and marine processes such as saltwater intrusion and SGD.

In the United States, the Clean Water Act protects the quality of terrestrial fresh surface water bodies. The extent of protected water bodies has expanded and contracted with the judicial interpretation of what constitutes 'navigable waters' over the decades. Recently, the US Supreme Court relied on scientific evidence[254] to decide on the applicability of the Clean Water Act to groundwater pollution that reaches the ocean[255]. The case was based on a demonstration that wastewater effluent injection into a coastal aquifer would damage the nearby marine environment in Hawaii. This court ruling seems to be the first example (at least in the USA, and, perhaps, the world) where legislation has been used to protect a connected coastal surface water–groundwater system. It sets a precedent for new legislation and policies to acknowledge the critical role of groundwater in coastal water quality.

At the local scale, some measures have been introduced to link fresh SGD to coastal seawater pollution.

Table 1 | **A summary of key research topics that require further investigation in the field of submarine groundwater discharge**

Topic	Research question	Major obstacles and challenges	Research priorities	Key references
Fresh vs saline SGD	What are the local and global contributions of fresh vs saline SGD and new vs recycled nutrients?	Geochemical tracer investigations often quantify total SGD. Multiple techniques are required to separate fresh from saline SGD.	Combine tracers and other approaches to quantify both fresh and saline SGD. Integrate marine and terrestrial investigations. Adopt a nomenclature that better represents the different processes.	51,79,112
Spatial and temporal scales	What are the temporal and spatial scales represented by specific SGD estimates?	Models quantify specific driving forces, whereas geochemical tracers integrate multiple processes on timescales comparable to the tracer residence time.	Understand the role of spatio-temporal heterogeneity in regional-scale estimates to allow predictions in space and time.	31,34,56,120
Nutrient transformations	What biogeochemical processes control nutrient transformation in the subsurface?	Defining the nutrient endmember in SGD requires understanding of sources and pathways. Transformations are governed by dynamic hydrological and biogeochemical processes at multiple scales.	Identify how microbial communities drive nutrient cycling. Quantify the effect of subterranean estuaries in regional-scale land–ocean nutrient budgets.	145,148,266
Long-term observations and predictions	How will ongoing climate change, sea-level rise and land-use intensification modify SGD?	Poor quantitative understanding of drivers of SGD. No straightforward typological classification is available for both fresh and saline SGD. Case studies often represent snapshot estimates.	Make long-term observations. Enhance collaborations with climate change experts and modellers to estimate uncertainty and improve the compatibility between observations and predictions.	193,203,267
Spatial bias	Is our current knowledge of SGD biased owing to spatial gaps and site selection?	Ongoing focus on areas of known SGD, such as visible springs or locations with polluted groundwater. Poorly represented areas (such as South America, Africa and the poles).	Quantify SGD in poorly represented regions. Representative regional-scale quantification of SGD to understand occurrence, heterogeneity and/or patchiness.	66,67
Management	How can SGD be incorporated into water quality management plans?	Groundwater and surface water often seem disconnected. SGD perceived to be a highly specialized research niche.	Promote outreach activities and exchange knowledge on SGD with society and local/regional managers. Develop best-practice recommendations for management.	138,170,232
Biological effects	Is supply of nutrients via SGD beneficial or harmful to marine ecosystems?	SGD effects are complex and site-specific. Most investigations focus on individual species or small-scale organisms.	Include biota assessments in SGD studies. Explore effects of SGD from the base of food webs through the entire ecosystem. Use manipulative experiments to explore biological effects.	204,215,216
Uncertainties	What are the uncertainties associated with local and global SGD estimates?	Uncertainties of methods used to derive SGD are difficult to constrain and often not reported. Uncertainties linked to spatial or temporal integrations are unknown.	Report real uncertainties in SGD estimates, including errors in model conceptualization. Apply mathematical methods to express uncertainties based on unavertable limitations in the representation of SGD.	70,75

For example, the flow of groundwater from a large septic system in California (USA) has been managed to prevent pollution of popular swimming beaches[256] affected by groundwater-borne faecal contamination[257]. Engineering solutions have been attempted to reduce fresh SGD and secure onshore groundwater use. In particular, attempts to close karstic caves or tap submarine springs were made in the French Mediterranean coast[258]. In China's Bohai Sea, underground concrete dams were constructed to prevent connections between seawater and fresh groundwater, reducing SGD and seawater intrusion, and improving local freshwater availability[259].

SGD is relevant to a wide range of the United Nations Sustainable Development Goals. For example, SGD connects clearly to Goal 14 'Life Below Water; and Target 14.1 to reduce pollution in marine ecosystems. Hence, SGD-derived nutrient fluxes should be considered particularly when sensitive coastal ecosystems degrade[194] or during coastal development modifying groundwater–surface water connectivity, such as the construction of drains and canals[260]. Nutrient fluxes via SGD have been shown to be particularly high in urbanized areas in developing countries such as Indonesia[194], the Philippines[261] and China[172]. Because SGD can enhance primary productivity and fish abundance[229,230], it would also connect to Goal 2 'Zero Hunger' (Target 2.3), particularly in the context of regional-scale fisheries that are sometimes sustained by SGD-derived nutrient inputs[231]. SGD affects artisanal fisheries in small-island, tropical developing countries[262], where fresh SGD is also especially relevant[66,69]. Interventions like China's underground dams that are intended to increase drinking water availability also link SGD management to Goal 6's Target 6.4 to "ensure sustainable (water) withdrawals" and Target 6.6 to "protect and restore (fresh-) water-related ecosystems" that could exist around submarine springs[263]. Through sustaining marine ecosystems as well as releasing alkalinity and carbon dioxide to surface waters[264], SGD is relevant to Goal 13 'Climate Action'.

The cultural value of places is traditionally recognized in planning and legislation. In addition to apparent links to the Sustainable Development Goals, SGD also has local cultural relevance[232]. Many submarine springs have significant spiritual value and relate to local legends. For example, the magical Hawaiian sea turtle Kauila has been told to have dug local springs for its offspring. The Kaurna Aboriginal people in Australia tell of Tjilbruke, a magical spirit who wept at the beach and made the springs flow. In Bali, the Tanah Lot temple, which was built on a submarine spring to worship a magical being (Dang Hyang Nirartha) that moved the spring from land to the sea, attracts around 2 million visitors annually[232]. We do not know the abundance of such cases, since the cultural significance of SGD has not been documented in detail.

The connections to multiple Sustainable Development Goals and their cultural relevance illustrate the complexity with which SGD can be intertwined to livelihoods. These connections should justify the assimilation of SGD into coastal management plans, but assimilation has seldom occurred. A more integrated approach considering SGD, not only rivers, is needed to maximize coastal water quality management outcomes[250]. The slow movement of SGD relative to rivers implies that current contaminant and nutrient flows reflect past inputs, and management approaches must prepare for increasing loads in the decades to come[93].

Summary and outlook

Quantifying SGD-derived nutrient fluxes is challenging and involves nuanced assumptions and interpretations, and a wide range of skills in oceanography, hydrology and biogeochemistry. A disciplinary fragmentation, time lags in groundwater flows and slow management responses have created barriers to scientific progress and incorporation of SGD in coastal nutrient budgets. To further build the SGD field and understand how it contributes to coastal nutrient budgets, a number of major research questions remain open (TABLE 1).

Our growing knowledge in the last decade shows that considering SGD is clearly essential for developing coastal and marine nutrient budgets on local and global scales. About 60% of the reviewed investigations revealed that total SGD-derived nutrient fluxes exceed rivers on local, regional or global scales. However, SGD studies are generally site-specific and fixed in time, without predictive power. Climate and land-use change are expected to modify patterns of global water use, drive sea-level rise, push or pull seawater into coastal aquifers and modify the chemical composition of groundwater[93,203]. Combined, these changes are expected to modify fresh and saline SGD. A better understanding of SGD fluxes, drivers and pathways is essential for determining the carrying capacity of coastal seas and their response to increased anthropogenic pressures (TABLE 1). Nutrient budgets considering SGD are required for the effective interpretation of natural and anthropogenic sources, as well as creating management solutions in highly modified coastal systems.

Large investments have been made on the mitigation of coastal eutrophication and the protection of marine biodiversity. However, recent reductions in river and atmospheric nutrient inputs in developed countries have not been enough to reduce coastal eutrophication and related hypoxic events in key areas such as the Baltic Sea[7], the shelf off the Mississippi River[265] and the China coast[172]. As SGD fluxes, pathways and drivers are better understood, it will be possible to detect how changes in SGD relate to disturbances such as land-use change, habitat clearing and climate change.

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I.R.S. conceived the paper with input from all authors and wrote several passages. X.C. did most of the data compilation with support from all authors. A.L.L. and R.S. wrote most of the biological implications section. A.H.S. wrote about scales of SGD and made global maps. N.D. wrote about methods of SGD. N.M. and H.L. wrote most of the societal implications section. V.R. and J.T. wrote some of the river versus SGD and global distribution sections. H.-M.C. wrote some of the nitrogen speciation section. M.-C.H. and L.L. performed some of the data analysis. S.B. wrote about nitrogen cycling. All authors edited the manuscript and contributed to general discussions and literature reviews.

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